Satellite Imagery Proves Essential for Monitoring Erupting Aleutian Volcano

Mt. Cleveland is one of more than 40 active volcanoes in Alaska that is monitored by the Alaska Volcano Observatory (AVO). It is located on the western half of Chuginadak, a remote and uninhabited island in the east central Aleutians that lies 1526 km southwest of Anchorage. The closest inhabited community, Nikolski, is 75 km to the east on Umnak Island (Figure 1).

Mt. Cleveland erupted explosively on 19 February and on 11 and 19 March 2001. Because the volcano is not yet monitored with seismic, deformation, or other geophysical instruments, satellite imagery was the only effective tool for detecting and monitoring this activity. Eruption clouds and elevated surface temperatures were detected on multiple satellite data sets. The largest eruption was in February. This first eruption cloud and the subsequent wave of ash (Figure 1) that drifted across Alaska extended up to flight levels and prompted cancellation and re-routing of air traffic throughout the North Pacific region on 19 and 20 February.

AVO made observations during and after these three eruptions using National Oceanic and Atmospheric Administration (NOAA) satellite data that permitted effective monitoring and hazard mitigation, despite the fact that ground-based geophysical instruments were not available. The Mt. Cleveland event provides an important case study of eruption detection and plume tracking methods, characterization of the ash cloud, and weather pattern effects at a remote location.

Satellite Monitoring

Volcanoes in Alaska are monitored in real or near real-time using satellite [Schneider et al., 2000; Dean et al., 1998] or seismic techniques. Often, observers on the ground and pilots report anomalous activity. In the Alaska region, approximately half of the volcanoes are monitored using seismic techniques, and all surface temperatures and airborne plumes are monitored using satellite techniques.

Satellite systems routinely used by AVO for daily, real-time monitoring include the NOAA Advanced Very High Resolution Radiometer (AVHRR) and the Geostationary Operational Environmental Satellite (GOES). Both of these data sets include visible and thermal infrared wavelength images. AVHRR data, recorded from a polar orbiting satellite, has a 1.1 km spatial resolution at nadir. AVHRR records approximately 10 images of any one volcano every 24 hours due to overlapping data from successive orbits at high latitudes. These images are not collected at regular intervals, but instead tend to come in two batches a day over several hours. The frequency of coverage decreases for regions well to the east and west of the receiving station at Fairbanks.
Fig. 1. This time-sequential satellite image shows the position of the eruption cloud from Mt. Cleveland over a 3-day period, 19-21 February 2001. Each ash cloud was observed on a single GOES-10 satellite image recorded at a single time step. Thirteen images recorded at consecutive time-steps using the split-window technique were used to form this composite. The first image, 1615 UTC on 2/19/01, was taken approximately 2 hours after the initial eruption start time. Image noise has been removed for clarity. (Image created by K. Papp.)

The GOES satellite is located over the equator and records data every 0.25 to 0.5 hour, depending upon wavelength, with approximately 1 km (visible bands) and 4 km (thermal bands) spatial resolution at the equator. However, because of the GOES position, it looks obliquely at polar regions. Thus, its spatial resolution is approximately 4 km and 8 km, respectively, at the 60° N latitude of Mt. Cleveland. These data are only able to reveal intermediate to large eruption clouds or large, hot surfaces at this latitude.
Air Traffic has the largest Risk

The volcanoes in the North Pacific Region produce an average of one to two eruptions annually that result in ash clouds 9 km or higher, and some lesser forms of activity are detected in seismic and satellite data regularly. These volcanoes are remote, and surrounding regions are lightly populated. The gravest danger from these volcanoes is to local and global air traffic. Local communities depend on aircraft to provide daily supplies, and planes are often the only regularly scheduled mode of transportation to and from the communities. In addition, the North Pacific region is one of the busiest global air transportation corridors in the world, with approximately 200 passenger and cargo flights daily. These large jets fly at altitudes of 9-12 km, where ash is often located during eruptions. Volcanic ash can seriously damage the aircraft [Miller and Casadevall, 2000].

In the case of the 19 February eruption of Mt. Cleveland, a number of intrastate flights in western and southern Alaska were cancelled. Westbound and eastbound trans-Pacific flights were directed well north and south of Mt. Cleveland. On 20 February there was increased traffic on the more northerly Russian routes, presumably to avoid the projected track of the ash cloud that was drifting across Alaska. We are not aware of any damaging encounters reported to aviation authorities, although several pilots at locations well south and southeast of the volcano mentioned smelling sulfur. Except for local air traffic, the March eruptions caused relatively minor disruptions compared to the February event, due to the limited area affected by the ash cloud. The FAA restricted air traffic within 30 km of Mt. Cleveland through the end of May, due to concern for additional explosive events that may have been preceded by little or no warning.

The Mt. Cleveland Volcano

Mt. Cleveland is a distinctively conical, young stratovolcano, 1730 m high with steep slopes. At sea level the base of the cone is approximately 8 km across, suggesting a volcanic cone volume above sea level of about 29 km$^3$. The cone is completely undissected, suggesting that much of the exposed volcano is Holocene in age.

Mt. Cleveland has erupted 11 times since 1893 [Miller et al., 1998]. These eruptions have been characterized by short-lived explosive bursts of ash that are at times accompanied by lava fountaining and lava flows. Prior to the 2001 eruption, the most recent activity was a short-lived ash plume that rose to an altitude of approximately 10 km on 25 May 1994 [Neal et al., 1995].

As previously noted, Mt. Cleveland is not yet monitored with seismic or other geophysical instruments, and no geologic mapping or chemical analyses of lava and pyroclastic deposits presently exist. Aerial photographs show many young, leveed lava flows and debris fans with varying types of vegetative cover forming essentially a continuous apron around the cone.
The 2001 Eruption Chronology of Events

The first indication to AVO of activity at Mt. Cleveland was the 19 February eruption. However, after the eruption, AVO received reports indicating that precursory activity had taken place. Most graphic was a photograph taken on 2 February by a pilot flying by the volcano showing a dark, lobate deposit on the snow-covered southwest flank and robust steaming from the summit crater (Figure 2). During this same period, residents of Nikolski observed steaming at the summit and snowmelt on the flanks of the cone.

On 19 February, Mt. Cleveland erupted explosively at approximately 1430 UT. Pilot reports indicate that the altitude of the plume increased with time from 7.5 km a few hours after the start of the eruption, and up to 12 km eight hours later. The eruption cloud and a thermal anomaly were detected on AVHRR satellite data at 1655 UTC. The plume was complex and extended in two directions, 40 km northwest and 60 km southeast of the volcano. The northwest portion of the cloud was at 8 km and the southeast portion was at 5 km altitude based on cloud/atmospheric temperature correlations. Also, wind field data indicated a shear at approximately 6 km, which caused the bi-directional flow of the plume. The southeast portion of the cloud had a strong ash signal that was detected using the split-window technique (subtraction of two thermal infrared bands of data, AVHRR B4 minus B5; Prata [1989]), but the northwest portion was not detected at this time due to its high opacity. Satellite analysis suggests that ash production was more or less continuous for approximately 8 hours.
Figure 3. Landsat 7 Enhanced Thematic Mapper satellite image of the 11 March eruption of Mt. Cleveland. The image shows a hot deposit on the west flank of the volcano (yellow and orange), the plume blowing to the NE and snow (blue) on the south and SE flanks of the volcano. The image is a color composite using the infrared bands in the following channels: B - 7 = red, B - 5 = green, and B - 4 = blue.
The volcano erupted into an atmospheric deformation zone formed by a low-pressure system to the south and east, and a front moving to the north. As a result the ash cloud became an elongated arc moving to the northeast over the Alaska Peninsula and across the Alaska mainland. It was easily detected for 48 hours on time sequential GOES data processed using the split-window technique (Figure 1). By 21 February (0300 UT), 35 hours after the eruption, the ash cloud was over 1000 km long and extended from Cook Inlet, Alaska, to Chukotsk Peninsula, Russia. Eventually this long, arcing cloud split into three segments that drifted north over the Arctic Ocean, over Fairbanks near the center of the state, and south into the Gulf of Alaska. After 21 February, 1930 UT, the Fairbanks and Gulf of Alaska segments were pulled into a low pressure system in the southern Gulf of Alaska and became too diffuse or masked by weather clouds to be detected in the GOES data.

Mt. Cleveland erupted again on 11 March (Figure 3). This explosive eruption lasted 3 hours (1400 to 1700 UT) based on satellite observations, with an estimated cloud height of 8 km. AVHRR split-window satellite data showed ash in two regions 250 km and 400 km east of Mt. Cleveland. These clouds drifted northeast over 1,000 km until they fell below detection thresholds near Kodiak Island about 42 hours later on 13 March.

The 19 March eruption lasted up to 6 hours (2330-0530 UT) with an estimated cloud height of up to 9 km according to the National Weather Service. AVHRR data at 0330 UTC showed a fan-shaped volcanic cloud with the apex at the volcano and facing southeast. The plume was still attached at this time. A strong ash signal was detected in the northern leg of the cloud in the AVHRR split-window data. At the time of the image the cloud extended approximately 200 km from the volcano. South- and east-drifting ash clouds were detected in GOES split-window images for about 9 hours. An observer in Nikolski reported a strong haze, but no ash fall was observed in the town. Throughout March and April, elevated surface temperatures and low altitude ash clouds were periodically observed on satellite data. Ground and air observers noticed minor ash clouds over volcano during the same period.

Elevated Surface Temperatures

Elevated surface temperatures have been observed at volcanoes prior to explosive eruptions, and hence, they may be useful as precursory signals [Dehn et al., 2000]. Post-eruption analysis of AVHRR data at 1620 and 1728 UTC revealed a possible increase in surface temperature on 4 February at the summit of Mt. Cleveland. This weak signal in nighttime AVHRR Band 3 data (3.55-3.93 um), was 11-12 °C above background, which can be difficult to detect during routine monitoring. The pilot report 2 days earlier of a fresh deposit on the flank of the volcano (Figure 2) added some credence to the possible elevated temperature observation. No other increases in surface temperatures were observed in these data until the 19 February eruption. The lack of additional observed thermal anomalies during this period can be attributed to extensive cloud cover. If the activity were low-level strombolian, which is episodic, then the satellite pass would have to coincide with an event to record a signal. This, combined with the cloud cover, would have a low probability of recording many thermal anomalies in this situation.
A large thermal anomaly at the summit was detected in AVHRR data at the time of the first explosive eruption on 19 February. Within a few days, the thermal anomaly extended down the west flank of the volcano to the coast, forming a delta (Figure 4). Surface temperature and size of the thermal anomaly decreased and were not observed after approximately 1 week.

Thermal anomalies were observed during or shortly after the second and third explosive eruptions on 11 and 19 March. A Landsat 7 satellite image (Figure 3), which has a 30-m spatial resolution, recorded the 11 March eruption, also showing a narrow thermal anomaly extending down the west flank of the volcano from the summit to its base. For over a month following this eruption, thermal anomalies were observed almost daily in the AVHRR data. On 12 March, elevated temperatures were detected on AVHRR data in two non-adjacent areas: at the summit and down the west flank. The size and temperature of thermal anomalies decreased within a few days of these eruptions, ruling out a second vent at the source.

Field observations in September 2001 revealed the source of the thermal anomalies detected on the satellite data as an a a lava flow and volcanoclastic debris-flow deposits on the west flank of the volcano.

**Seismic Observations**

The nearest permanent seismometers to Mt. Cleveland are located ~230 km east, at Makushin volcano. These sensors recorded probable volcanic tremor during each of the three eruptions, as did individual seismometers from other networks located even farther east, such as one at Akutan volcano, ~300 km away, and Westdahl volcano, ~400 km away. The signal appeared on spectrograms as a narrow band, 0.5-4 Hz, strongest at 2 Hz, on stations with 1-Hz vertical component, and at slightly higher frequencies of ~6 Hz on the one station with a 2-Hz three-component seismometer. The tremor exceeded 8 hours for the 19 February and 11 March eruptions. The 19 March eruption lasted for only 2 hours, but began several hours after the first ash cloud was detected on satellite data. Tremor was intermittent rather than continuous in all three cases. Amplitudes were converted to reduced displacement, a normalized measure of tremor, and found to be as high as 27 cm$^2$---a value consistent with eruptions elsewhere of similar size (Volcanic Explosivity Index =3 based on plume height, *McNutt* [1996]).

**Ash Fall**

Despite the extensive area traversed by the February plume, ash fall was observed only at Nikolski over a period of approximately 5 hours on 19 February. Residents reported that the ash fall occurred under a hazy sky and consisted of a very light dusting of fine-grained material. School children in Nikolski were given paper masks to wear home and residents were advised to stay indoors. No injuries or health impacts have been reported; one resident noted that breathing outside without a mask made you want to cough.
Figure 4. The thermal anomaly observed on AVHRR data on 22 February (top) is draped over a digital elevation model. The hot ground extends from the summit to the ocean. An aerial photograph (bottom) recorded a day earlier than the satellite image shows the source of the hot ground is an a‘a and hot clastic flow in a narrow channel ending at a newly formed delta. Steam can also be seen blowing off of the deposits. Each pixel in the top image is approximately 1x1 km. [Photo by Burke Mees]

A sample from Nikolski shows that the ash is composed of glass shards, crystals, and lithics. The median grain size is 54 [NOTE: Insert Greek mu]m, well-sorted, and contains 70.4% fines (ash < 63 [NOTE: Insert Greek mu]m). Glass shards made up more than 90% of the deposit. The glass is dacitic and has a magmatic morphology rather than phreatomagmatic. Crystals are plagioclase (dominant phase), orthopyroxene, clinopyroxene, and Ti-magnetite. Lithics are mainly vesicular scoria (P Izbekov, B. Browne, J. Gardner, unpublished data, 2001).
Tracking Model Predictions

The Puff dispersion model [Searcy et al., 1998] was used to predict the shape and position of the Mt. Cleveland eruption clouds to assist in the analysis of satellite data, primarily in the area of estimating cloud height based on wind shear. This and other dispersion models rely on three-dimensional gridded wind fields for regional or global predictions. The accuracy of these models is controlled by the accuracy of the forecast wind data and evaluated by comparing the simulations to satellite images of eruption clouds [Searcy et al., 1998]. Satellite data are critical to simulations, since the type and accuracy of input information and wind fields vary with each eruption and will affect the results.

Puff accurately predicted the first day’s arc of ash drifting to the northeast across Alaska from the 19 February eruption as seen on the GOES satellite images (Figure 1). It predicted the expansion of the arc of ash to the northwest and southeast that was caused by a wind shear at approximately 5 km altitude during the first few hours of the eruption. Puff correctly predicted the time of ash fall over Nikolski. After the first 10 hours of the eruption, the simulation showed that the arc of ash would continue to drift to the northeast and that the length of the arc would continue to expand to the northwest and southeast. The model gave no indication that the ash cloud would segment into three parts as observed in the GOES data on the second day; however, that segmentation may be the result of the inherent ash detection limits of the split-window technique.

For the 11 March eruption, Puff predicted a v-shaped cloud with its apex at Mt. Cleveland and open to the northeast. The shape of this cloud was due to a wind shear at approximately 8 km altitude with the northern leg of the simulation above 8 km and the southern leg below 8 km. Satellite data detected only the southern leg of the plume, indicating that plume height was below 8 km. Satellite-derived plume temperatures, when compared to atmosphere temperature profiles, indicated 7 km altitude, which is close to the model prediction. Also, the satellite data showed the plume drifting to the northeast, as predicted by Puff.

For the 19 March eruption, Puff predicted that the plume would initially drift southeast at all elevations and would turn south approximately 5 hrs into the eruption. The Puff trajectory predictions in general agree with the AVHRR and GOES satellite observations, but the model failed to predict the east-southeast portion of the ash cloud. There were differences in the accuracy of the 19 March predictions depending upon the wind fields used.

Automated Ash Detection/Alarm

In response to the Mt. Cleveland eruption, an automated ash detection algorithm based on the split-window technique was developed to augment the manual analyses conducted by AVO staff. The alarm utilizes GOES data that is automatically received every 15 minutes by AVO. The three major ash plumes at Cleveland were easily observed in GOES data by using the split-window algorithm. The simple alarm automatically subsections a 40 x 40 km area of the GOES data centered on Mt. Cleveland, filters the data to reduce noise, and subtracts the two long, thermal infrared bands. It then alerts AVO staff via beeper and e-mail if a single pixel in one image has a split-window signal less than -1.4.
Though preliminary, this empirical threshold was able to detect ash in the first image in which it was visible to an analyst, and it produced very few false alarms. The threshold is critical for balancing the actual ash event detections with false alarms. Because the threshold has derived from empirical observations, it should be noted that the value used for the Cleveland events would not necessarily have widespread applicability worldwide. Although it is still under development, the new alarm will be implemented whenever a new volcanic crisis arises in the region, hopefully allowing unexpected significant ash emissions to be automatically detected within approximately 30 min of their occurrence. Though the split-window technique does not detect volcanic ash in all instances [Simpson et al., 2000], most ash plumes in this region have shown a detectable signal in satellite imagery during the course of their development.

Satellite remote sensing was a very effective tool for detecting and monitoring the recent eruptions of Mt. Cleveland, and it was the only source of information available for hazard mitigation. The event provided an important case study of eruption detection and plume tracking methods, characteristics of the ash cloud, and weather pattern effects at a remote location.

Acknowledgments

This work was supported by the U.S. Geological Survey as part of the Volcano Hazards Program, through the Alaska Volcano Observatory, a collaborative effort of the USGS, University of Alaska Fairbanks, and the Alaska Geological and Geophysical Surveys. Data, information, and observations used in this article were compiled during the Cleveland eruption by all of the AVO staff in Fairbanks and Anchorage. Pilots Burke Mees and Dean Cully and C. Cahill provided many photographs of the eruption. Diana McGlashan, Nikolski Clinic, collected the ash sample.

Authors

Kenneson Dean, Jonathan Dehn, Steve McNutt, Christina Neal, Richard Moore, and Dave Schneider

For more information, contact K. Dean, Geophysical Institute, University of Alaska Fairbanks, P.O. Box 757320, Fairbanks, Alaska, USA; E-mail: ken.dean@gi.alaska.edu

References


