# A Prototype Global Volcano Surveillance System Monitoring Seismic Activity and Tilt

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## Abstract

The Earth Resources Technology Satellite makes it feasible for the first time to monitor the level of activity at widely separated volcanoes and to relay these data almost instantaneously to one central office. This capability opens a new era in volcanology where the hundreds of normally quiescent but potentially dangerous volcanoes near populated regions around the world can be economically and reliably monitored. A prototype global volcano surveillance system has been established beginning in the fall of 1972 with the help of local scientists on 15 volcanoes in Alaska, Hawaii, Washington, California, Iceland, Guatemala, El Salvador, and Nicaragua. Data on earthquake activity and ground tilt are received 6 to 10 times daily in Menlo Park, California, within 90 minutes of transmission from the sites. Seismic event counters were installed at 19 locations with biaxial borehole tiltmeters with 1 microradian sensitivity installed at seven sites. Direct comparison of seismic events that are counted with records from nearby seismic stations show the event counters work quite reliably. An order of magnitude increase in seismic events was observed prior to the eruption of Volcán Fuego in Guatemala in February, 1973. Significant changes in tilt were observed on volcanoes Kilauea, Fuego, and Paçaya. This study demonstrates the technological and economic feasibility of utilizing such a volcano surveillance system throughout the world.

## Introduction

The Earth Resources Technology Satellite (ERTS) has opened a new era in volcanology in which the hundreds of normally quiescent but potentially dangerous volcanoes near populated regions around the world can be economically and reliably monitored daily to warn when any one volcano is becoming active again. In the past only a few volcanoes have been monitored for long periods of time because of the high cost of building and staffing volcano observatories. Yet it is known from data collected in this century that while perceptible signs of pending eruptions may occur only minutes to days in advance, measurable signs may be detected days, weeks, months, or even years before a major eruption. Although prediction of specific eruptions is still an elusive goal, early warning of increased activity at quiescent volcanoes is now a distinct possibility. Such early warnings

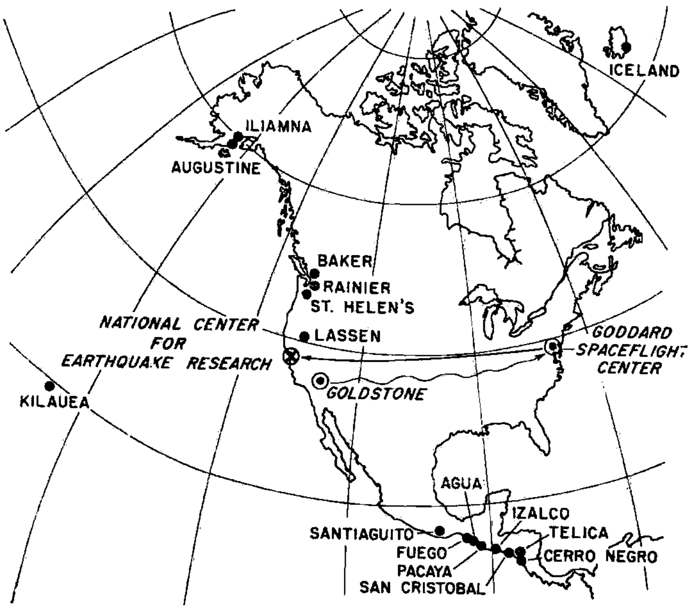


FIG. 1 - Volcanoes monitored in this study. Seismic event counters were placed at all volcanic sites. Tiltmeters were placed on Lassen, Kilauea, Fuego, and Pacaya.

can be used to reduce volcanic hazards and to focus research aimed at volcano prediction on those volcanoes throughout the world that are most likely to erupt at any given time.

A prototype volcano surveillance system was established during the latter part of 1972 and early 1973 on 15 volcanoes in Alaska, Hawaii, Washington, California, Iceland, Guatemala, El Salvador, and Nicaragua (Fig. 1, Table 1). Nineteen seismic detectors that count four different sizes of earthquakes and six biaxial, borehole tiltmeters that measure ground tilt with a resolution of 1 microradian have been installed. Data from these instruments are relayed through the ERTS-1

Table 1 - Event counter (E), tiltmeter (T), and high gain short period (S) seismometer station locations.

| State or Country | Station Name | Latitude N | Longitude W | Elevation Meters | Instruments Installed | Date Installed |
|---|---|---|---|---|---|---|
| Alaska | Iliamna | 60° 10.92′ | 152° 10.92′ | 549 | E | 9-30-72 |
| | Augustine | 59° 22.55′ | 153° 22.25′ | 106 | E | 9-24-72 |
| California | Lassen | 40° 28.52′ | 121° 30.50′ | 2658 | E, T, S | 9-30 to 10-13-73 |
| El Salvador | Izalco | 13° 49.25′ | 89° 37.80′ | 1600 | E, S | 3- 7-73 |
| Guatemala | Agua | 14° 26.55′ | 90° 41.55′ | 1600 | E | 2-13-73 |
| | Buena Vista | 14° 40.00′ | 90° 38.45′ | 2256 | E, S | 2-21-73 |
| | Fuego | 14° 26.65′ | 90° 50.62′ | 1402 | E, T, S | 2-17-73 |
| | Los Dolores | 14° 20.61′ | 90° 34.48′ | 1345 | T | 11-29-73 |
| | Pacaya | 14° 23.05′ | 90° 37.35′ | 1661 | T | 3-22-73 |
| | * Santiaguito 1 | 14° 46.60′ | 91° 33.75′ | 1676 | E, S | 2-15-73 |
| | San Carlos | 14° 23.85′ | 90° 33.65′ | 2713 | E | 3-18-73 |
| | Santiaguito 2 | 14° 42.59′ | 91° 34.51′ | 1410 | E | 11-21-73 |
| Iceland | | 64° 01.30′ | 21° 51.00′ | — | E | 12-19-72 |
| Hawaii | † Ahua | 19° 23.75′ | 155° 16.53′ | 1070 | E, T | 4- 4-73 |
| | Northpit | 19° 20.20′ | 155° 17.00′ | 1115 | E | 3-10-73 |
| | † Summer Camp | 19° 24.6′ | 155° 15.6′ | 1143 | T | 12- 3-72 |
| | † Uwekahuna | 19° 25.40′ | 155° 17.60′ | 1242 | T | 12- 7-72 |
| Nicaragua | Cerro Negro | 12° 31.35′ | 86° 42.08′ | 351 | E, S | 4- 3-73 |
| | Mina Limon | 12° 45.95′ | 86° 44.18′ | 299 | E, S | 4- 4-73 |
| | San Cristobal | 12° 40.88′ | 87° 01.43′ | 750 | E, S | 4- 2-73 |
| | Telica | 12° 36.20′ | 86° 51.55′ | 61 | E | 8-11-73 |
| Washington | Mt. Baker | 48° 47.00′ | 121° 54.20′ | 1676 | E, S | 10- 9-72 |
| | Mt. Rainier | 47° 56.49′ | 121° 40.38′ | 1890 | E, S | 10-11-72 |
| | Mt. St. Helens | 46° 11.58′ | 122° 14.20′ | 1423 | E, S | 10-12-72 |

* Santiaguito 1 discontinued - 10-20-73.
† 3 tiltmeters are connected to the analog input of one transmitter at Uwekahuna.

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satellite and through a teletype link to the U. S. Geological Survey Office in Menlo Park for rapid analysis.

Earthquakes and tilt of the ground are monitored because these are two phenomena that have been observed most consistently to change prior to and during volcanic eruptions. For hundreds of years strong earthquakes have typically been felt just prior to major eruptions (*e.g.* HARLOW, 1971; SHIMOZURI, 1971). Since the advent of sensitive seismometers, orders of magnitude increases in the numbers of earthquakes have been observed hours, days, and months prior to eruptions (*e.g.* OMORI, 1914-1922; GORSHKOV, 1960; MINAKAMI, 1960; ADAMS and DIBBLE, 1967; SHIMOZURU *et al.*, 1969). All earthquake swarms that occur near volcanoes are not associated with eruptions so that such increases in seismic activity cannot be used to predict specific eruptions. Nevertheless, the swarms do provide a reliable indication of the potential increase in volcanic activity in a given region. Local tilts of the ground of up to 1000 microradians are also typically related to volcanic eruptions (OMORI, 1914-1922; OMOTE, 1942; MINAKAMI, 1950; DECKER and KINOSHITA, 1971). While continuous measurements of tilt are rare, they typically show (*e.g.* MINAKAMI, 1942; EATON and MURATA, 1960) inflation of the volcano over a relatively long period of time prior to an eruption and rapid deflation during an eruption. Other types of measurements of fumarole temperature, pressure, and gas composition (*e.g.* NOGUCHI and KAMIYA, 1963; MENIAYLOV and NIKITINA, 1967; STOIBER and ROSE, 1970; MOXHAM, 1971; TAZIEFF, 1971; and TONANI, 1971), and of gravitational, magnetic, or electric fields (*e.g.* YOKOYAMA, 1971; JOHNSTON and STACEY, 1969) appear to be of potential application in the future but thus far have not been extensively developed or observed.

This initial experiment shows that for the first time it is both technologically and economically feasible to build a global volcano surveillance system because of the advent of inexpensive satellite telemetry. Experience during this project demonstrates the feasibility of building inexpensive, low power, reliable instruments for such a system that can be installed in remote locations and can be expected to run unattended for a few years. Several details in the design and deployment of appropriate low-power, inexpensive, and reliable instruments still need to be worked out.

Comparison of data from these new earthquake counters with data from nearby standard seismometers shows that the counters do normally indicate the level of seismic activity. During periods of high seismic background noise, there may be a significant number of spurious counts, but the existence and duration of such noisy periods are reliably indicated by data sent by the earthquake counters. The one eruption to occur to date, for which data were recovered via satellite, was on Volcán Fuego in Guatemala and was preceded several days by an abnormally large swarm of earthquakes. An apparent inflation of Volcán Fuego was observed in the six months after the eruption. In Hawaii, in addition to an increase in microearthquakes, recordings from three tiltmeters showed large tilt changes as a result of a rift eruption on May 5, 1973.

The design and response of this prototype global volcano surveillance system are summarized briefly in this paper together with an evaluation of the potential use of this system. These topics are described in considerable detail in a report by WARD, *et al.*, 1974.

## The ERTS Data Collection System

The Earth Resources Technology Satellite (ERTS) is an experimental satellite launched by the National Aeronautics and Space Administration (NASA) on July 23, 1972. It travels in a polar orbit with a semi-major axis of 7286 km, circles the earth in 1.7 hours, and retraces the same flight path every 18 days. The satellite contains in addition to several cameras, a radio relay system that receives and instantaneously relays data from small transmitters located on the ground and within sight of the satellite at any given time. These data are then received at tracking stations in either Goldstone, California or Greenbelt, Maryland if the satellite is visible from one of these sites at that time. The data are relayed by telephone lines to Goddard Spaceflight Center in Maryland and recorded. Within 90 minutes the data are processed and relayed by teletype to different users. Data are normally received from each remote site that is within 40 degrees of a tracking station three to five times during a 2-hour period every 12 hours.

The transmitters for sending data to the satellite were provided by NASA (1972). Each transmitter accepts 64 digital bits in serial or parallel format or accepts 8 analog voltages (0 to + 5 volts) that it converts to 8-bit digital words. In this study the seismic event counters are interfaced to the serial digital input. The tiltmeters are connected to the analog inputs. A digital controller in the transmitter adds to the data a 15-bit preamble, a 12-bit address code that is unique to each transmitter, and 4 bits runout. These 95 bits are convolutionally encoded, formatted to a nonreturn-to-zero level, and converted to a biphase format. This formatting provides a redundancy in the data that can be used to detect transmission errors. This signal is then transmitted in a 38 millisecond burst at a frequency of 401.55 MHz and at a minium power of 5 watts. The transmission rate can be set to once every 90 or 180 seconds and the average power consumption is 0.085 watts at 24 volts d.c. The transmitter weighs about 7 kg (Fig. 2).

FIG. 2 - Demonstration set-up of transmitter for sending data to the satellite (left), multi-level seismic counter (center), and one year's supply of batteries (right). Except for geophone (left, front) and transmitter antenna (not shown), components are placed in a metal box for transportation and semi-permanent field installation.

A crossed dipole antenna with a ground plane that is 1.2 m in diameter was provided with each transmitter. During the latter half of 1973, a more compact helical antenna, 7 cm in diameter and 28 cm high, was installed at sites in Washington and California where ice and snow loading are a problem.

Analysis of over 72,000 messages relayed through the satellite for this project shows that up to 8 % of the messages from the more distant transmitters contain trasmission errors, but that all such errors were properly identified by the system as a result of the redundancy used in the data encoding. Thus the satellite does relay the data reliably.

A data collection system such as that used on the ERTS-1 Satellite provides a relatively low cost method of collecting data from remote sites around the world. It would cost on the order of $ 3.5 million to build and launch a data collection satellite and build and operate four ground receiving stations around the world for the expected 5-year life of the satellite (E. PAINTER, oral comunications, 1973). It is reasonable that such an operational satellite could relay data from 10,000 ground stations monitoring volcanoes, stream flow, rainfall, pollution, and many other phenomena for many different agencies. For these purposes data from any one site could be relayed for less than $ 100 per year. This cost could be substantially reduced if the satellite were launched « piggy-back » with commercial or military satellites. Two satellites might be launched 180 degrees out of phase to provide reliable coverage every 6 hours.

An alternative system could utilize a stationary satellite that could provide data at any regular interval or at any time. This type of satellite would cost about $ 12 million to build, launch, and operate, and several satellites would be needed to cover the volcanic zones in the world. Thus such a system is not as economical as a polar orbiting satellite unless there is a wide demand for its use.

## Design of the Tiltmeters

The borehole tiltmeter used in the surveillance program to measure earth tilt is a bull's-eye level bubble whose electro-chemical liquid is an active part of a resistance bridge forming a two-axis level detector (COOPER, 1970). The bridge is excited by a 3 KHz square wave, and the resultant signal is demodulated to give two electrical outputs that are a function of rotations about two orthogonal horizontal axes. The level bubble is housed in a 5-cm diameter stainless steel tube 1 m long for borehole emplacement and is wired to external electronics by cables contained in flexible conduit, thus allowing the bubble sensor to be isolated in the most temperature-stable part of the site. Stability of the tiltmeter was tested by operating 8 meters on a single base (KOHLENBERGER, *et al.*, 1973), by operating one meter hanging by a thin wire (JOHNSTON, 1974), and by operating one meter in a tub of sand next to a mercury-tube meter in San Francisco that had operated reliably for six years. All tests show that the meter has a drift of less than 0.6 microradians per month with a 95 % confidence level.

Installations in Hawaii and Guatemala consist of a pit 1 m in diameter and 2 m deep, cased with steel culvert and covered with a steel lid. From the bottom of this pit, a 14-cm hole is bored down another 2 m. In this hole is placed a 10-cm pipe sealed at the lower end and packed in place with clean fine sand or with local material that is sufficiently dry and easily packed. The tiltmeter sensor is placed in this pipe and packed with fine (80-mesh), pure silica sand. During emplacement of the tiltmeter, the X and Y outputs are observed on an oscilloscope and the meter moved to a level position. After mechanical zeroing, the tiltmeter sensor is completely buried in sand, and the 10-cm pipe filled to the top. The tiltmeter electronics are placed on a shelf or low table in the pit. In some installations batteries, power supply, and (where used) analog telemetry equipment also occupy the same pit. The satellite transmitter and batteries are typically placed in a steel box nearby. This installation technique was developed over several years of trial and error and has proved quite suitable (ALLEN, 1972; ALLEN, *et al.*, 1973). The surface material at the various sites include, in Hawaii, pumice from the 1959 eruption as well as older weathered ash at other sites and, in Guatemala, lightly weathered ash with a low clay content.

At Lassen Peak, a 10-cm diameter hole was drilled 1.5 m into dacite. The tiltmeter was placed in the hole and packed with sand as described in the previous paragraph. The hole was then capped with wax. The tiltmeter electronics box was placed on the surface a few meters away with cables leading to batteries and the satellite transmitter.

## Results from the Tiltmeters

In late 1972 three level-bubble tiltmeters were placed around Kilauea Caldera in Hawaii. The data were telemetered via cables to the Hawaiian Volcano Observatory where they were recorded and also connected to one satellite transmitter. These tiltmeters generally operated reliably but were damaged several times by lightning that apparently induced high electric currents in the long cables. This problem was remedied by using a light emitting diode and photo-transistor to isolate electrically the tiltmeter and electronics in the ground from the long cables.

The record from the east-west component of the level-bubble tiltmeter near Uwekahuna vault in Hawaii compared with simultaneous records from a mercury-tube tiltmeter and a water-tube tiltmeter operated in the vault from December 1972 to February 1973 is shown in Fig. 3. During this 3-month period there was almost no tilt activity at Kilauea, and data from all three instruments agree within a few microradians. The rather noisy record from the water-tube tiltmeter reflects the relatively low consistency of readings to be expected from this type of instrument.

The record of both components of tilt at the Summer Camp site (Fig. 3), before the instrument was damaged by lightning on May 28, shows no appreciable change in tilt until the volcano began deflating on May 5, only three hours before an eruption began about 7 km to the southeast at Pauahi Crater. There was no noticeable change in tilt response to the more than 50 cm of rain that fell in March.

The detailed tilt response of the level-bubble tiltmeters at Summer Camp, Uwekahuna, and Ahua to the collapse of the summit of Kilauea on May 5, 1973, are shown in Fig. 3 At this time only the Summer Camp tiltmeter was fully operational. The Uwekahuna and Ahua meters had excessive long term drift (about 20 microradians per month) after they were damaged by lightning in February. These meters, however, provided coherent short-term records. The instataneous

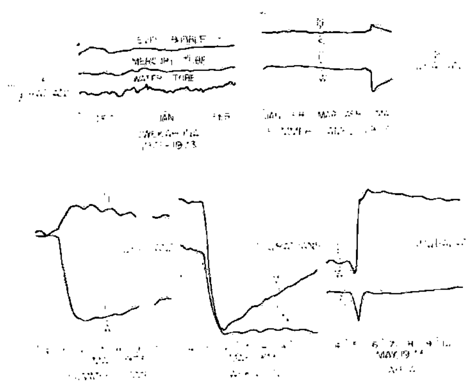

Fig. 3 - Typical data from three tiltmeters located around the central caldera of Kilauea Volcano, including a collapse of the caldera area on May 5, 1973. The data in the upper left, separated for clarity, shows a comparison of the new level bubble tiltmeter with two other types of tiltmeters operated in Hawaii for several years.

tilt vectors from the three instruments are superimposed on a map of the summit area in Fig. 4. The data from Summer Camp and Uwekahuna show collapse toward the center of Kilauea Caldera, whereas the data from Ahua suggest collapse into the caldera followed by collapse toward the eruptive center at Pauahi Crater and Heake Crater. A comparison of these data with a chronology of the eruption provided by the staff of the Hawaiian Volcano Observatory shows a close correlation. The eruption of lava began in Pauahi at about 1025 hrs and ended by 1200 hrs with all but about 20,000 m³ of lava draining back down the vent by 1230 hrs. Note the tilt at Ahua at this point was inward toward Kilauea Caldera and Halemaumau. At about 1255 hrs a new lava outbreak was spotted near Heake Crater. Lava erupted from many fissures, increasing until about 1500 hrs and ending about 1700 hrs, leaving about 440,000 m³ of new lava in Heake Crater and about 500,000 m³ of new lava flows outside the crater. During this phase of the eruption, the tiltmeter at Ahua showed rapid tilt down toward the eruptive center until about 2000 hrs when the tilt rate decreased. The tilt continued on for at least another 16 hours in the same direction. These three tiltmeters showed more details of a summit collapse than previously available.

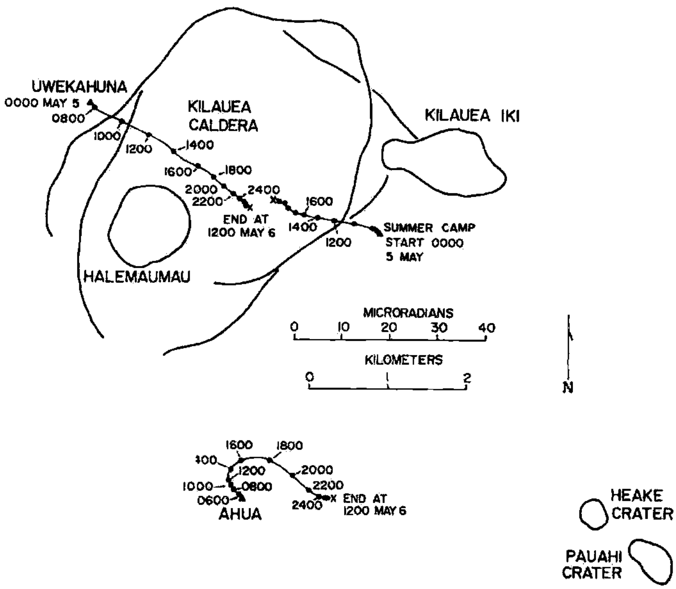


FIG. 4 - Cumulative changes in tilt (plotted vertically) for the three tiltmeter sites shown as triangles. Tilt vectors are plotted for every two hour period during the May 5-6, 1973, eruption of Kilauea. The eruption took place in and around Heake and Pauahi Craters.

Volcán Fuego in Guatemala erupted in mid-February about two months before the tiltmeter was installed and has since been very quiet. Tilt data from April 9, 1973 (Fig. 5) suggest that Volcán Fuego swelled about 35 microradians by early August and has remained quiet since that time. Although it is still premature to conclude the significance of this swelling, it might be interpreted as evidence that Fuego is primed for more eruptive activity since it has swollen rather than subsided.

Ground tilts of up to 150 microradians were recorded on Volcán Pacaya in Guatemala between July and December, 1973. The flank of the volcano appeared to tilt outward 150 microradians and tilt back nearly the same amount, all during a period between active extrusions of lava. The magnitude of the tilt seems large and may be explained by the placement of the meter in a region of block-faulting on the west flank of the volcano. A second tiltmeter has been installed on the southeast side of Pacaya to examine the apparent tilting in more detail.

Tilt data recorded at Lassen Peak in California during the winter of 1972-1973 show significant changes in tilt (Fig. 6). The authors be-

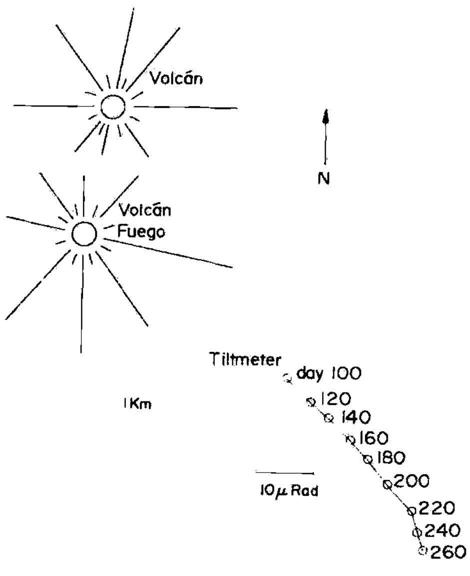


FIG. 5 - Cumulative changes in tilt plotted by vectors at 20-day intervals for a tiltmeter installed about two months after the eruption began, February 22, 1973, at Volcán Fuego in Gatemala. Since April 9, 1973, day 100, the volcano appears to have gradually inflated.

lieve the tilts measured are related to freezing and thawing of water in the joints in the rock outcrop containing the tiltmeter and to a leak in the case of the tiltmeter in the spring. If this interpretation is correct, then it appears, as suggested by KING (1971), that shallow installations of tiltmeters in volcanic ash or sand are probably better than shallow installations in solid rock.

These results show that the portable, easy-to-install tiltmeters, with a sensitivity of 1 microradian, are working quite stably at several sites in the field, that they are recording real tilts associated with volcanic activity, and that they are not affected by heavy local rainfall, examined in detail in Hawaii and Guatemala (WARD, *et al.*, 1974). Continued recording for a much longer period of time is needed before the value of these tilt data in providing early warning of eruptions can be clearly calculated. At this point the most important observation is that large changes in tilt from 30 to possibly 150 microradians have been observed on three volcanoes occurring before, during, and after eruptive periods, whereas no significant changes in tilt, except

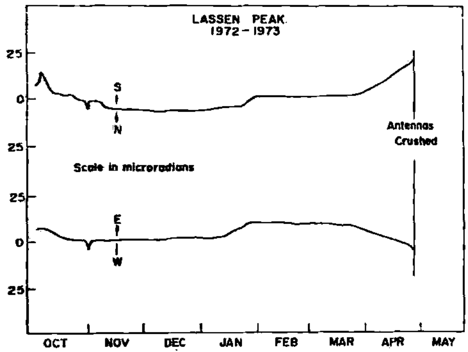


FIG. 6 - Recorded tilt of ground on Lassen Peak through the winter of 1972-73. Melting snow crushed the transmitter antenna in late April, 1973.

those apparently related to freezing and thawing, has been noted on Lassen Peak, the one volcano where tilt is being monitored that has had no observed volcanic activity for more than 50 years.

## Design of the Seismic Event Counters

Since the satellite relay system can only transmit 64 digital bits of data each 12 hours and seismic data are normally gathered at a rate of about 20 million digital bits during the same time, it is necessary to process the seismic data at each remote site. The data that have been observed most often to change prior to volcanic eruptions are simply the numbers of small earthquakes of different sizes. These numbers typically change by orders of magnitude before eruptions. Some experience was developed from automatic earthquake counters built by PERRET (1937) and DECKER (1968). Their experience plus experience from prototype seismic event counters built by several different individuals and companies (unpublished results from T. Matumoto, J. Unger, Kinemetrics, Inc., Systron-Donner, and Bendix) has been used to develop a significantly new design in seismic event counters for this project.

The seismic event counter system (Fig. 7) utilizes a geophone, which produces a voltage proportional to ground velocity. The geophone was selected to have a natural frequency of 4.5 Hz because of the high-frequency characteristics of microearthquakes and is operated at 80 % of critical damping. An attenuator switch is placed between the second and third amplifier stages for field gain adjustment. The amplified signal is full-wave rectified for the level-detection circuit. The rectified signal is then connected parallel to four level detection circuits whose reference voltages are set by a voltage divider circuit across a zener diode. The most sensitive level detector puts out a logic 1

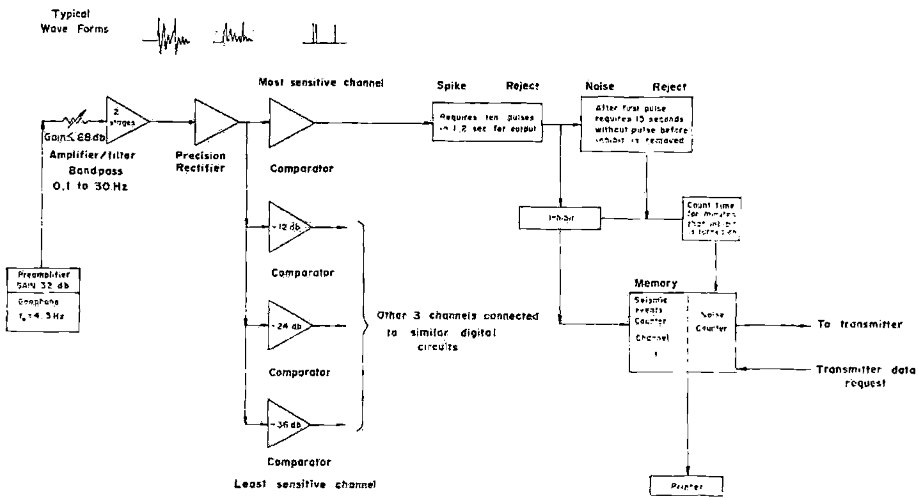


FIG. 7 - Block diagram of the multi-level seismic even counter logic.

output pulse when the level of any peak in the rectified signal exceeds the 40 to 50-millivolt reference voltage. The output from the level detector then goes to a divide-by-10 counter, reset by a one-shot timer every 1.2 seconds. The counter requires 10 pulses to occur in 1.2 seconds to register a count. This requirement makes the counter insensitive to seismic signals with predominant frequencies of less than 4.2 Hz. When a count is registered, another one-shot timer is triggered to inhibit the count circuit for 15 seconds. The event counter is then registered in a 10-bit binary counter. Three additional level detectors at 12 db, 24 db, and 36 db below the maximum gain settings function in the same way. The 12 db interval gives the seismic event counter a 36 db range of detection. The extended range allows detection of major changes in the seismicity and determination of the numbers of earthquakes of different sizes.

In order to distinguish noise from earthquakes, the output of the 15-second one-shot timer in the noise reject circuit goes to an elapsed time interval counter. If this noise reject signal is on for 60 to 70 seconds, or in other words if the counter is inhibited for such a period of time, one noise count is registered.

There are inhibit counters for the three most sensitive levels of detection, and all the data except the seven most significant bits of the third counter are transmitted, together with a parity bit.

As a back up system for data recovery, a thermographic recorder records data at a 6-hour print rate. The printer uses a simple 4 by 5 matrix system for binary-coded data from the counters. At the 6-hour print rate a 75 meter roll of paper tape lasts approximately one year. A solenoid-activated stepping motor

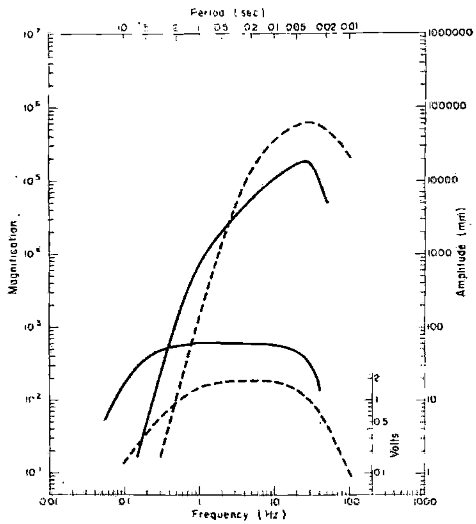


FIG. 8 - Response curves for the multi-level seismic event counter (dashed lines) and high gain short period seismographs (solid lines). Lower set of curves are for the electronic responses of both systems and upper curves include geophone respinses.

is used for the tape advance mechanism and is the only moving part in the system aside from the geophone.

The geophone assembly and seismic event counter weigh approximately 10 kg. Power to the unit is supplied by external batteries. Less than 50 milliwatts of power are required for a 24-hour period. As a result of the extensive use of CMOS integrated circuits the seismic event counter can be operated continuously for years.

Eleven short-period, high-gain seismometer stations were installed adjacent to event counters in Washington, California, Guatemala, El Salvador, and Nicaragua (Table 1) to allow comparison of the counts with standard seismic records. The seismometer telemetry systems installed are similar to systems described by SMITH. *et al.* (1971) and WESSON. *et al.* (1973). These seismometers have natural frequencies of 1 or 2 Hz and are operated at 80 % of critical damping. After being telemetered via VHF radio. FM signals are demodulated and subsequently recorded on heat-sensitive paper at 60 mm/min. The unit magnification curves for both the event counter system and the standard short-period high-gain system (Fig. 8) show that approximately three times more output is derived from the event counter system geophone.

## Verification of the Seismic Event Counters

The seismic event counter is designed to process seismic data that occur at the rate of about 20 million digital bits per twelve hours and to provide only 64 digital bits of data in the same time. This compression is accomplished by requesting to know only the number of earthquakes with amplitudes greater than four discrete levels and by designing an electronic circuit to detect earthquakes and measure their amplitude. Detecting earthquakes is not always easy. Even two seismologists might disagree whether a small event recorded at only one station is an earthquake or is spurious noise caused by people, animals, wind, and so on. Thus, it is of prime importance to establish how reliably the new event counters detect and count earthquakes and under what conditions these counts may be contaminated by counts of spurious seismic noise.

One event counter was placed in Hawaii next to a standard seismic station with data telemetered to the Hawaiian Volcano Observatory. A special interface board was attached to the event counter that, with the use of seven one-shot timers, put out d.c. pulses of varying length, depending on which of the seven counters in the seismic event counter was activated at a particular time. These pulses modulated a voltage-controlled oscillator. The resulting signal was telemetered with the seismic signal, discriminated at the central recording site, and recorded next to the seismic trace. This system, in addition to the data printed by the event counter every 1.5 hours, gave a direct indication of what the event counter was detecting.

Comparison of the data from the event counter printer with the corresponding number of pulses on the telemetered trace for 1.5 hour intervals shows a one-to-one correspondence. Thus, the special interface circuit worked as designed and did not appear to introduce spurious data. As expected, all earthquakes with sufficient amplitudes and frequency content were counted. The magnitudes of earthquakes counted only on the most sensitive detection level range from 1.1 to 2.5, and the magnitudes of earthquakes counted on the second most sensitive detection level range from 1.6 to 2.8. This range of earthquake magnitudes is expected since amplitudes vary with distance to the epicenter. High ground noise caused by wind and vehicle traffic on a road 0.25 km from the event counter site caused spurious counts on the most sensitive counting level. Noise counts were also recorded during periods of wind and serve to indicate periods of probable high wind activity. « Noise » counts in general were not triggered by pass-

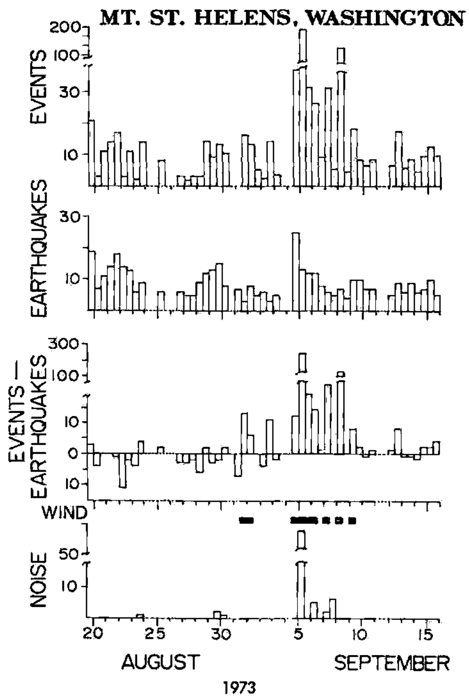


FIG. 9 - Seismic events counted by the event counter on Mt. St. Helens in Washington compared to earthquakes detected by a seismologist using seismograms from a seismograph station operated nearby.

ing vehicles. Thus, it is important that sites be located away from sources of cultural noise to increase the reliability of the data.

A comparison of events counted electronically on Mt. St. Helens in Washington with earthquakes counted by a seismologist studying typical seismograms is shown in Fig. 9. This figure shows a close correlation of event counts to earthquakes except during periods of high wind when there are significant numbers of noise or counts. These types of data together with the detailed comparison of the event counter done in Hawaii provide the basis for the following conclusions about the reliability of these seismic event counters.

Nearly all local earthquakes are detected and counted unless they are too small to have 10 peaks of their full-wave rectified signal occur above the threshold of the most sensitive counter or they occur at a time when the counter is inhibited by high background noise or by the occurrence of another earthquake less than 15 seconds earlier. A typical earthquake counted is shown in Fig. 10 A. Failure to detect

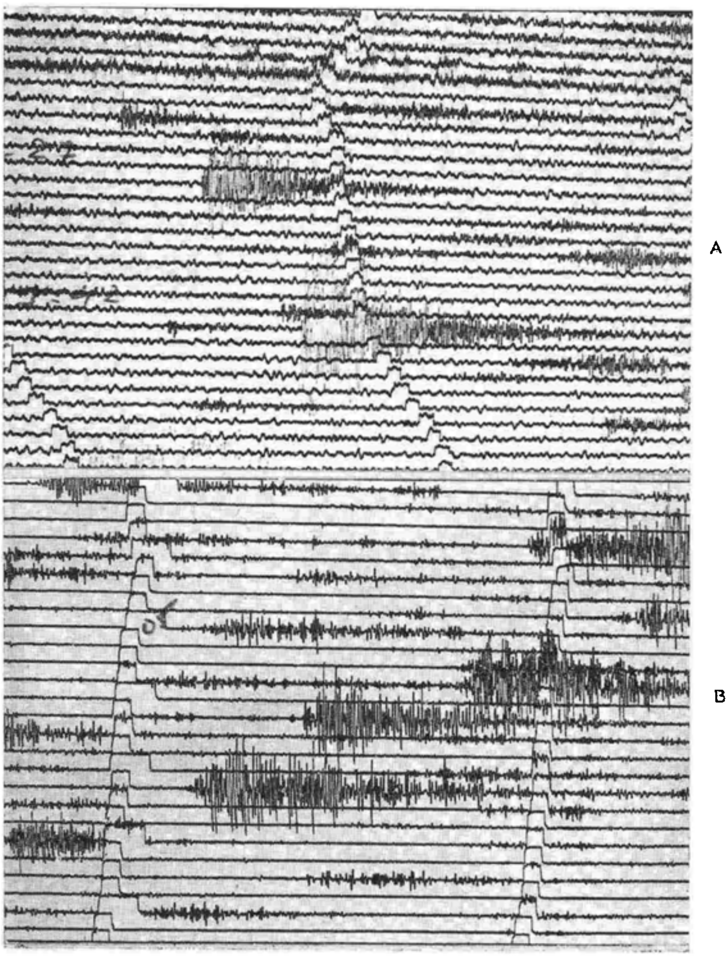


FIG. 10 - Examples of microearthquakes from two Central American volcanoes. The top example from Izalco Volcano, El Salvador, illustrates the high frequency microearthquakes that the event counters normally count reliably. Recorded on the lower record are low frequency microearthquakes recorded at Pacaya Volcano, Guatemala. These events, associated with ash eruptions, are often not counted by the event counter. One minute between time marks.

earthquakes during periods of high background noise is not serious, since the noise will inevitably cause some spurious counts and the high noise counts will flag the number of event counts as being suspect. Failing to detect earthquakes that occur rapidly in succession is also not serious since such events will occur rarely except during swarms of earthquakes when the percentage of such undetected earthquakes will be low.

The only other types of local earthquakes observed in this study that are typically not counted are low frequency, emergent events like those shown in Fig. 10 B. The event counter is totally insensitive to frequencies below 4.2 Hz because of the criterion for counting that requires 10 peaks of the full wave rectified signal occur above a given threshold in 1.2 seconds. This criterion was chosen to reduce the number of teleseismic events counted, but we have found out that at some volcanoes, particularly Pacaya, San Cristobal, and St. Helens in this study, there are many local earthquakes with significant low-frequency content. Such events have also been noted at Rainier (UNGER and DECKER, 1970), Kilauea (R. KOYANAGI, personal communication, 1973), and Augustine (J. KIENLE, personal communication, 1973). These events are generally not counted because they begin with small ground amplitudes that build up to a maximum in about 5 seconds. In many instances one peak in amplitude may start the detection counting circuit, but more peaks in the signal large enough to exceed the threshold do not occur for another 0.5 or 1 second. These events might well be detected if the criterion were changed to something like 10 peaks in 2 seconds. Experimentation with this criterion continues.

Spurious counts can be caused by ground noise from cultural sources but are predominantly caused by wind induced ground noise. Such spurious counts either are infrequent or are usually accompanied by significant noise counts. Noise from cultural sources can be successfully avoided at nearly all sites by placing the instrument in remote areas away from frequently traveled roads or trails. Wind-induced ground noise is reduced by placing the sensors at low elevation, sheltered from high winds, away from trees, at 25 to 30 m from the large antennas, and by using smaller types of antennas. Major changes in the background noise level caused by wind can not be totally avoided. Spurious even counts caused by high wind, however, can be readily identified by the simultaneous registration of high noise counts. Moderate levels of ground noise may cause spurious event counts but may not trigger counts. Such cases can usually be identified, however, since when a large number of event counts triggered by earthquakes is recorded on one channel, approximately 15 to 30 % of these events should be counted on the next most sensitive channel. This relationship occurs because earthquakes are known to be distributed in size according to the GUTENBERG and RICHTER (1949) relationship modified by SUZUKI (1953)

$$\log \mathrm{N} = -\mathrm{b} \log A + \mathrm{C}$$

where N is the number of earthquakes with maximum amplitude greater than or equal to $A$. C and b are constants for a given region and b, which is of interest here, is typically between 0.8 and 0.9 (ISACKS and OLIVER, 1964; PAGE, 1968) but may be as high as 3.5 for shallow earthquakes within a kilometer of the summit of some volcanoes (MINAKAMI, 1960).

Thus, an order of magnitude increase in seismic events accompanied by a small increase in events on the next most sensitive channel, and no noise or inhibit-time counts, can be reasonably assumed to indicate an order of magnitude increase in seismicity. The occurrence of may inhibit-time counts for the most sensitive channel would indicate that the events are probably spurious counts and do not represent a change in seismicity. It is possible that a short-term (such as one day) increase in seismicity might occur during a storm when the background noise is high. The probability of such an occurrence is low. Furthermore, an increase in seismicity related to a large eruption can be expected to be several orders of magnitude (MINAKAMI, 1960, 1968; SHIMOZURU, 1969), so that noise on one channel will not obscure the changes on the lower gain channels.

Thus, we can conclude that the event counters do normally and quite reliably indicate the level of seismicity within an order of magnitude. These seismic event counters are significantly more reliable than earlier counters because they combine the following design features:

*a*) There must be several cycles of ground motion above a given threshold.

*b*) There must have been no peak above the threshold in the 15 seconds preceding the detected signal.

*c*) Some indication of the noise level is provided.

*d*) Several different thresholds are used.

There are a number of tradeoffs in the choice of these design features and particularly in the choice of appropriate time costants. Perhaps the least obvious choice relates to what should constitute a noise count. In the present design a noise count is registered if at least one peak occurs above a given threshold every 15 seconds for a continuous period of 60 to 70 seconds. The resulting count is significantly less than one would get by counting the individual periods of 15 second inhibits and dividing by 4. The method adopted will not count many short periods when the counter is inhibited or periods when the noise level is causing separate inhibits. The main benefit of this method is that it will not count the codas of most local earthquakes as periods of noise.

The results from these new seismic event counters are very encouraging and show that significant compression of seismic data can be done with processing by relatively simple electronic circuits. These counters are adequate to operate in a global volcano surveillance system, but we also have begun to think of ways to improve the amount and quality of the compressed data and thus are continuing to experiment with other types of counters.

## Changes in Seismicity Observed

A microearthquake swarm occurred near Augustine Volcano in Alaska between January 11 and 23, 1973. There is an excellent correlation (Fig. 11) between the numbers of microearthquakes observed on a standard seismigraph (J. KIENLE, personal communication, 1973) and those counted on the third most sensitive event counter channel. The two most sensitive counter channels were inoperative because of an electronic oscillation caused by low temperature that was not discovered until it was impractical to reach the instrument in the winter. Since the third channel is 16 times less sensitive than the most sensitive channel, the number of events counted would be on the order of 16 times less than the number of earthquakes counted on the seismograms. The actual difference is a factor of 22 and depends on the value $b$ of this particular swarm and the amplifications set in the two different instruments.

No significant change in volcanic activity was noted to accompany or follow this swarm. Augustine is an island that is uninhabited in the winter, however, so that a minor eruption might well go undetected. This volcano has been quite active since a violent explosion in 1883 during which a mud flow, or lahar, generated a destructive tidal wave (KIENLE, *et al.*, 1971). A lava dome has continued to grow in the central crater by over 85 meters since 1957. This swarm clearly illustrates why a two or even three orders of magnitude change in seismicity does not necessarily allow one to predict a specific eruption. However, such a change does indicate, particularly when these swarms occur regularly, that this volcano is very active and has a relatively

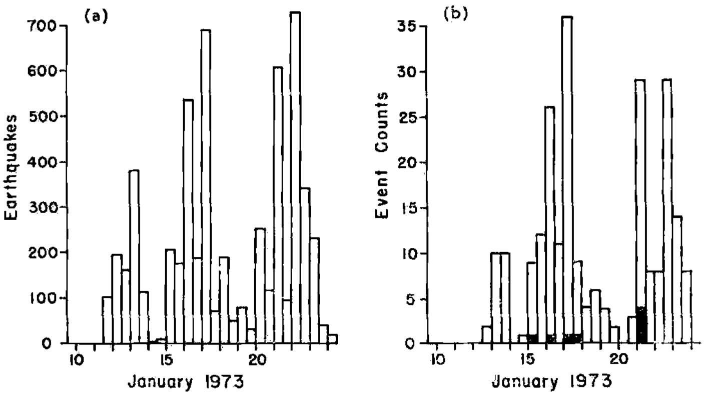


FIG. 11 - A histogram of (a) earthquakes counted on short period seismograms from standard seismograph, Augustine Volcano, Alaska (J. KIENLE, personal communication, 1973), and a histogram of (b) events detected by a multilevel seismic event counter showing excellent correlation on the third most sensitive channel of detection.

high potential for eruption. After the seismic activity has been monitored for a period of months and years at a given volcano, it should be possible to say with some certainty whether an eruption is likely in terms of days, weeks, months, or years.

The number of seismic event counts recorded at Santiaguito Volcano in Guatemala from March through mid-October, 1973, are shown in Fig. 12. The number of events increased by about an order of magnitude three times, but each of these periods was accompanied by a significant number of noise counts. Thus, no changes in the event counts in Fig. 12 stand out as designating changes in seismicity. The seismicity in this region does, however, stand out as generally high.

ROSE (1974) described a nuée ardente eruption of Santiaguito on April 19, 1973, that was the largest since 1929. The eruption occurred on a cloudy night and was not observed. Only steady rumbling and a strong odor of $SO_2$ were detected by inhabitants 7 km to the south. The deposit appeared to originate from the Caliente Vent area of Santiaguito. A second, smaller nuée ardente occurred on September 16, 1973, and originated at the toe of a lava flow coming off of the dome. ROSE and BONIS (personal communication, 1973) suggest the possibility that both of these nuée ardentes may have originated at or

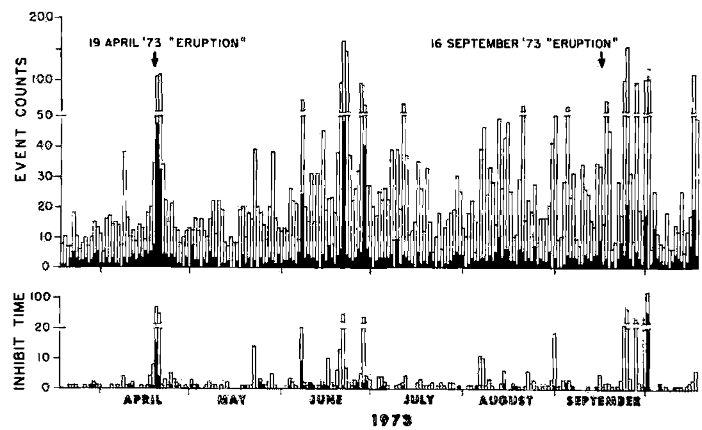


FIG. 12 - Histograms of seismic event counts and noise counts for two channels of a seismic event counter installed within 7 km of an active dacite dome at Santa Maria Volcano in Guatemala (Channel 2 shaded).

very near the surface and may not be related directly to changes in the volcano at depths where earthquakes typically occur.

Seismic events associated with the eruption of Volcán Fuego in Guatemala are shown in Fig. 13. This volcano erupted on February 22, 1973, only nine days after the event counter was installed. The small eruption ended on March 2 and was confined only to the summit area.

An order of magnitude increase in seismic events was observed on the low gain (second most sensitive) channel five days before the eruption and a similar, but larger, increase occurred on the high gain (most sensitive) channel. These seismic events can be assumed to be mostly earthquakes since very few noise counts were recorded at the same time. A similar but smaller increase was noted on a counter operating 15 km away from Fuego, but no change at all was noted on a counter 30 km away. Thus the change in seismicity was obviously in the vicinity of Fuego. During the eruption the number of events remained high, but after the eruption very few events were recorded. It seems reasonable to assume that the level of activity prior to February 13 was low and similar to that after March 4, but there is no way to be sure.

A seismograph installed next to the event counter on Fuego began operating four days after the eruption began. The level of harmonic

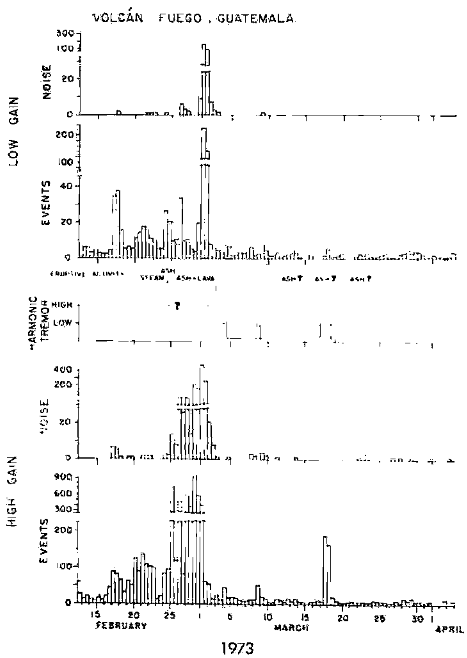


FIG. 13 - Histograms of seismic event counts and noise counts for two channels of a seismic event counter installed near Volcán Fuego in Guatemala in early 1973. Note the increase in seismic activity during the eruption which began in February 22, 1973. A high gain short period seismograph installed adjacent to the event counter recorded the relative changes in the level of harmonic tremor. Intervals of eruptive activity are indicated.

tremor or ground noise that is commonly believed to be associated with underground movement of lava was approximately 100 times greater than the background seismic noise one month after the eruption. As expected, there are large numbers of event counts and noise counts on the two most sensitive channels during the periods of high tremor.

On March 18, two peaks of over 150 event counts recorded on the highest gain counter channel correspond to a period of increased tremor. There are no noise counts to suggest that this is a period of high ground noise. Such a condition occurs when the signal level is just high enough to occasionally trigger event counts but does not remain above the detection level longer than a minute to trigger noise counts. These peak in event counts can be readily identified as spurious, however, because there are not sufficient corresponding counts on the next most sensitive channel.

This example from Fuego shows one type of increase in seismic activity prior to eruptions that a surveillance system might monitor, except that the time between the increase in seismicity and the eruption might, from historic accounts, be expected to increase as the size of the eruption and thus the volcanic hazard increases. As recording continues, long-term changes in seismicity from year to year should be very significant for delineating changes in the state of volcanic activity at different volcanoes.

## System Evaluation

The cost of installing an event counter, tiltmeter, and satellite transmitter on a volcano in some quantity is about $ 5,000 or roughly similar to installing this equipment with analog recorders located near the volcano. The yearly maintenance cost for the satellite telemetry equipment would at most be a small fraction of the cost of maintaining local on-site recording, however. Furthermore, experience during this project clearly demonstrates that the satellite telemetry system is substantially more reliable than on-site recording methods commonly used now unless a skilled technician is available in every region to maintain the equipment. This high reliability of the satellite relay system stems primarily from the fact that the self-contained, small event counters, tiltmeters, and transmitters that can be located almost anywhere and, based on experience in this study, are less susceptible to battery failure and to damage by lightning, vandalism, and climatic extremes than are equivalent systems connected to local recording stations by cable, telephone lines, or radio. The satellite system provides for rapid data collection and rapid analysis by specialists. The standard local recording techniques provide more data when the equipment functions properly but the equipment can be expected not to function for long periods of time unless skilled technicians are paid to be available at any time for repairs. Thus the maintenance of a local analog recording system would cost at least an order of magnitude greater more than maintaining the satellite system.

A satellite volcano surveillance system has two principal purposes: basic research and early warning of increased hazard. Basic research ultimately is aimed at providing more reliable early warning and even specific predictions of eruptions. The need for early warning is probably best served by a satellite system with rapid data relay, in which a few specialists could examine the data rapidly and notify local scientists or officials when abnormal activity is noted. The need for basic research might best be served by on-site recording or by spending the same dollars on more intensive studies of fewer volcanoes. In order to weigh these considerations, continuing research is directed toward demonstrating the types and reliability of data collected by the different approaches and determining how complete the data, for example on seismicity, could be made by further development of on-site data processing schemes.

The economic impact of a global volcano surveillance system is difficult to estimate reliably. Such a system would safeguard lives and reduce loss of mobile property by providing an early warning of the reawakening of a volcano and criteria for judging the degree of unrest of each volcano. Such information would aid in minimizing the disruption to the local economy caused by a volcanic eruption. Loss of life depends critically on the location of population centers near volcanoes. As populations increase, so do concentrations of people on and near the fertile flanks of many volcanoes. Thus the exposure to volcanic hazards continues to increase. Furthermore, as construction of facilities such as the nuclear power plant just west of Mt. St. Helens in Washington State proceeds, it becomes increasingly important that early warning of an eruption is sufficient to consider closing down such reactors. The ultimate risk from many volcanoes may be damage and loss of life resulting from failure of dams, nuclear power plants, and other facilities caused by eruptive activity. An average of several hundred people per year have been killed by volcanoes during the last 500 (VAN BEMMELEN, 1949) and 1000 (R. DECKER, personal communication, 1974) years. Specific eruptions may kill over a hundred times this number of people in one small area and cause extremely large and concentrated economic loss. Even the reduction by a few percent in the number of deaths from volcanic eruptions might « pay » the cost of a global volcano surveillance system.

The direct criteria for judging the degree of unrest of various volcanoes provided by such a surveillance system would aid in land-use planning for regions around volcanoes. Construction and development should proceed, if no other choice is possible, on those volcanoes showing the least amount of activity over several years and should be avoided around those volcanoes showing the greatest amount of activity or showing rapid changes in activity.

A global volcano surveillance system would also focus use of available resources on detailed studies of volcanoes that have the higest probability of erupting, increase the efficiency of research on prediction of specific volcanic eruptions, and thus decrease the related costs in dollars and manpower. With present technology it is feasible to install large, temporary, portable networks of instruments rapidly anywhere in the world. Several international teams of experts could be established to study those volcanoes most likely to erupt. These teams could move rapidly into areas where eruptions are considered imminent not only for research purposes but to advise local leaders regularly and rapidly on the probability and possible scope of a potential eruption. The reliability of such predictions should increase rapidly with a global surveillance system for focusing use of the research funds and talents of many different countries.

## Conclusions

A global volcano surveillance system is now technologically and economically feasible but more work is required to demonstrate that such a system will be effective and reliable for predicting eruptions. More specific results are as follows:

*a*) A new seismic event counter that reliably indicates order of magnitude changes in seismicity has been designed, deployed at 19 locations, and thoroughly tested. This event counter is significantly more reliable than any such system previously available.

*b*) A tiltmeter that can be installed quickly and easily has been successfully deployed at seven remote locations and shown to operate reliably and stably for at least a year.

*c*) The seismic event counters and tiltmeters have been interfaced with satellite transmitters and installed simply, reliably, and securely in remote areas and in many environmental extremes.

*d*) The instrumentation has worked extremely well, but experience developed in this project is being used to develop even more reliable design, construction, and installation techniques. Even though we conclude that a global system is technologically feasible, there are still many details in design that need to be worked out in an orderly development program.

*e*) Local earthquakes were detected on all volcanoes monitored in this study, suggesting that even the volcanoes of the Cascade Range are not extinct.

*f*) An order of magnitude increase in seismicity was observed several days prior to the eruption of Volcán Fuego in Guatemala in February, 1973.

*g*) Tilts of from 20 to 150 microradians were observed on the volcanoes Kilauea, Fuego, and Pacaya.

*h*) A volcano surveillance system monitoring seismicity and tilt at 1000 locations around the world could be installed and operated for five years at a cost of about $ 11 million if the satellite relay system were shared with many users. This expense might be shared by many countries.

The results of this initial project are extremely encouraging. It appears that a global volcano surveillance system utilizing satellite telemetry may be very practical and desirable and that it offers a radically new approach to the surveillance of potentially hazardous volcanoes. Considerable evaluation and development still needs to be done, however, to demonstrate just how valuable such a system would be and how soon it should be built.

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## References

ADAMS, R. D. and DIBBLE, R. R., 1967, *Seismological studies of the Raoul Island eruption, 1964*, New Zealand Jour. Geology and Geophysics, *10*, p. 1348-1361.

ALLEN, R. V., 1972, *A borehole tiltmeter for measurements at tidal sensitivity*. Bull. Seism. Soc. Amer., *62*, p. 815-821.

———, WOOD, D. M., and MORTENSEN, C. E., 1973, *Some instruments and techniques for measurements of tidal tilt*. Phil. Trans. R. Soc. Lond., *274*, p. 219-222.

COOPER, G. L., 1970, *Development and use of a two-axis electrolytic bubble level as a precision vertical reference and tilt indicator*. Am. Inst. Aeron. and Astron. Paper 70-949, Sta. Barbara, Calif., 11 pp.

DECKER, R. W., 1968, *A seismic event counter for Active Volcanoes*. Bull. Seis. Soc. Am., *58*, p. 1353-1358.

——— and KINOSHITA, W. T., 1971, *Geodetic Measurements*, in *The Surveillance and Prediction of Volcanic Activity*. UNESCO, Earth Science Monograph 8, Paris, p. 47-74.

EATON, J. P. and MURATA, K. J., 1960, *How volcanoes grow*. Science, *132*, p. 925-938.

GORSHKOV, G. S., 1960, *Some results of the seismometric investigations, at the Kamchatka Volcanological Station*. Bull. Volcanol., *23*, p. 121-128.

GUTENBERG, B. and RICHTER, C. F., 1949, *Seismicity of the Earth*. Princeton Univ. Press, Princeton, N. J., 210 pp.

HARLOW, D. H., 1971, *Volcanic Earthquakes*. Unpublished M. A. Thesis, Dartmouth College, Hanover, N. H., 66 pp.

JOHNSTON, M. J. S. and STACEY, F. D., 1969, *Transient magnetic anomalies accompanying volcanic eruptions in New Zeland.* Nature, *224*, p. 1289-1290.

ISACKS, B. and OLIVER, J., 1964, *Seismic waves with frequencies from 1 to 100 cycles per second recorded in a deep mine in northern New Jersey.* Bull. Seis. Soc. Am., *54*, p. 1941-1979.

KIENLE, J., FORBES, R. B., and HARLOW, D. H., 1971, *Recent microearthquake swarm activity at Augustine Volcano, Alaska* (Abstract). Trans. Am. Geophys. Un., *52*, p. 925.

KING, G. C. P., 1971, *The siting of strainmeters for teleseismic and tidal studies.* Royal Society of New Zealand, Bull. *9*, p. 239-247.

KOHLENBERGER, C. W., COOPER, G. L., and SCHMARS, W. T., 1973, *Dynamic properties of a new biaxial tiltmeter* (Abstract). Earthq. Notes, *44*, p. 11.

MENIAYLOV, I. A. and NIKITINA, L. P., 1967, *The behavior of sulphur and chlorine in fumarolic gases before intensification of activity of volcanoes, Coll. Volcanicity and Geochemistry of its products.* Publ. Nauka, p. 72-81.

MINAKAMI, T., 1942, *On volcanic activities and tilting of the earth's surface.* Bull. Earthq. Res. Inst., *20*, p. 431-504.

————, 1950, *Recent activities of Volcano Usu. Part 6: Precise levelling around Mt. Usu in 1949.* Bull. Earthq. Res. Inst., *28*, p. 153-160.

————, 1960, *Fundamental research for predicting volcanic eruptions (Part 1) earthquakes and crustal deformations originating from volcanic activities.* Bull. Earthq. Res. Inst., *38*, p. 479-544.

MOXHAM, R. M., 1971, *Thermal surveillance of volcanoes* in *The Surveillance and Prediction of Volcanic Activity.* UNESCO, Earth Science Monograph 8, Paris, p. 103-123.

NATIONAL AERONAUTICS and SPACE ADMINISTRATION, 1972, *Earth resources technology satellite data collection platform field installation, operation and maintenance manual.* Report 72 SD 4208, 256 pp.

NOGUCHI, K. and KAMIYA, H., 1963, *Prediction of volcanic eruptions by measuring the chemical composition and amount of gases.* Bull. Volcanol., *26*, p. 367-378.

OMORI, F., 1907, *Tilting of the ground during a storm.* Bull. Imp. Earthq. Invest. Com., *1*, p. 167-171.

————, 1914-1922, *The Sakura-jima eruptions and earthquakes.* Bull. Imp. Earthq. Invest. Com., *8*, No. 1-6, 525 pp.

OMOTE, S., 1942, *Crustal deformation in Miyake-sima Island that accompanied the volcanic activities in 1940.* Bull. Earthq. Res. Inst., *20*, p. 127-140.

PAGE, R., 1968, *Aftershocks and microaftershocks of the Great Alaska Earthquake of 1964.* Bull. Seis. Soc. Am., *58*, p. 1131-1168.

PERRET, F. A., 1937, *An experimental « seismeter ».* Am. J. Sci., *34*, p. 469-474.

ROSE, W. I., Jr., 1974, *Nuée Ardente from Santiaguito Volcano, April 1973.* Bull. Volcanol., *37-3*, p. 365-371.

SHIMOZURU, D., 1971, *A seismological approach to the prediction of volcanic eruptions,* in *The Surveillance and Prediction of Volcanic Activity.* UNESCO, Earth Science Monograph 8, Paris, p. 19-45.

————, MIYAZAKI, T., GYODA, N., and MATAHELUMUAL, J., 1969, *Volcanological survey of Indonesian volcanoes - Pt. 2, Seismic observation at Merapi Volcano.* Bull. Earthq. Res. Inst., *47*, p. 969-990.

SMITH, B. E., HAMILTON, R. M., and JACKSON, W. H., 1971, *Seismicity of the central Nevada test area.* U. S. Geol. Survey, 27 pp.

STOIBER, R. E. and ROSE, W. I., Jr., 1970, *Geochemistry of Central America volcanic gas condensates.* Bull. Geol. Soc. Amer., *81*, p. 2891-2912.

SUZUKI, Z., 1953, *A statistical study on the occurrence of small earthquakes, Chapter 1.* Sci. Rept. Tohoku Univ., Ser. 5, Geophys., *5*, p. 177-182.

TAZIEFF, H., 1971, *A dynamic approach to the problem of forecasting volcanic paroxysms.* In *The Surveillance and Prediction of Volcanic Activity.* UNESCO, Earth Science Monograph 8, Paris, p. 127-130.

TONANI, F., 1971, *Concepts and techniques for the Geochemical forecasting of volcanic eruptions.* In *The Surveillance and Prediction of Volcanic Activity.* UNESCO, Earth Monograph 8, Paris, p. 145-166.

UNGER, J. D. and DECKER, R. W., 1970, *The microearthquake activity of Mt. Rainier, Washington.* Bull. Seis. Soc. Am., *60*, p. 2023-2035.

VAN BEMMELEN, R. W., 1949, *The Geology of Indonesia and Adjacent Archipelagos.* Netherlands Govt. Printing Office, The Hague, 732 pp.

WARD, P. L., ENDO, E. T., HARLOW, D. H., ALLEN, R., MARQUEZ, D., and EATON, J. P., 1974, *Development and evaluation of a prototype global volcano surveillance system utilizing the ERTS-1 Satellite Data Collection System.* U. S. Geol. Survey open file report, 154 pp.

WESSON, R. Y., MEAGHER, K. L., and LESTER, F. W., 1973, *Catalog of earthquakes along the San Andreas fault system in central California - July - September 1972.* U. S. Geol. Survey open file report, 49 pp.

YOKOYAMA, I., 1964, *Seismometrical observation of the 1962 eruption of Volcano Tokati, Hokkaido, Japan.* Bull. Volcanol., *27*, p. 217-223.

*Manuscript received Aug. 1974*