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# DEVELOPMENT AND EVALUATION OF A PROTOTYPE GLOBAL VOLCANO SURVEILLANCE SYSTEM UTILIZING THE ERTS-1 SATELLITE DATA COLLECTION SYSTEM

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Final Report to
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Contract S-70243-AG-2
Task No. 434-641-14-03-22
Period June, 1972 to February, 1974

February, 1974

(E74-10689) DEVELOPMENT AND EVALUATION OF A PROTOTYPE GLOBAL VOLCANO SURVEILLANCE SYSTEM UTILIZING THE ERTS-1 SATELLITE (National Center for Earthquake Research) 168 p HC $11.50 CSCL 08F G3/13
N74-31786
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# 1.0 ABSTRACT

The ERTS Data Collection System makes it feasible for the first time to monitor the level of activity at widely separated volcanoes and to relay these data rapidly to one central office for analysis. 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 daily to warn when any one volcano is becoming active again. Before ERTS was launched only a few volcanoes in the world were monitored continuously because of the high cost of building and staffing volcano observatories. Yet it is known from data collected in this century, that while visible signs of pending eruptions may occur only minutes to days in advance, invisible but measurable signs may be detected days, weeks, months and even years before a major eruption. While prediction of specific eruptions is still an elusive goal, early warning of a reawakening of activity at quiescent volcanoes is now a distinct possibility.

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. 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 satellite and through a teletype link to the U.S. Geological Survey Office in Menlo Park for rapid analysis. Only seismic and tilt data are collected because these have been shown in the past to indicate most reliably the level of volcanic activity and also because they can be measured relatively easily with available instrumentation. Experience

during this project demonstrates the feasibility of building inexpensive, low power, reliable instruments that can be installed in remote locations and can be expected to run unattended for a few years.

Comparison of the 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 other data collected by the earthquake counters. An eruption of Volcán Fuego in Guatemala was preceded by an order of magnitude increase in the number of seismic-event counts several days before.

The tiltmeters operated stably in several different environments. A twenty-microradian collapse of the summit of Kilauea Volcano in Hawaii was observed on three tiltmeters.

This initial experiment shows that now with the advent of inexpensive satellite telemetry it is both technologically and economically feasible to build a global volcano surveillance system. Several details in the design and deployment of appropriate low-power, inexpensive, and reliable instruments still need to be worked out. Work continues to evaluate the scientific feasibility of this system by collecting and analyzing data that clearly demonstrate the ability of this system to detect changes in volcanic activity.

## 2.0 INTRODUCTION AND PROGRAM DESCRIPTION

Eruptions at the more than 500 historically active volcanoes around the world usually occur with virtually no warning to the surrounding populace. Visible signs of increasing restlessness at quiescent volcanoes normally are not observed, or at least are not recognized, before even catastrophic eruptions, whereas measurable changes in a number of geophysical parameters, such as the frequency of occurrence of microearthquakes and the rate of tilting of the ground surface, have been observed days, weeks, months, and even years before large eruptions. Although accurate prediction of the outbreak of specific eruptions is generally not yet possible even for densely instrumented volcanoes, it does appear to be feasible to detect changes associated with revival of a quiescent volcano and to provide an early warning of the activity that might follow. Such warnings can provide time for implementation of precautionary lifesaving measures as well as for focussing research efforts on volcanoes with the highest probability of erupting and thereby contributing rapidly to the understanding of eruptions and to the development of reliable methods for predicting them.

Few permanent volcano observatories have been established because they are costly to maintain and because most volcanoes erupt so infrequently that they must be monitored for decades to record a single eruption. Recent advances in instrumentation technology now permit large temporary networks of instruments to be established in remote areas very rapidly. Thus, a new era in volcanology can be introduced by application of a widespread network of relatively simple and inexpensive instruments to identify areas that merit intensive research with dense portable networks of instruments.

The Earth Resources Technology Satellite (ERTS) launched by the National Aeronautics and Space Administration (NASA) on July 23, 1972, provides for the first time a practical system for collecting data from hundreds of remote areas of the globe and making these data rapidly available in one or more locations for analysis by specialists. This polar orbiting satellite relays 64 binary bits of data plus a station identification code from scattered remote ground transmitters at least once every 12 hours to a NASA tracking station in Maryland or California.

Beginning in June, 1972, a prototype global volcano surveillance system was established under the ERTS program to explore the technological, economic, and scientific feasibility of monitoring hundreds of potentially hazardous volcanoes. Instruments were installed in close cooperation with local scientists on 15 volcanoes in Alaska, Hawaii, Washington, California, Iceland, Guatemala, El Salvador, and Nicaragua at the sites shown in Figure 2.1. Data from low powered instruments at 22 different sites are relayed through the satellite and ground tracking stations to Goddard Spaceflight Center in Maryland. The data are processed after each satellite pass and relayed within 90 minutes by teletype to the U. S. Geological Survey Office in Menlo Park, California.

The sensors include 19 multilevel seismic event counters that provide separate counts of earthquakes with amplitudes greater than four different reference levels and 6 biaxial borehole tiltmeters that measure ground tilt with a resolution of one microradian. Seismic and tilt data are collected because these have been shown to be closely related to the level of activity at many different volcanoes in the past. Furthermore, these parameters can be measured relatively easily with new instrumentation.

The fourth generation seismic event counters developed for this project (Photos 2, 3, 4) analyze about 20 million digital bits of seismic data monitored during each 12 hour interval and provide the 64 bits that can be relayed through the ERTS satellite. This data compression is

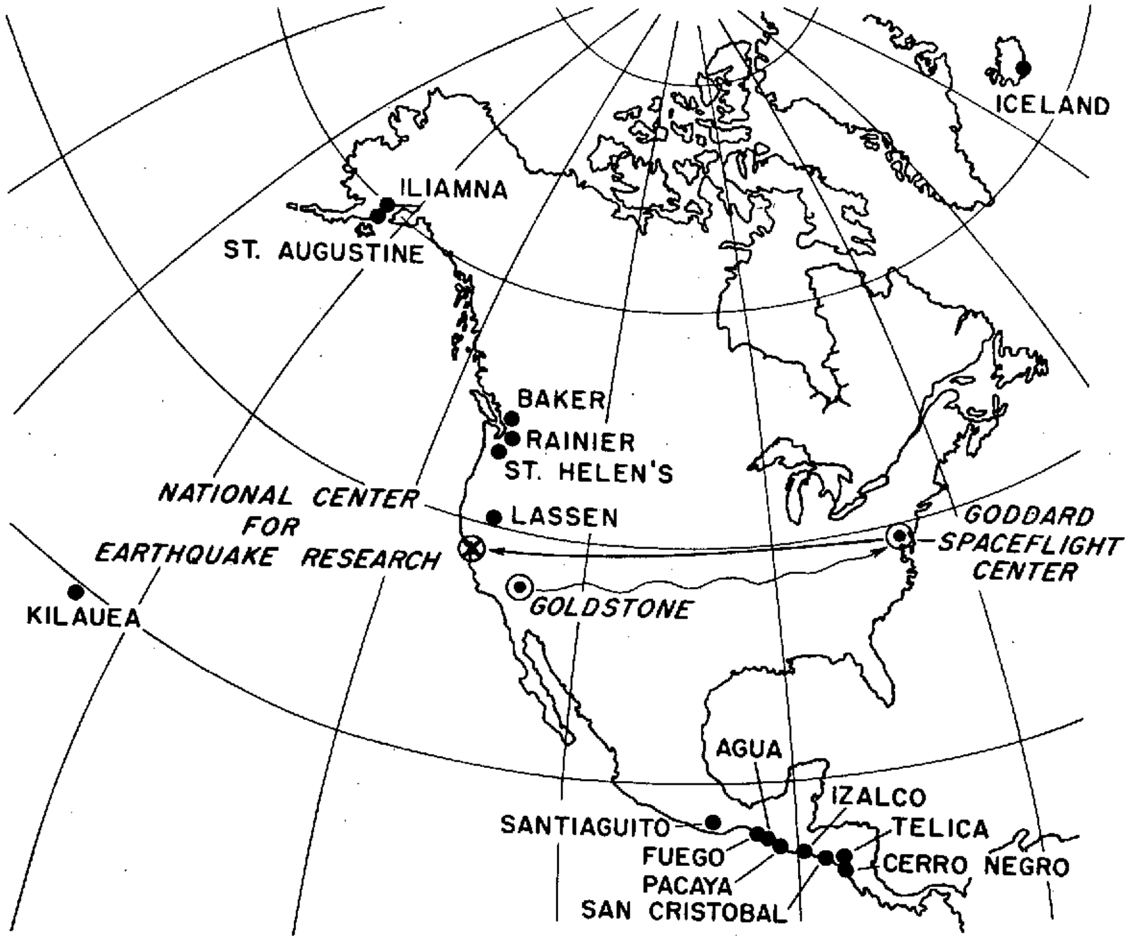


FIGURE 2.1. Map of volcanoes monitored in this study. Event counters were placed at all sites. Tiltmeters were placed on Mt. Lassen, Kilauea, Fuego, and Pacaya.

extreme, and much information is lost. For the purposes of the volcano surveillance network, however, the essential data required are simply the numbers of small earthquakes of different sizes that occur during the 12-hour sampling interval. These numbers typically change by orders of magnitude before eruptions. The criteria adopted for detecting earthquakes are first that 10 peaks of the full-wave rectified seismic signal must be above the detection threshhold in 1.2 seconds and second that no peaks may have been above this threshhold in the previous 15 seconds. This second criterion effectively inhibits the counter during periods of high ground noise caused, for example, by wind, harmonic tremor, or cultural activities. The time that a channel is inhibited is counted separately. Comparison of data from the event counters with data from standard seismometers located nearby show that these instruments will reliably detect order of magnitude changes in local seismicity under normal conditions. Such a change was detected 6 days prior to a small eruption of Volcán Fuego in Guatemala in February, 1973. A similar swarm of earthquakes was detected in January, 1973, on St. Augustine Volcano in Alaska, but no eruption was reported at this remote and uninhabited volcano. Longer term changes in the level of seismicity are also being sought as the network continues to operate.

The borehole tiltmeters used in this network contain a precisely-made, electronically-monitored level bubble initially developed as part of an inertial guidance system. These meters are only 5 cm in diameter and can be easily installed in a 1 to 2 meter deep hole in rock or more typically in sandy soil or ash. Extensive tests show that with proper care in installation these meters reliably measure tilts on the order of a few microradians (a few millimeters in one kilometer). A collapse of the summit of Kilauea Volcano in Hawaii, by over 20 microradians, associated with an eruption of lava from the flank of the volcano, was measured on May 5, 1973, by three tiltmeters located around the summit. The flanks of Volcán Fuego tilted outward about 35 microradians in the 6 months following its eruption in early 1973.

Results to date from this prototype global volcano surveillance system clearly demonstrate that, while further refinement of the instrumentation is desirable, it is technologically and economically feasible:

1) To build hardy, compact, low-powered instruments that can be deployed for unattended operation in remote locations around the world;

2) To collect data rapidly from all these instruments by means of an ERTS-type data relay system; and

3) To provide a measure of the level of activity of hundreds of widely scattered volcanoes. Work is now under way to increase the information that can be derived from the event counter and tiltmeter data and to explore the use of other types of sensors and other methods of compressing data that may be useful for monitoring volcanoes. This semi-automatic monitoring system of potential global application offers a radically new approach to the surveillance of potentially hazardous volcanoes.

## 3.0 ACKNOWLEDGEMENTS

Establishment of a network of instruments on 15 volcanoes in 5 countries involves the close cooperation and hard work of many people. In addition to the authors, Roland La Forge worked full-time on this project, beginning in October, 1973. Professor Richard Stoiber of Dartmouth College, Hanover, N. H. provided invaluable advice for the field work in Central America. The following is a list of persons and organizations who assisted in the installation and maintenance of equipment in the field. The underlined names are those of scientists who also have assisted in the data analysis.

Alaska

| | |
|---|---|
| Dr. Jurgen Kienle | University of Alaska, College, Alaska |
| William Feetham | Homer, Alaska |

California

| | |
|---|---|
| Superintendent and Staff | Mt. Lassen Volcanic National Park<br>Mineral, California |

El Salvador

| | |
|---|---|
| Ing Mauricio Aquino H. (Director)<br>Ing Mauricio Cepeda | Centro de Investigaciones Geotecinicas<br>San Salvador, El Salvador |
| Ing Jose Gonzales G. | Instituto Geografica Nacional<br>San Salvador, El Salvador |
| Albert Holburn | Inter American Geodetic Survey<br>U. S. Defense Mapping Agency<br>San Salvador, El Salvador |

Guatemala

| | |
|---|---|
| Dr. Samuel Bonis<br>Dr. Oscar Salazar<br>Carlos Estrada Q. | Instituto Geografico Nacional<br>Guatemala City, Guatemala |

Hawaii

| | |
|---|---|
| Dr. John Unger )<br>George Kojima )<br>Kenneth Honma ) | Hawaiian Volcano Observatory<br>Hawaii National Park, Hawaii |

Iceland

| | |
|---|---|
| Sveinbjörn Björnsson | National Energy Authority<br>Reykjavik, Iceland |

Nicaragua

| | |
|---|---|
| Cap. and Ing. Orlando Rodriguez M. )<br>Ing Arturo Aburto Q. ) | Servicio Geologico<br>Managua, Nicaragua |
| Leroy Anstread | Inter American Geodetic Survey<br>U. S. Defense Mapping Agency<br>Managua, Nicaragua |
| Edward Hagie (Director) )<br>Adolfo J. Bengoechea )<br>Ing. Jose Antonio Gonzales ) | Mina El Limon, Nicaragua |

Washington

| | |
|---|---|
| Dr. Robert Crossen )<br>Lee Bond ) | Department of Geophysics<br>University of Washington<br>Seattle, Washington |
| Superintendent and Staff | Mt. Ranier National Park<br>Longmire, Washington |
| Staff, Mt. Baker National Forest | Glacier, Washington |
| Staff, St. Helens National Forest | Cougar, Washington |

General Assistance with the equipment preparation

| | |
|---|---|
| Jim Ellis )<br>John R. VanSchaack )<br>Wayne Jackson ) | USGS, Menlo Park, California |

The EROS program of the USGS provided a loan of $65,000 to expedite construction of the event counters prior to launch of ERTS when NASA continued to delay finalization of this contract. NASA provided $285,000 to carry out this contract. Funds to continue this research after the NASA provided funds ran out as anticipated October 1, 1973, were provided by several small grants from the EROS program totaling $55,800 to cover the period up to February 28, 1974.

Three tiltmeters, two in Hawaii and one in Guatemala were provided for this study with funds from the USGS Office of Earthquake Research and Crustal Studies.

## 4.0 OBJECTIVES OF THIS INVESTIGATION

The original objectives of this investigation as outlined in the proposal written in April, 1971, and modified slightly in June, 1972, to become part of the contract for this work are given below together with cross references in parentheses to sections of this report that specifically discuss how these objectives were met.

The overall objective of the project is to test a prototype volcano surveillance network that monitors seismic activity and tilting of the ground at selected volcanoes in Central America, the Pacific Northwest, and southern Alaska (total report). From this experience it should be possible to establish the requirements for a truly-global volcano surveillance and eruption warning system (9.0 and 10.0). More limited short-term objectives include:

a) Evaluate the performance of available multilevel event counters (6.1 and 7.2) and telemetering borehole tiltmeters (6.2 and 7.3) under the field conditions prevailing on volcanoes from Central America to Alaska. Identify and solve the problems encountered in maintaining a thin network of geophysical instruments over large geographical areas (7.0 and 10.4).

b) Evaluate the adequacy of the condensed data obtained from the event counters and tiltmeters for characterizing the internal state of a volcano (9.1 and 9.2).

c) Develop and refine the relationships between earthquake counts, ground surface deformational activity, and volcanic outbursts at various types of volcanoes (9.1 and 9.2).

d) Provide a means for determining which of the many "dormant" volcanoes around the world are ripe for intensive short-term studies that should be carried out during their reawakening to obtain information on their internal structure and eruptive mechanism (total report).

## 5.0 A BRIEF HISTORY OF PREVIOUS INSTRUMENTAL OBSERVATIONS PRIOR TO VOLCANIC ERUPTIONS

### 5.1 Seismic Activity before Volcanic Eruptions

Volcanic eruptions are typically preceded by individual large earthquakes or swarms of earthquakes. Most of the evidence is from felt reports and it is not possible to establish the true relationship of these earthquakes to the eruptions. Several examples are given by Shimozuru (1971). A partial list of such observations is given in Table 5.1 modified from Harlow (1971). Many references to earthquakes prior to eruptions are so widespread that a complete list would be nearly impossible to compile.

At adequately instrumented volcanoes some data has been collected that helps clarify the relationship between earthquakes and subsequent eruptions. Examples are shown from Sakura-jima in Japan (Figure 5.1), Kliuchevskaya in the U.S.S.R. (Figure 5.2), Asama in Japan (Figure 5.2), Raoul Island in the Kermadec Islands (Figure 5.3) and Merapi in Indonesia (Figure 5.3). Similar sequences are well observed on Kilauea and Mauna Loa volcanoes in Hawaii (Hawaiian Volcano Observatory, unpublished data). Care must be used in comparing these data to allow for the large differences in instrument response, in distance from the earthquake hypocenters to the seismometers, in the size of the ensuing eruption, and in what different seismologists choose as the minimum amplitude of earthquakes to be counted from the records. Nevertheless these data show significant increase in seismicity hours to days prior to eruptions. These same sequences recorded on the high-gain multilevel, seismic event counters used in this study would have increases in seismicity generally in excess of 3 or 4 orders of magnitude. Larger eruptions generally seem to be preceded by larger and more numerous earthquakes, although this relationship can not be clearly documented with the few data available.

TABLE 5.1. Volcanic eruptions preceded by a significant increase in earthquake frequency.

| LOCATION | DATE | EARTHQUAKE ACTIVITY | REFERENCE |
|---|---|---|---|
| Mt. Misery West Indies | 1692 | Felt earthquakes followed by eruption. | Perret (1939) |
| Soufrière West Indies | 1694<br>1798 | | |
| Mt. Pelée West Indies | 1851 | | |
| Fuji, Japan | 1707 | Swarm of felt earthquakes preceded the eruption. | Omori (1911) |
| Usen-dake, Japan | 2/12/1792 | Swarm of felt earthquakes preceded the eruption. | |
| Usu-san, Japan | 8/16/1663 | Numerous felt earthquakes began on 13 August and continued up to the time of the eruption. | |
| | 3/12/1822 | 3, 44, and 75 felt earthquakes on 9, 10, and 11 March respectively. 100 shocks were felt on 12 March prior to eruption at 2:00 P. M. | |
| | 7/25/1910 | 25, 110, 351, and 162 felt earthquakes on 22, 23, 24, and 25 July respectively. 240 events recorded instrumentally during 10 days leading up to the eruption. | |
| Sakura-jima, Japan | 10/8/1476 | Strong earthquakes felt during five days prior to the eruption. | Omori (1914-1916) |
| | 11/9/1779 | Large number of felt earthquakes on the day preceding the eruption. | |
| | 1/12/1914 | Large increase in recorded earthquakes one day prior to eruption (Fig. 5.1). | |
| Santa María, Guatemala | 1902 | Unusually large numbers of felt regional and local earthquakes beginning 10 months prior to the eruption. | Rose (1973) |
| Katmai, Alaska | 1912 | Many strong earthquakes were felt by local inhabitants during five days preceding the eruption. | Fenner, 1928 |

| LOCATION | DATE | EARTHQUAKE ACTIVITY | REFERENCE |
|---|---|---|---|
| Merapi, Indonesia | 11/22/1930 | A large increase in seismicity was recorded for a 2 month period 2 months prior to the eruption followed by a decrease in the number of earthquakes. Seismicity then increased slightly one month before and dramatically a few days before the eruption. | Neumann Van Padang 1933 |
| St. Vincent, West Indies | 4/1812<br>5/1902 | Both eruptions followed a swarm of felt earthquakes. | Robson (1964) |
| Una-Una, Celebes Is. | 5/2/1898 | Felt earthquakes occurred 3 weeks prior to eruption. | Katili et al. (1963) |
| Pelée, West Indies | 9/16/1929 | Felt shocks occurred prior to eruption. | Perret (1935) |
| Usu-san, Japan (Showa Sin-Fan) | 7- 8/1944 | Several large paroxysmal eruptions preceded by large increases in seismicity. | Minakami et al. (1951) |
| Asama, Japan | 12/4/1941<br>9/3/1949<br>9/21/1949<br><br>11/7/1935<br>3/25/1938<br>4/1/1941 | These eruptions were preceded by recorded earthquakes. | Minakami (1959) Pt. 1 |
| Asama, Japan | 10/3/1958 | Large recorded increase in very shallow earthquakes prior to eruption (Figure 5.2). | Minakami (1959) |
| Kliuchevskaya, Kamchatka | 1951<br>1953<br>1954<br>1956 | Magnitude of recorded swarm proportional to violence of the following eruption. Number of shocks decreased just prior to the 1951 eruption (Figure 5.2). | Gorshkov (1960) |
| Sakura-zima Japan | 10/13/1955 | Anomalous increase in seismicity was recorded during the 5 months preceding the eruption. | Shimozuru, 1971 |
| Bezymianny, Kamchatka | 1955-1956 | 30,000 earthquakes recorded before the first historic eruption. Earthquake frequency was at its maximum at the onset of volcanic activity. | Gorshkov (1959) |

| LOCATION | DATE | EARTHQUAKE ACTIVITY | REFERENCE |
|---|---|---|---|
| Guadelupe, West Indies | 1956 | Eruption followed recorded earthquake swarm. | Robson and Tomblin (1966) |
| Bezymianny, Kamchatka | 2/13/1958<br>2/27/1958<br>3/27/1959<br>11/28/1959<br>4/13/1960<br>3/26/1961 | Increasing seismicity beginning 30 - 50 days prior to these eruptions was recorded | Tokarev (1963) |
| Fayal, Azores | 1957-1958 | Earthquakes before the Capelinhos outbreak | Machado (1966) |
| Manam, New Guinea | 3/17/1960 | Few felt and recorded shocks prior to the eruption. Instrument magnification was 10. | Taylor (1963) |
| Tokati, Japan | 6/29/1962 | Daily recorded earthquakes began to rise and fall at the beginning of May. 12 felt shocks were noted during the month preceding eruption. | Yokoyama (1964) |
| Miyake-sima, Japan | 8/24/1962 | Series of felt earthquakes 110 days, 1 week, and 1 hour before the eruption. | Minakami (1964) |
| Shiveluch, Kamchatka | 11/12/1964 | 10 month preliminary seismicity increase and 1 month direct seismic increase prior to volcanic activity. | Gorshkov and Dubik (1970) |
| Raoul Island, Kermadec Is. | 11/21/1964 | Increased seismicity began on 10 November with a maximum of 80 shocks per hour before eruption (Figure 5.3). | Adams and Dibble (1967) |
| Mihara-yama, O-sima, Japan | 12/26/64 | Large increase in recorded seismicity beginning two days before the eruption. | Shimozuru (1971) |
| Piip Crater, Kamchatka (Kliuchevskaya) | 10/6/1966 | Up to 457 shocks per day recorded during 5 days prior to eruption. | Gorshkov and Kirsanov (1968) |
| Deception Island, Antarctic | 12/4/67 | Normal seismicity of 4-30 recorded events per month rose to 300 per month in November. | Smithsonian Institute, Event 1-67, Card 222, 1967 |

| LOCATION | | EARTHQUAKE ACTIVITY | REFERENCE |
|---|---|---|---|
| Fernandina Caldera, Galapagos Is. | 6/11/1968 | 20 earthquakes with magnitudes between 3.9 and 4.6 located nearby by USCGS during first week of June | Simkin and Howard (1970) |
| Merapi, Indonesia | 1/7/1969 | Greater than 2 orders of magnitude increase in seismicity was recorded beginning approximately 3 weeks prior to the eruption. | Shimozuru et. al. (1969) |
| Deception Island, Antarctic | 2/21/69 | Daily felt tremor began on Feb. 14 and increased up to time of eruption. | Smithsonian Institute, Event 17-69, Card 423, 1969 |
| Bezymianny Volcano, Kamchatka, USSR | 10/11/69 | Recorded earthquakes increased for 2 months leading up to the eruption. | Smithsonian Institute, 1969, Event 135-69, Card 822 |
| Taal, Phillippines | 10/28/1969 | Eruption was preceded by recorded earthquake swarm. | Troncales (1970) |
| La Palma Island, Canaries | 10/26/71 | Eruption started after several days' microseismic activity. | Smithsonian Institute, Event 90-71, Card 1305, 1971 |
| Sakurazima Vol-cano, Japan | 10/27/72 | Swarms of shallow recorded earthquakes occurred after a volcanic explosion on Oct. 6 and before another eruptive period beginning this date. | Smithsonian Institute, Event 60-72, Card 1487, 1972 |
| Asama Volcano, Japan | 2/1/73 | First major activity for 11 years. Minor eruption 8 years ago | Smithsonian Institute, Event 19-73, Card 1565, 1973 |
| Tiatia Volcano, Kuriles | 7/14/73 | Eruption preceded by a series of earthquakes of "considerable magnitude." | Smithsonian Institute, Event 92-73, Card 1684, 1973 |

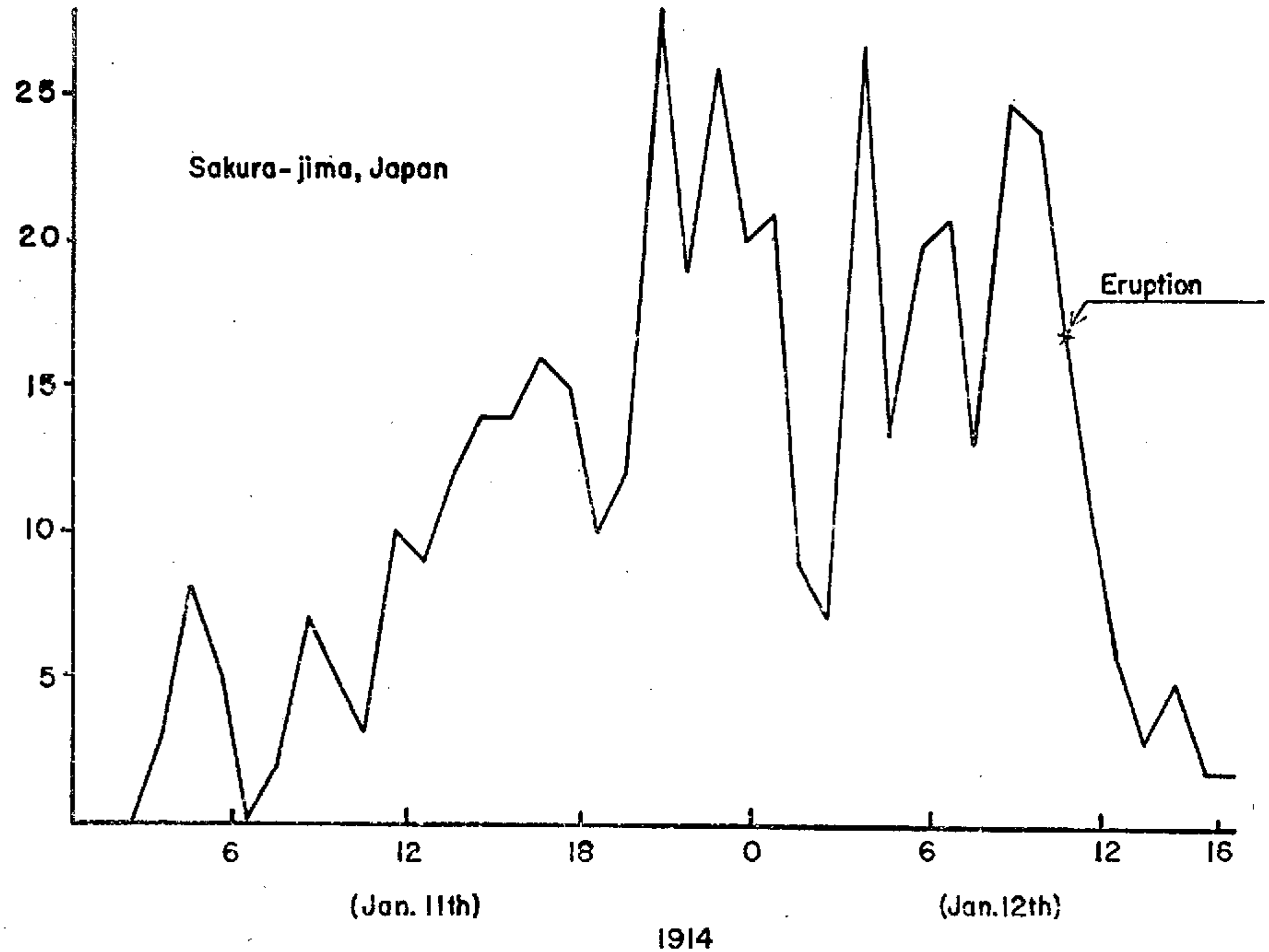


FIGURE 5.1. Number of earthquakes per hour preceding the Sakura-jima eruption of 12 January 1914 in Japan (after Omori, 1914). The instrument had a gain of 10 and was located about 11 km from the volcano.

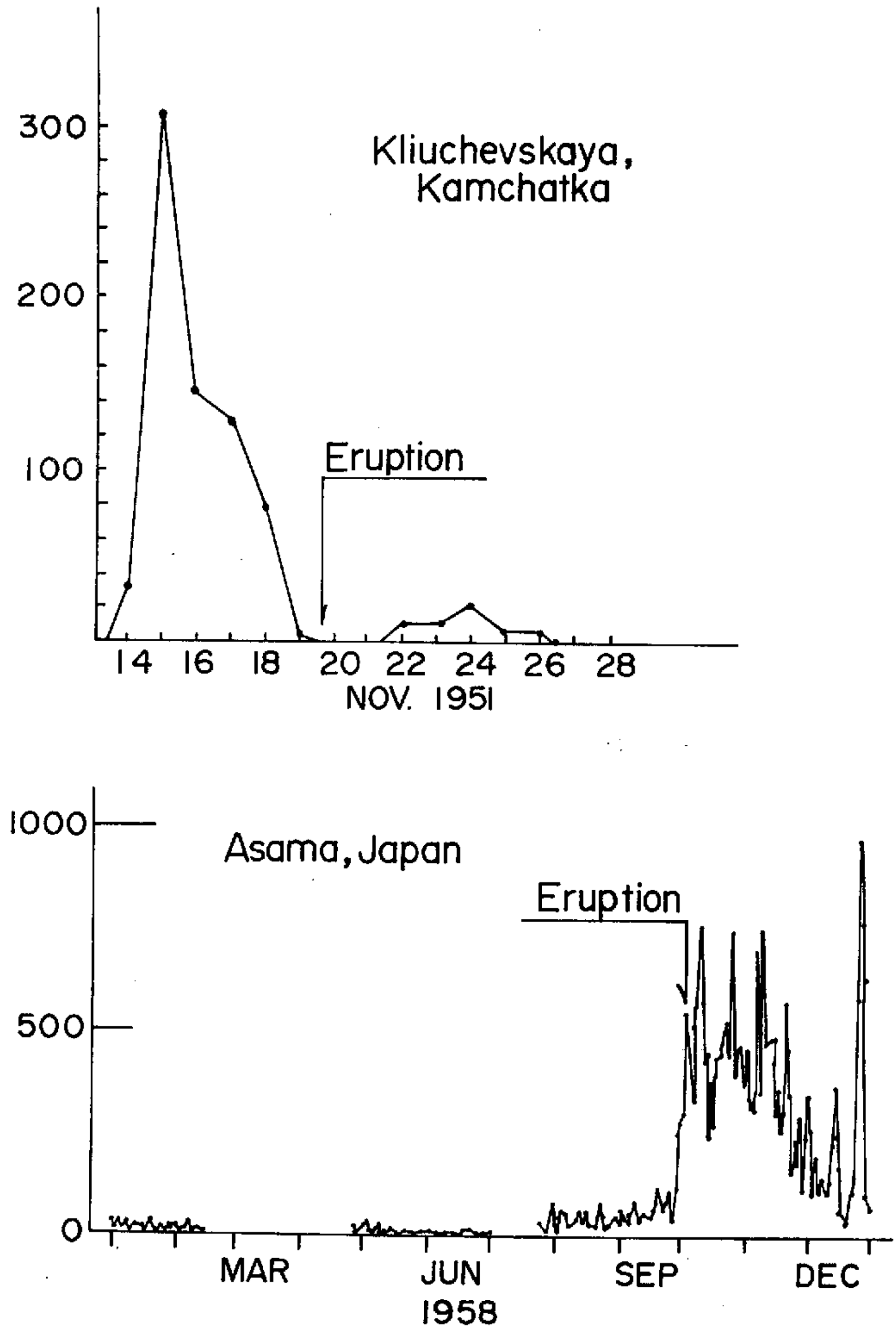


FIGURE 5.2. Number of earthquakes per day prior to the eruptions of Kliuchevskaya on 19 November 1951 (Gorshkov, 1960) and Asama on 3 October 1958 (Minakami, 1960). The instruments had gains of 10,000 and 4,000 and were located 30 km and 2 km respectively from the centers of the volcanoes.

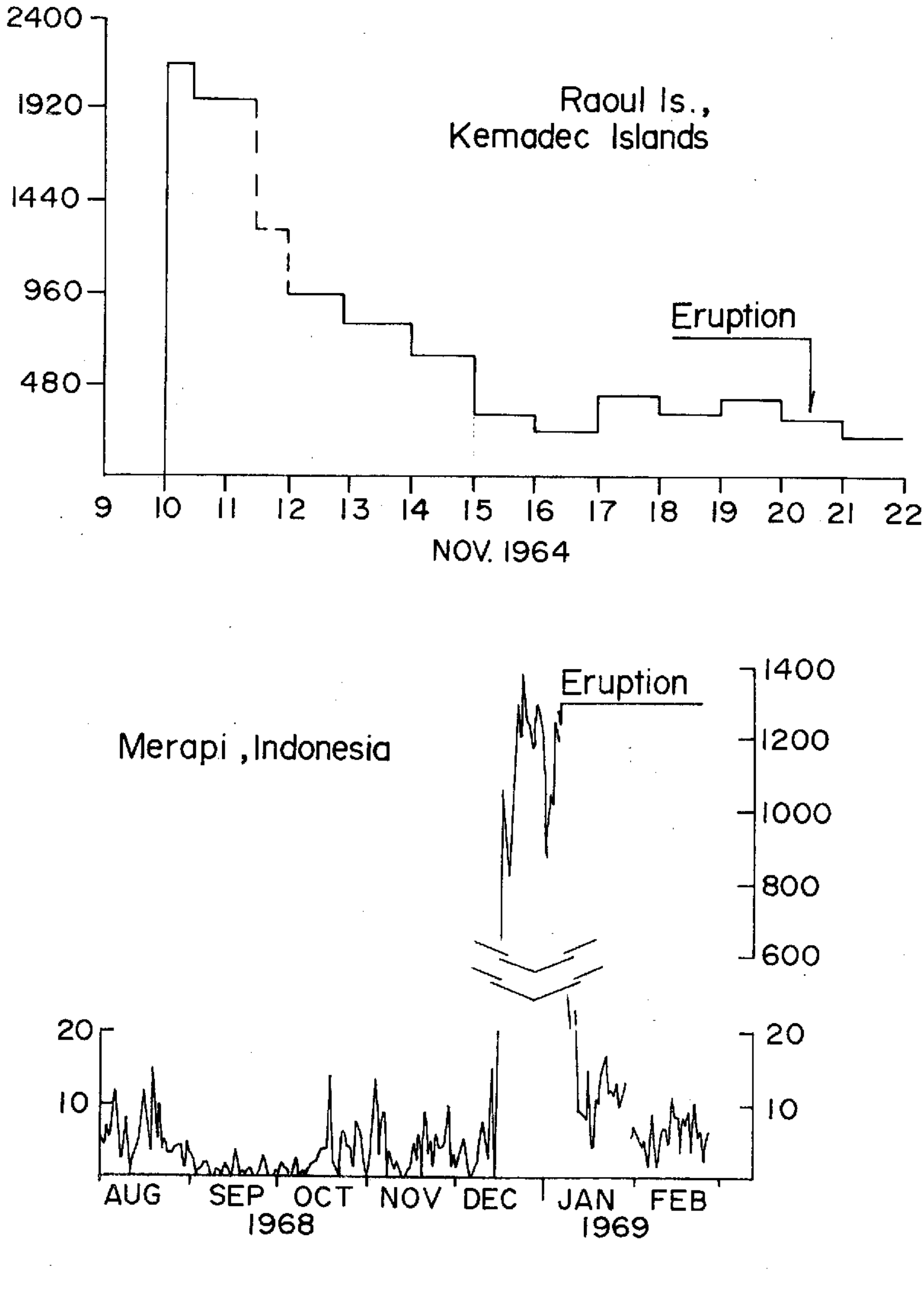


FIGURE 5.3. Number of earthquakes per day prior to the eruptions of Raoul Island on 20 November 1964 (Adams and Dibble, 1967) and Merapi on 7 January 1969 (Shimozuru *et al.*, 1969). The instruments had gains of 4,700 and 15,000 and were located 2 km and 3 km respectively from the centers of the volcanoes.

The time between an increase in seismicity and an eruption also seems to vary with the sensitivity of the seismographs and the size of the eruption. The few data available suggest that an increase in seismicity could be detected by high-gain seismographs days to months before earthquakes are felt or recorded by low-gain instruments.

A few cases have been reported of eruptions that were not preceded by perceptible earthquakes (Kizawa, 1952; Cucozza-Silvestri, 1949; Cumin, 1954; Minakami and Sakuma, 1953). In some of these cases no seismometers or very low-gain seismometers were used so that the seismic observations are inadequate. In the other cases the so-called eruptions were either short phases of activity during a larger eruption or were minor outbreaks of fume or pyroclastics of no danger even to persons living high on the side of the volcanoes.

Some earthquake swarms at volcanoes are not associated with eruptions (Shepard et al., 1971; Minakami et al., 1969; Gorshkov, 1960) so that increases in seismicity can not be used to predict specific eruptions. Nevertheless the swarms do indicate an increase in activity in volcanic regions and are a reliable indicator of a reawakening of volcanic activity. Continued research spurred by the rate of data collection now possible with the ERTS system should allow considerable refinement in our understanding of how to predict eruptions on the basis of seismic activity particularly now that identical instruments can be operated on a wide variety of volcanoes.

## 5.2 Tilt of the Ground before Volcanic Eruptions

Observations of surface deformation around volcanoes date from about 1904 (Omori, 1907) with the most detailed observations in Japan and Hawaii. Most of the early reports were based on precise geodetic leveling surveys repeated at intervals of years and usually re-run shortly after an eruption. Typical tilts associated with eruptions were up to 1000 microradians for Sakura-jima(Omori, 1914-1922); 300 microradians for Miyake-Sima (Omote, 1950 and Minakami, 1950). One microradian of tilt is 1 mm of elevation change per kilometer of distance. The spacial distribution of surface deformation can be delineated by leveling surveys, but the data can only show that tilt of a certain magnitude was associated with an eruption without showing for sure whether the tilt changes occurred before or during the eruption. Precise geodetic surveys are expensive so that they can normally only be made sporatically. Thus continuous monitoring of ground tilt is necessary before this phenomena can be used to provide an early warning of eruptions.

An excellent example of early continuous tilt measurements is shown in Figure 5.4 from Minakami (1942) who studied the relation of tilt on Asama volcano to explosion swarms. Minakami concludes, ". . . we find that marked variations in tilt appeared associated with every one of these explosion swarms. In comparing the times of occurrence of these two phenomena, we find the very marked fact that the first explosion of an explosion-swarm occurred one or one-and-a-half months after the appearance of abnormal tilt."

Eaton and Murata (1960) demonstrated with detailed tilt records from short based water level tiltmeters at many sites around Kilauea Caldera in Hawaii that tilts of 300 microradians accompanied the 1959 eruption and that the rate of tilt increased very significantly in the weeks preceding the first visible eruptive activity. Similar swelling of the volcano

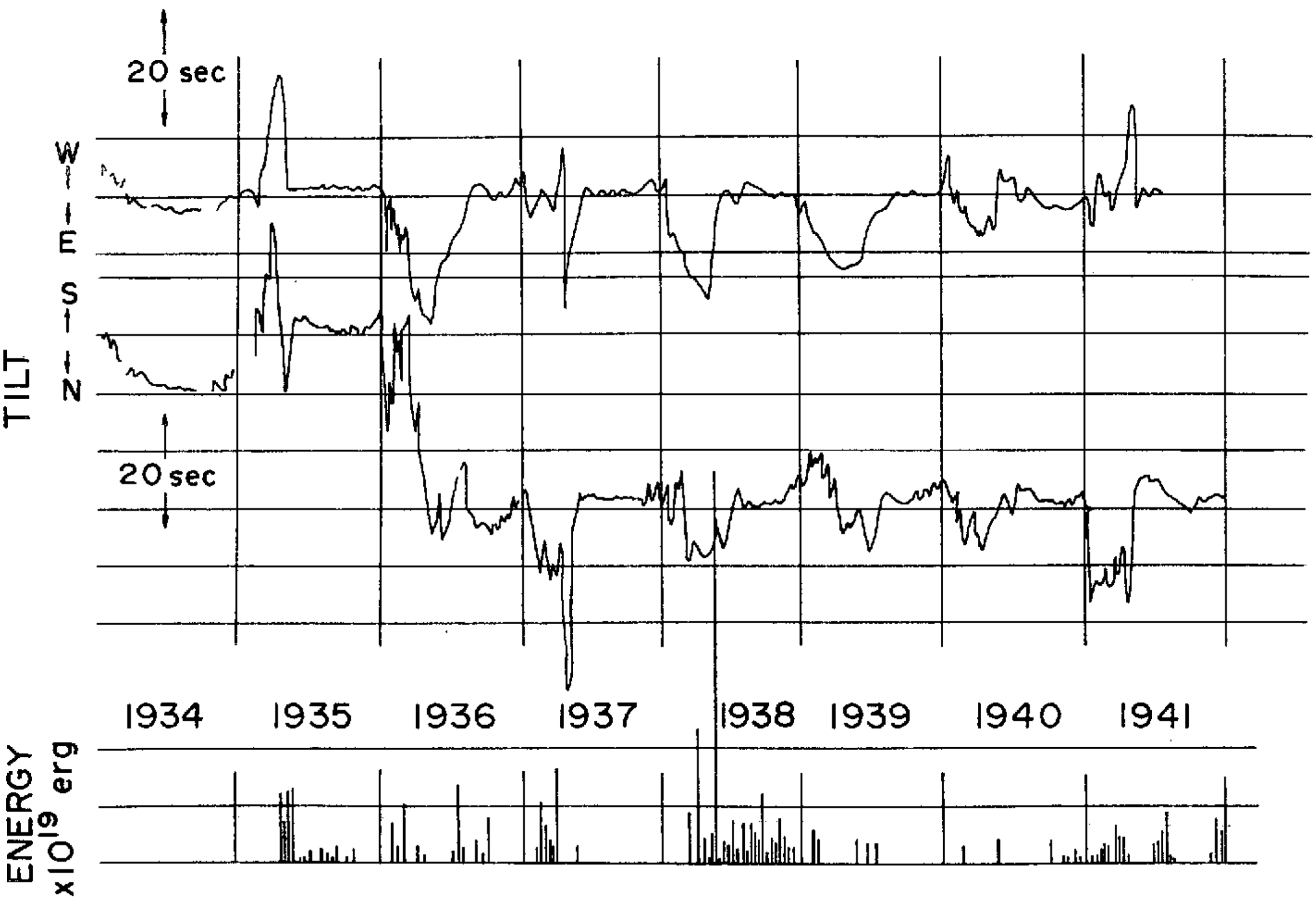


FIGURE 5.4: Tilting of the earth's surface at Nakanosawa, and the sum of the explosion energies for every ten days (after Minakami, 1942).

occurred prior to the 1961 eruption (Figure 5.5) (Richter *et al.*, 1964).

These few examples of the presently available data illustrate how volcanoes have been observed to swell prior to eruptions apparently in response to magma being intruded at comparatively shallow depth under the mountains. An excellent summary of these phenomena is provided by Decker and Kinoshita (1971).

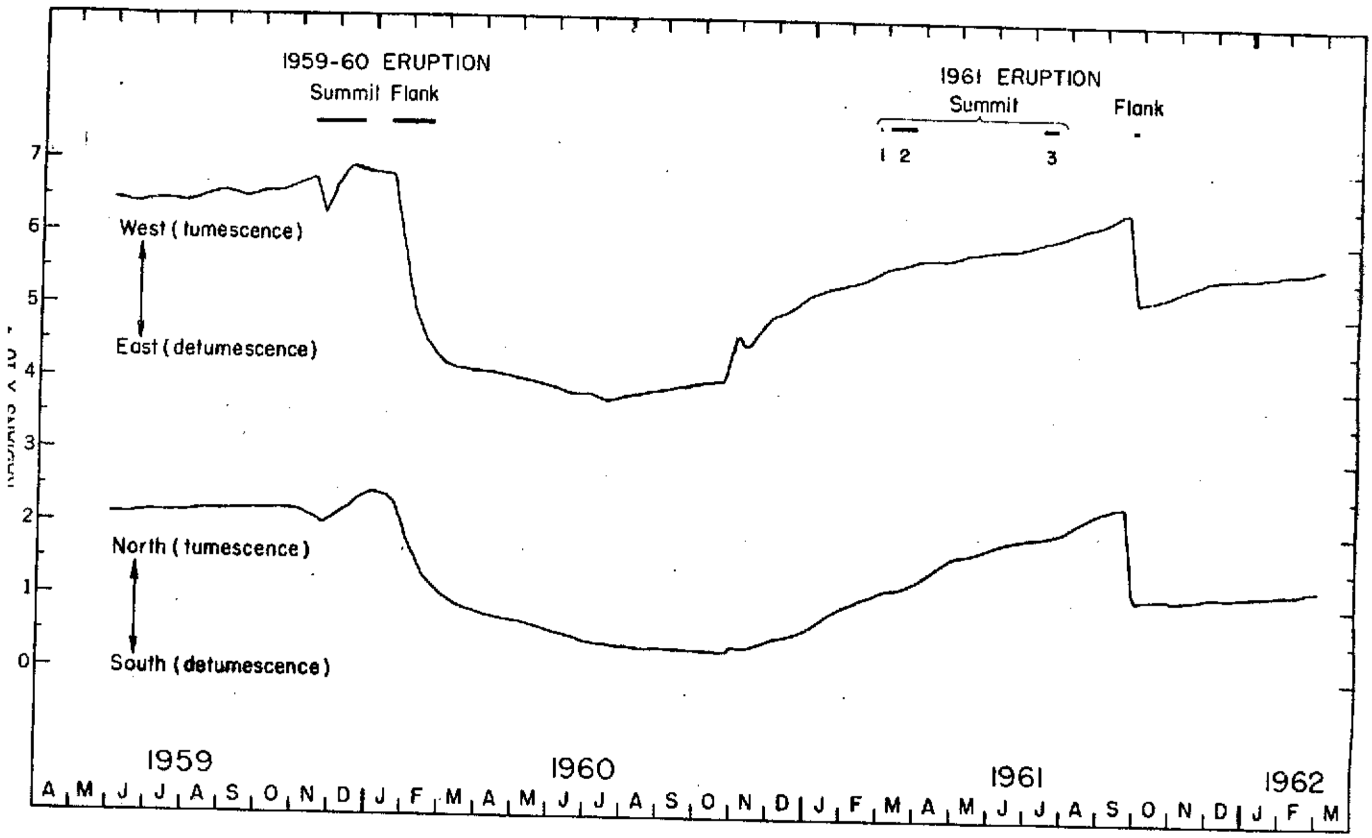


FIGURE 5.5. Ground tilting of the Kilauea summit area as indicated by daily readings of the short base water-level tiltmeter at Uwekahuna from late 1959 to early 1962. Periods of eruption (actual extrusion of liquid lava) are shown by bars at the top.

## 5.3 Other Types of Instrumental Observations

Measurements of fumarole temperature, pressure, and gas composition have been reported by several authors (e. g. Stoiber and Rose, 1970; Meniaylov and Nikitina, 1967; Noguchi and Kamiya, 1963; Moxham, 1971; Tazieff, 1971; and Tonani, 1971). These techniques have not been extensively developed. Methods for measuring temperature and gas analysis are being developed for use with ERTS by Jules Friedman and Moto Sato respectively of the U. S. Geological Survey.

Yokoyama (1971) summarizes gravimetric, magnetic and electric methods used around volcanoes. None of these methods have proved particularly useful for providing early warning of eruptions. Johnston and Stacey (1969) discuss a volcano-magnetic effect and show that "a magnetic anomaly built up over a period of days before the April 1968 Ruapehu eruptions, but no more than a few hours' notice seems possible from the" record of the 1968 Ngauruhoe eruption.

Thus the most promising and proven methods now available for continuously monitoring the level of activity of volcanoes are recording seismicity and tilt. These two methods are complementary and together seem to provide a reliable indication of the level of activity at a given volcano.

## 6.0 INSTRUMENTATION

### 6.1 Seismic Event Counters

#### 6.1.1 A brief history of seismic event counters

An ingenious device to count the duration of seismic shaking for one or a series of earthquakes was built by Perret (1937). This instrument used three pedometers mounted in orthogonal directions to tally the total amount of strong ground motion in the vertical and two horizontal directions.

Different types of earthquake detectors have been developed by many different seismologists primarily to set off an alarm or to trigger a high speed chart recorder or tape recorder to record only earthquakes. The first use of such circuits to count the number of earthquakes that we are aware of was by Decker (1968). He, with the help of the Geotech Division of Teledyne Industries, Dallas, Texas, built a single channel event counter consisting of a geophone with 1 second period, a three-stage transistorized amplifier, a rectifier, integrator, and relay meter that actuates a mechanical counter when a preset voltage is attained. A time-delay circuit adjustable from several seconds to a few minutes prevents the instrument from counting the same event more than once. This system was self-contained in a small box and operated 90 days unattended on an internal battery. Decker tried this instrument on volcanoes in Hawaii, New Zealand, the Philippines, and Iceland and also operated it in Nevada with good comparison of the counts to the numbers of earthquakes observed in nearby seismographs in Hawaii and Nevada. He found some problems with spurious counts caused primarily by wind and cultural noise. Two of these instruments have been used for several years on volcanoes in Central America. While they do count earthquakes, the occurrence of many spurious counts from wind and cultural noise raises significant question about the reliability of these single channel counters. Furthermore the system, as designed, must be read manually.

T. Matumoto at Lamont-Doherty Geological Observatory, Palisades, N. Y., expanded on Decker's early work by building in 1966 four similar counters set at different levels and mounted with a camera and clock for recording the data daily. The multilevel counter gives a good check on the quality of the counts because earthquakes are usually distributed in size according to a well known logarithmic relation.

A group under G. Latham also at Lamont-Doherty Geological Observatory experimented with different designs of these four level counters in the late 1960's with thoughts of interfacing them to a satellite telemetry system. Kinemetrics, Inc., San Gabriel, California, built a prototype multi-channel event counter in 1970 in consultation with the U.S.G.S. This instrument displayed the feasibility of the multi-channel design using analog circuits and mechanical counters.

In 1971, J. Unger of the USGS had six multichannel event counters built as a prototype for use with ERTS. These were built after competitive bidding by Systron-Donner Corporation, Inertial Division, Concord, California (Photo 1). They used a geophone with a natural frequency of 4.5 hz, an amplifier-filter, a precision rectifier and comparators that triggered four different sets of mechanical counters. A 15 second delay was incorporated that prevented the counters from triggering more than once every 15 seconds. This was altered later to prevent counts unless the signal had been below that level for 15 seconds prior to the event. These units were built to interface with the parallel digital input of the ERTS transmitters. These multilevel counters detected earthquakes well during tests in Hawaii but they also counted a significant number of spurious events.

Bendix Aerospace Systems Division, Ann Arbor, Michigan, had bid on building the six event counters and decided to proceed to build a counter of their own design and at their own cost. They provided one of these for testing in Hawaii. This unit used digital counters and logic and introduced the idea of counting periods of high background noise. This idea provided a new way to flag spurious event counts and to give some estimate of the reliability of the different count totals.

When it became clear in late 1971 that the prototype volcano surveillance system would probably be funded, we set out immediately to draw up specifications for new event counters based on the experience from the designs discussed above. Two months were spent evaluating previous designs, discussing the basic design principles, and drawing up detailed specifications aimed at specifying exactly what was needed but in a way flexible enough to allow new ideas to develop during the bidding and bid evaluation stages. Funds were still not available from NASA but it was realized that any further delay would prohibit the installation of equipment in the Cascades and Alaska before winter. Thus with the aid of a loan from the EROS Program of the USGS, a Request For Proposals was sent out on March 10, 1972. Six proposals were submitted on April 21, 1972.

These proposals were carefully reviewed with detailed questions sent back to the bidders asking for clarifications. On May 26, 1972, a contract for 22 event counters was awarded to Electra-Physics Co., Folsom, California, who had showed considerable understanding of the scientific need, had provided the best tradeoff between cost and reliability, and had suggested several novel innovations in the design including the use of a thermal printer. The first event counter was available for testing in early September, 1972, less than two months after NASA finally awarded the contract to us for this program.

6.1.2 Design of the event counters used in this experiment

The event counter built for this experiment is shown in Photos 2, 3, and 4. The basic requirements for the design included the following:

1. As few moving mechanical parts should be used as possible to improve reliability, especially at low temperatures.

2. The electronics should be sealed in a water-tight and air-tight case with an enclosed drying agent.

3. A printer should be included for recording the data should the satellite fail or should operation be desired in a region out of range of the satellite.

4. Power consumption should be as low as practical.

5. Reliability is the primary requirement and thus proven techniques of design and construction should be used wherever possible.

6. The counter should be rugged and light for use in the field in remote locations.

The physical characteristics of these counters are as follows:

SIZE:

| | |
|---|---|
| Counter | 25.4 cm. (10-inches) High;<br>35.6 cm. (14-inches) Wide;<br>30.5 cm. (12-inches) Deep |
| Geophone Assy. | 7 cm. (2-3/4-inches) Diameter;<br>8.25cm. (3-1/4-inches) Long;<br>0.95cm. (3/8-inch) Diameter 6 Conductor Cable<br>7.6 m. (25-feet) Long |

WEIGHT:

| | |
|---|---|
| Counter | 9.75 kg. (21-1/2 pounds) |
| Geophone Assy. | 1.47 kg. ( 3-1/4 pounds) |
| Transmitter Cable | 0.34 kg. ( 3/4 pounds) |

POWER REQUIREMENTS:

| | |
|---|---|
| Voltage | 24 Volts DC tapped at 12 V and 6 V |
| Power Consumption | 50 Milliwatt Hours/Day |

OPERATIONAL ENVIRONMENT:

| | |
|---|---|
| Temperature | -40 to +60 Degrees C; (-40 to +140 Degrees F) |
| Altitude | -60 to 5400 m. (-200 to +17,500 Feet) |
| Humidity | Up to 100% (with condensation) |

The event counter counts seismic events of four different sizes separated in amplitude by a factor of 4. The criteria for an event to be counted are that 10 peaks of a full-wave rectified seismic signal must occur above a given threshold in 1.2 seconds and there must have been no peak above that threshold for the previous 15 seconds. If the seismic background noise increases so that peaks occur at least once every 15 seconds above a given threshold, the duration of this condition is counted in minutes on separate "inhibit-time" counters.

The electronics will be divided into an analog and a digital section for explanation of the detailed design.

The analog section includes the electronics from the transducer amplifier to the output of the threshold detectors. A simplified schematic is shown in Figure 6.1. Amplifiers A1 through A5 are operational amplifiers. They are used because the gain of operational amplifiers depends on the value of the feedback resistors and are virtually immune to power supply voltage, temperature, and variations in manufacture. Amplifier A1 is in the transducer. It is operated at a gain of 32 db. Resistor $R_i$ provides 0.8 critical damping of the transducer. This configuration provides the best signal-to-noise ratio since all the transducer power is applied to the input of the amplifier. High frequency rejection above 25 hz is controlled by $C_f$ in the transducer feedback loop and $C_f^1$ in amplifier

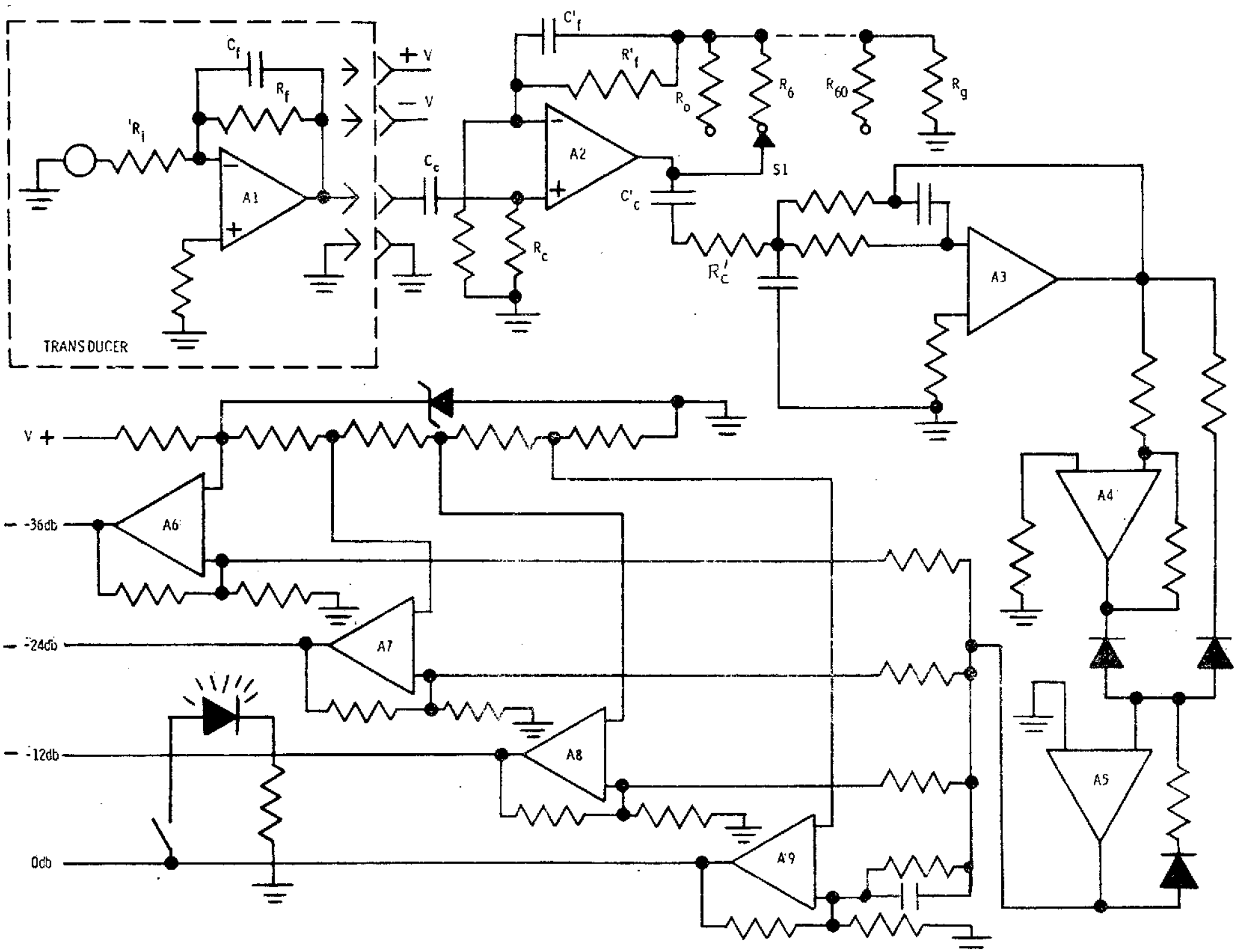


FIGURE 6.1. Event counter analog section, simplified schematic.

A2. Each provide 6 db/octave roll off for a total of 12 db/octave. The low frequency rejection of 12 db/octave below 1 Hz is provided by the RC coupling circuits $C_c$, $R_c$ and $C_c^1$, $R_c^1$. Gain is controlled in the feedback loop of A2. This configuration provides for a uniform input impedance to A2. An additional high frequency rejection of 12 db/octave is provided by A3. The seismic response of the analog section is shown in Figure 6.2.

Because of the large dynamic range (36 db) over which the four threshhold detectors must operate, a precision absolute value circuit (A4 and A5) is provided. This configuration acts as an inverting amplifier with a gain of one for negative signals and a non-inverting amplifier with a gain of one for positive signals. Operational amplifiers with positive feedback are used as comparators with hysteresis (A6 through A9). This hysteresis prevents multiple output pulses from low level noise when the input signal dwells near the threshold level.

The digital logic is shown in Figure 6.3. A simplified schematic of the counter of each threshold detector is shown in Figure 6.4. The divide by 10 counter puts out one pulse for each 10 pulses that it receives. The first pulse starts a one shot delay set for 1.2 seconds. If 10 pulses (5 cycles full-wave rectified) are not received within 1.2 seconds, the counter is reset and no counting occurs in the memory register. The 1.2 second period provides for at least 5 full cycles at frequencies greater than 4.2 Hz.

The output of the divide-by-10 circuits starts a resetable 15 second one-shot. Each additional pulse restarts the one-shot so that it will inhibit for 15 seconds after the last pulse is received. Its design is different from the 1.2 second one-shot which resets 1.2 seconds after the first pulse is received.

The output of the 15 second one-shot inhibits further counting in the first gate. A second gate is connected to other inhibit circuitry.

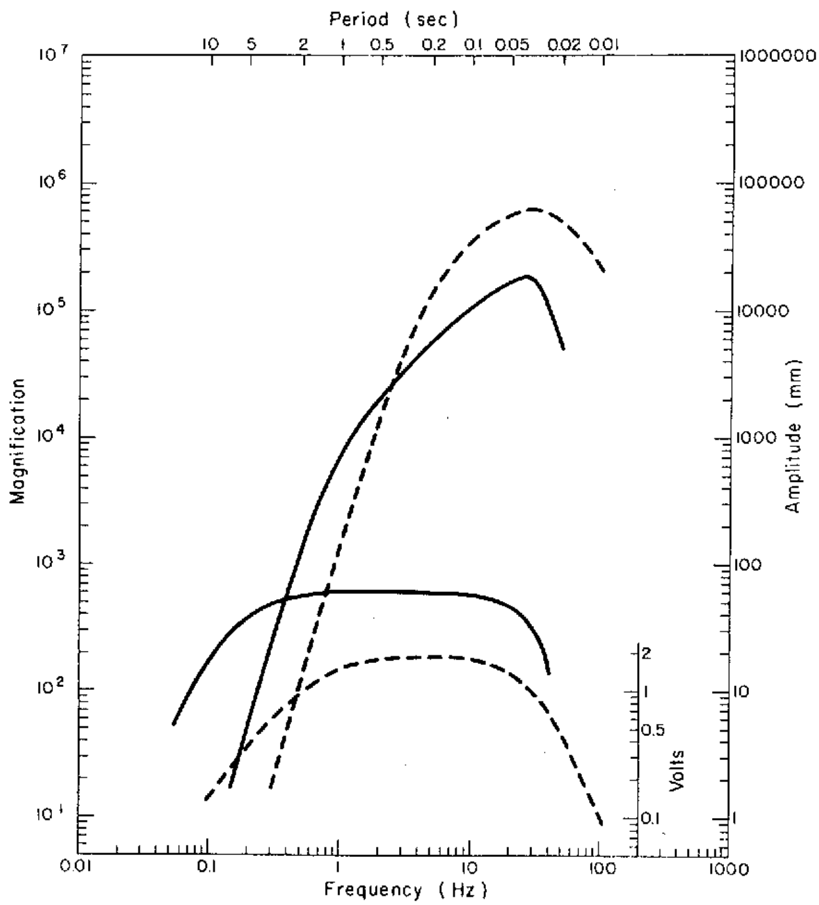


FIGURE 6.2. Frequency response curves for the multilevel, seismic event counters (dashed lines) and the high-gain, short-period seismographs (solid lines). The lower set of curves shows the response of the electronics and the upper set of curves shows the system response, including the displacement response of the geophone.

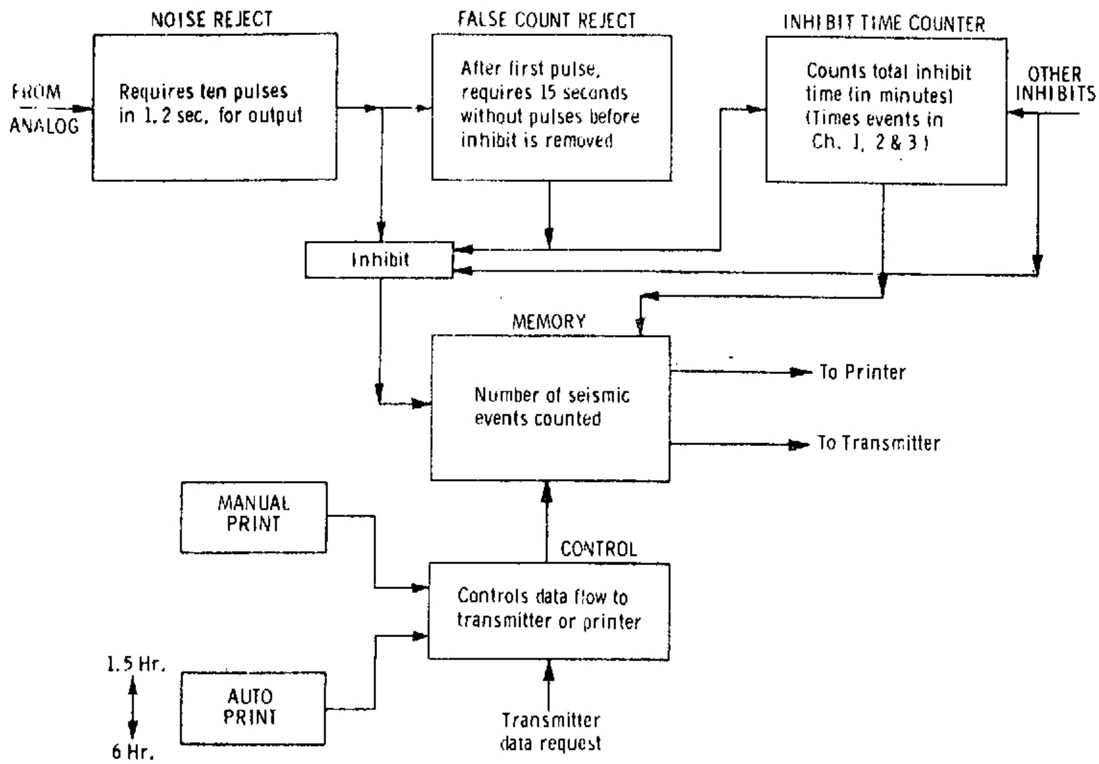


FIGURE 6.3. Digital logic, block diagram.

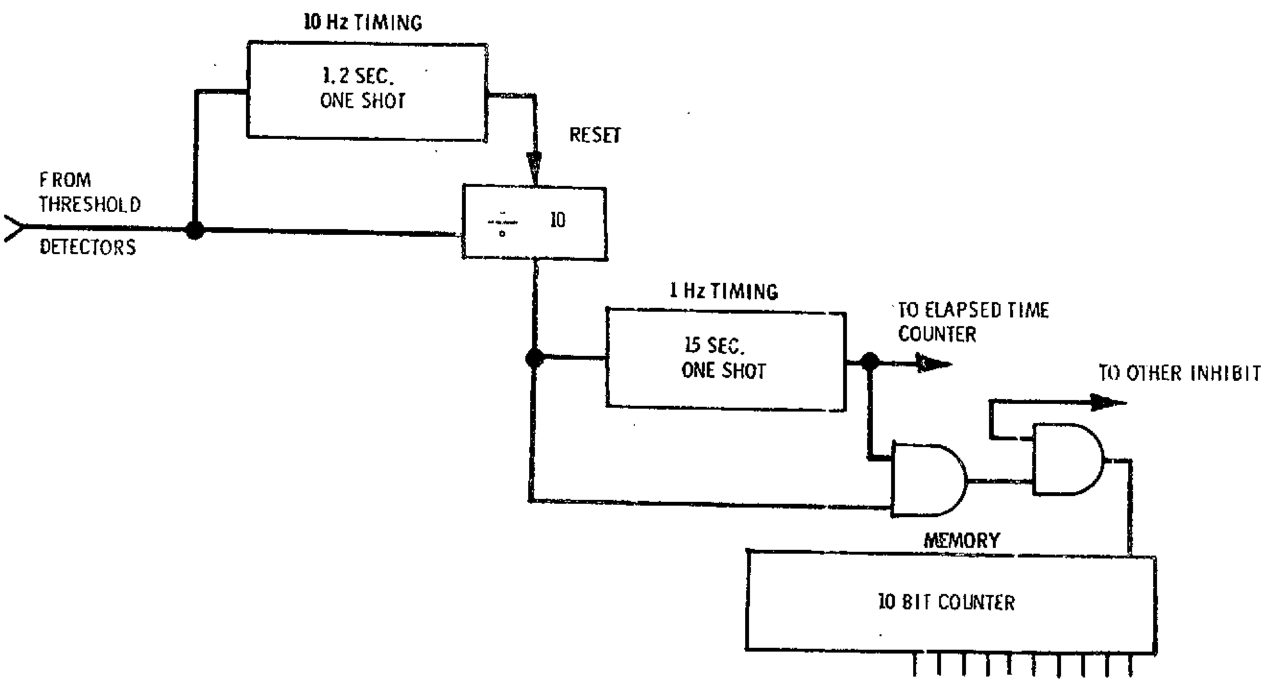


FIGURE 6.4. Noise reject and event counter circuit, simplified schematic.

This includes inhibit on transmit through a front panel switch and inhibit on the making of an external connection such as a signal from an anemometer during high wind or any time signal of interest. The gates are arranged so that no false pulses are counted. The output of three of the 15 second one-shots goes to the inhibit time counter (Figure 6.5). The inhibit-time circuitry utilizes one clock pulse every 10 seconds to ensure low power consumption with only 10 second ambiguity in the period for the first count. The inhibit must be on continuously for 1 minute to 1 minute 10 seconds before counting occurs. The output of the 6 counters and 3 most significant bits of the seventh goes to the transmitter through C-MOS/TTL level shifters. The power to the level shifters is gated "on" by the transmitter.

Principal elements of the recorder are a thermal printer, a thermographic paper tape cassette, and a solenoid operated tape advance mechanism. The only moving mechanical part of the event counter is the solenoid. The thermal printer has twenty discrete heating elements (a five row by four column matrix) which can be selectively energized to form permanent characters on thermographic paper. Printed data are arranged in two rows of 5 bits for each data word, and thus two parallel data channels must be generated. Printer channel one prints bits 1 through 5 of each data word and printer channel two prints bits 6 through 10. The printer logic is shown in Figure 6.6.

A cassette is provided that contains approximately 79m (260 ft.) of 0.635 cm (1/4 inch) wide thermographic paper tape. The cassette also contains a felt pad, spring loaded to provide a mating pressure between the printer and paper of approximately 0.7 $kg/cm^2$ (10 psi). This is the required pressure for adequate printing density. When the paper temperature exceeds its threshold of approximately 110° C (230° F) a black dot begins to form.

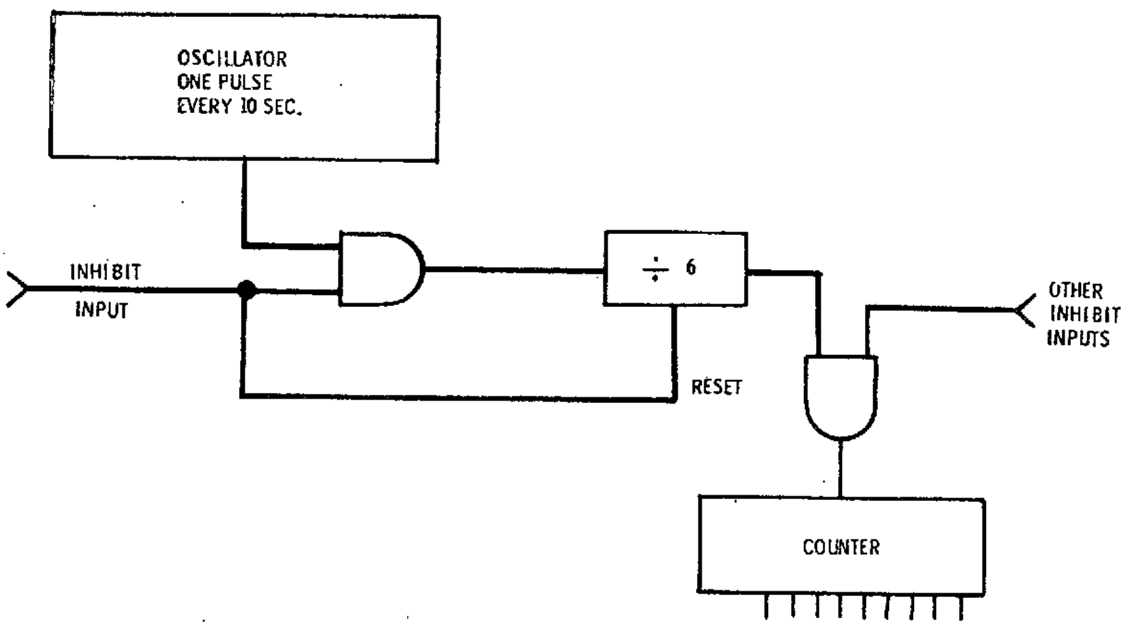


FIGURE 6.5. Inhibit time counter, simplified schematic.

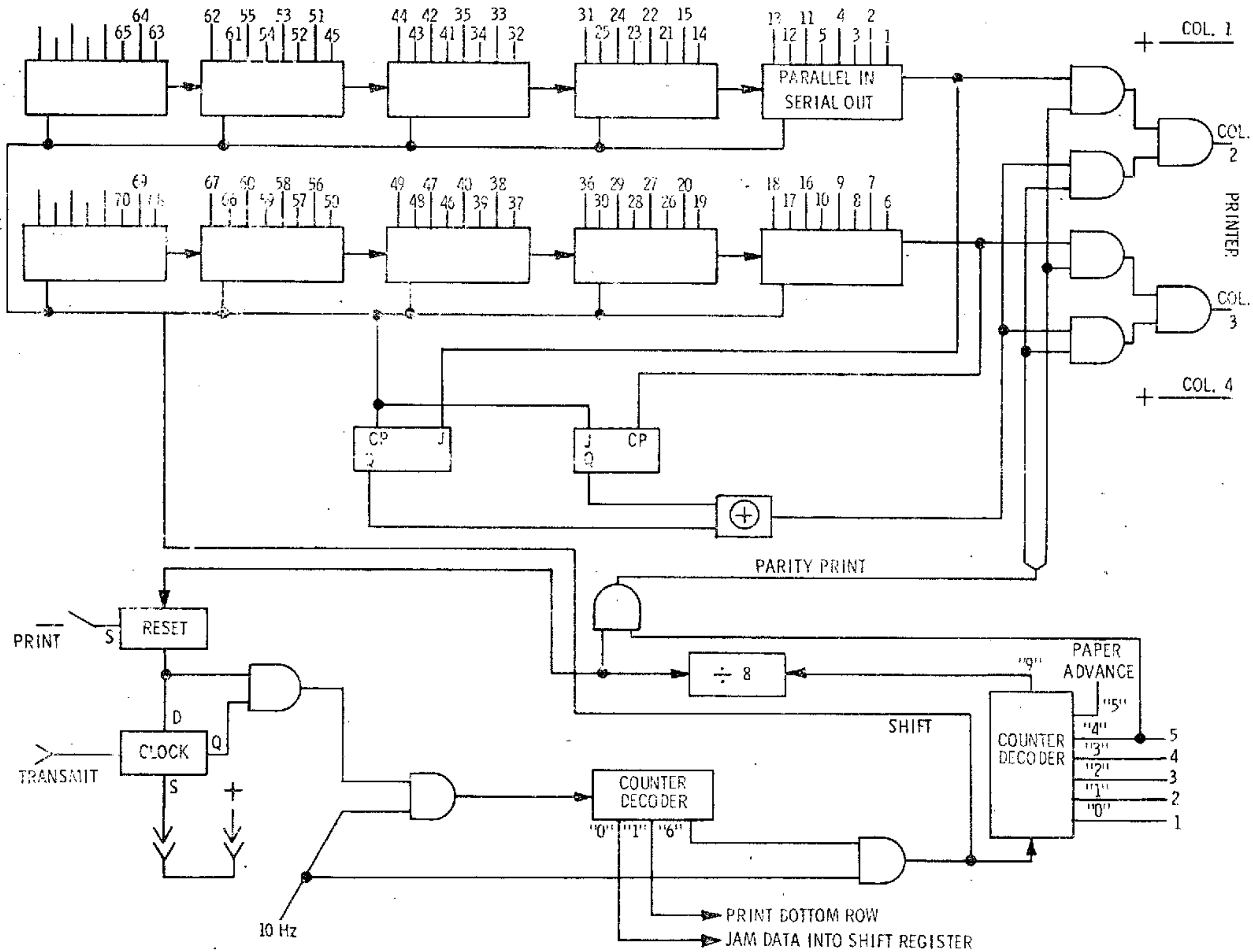


FIGURE 6.6. Event counter printer logic, simplified schematic.

Because of the thermal coupling required between the heated printer mesa and the paper, it is necessary to heat the mesa to a higher temperature. The peak temperature of an energized mesa is typically between 172° C (340° F) and 250° C (480° F). Approximately 12 milliseconds are required for the mesa to reach the required printing temperature. Tape advance is provided by a stepping motor geared to the shaft of the take-up reel. The stepping motor receives a pulse from charged capacitors C30, C49, and C50 after the thermal printer has been energized to print a data word. The tape is advanced one step after each of the first seven data words and twice after each eighth data word.

The tape output format is illustrated in Figure 6.7. The unit contains four counting channels with 12 db separation so that channel 1 is 0 db, channel 2 is 12 db attenuation, channel 3 is 24 db attenuation, and channel 4 is 36 db attenuation below the overall gain setting. The first four data words of a recorded data block are therefore the number of seismic disturbances since the counter was started with channel 1 being the most sensitive. Data for the three inhibit-time channels are printed for channels 1 through 3 in one minute increments. Channel 4 does not have a corresponding inhibit-time channel. At least one peak must occur above the amplitude threshold every 15 seconds for at least one minute in order to produce an inhibit time count. Though time channels 1 through 3 will record the full complement of 10 bits each, only 23 bits are transmitted. Time channel 3 transmits only the three least significant bits. Thus 63 data bits and a parity bit derived from these data bits are transmitted.

The last data word contains parity and time of day data. The parity bit is used to check validity of print out or transmission by indicating whether the total number of recorded bits in all channels is an odd or even number. The time of day bits are the first four double bits from the

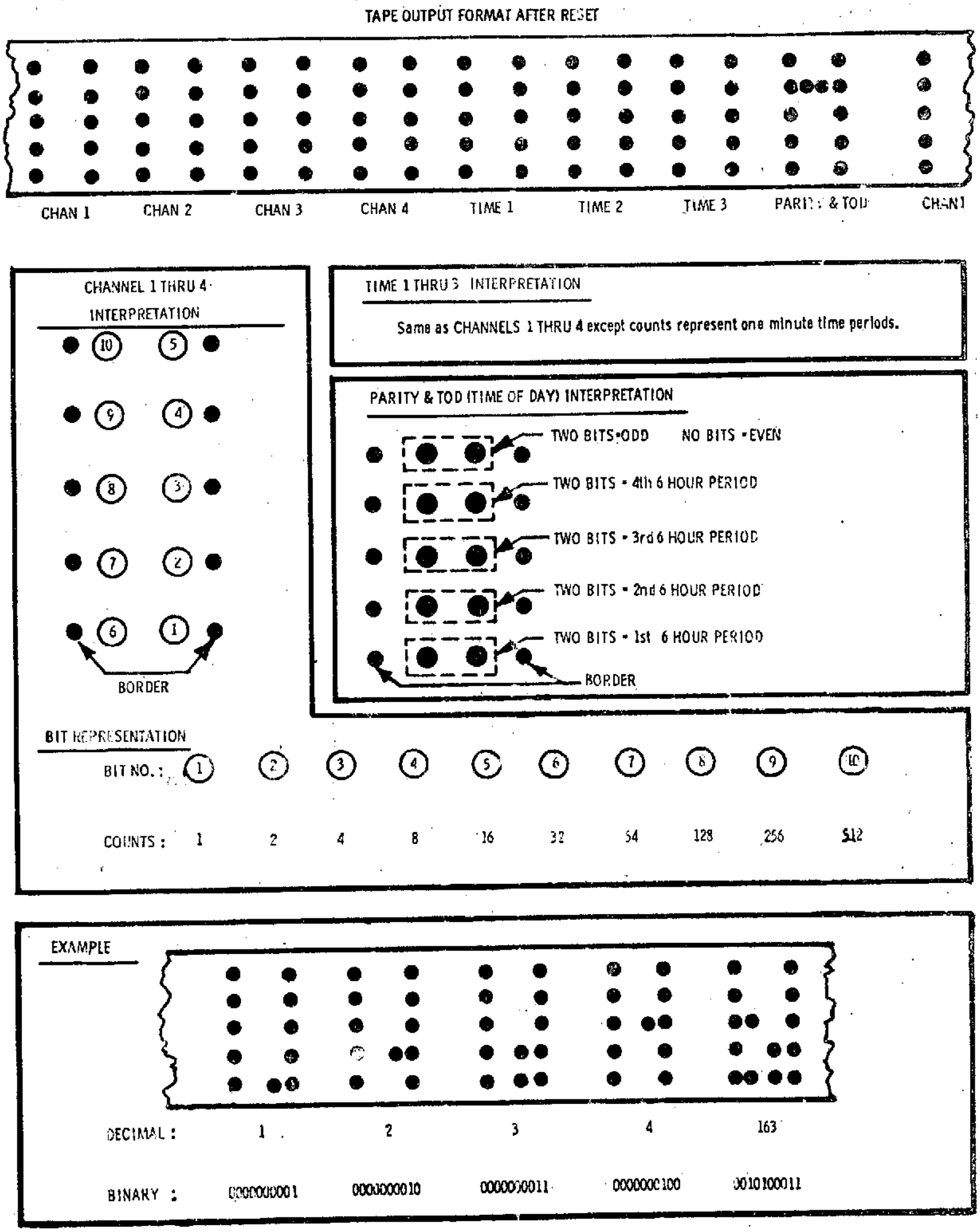


FIGURE 6.7. Data format and interpretation of the event-counter's printer tape.

bottom of the data word. The presence of a double data bit indicates the 6 hour period in which the print-out occurred. It should be noted however that these time periods do not correspond to the actual time of day. For example the first 6 hour period does not represent clock time from 12 midnight to 6 A. M. The unit has an internal clock which operates only when the unit is connected to an external power source. When the unit is connected and set for operation the COUNTER RESET switch is actuated, which resets the clock to the fourth 6 hour period. Recording the time of day when the unit is set up for operation is therefore important for subsequent data interpretation. In addition, when the unit is initially set up, the fourth 6 hour period will be a random time period of 7 hours or less.

The event counters contain one board of analog circuits, six of digital circuits and one for both power regulation and a simple clock circuit that utilizes a 100 hz solid state tone oscillator (Motorola K1000A Vibrasponder). The boards measure 12.1 by 21.9 cm. (8-1/2 by 4-3/4 in.) There are 117 digital integrated circuits in each counter. The electronics are housed in a rugged aluminum case with a tire valve for air pressure release and six military type environmental connectors. Twenty-three seismic event counters cost with development charges about $3760 each and could be reproduced at a cost of about $1900 each (1972 prices).

### 6.1.3 Verification of the seismic event counters

The seismic event counter is designed to process an analog seismic signal that would require about 20 million digital bits to represent twelve hours of data and to produce a rate of only 64 digital bits in the same time. Processing consists of counting the number of earthquakes with amplitudes greater than four discrete levels. This processing is accomplished by an electronic circuit designed 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, etc. 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 seismic noise.

In order to evaluate this reliability, 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 which, with the use of seven one shot timers, puts out DC pulses of varying length depending on which of the seven counters in the seismic event counter is activated at a particular time. The pulse widths range from 0.4 sec long for channel 1 to 4.1 sec long for channel 7. These pulses modulate a voltage controlled oscillator. The resulting signal is 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 gives a direct record of what the event counter is detecting.

Comparison of the data from the event counter printer with the corresponding number of pulses on the telemetered trace for 1.5 hour print intervals shows a one to one correspondence. Thus the special interface circuit works as designed and does not appear to introduce spurious data.

As expected all earthquakes with sufficient amplitudes and frequency content were counted. At 42 db attenuation the magnitudes of earthquakes counted only on the most sensitive detection level range from 1.1 to 2.5 and the magnitudes of earthquakes which were also counted on the 2nd 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. (The earthquake magnitudes were estimated from coda lengths because record amplitudes can not be accurately measured on these 16mm film records).

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. "Inhibit time" counts were also recorded during periods of wind and serve to indicate periods of probable high wind activity. "Inhibit time" counts in general were not triggered by passing vehicles. Therefore, it is important that sites be located away from sources of cultural noise to increase the reliability of the data.

This direct comparison of event counter data to standard seismic data shows that the event counter works as anticipated. Other comparisons of these types of data are given in Section 9.1 along with a summary of criteria necessary for interpretation of the event counter data.

## 6.2 Tiltmeters

### 6.2.1 A brief history of tiltmeters

The earliest measurements of tilt on volcanoes, as mentioned earlier, did not rely on tiltmeters but rather on repeated level-line surveys. The great weakness of this system is the large expense in re-leveling a long line and the absence of a continuous record of tilt at a desired measurement point. The strength of the system is that data thus acquired are undoubtedly representative of ground motion over a large area.

Tiltmeters for measuring tilt at a given location fall into one of two types.

The first type measures elevation differences of two points some meters or tens of meters apart using the surface of a liquid to define an equi-potential or level surface. In practice this is usually accomplished by placing containers on two piers and linking them with a tube. The containers and connecting tube are then filled with a liquid and level changes of the system are measured by noting the differential movement of the liquid level in the two end containers. This instrument is in a sense a very short level line capable of being read to a higher degree of precision than is possible with surveying techniques.

The second type of tiltmeter measures changes in attitude with respect to local gravity vertical of the support on which it rests, and is essentially a point-measurement device. Early meters of this type were adaptations of the horizontal-pendulum seismograph and were used for investigations of geophysical phenomena at least as early as 1904 by Omori (1907). These horizontal pendulum instruments were continually refined in design and construction and later versions are typified by the Ishimoto clinometer, constructed entirely of fused silica in an attempt to minimize instrumental response to ambient temperature variations.

These Ishimoto clinometers were used by various investigators including Minakami (1942) and Hagiwara, et al. (1951).

Hagiwara and his coworkers compared their results obtained by horizontal pendulums with those from a long-base liquid-level instrument in the same vault and concluded that the long-base instrument was greatly superior due to its immunity to very small shifts of the instrument mounting piers.

The most accurate and generally useful long-base design is probably that described by Eaton (1959). This is a portable liquid-level instrument using water as the reference liquid and with a base length of 55 m. With careful attention to details of measurement it is possible to use this instrument at surface sites and to occupy several sites in one night, making it practical to carry out detailed surveillance of an area on a periodic basis.

Minakami (1942) made observations on Mt. Asama between 1934 and 1941 with two Ishimoto fused quartz horizontal pendulums. Results at one of these sites were very unsatisfactory, due, according to Minakami, to the "structure of the ground." At the Nakanosawa station, however, he obtained sufficient stability in instrumental drift to provide an excellent long-term record, as may be seen from figure 5.4.

These results suggest that it should be possible to obtain satisfactory results from "point measurement" tiltmeters if sufficient care is exercised in picking sites for their operation. Such meters are significantly easier to install and maintain than the long-base type instruments.

At the U.S.G.S. a tilt measurement and tiltmeter development program has been under way since 1966. The first effort was in medium-base liquid level instruments (length 5 m.) similar in design to the long-period seismograph developed by Benioff (1965). This instrument makes use of mercury as the leveling fluid, and a continuous record of tilt is obtained by monitoring the relative levels of the two end pots with a capacitive distance sensor mounted immediately over the mercury surfaces. Two of these tiltmeters are operated at each location, one to measure E-W tilt and one N-S tilt. Two sets of these instruments have been operated successfully in the San Francisco Bay area for about six years. Their operational characteristics and some of the results derived were described by Wood and Allen (1971).

The extreme temperature sensitivity of tiltmeters has been a continuing obstacle to their wide use in field environments, since most of those previously mentioned require temperature-stable vaults for successful operation. The simplest and cheapest way to achieve temperature stability in arbitrary locations is to bore a hole several meters deep, place the instrument at the bottom, and cover it with earth. Several commercially-built tiltmeters have been constructed for borehole operation, but until recently all were prohibitively expensive and their power requirements were far too high for use in battery-powered applications in remote field locations.

A tiltmeter whose design was aimed at fulfilling requirements for a field instrument was developed by Allen (1972) of the USGS, and techniques for site selection and emplacement have been extensively investigated by Allen (1972) and Allen, Wood, and Mortensen (1973). This original instrument met several of the requirements but still had problems of temperature sensitivity and calibration, and the fully assembled instrument was too delicate to take rough handling during transport. Before these problems could be solved the Autonetics Bubble-Level Tiltmeter became available, and it demonstrated such clear superiority in all respects that the effort was changed from developing instruments to developing emplacement techniques.

### 6.2.2 Design of the tiltmeter used in this network

The Autonetics tiltmeter was originally developed in the late 1950's as a part of an inertial guidance system and is the result of a very extensive development program. Many of the details of fabrication and test of this meter are proprietary, but some discussions of the instrument have been published by Cooper (1970), Kohlenberger, Cooper and Schmars (1973), and Cooper and Schmars (1973). The heart of the instrument is a bullseye level bubble whose liquid is a conductive electrolyte. The position of the bubble is sensed by means of very sensitive resistance measurements between orthogonal pairs of sensing electrodes in the upper surface of the fluid chamber and a common electrode in the bottom of the fluid chamber.

Figure 6.8 (after Kohlenberger et al., 1973) is a cutaway drawing of a bubble sensor, illustrating the internal geometry of the bubble and electrodes. The sensor is about 2.5 cm. (1 in.) in diameter and is less than 1.8 cm. (0.75 in.) thick. The inner top surface is an optically prepared concave surface with a 30.5 cm. (12 in.) radius of curvature. The bubble rests in equilibrium against the concave surface masking portions of the four strip electrodes on the cap. A common electrode is connected to the bottom of the fluid cavity and the electrodes are connected in orthogonal pairs in an AC electrical bridge configuration (Figure 6.9). In effect, the sensor acts as a slightly overdamped fluid pendulum that has a resonant period of approximately one second. The electronic package uses 650 milliamperes of power from $\pm 12$ volt power sources. The tilt resolution is limited by the Brownian noise and input noise of the amplifiers at approximately $6 \times 10^{-9}$ radians/Hz$)^{1/2}$. Referring to the block diagram shown in

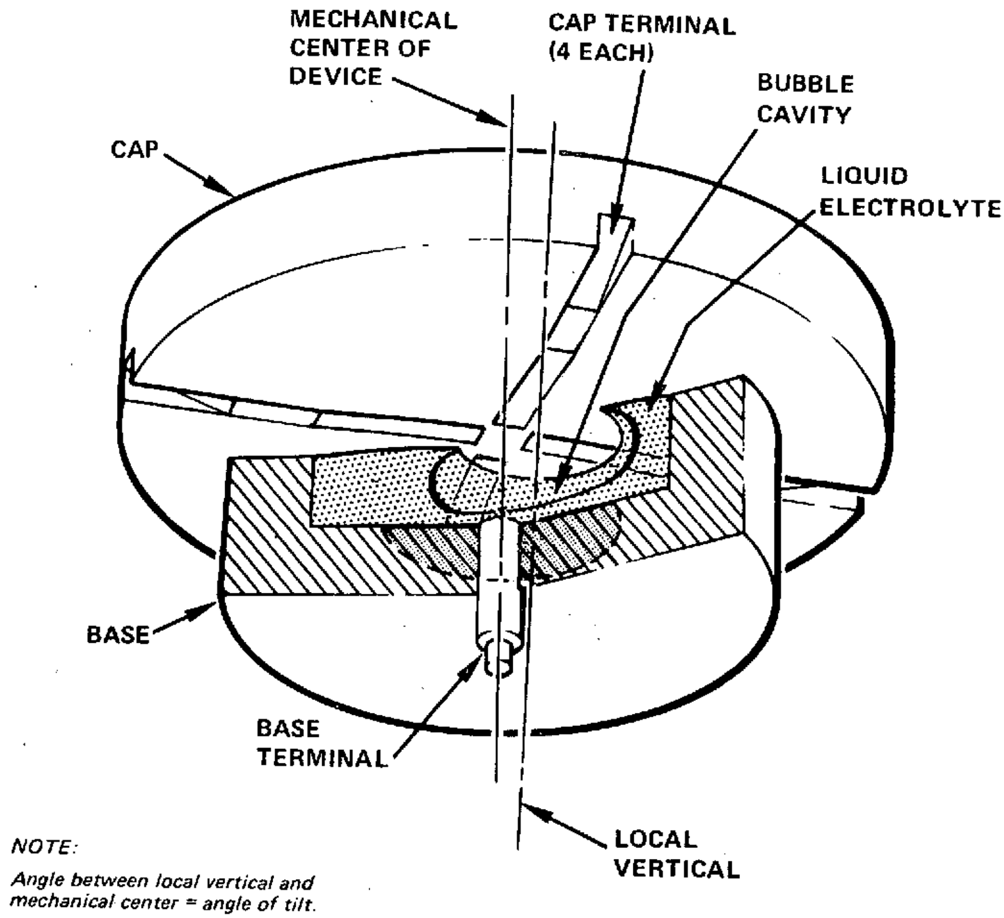


FIGURE 6.8. Tiltmeter sensor assembly.

Figure 6.9, the AC signal from the sensor bridge is amplified and then demodulated to give a DC output which is then DC amplified in the output stage. The output stage is an operational amplifier low pass filter used to attenuate microseisms and surface waves.

The meter as originally produced by Autonetics was designed to be used in a laboratory or observatory environment and was entirely unsuitable for use as a field instrument. The development group at Autonetics worked closely with the USGS in modification of the original geometry to a configuration suitable for use in the field.

In the present design the level bubble and a few of the most critical resistors of the bridge circuit are housed at the lower end of a heavy-walled stainless steel tube 5 cm. (2 in.) in diameter and 1.2 m. (4 ft.) long (Photo 10 and 11). The remainder of the sensor electronics are housed in a waterproof box connected by a 3 m. (8 ft.) cable. This electronics box has provisions for power input and analog tilt output. This design was adopted to allow the most temperature sensitive elements of the system to be buried a few meters deep in the earth, thus isolating them from surface temperature changes and minimizing thermal gradients in the bubble.

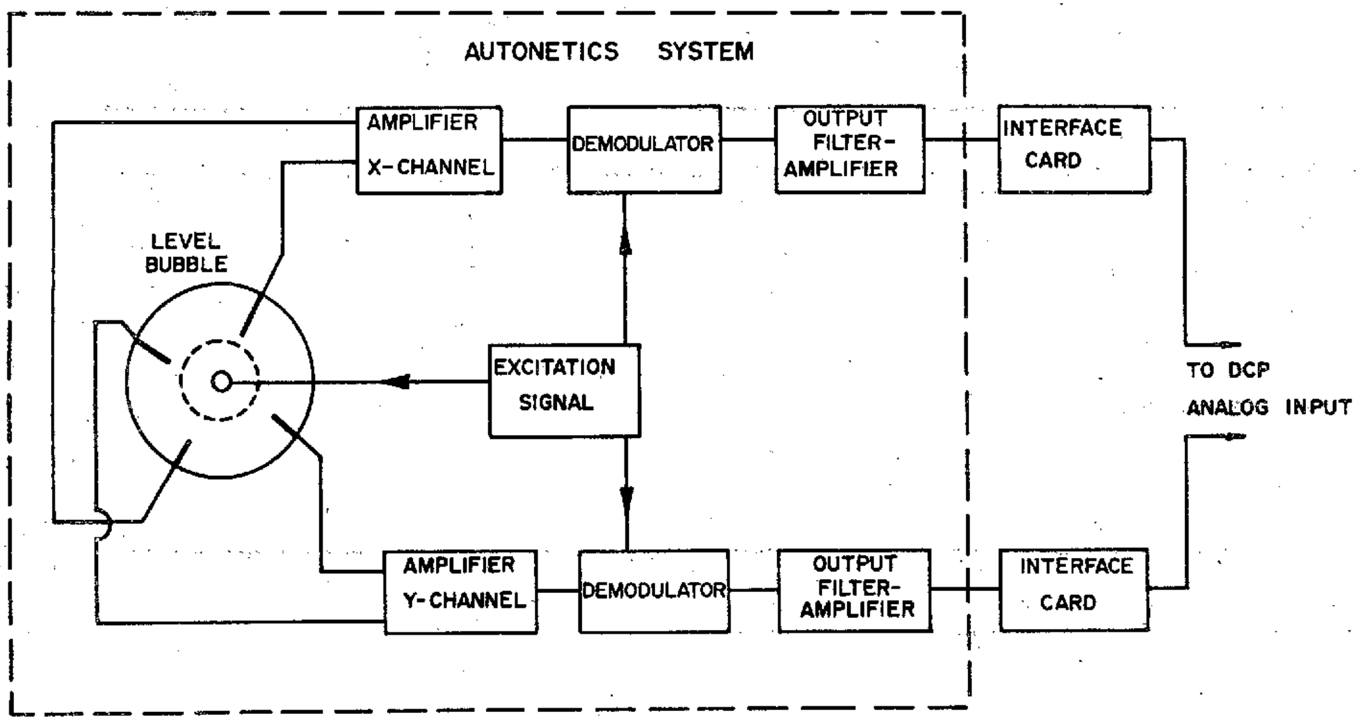


FIGURE 6.9. Block diagram of the tiltmeter electronics.

### 6.2.3 Emplacement of the tiltmeters

The Autonetics meters are emplaced in the earth by a method originally developed for a vertical pendulum borehole tiltmeter built by the USGS. The method is detailed by Allen, et al. (1973). It is suitable primarily for emplacement of tiltmeters in well-drained alluvium or relatively unweathered volcanic ash. The advantages of siting strain-measuring instruments in such "soft" locations rather than in hard rock are examined in detail by King (1971), and our experiences in ERTS and previous tilt investigations tends to support his conclusion. In placing a meter in the ground it must be buried as deep as is practical, and it must be isolated from immediate surface effects due to rainfall or diurnal temperature changes and displacement caused by close approach of men, large animals, vehicles, etc. The actual interface between the earth and the meter must be such that it does not change with age. This rules out the use of most polymeric resins, for example, because of their long and unpredictable curing times and dimensional changes associated with curing.

The typical field installation used at this time is illustrated in Fig. 6.10. A pit 1.5 to 2 m. deep is dug and cased with a steel culvert. From the bottom of this pit a hole about 15.2 cm. (6 in.) in diameter is bored a further 2 m. A steel pipe of about 0.635 cm. (1/4 in.) wall thickness and 10.2 cm. (4 in.) I.D. with the bottom end sealed is packed into this hole using clean dry sand. The tiltmeter sensor is next lowered into the pipe and packed into place, again with clean dry 80 mesh silica sand. The sand is packed by vibrating the pipe with a hammer during the process of adding sand. When properly carried out, this process results in a coupling between the meter and the earth that is essentially elastic for small strains.

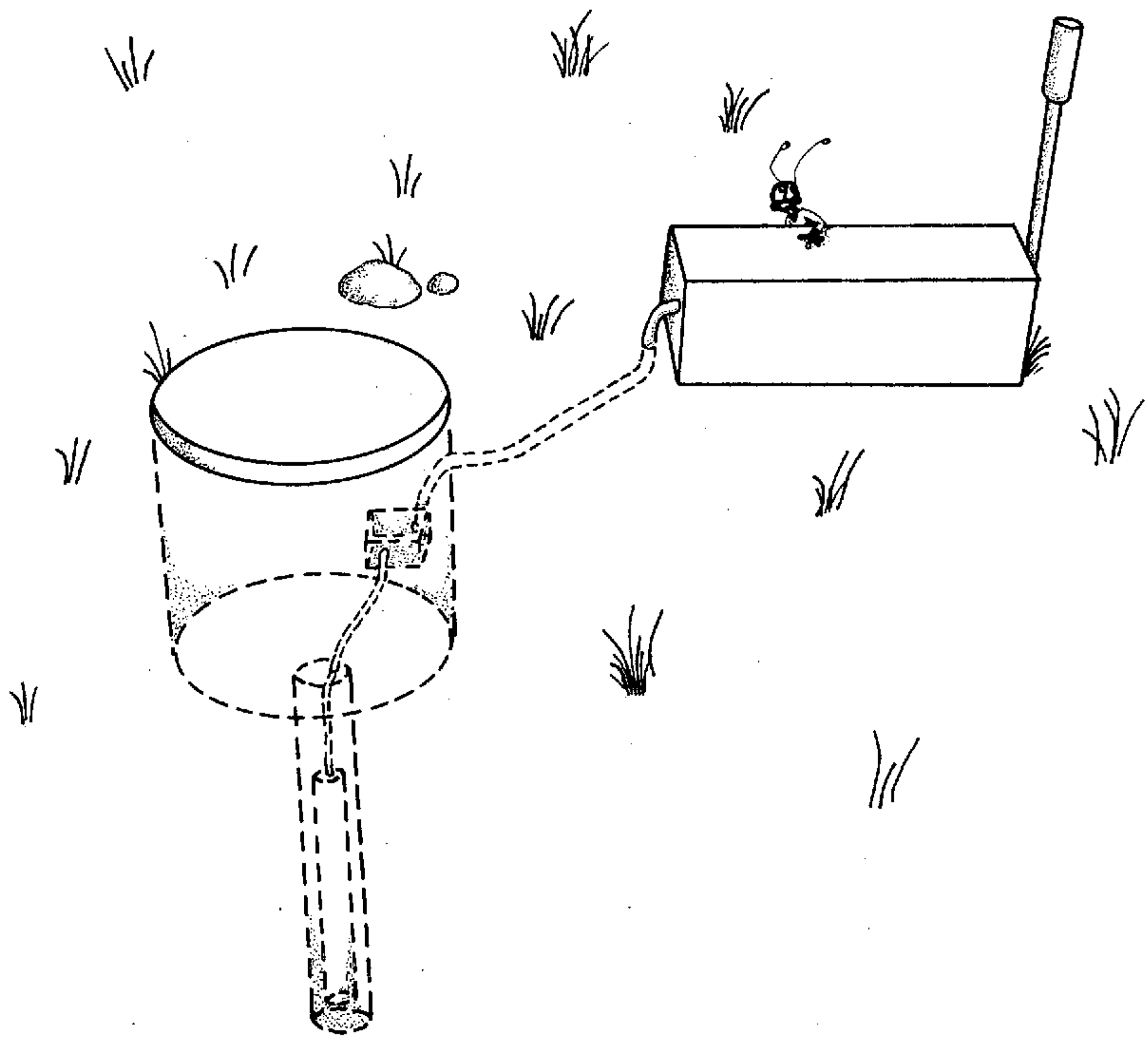

FIGURE 6.10. Typical tiltmeter installation including culvert-lined pit (left), pipe containing the tiltmeter, and steel box (right) for batteries and DCP equipment.

The electronics box remains in the steel-cased pit which is covered by a locked steel lid. The battery power supply for the tiltmeter, along with the DC-DC converter and the satellite (DCP) transmitter with its batteries are placed in a locked steel box about twenty feet away from the pit. Cables carrying ±12 volts to the tiltmeter and analog tilt voltages to the DCP transmitter are fed through a buried flexible steel conduit between the pit and the transmitter box.

The tiltmeter's analog output is nominally zero volts, ±6 volts, with a scale factor of 40 mv/microradian. This is converted to +2.5 volts, ±2.5 volts, with a scale factor of 20 mv/microradian to interface with the analog input of the DCP. This conversion is accomplished by an interface card mounted inside the tiltmeter electronics box.

At Mt. Lassen in California, no suitable site for the standard type of installation was found so an alternative procedure was used. After locating an expanse of solid bare rock, a 10 cm. (4 in.) diameter hole was drilled 1.5 m. into the rock using a portable diamond-drill (Photo 12). The tiltmeter was packed in this hole with sand in the usual way. The top of the hole was then sealed with a hot wax to keep out surface water. The tiltmeter electronics box was placed on the surface a few feet away, protected only by a small bush, and a cable for power in and signal out was laid to the nearby ERTS DCP equipment.

6.2.4 Tests of the stability of the tiltmeter and tiltmeter installations

The prime requirement of tiltmeters used in geologic investigations is stability, and the Autonetics meter has been tested for this characteristic for use in other Geological Survey applications. The tests were conducted with two Autonetics meters at the USGS test vault in the Presidio of San Francisco. The first meter was solidly emplaced in a cylinder of sand adjacent to one of the 5-meter baselength mercury instruments and its output in the parallel axis compared directly with the mercury instrument. After one month the Autonetics instrument was rotated 90° and the other axis compared for one month. A second Autonetics meter was suspended by a thin steel wire, thus isolating it from any environmental tilting of the vault, and both axes were recorded (Malcolm Johnston, oral communication, 1973). Results of the two tests were similar and give an apparent instrument drift of about $5 \times 10^{-7}$ radians per two months, or about $3 \times 10^{-6}$ radians per year.

The Development Group at Autonetics carried out an earlier statistical evaluation of stability characteristics using a group of eight sensors. Their results were reported by Kohlenberger et al. (1973) and are worth quoting at some length:

"An earlier evaluation of the biaxial tiltmeter was made during its development using a group of eight sensors mounted on a single monolithic block of aluminum. Absolute tilts were measured by means of an auto collimator which was calibrated from a mercury pool prior to and after each family of readings. The standard deviation of the set of 1798 readings covering a period of 326 days was 2 π radian per month, which is within the confidence interval allowed by the noise in the measuring process."

This data set indicates that tilt drift with randomly selected meters will be less than 0.57 microradians per month with a 95% confidence level and is in good agreement with our independent results at the Presidio Vault, of about 0.25 microradians per month.

Considering all the test data available, it appears that the instrument may be expected to maintain stability to well under one microradian per month. Our present telemetry system has a resolution of one microradian, and the volcanic phenomena we wish to observe usually involve tilts of tens or even hundreds of microradians, so it is clear that the Autonetics instrument is eminently suitable for this purpose.

A much more serious problem in the use of tiltmeters is stability of the emplacement: the interface between the meter and the earth. This is potentially the most serious source of drift error, and it is very difficult to design definitive tests of an emplacement method. We now have more than five years' experience with shallow borehole installations, and some have been very successful while others have been almost complete failures. Most of this trial-and-error development predates the ERTS program and we believe that we have been quite successful in the ERTS installations on volcanoes. The best proof of stability of an installation is a record for a long period during which the meter indicated no drift or during which its output can be compared with another meter at the same location. Such plots will be discussed in Section 9.2.

## 6.3 Transmitter to the ERTS Satellite

The transmitter for sending data to the satellite or data collection platform (DCP) is shown in Photos 4, 6, 7 and 8. These transmitters were provided by General Electric Space Division, Valley Forge Space Center, Pennsylvania, on contract to NASA and are described in detail in "Earth Resources Technology Satellite Data Collection Platform Field Installation, Operation and Maintenance Manual," publication 72SD4208 and "Earth Resources

Technology Satellite Data Collection Platform Field Installation, Operation and Maintenance Manual," publication 72SD4228 by General Electric.

The DCP accepts 64 digital bits in serial or parallel or accepts 8 analog voltages that are each converted into 8 bit digital words. The event counters are interfaced with the serial digital input. The tiltmeters are connected to the analog inputs. A digital controller in the DCP adds 15 bits preamble, 12 bits of address code, which is unique to each transmitter, and 4 bits runout to the 64 data bits. These 95 bits are convolutionally encoded, in a byphase, non-return-to-zero format and transmitted in a 38 millisecond burst at a frequency of 401.55 mhz and at a minimum RF output power of 5-watts. The transmission interval can be set to once every 90 or 180 seconds and the average power consumption is 0.085 watts at 24 volts. The transmitter measures 26.7 x 21.6 x 15.2 cm. (10-1/2 x 8-1/2 x 6 in.) and weighs about 6.2 kg. (15 lb.).

A crossed dipole antenna with a 117 cm. (46 in.) in diameter ground plane was provided with each transmitter (Photo 5 and 17). The bifolium radiation pattern is shown in Figure 6.12. A much smaller antenna was purchased from Chu Associates Incorporated, Littleton, Massachusetts. This model CA-3140 SATNAV antenna is 7.6 cm. (3 in.) in diameter and 40.5 cm. (15-7/8 in.) tall (Photo 6). The radiation pattern of this antenna is also shown in Figure 6.12. This antenna appears to work at least as well as the larger crossed dipole antenna and is substantially easier to use in the field and ship by air. It also has higher radiation near the horizon which is important as discussed in Section 7.4.

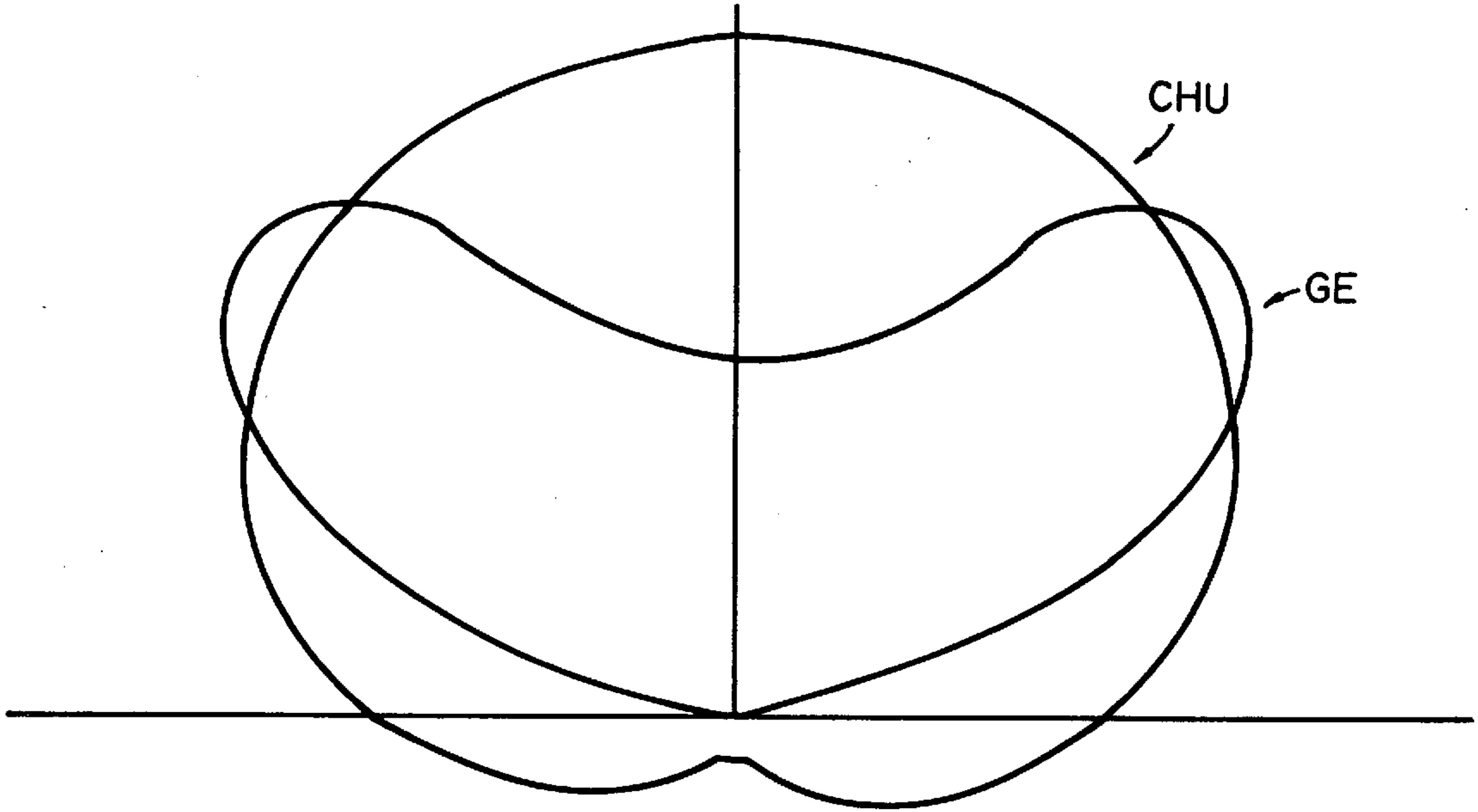


FIGURE 6.12. Radiation patterns of the GE and CHU antennas showing in a vertical plane. The relative gains are not shown.

## 6.4 Standard Seismic System

In the initial experiment standard seismometers were operated near most event counters to determine how well the event counters function in different environments and on different types of volcanoes. Standard seismometers were available in Alaska and Hawaii at sites of interest but eleven new seismometers were installed in Washington, California, Guatemala, El Salvador, and Nicaragua (Photo 15, Figure 6.13).

The equipment at each site in the field is housed in a metal box measuring 40.5 x 91.5 x 38 cm. (16 x 36 x 15 in.) bolted to a concrete slab where practical. The box is large enough to hold 6 batteries (Section 6.5) that have a 1000 ampere-hour capacity at 15 volts. A coupling for the antenna mast was welded on to most boxes for ease of field installation. Most antenna masts consist of a 3.7 m. (12 ft.) section of iron pipe 5 cm. (2 in.) in diameter. The seismometers are buried 15.2 to 23 m. (50 to 75 ft.) away from the boxes and antennas to minimize the effect of wind noise. The seismometers (Photo 13) which have a natural frequency of either 1 or 2 Hz, were calibrated prior to installation and appropriate individualized shunt resistors added to provide 80% of critical damping and a standard output of 0.5 volts/cm./second.

The JE202 amplifier and voltage controlled oscillator (Photo 13) developed at the USGS by J. Van Schaack are used. This amplifier has a maximum gain of about 100 db and 12db/octave filters with 3 db points set for the high cut at 30 Hz and for the low cut at 0.1 Hz. The attenuation is normally set at 30 to 36 db, which gives a total electronic gain of about 2000 to 4000. The voltage controlled oscillators operate in the 680 to 3060 Hz range and operate within a constant bandwidth of

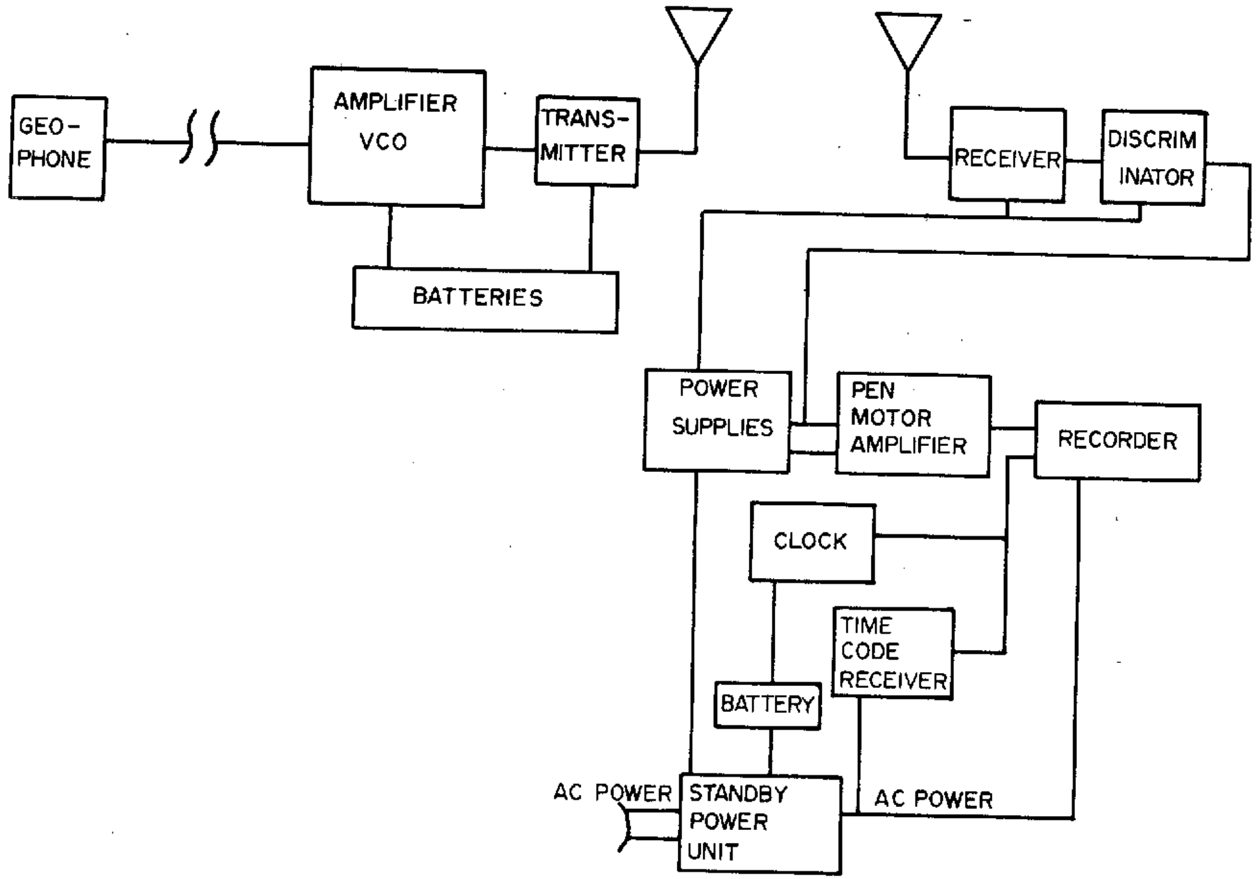


FIGURE 6.13. Block diagram of the standard seismic system used in this project.

$\pm$ 125 Hz for $\pm$ 2.0 volts at the oscillator input. Power consumption for the amplifier and oscillator is 250 milliwatts.

Modified VHF (163 to 173 mhz) transmitters and receivers (Motorola HT200) are used for telemetry of the data from remote sites. The transmitters (Photo 13), which require 550 milliwatts of power, produce 100 milliwatts of RF power. The receivers (Photo 14) require less than 200 milliwatts for operation. These radio links can be operated with Yagi antennas over distances of more than 100 km with clear line of sight between transmitter and receiver. The received FM audio signal is demodulated by a discriminator (Photo 14) and typically recorded on a drum recorder (Photo 16) utilizing heat sensitive paper (28 x 91.5 cm. or 11 x 36 in.) at 60mm per minute. A time signal is added from a crystal controlled oscillator. In Central America, where line power tends to be unreliable, standby power units were installed to maintain continuous power to the timing and recording system.

The overall frequency response spectrum of the standard seismograph units used in this experiment is shown in Figure 6.2. This magnification curve represents the combined responses of the seismometer and electronics. The system gain is periodically calibrated using a 5 Hz standard signal.

## 6.5 Batteries

Three different types of batteries were used to operate the event counters and satellite transmitters.

a. Gel Cell (GC12200) 12 volt, 20 ampere-hours.

b. A combination of alkaline batteries at 6 volts (EVEREADY 520) and 15 volts (EVEREADY 561).

c. Mallory SR-4845 alkaline batteries that were especially packaged for us consisting of 36 Mn1300 Alkaline "D" cells arranged to have 0, 6, 12, and 27 volt taps and a capacity of 20 Ampere-hours.

The event counter requires about 1 ampere-hour of power per year whereas the transmitter requires 10 to 20 ampere-hours per year for the 180 and 90 sec. transmission rates respectively. Generally 5 sets of batteries were used in parallel to allow ample safety factors to allow for loss of battery efficiency due to cold temperatures and long shelf-life and to correct the nominal capacity for a higher draw-down voltage. In no case after a year was the battery voltage low enough to cause any problems in the low temperatures of Alaska or the high temperatures in Central America.

The standard seismic system was operated on six Aircell (Union Carbide 2510) or Carbonaire (Edison ST-2-1000) batteries which produce 1000 ampere-hours at 2.5 volts for each cell. These operate the amplifier and transmitter for 14 to 16 months.

Some experimentation was carried out using two aircells to power the satellite transmitter. The 5 volts DC can be converted with a DC to DC converter to 24 volts DC and used to charge a 20,000 MFD capacitor through a resistor in series to keep the charging current low. The capacitor then provides the high current (70 watt) pulse (38 millisecond) required by the satellite transmitter. Testing of this system was carried out to show it was feasible and did work under laboratory conditions with no clear sources of problems. This approach was not pursued further because of other demands on our time. The advantage of this approach is that two aircells can provide all the power necessary to operate the system for 3 years, which is the shelf-life of these batteries once they have been activated. One aircell could also provide enough power if 2.5 or 3.75 volts could be used.

## 6.6 System Packaging

The event counter-satellite transmitter system was mounted in one steel box, the standard seismograph system was mounted in another box (Photo 15), and the batteries and transmitter for the tiltmeter were mounted in another box (Photo 20). Most of these boxes were made of 14 gauge steel with a kinked false cover mounted 7.6 cm, (3 in.) above the main cover of the box to reduce heating of the box by the sun. This sun shield allows the boxes to remain cool even in the direct sun in Central America when the top of the box is hot to the touch.

The steel box was also designed to discourage vandalism. In only one instance was a box broken into, and the batteries stolen (Telica, Nicaragua). In another instance antenna guy wires were cut. We consider this to be an exceptionally good record, particularly since most Central Americans consider it unwise to leave valuable equipment in any unguarded place.

The steel box and iron antenna mast were also designed to shield the equipment and cables from induced electro-magnetic fields resulting from lightning (Section 7.6).

Although there was no evidence of the steel boxes leaking, all electronics were put in their own waterproof boxes and sealed up with a dehydrating agent to minimize problems caused by moisture. Furthermore only environmental connectors were used. We consider this a small added expense compared to the cost of traveling to a station to repair the equipment. To date no equipment has been damaged by water.

This packaging allowed relatively rapid installation of the equipment. Generally it took two people 2 to 3 hours to install an event counter and transmitter system. Most of the time is spent digging holes and setting up the antenna guy wires. The use of crimp-type guy wire clamps reduces the installation time to less than two hours. The time could be reduced to about one hour if the antenna was an integral part of the box and did not need guy wires.

## 7.0 IMPLEMENTATION, EVALUATION, AND EVOLUTION OF THE NETWORK

### 7.1 Schedule

The schedule followed in the development and deployment of this volcano surveillance system is given in table 7.1. The distribution of instruments and dates of installation are given in table 7.2. The location of the instruments and the dates of operation of particular satellite transmitters (Plat. ID.) are shown in table 7.3.

### 7.2 Event Counters

The first event counter was delivered for test and evaluation on September 5, 1972. Initial tests indicated that the counter worked as anticipated except that the preamplifier molded into the geophone cable had a short circuit after a little use. Examination showed that an insulator had been left off before molding so that all geophone cables were taken apart and remolded.

By mid-October two more minor problems had been detected. Sometimes the printer solenoid turned on and stayed on. This problem was traced to a pad on the printed circuit board sometimes shorting to the case of the power transistor because the pad diameter was nearly the same size as the insulator around the transistor terminal. This was easily repaired. The second problem was that at low temperatures the comparator and precision rectifier circuit sometimes went into oscillation causing continuous inhibit-time counts on channel 1 and sometimes also on channel 2. This oscillation was corrected by changing the values of a resistor and capacit from the comparator inputs to ground. This problem had not been detected and corrected, however, until after the equipment had been installed in

Table 7.1. Schedule for the development and deployment of the prototype global volcano surveillance system.

| | | |
|---|---|---|
| 1971 | December | Visit Guatemala, El Salvador and Guatemala to find local collaborators. |
| | December | Begin writing detailed specifications for the event counters. |
| 1972 | March 10 | Send out request for proposals for the event counters. |
| | April-May | Receive agreements for collaboration from Central American Scientists. |
| | May 26 | Issue contract to build event counters. |
| | June 9 | Receive contract from NASA to fund this network. |
| | June | Begin to draw up designs for different equipment and urgently order the parts. |
| | July 23 | ERTS satellites launched. |
| | July-August | Find sites for installation of stations in the Cascades and obtain use permits. |
| | July 23 | Receive first DCP from NASA and install it for test purposes in Menlo. |
| | August 25 | Begin installation of most equipment at Mt. Lassen. |
| | September 5 | Receive first event counter for test and evaluation. |
| | September 21 | Attempt installation of stations in Washington but field work prohibited by snowstorm and 3 feet of snow. |
| | September 20-October 2 | Installation of equipment in Alaska. |
| | October 9-12 | Installation of equipment in Washington |
| | November 3 | Complete delivery of event counters. |

| | | |
|---|---|---|
| | November 14 | Begin finding sites for equipment in Central America and obtaining land use permits. |
| | December 10 | Begin installing equipment on Hawaii. |
| | December 19 | Install one event counter in Iceland. |
| | December | Receive Diplomatic approvals to carry out program in Guatemala, El Salvador, and Nicaragua. |
| | December 22 | Ship 6 tons of equipment to Central America by truck and boat. |
| 1973 | January | Installation of equipment in Central America delayed because of the devastating earthquake in Managua on December 23, 1972. |
| | February 2 | Ship via air 1 ton of equipment to Central America. |
| | February 8 | Begin installation of equipment in Central America. |
| | February 22 | Eruption of Volcán Fuego in Guatemala begins. |
| | April 8 | Complete installation of equipment at all sites except event counters on Telica in Nicaragua and standard seismographs in Nicaragua. |
| | May 5 | Collapse of the summit of Kilauea in Hawaii. |
| | July 18 | Complete installation of equipment in Nicaragua. |

Table 7.2. Prototype global volcano surveillance network funded under the ERTS-A program

| Country or State | Volcano | Event Counter + DCP* | Visibly recording seismic systems | Tiltmeter + DCP | Installed |
|---|---|---|---|---|---|
| ALASKA | Augustine | 1 | 1 existing | | 9/24/72 |
| | Iliamna | 1 | 1 existing | | 9/30/72 |
| WASHINGTON | Baker | 1 | 1 | | 10/9/72 |
| | Rainier | 1 | 1 | | 10/11/72 |
| | St. Helens | 1 | 1 | | 10/12/72 |
| CALIFORNIA | Lassen | 1 | 1 | 1 | 9/30-10/13/72 |
| HAWAII | Kilauea | 2 | U.S.G.S. network | 3 | 12/10/72 |
| ICELAND | near Reykjavik | 1 | 1 existing | | 12/19/72 |
| GUATEMALA | Pacaya | 1 | 1 | 1 | 2/15/73 |
| | Agua | 1 | - | - | 2/13/73 |
| | Fuego | 1 | 1 | 1 | 2/17/73 |
| | off volcanic axis (Buena Vista) | 1 | 1 | - | 2/21/73 |
| | Santiaguito | 1 | 1 | - | 3/18/73 |
| EL SALVADOR | Izalco | 1 | 1 | | 3/7/73 |
| NICARAGUA | San Cristobal | 1 | 1 | | 4/2/73 |
| | Telica | 1 | - | | 8/11/73 |
| | Cerro Negro | 1 | 1 | | 4/3/73 |
| | off volcanic axis (Mina el Limon) | 1 | 1 | _ | 4/8/73 |
| | | 19 | 12 new | 6 | |

*DCP - Data Collection Platform - Transmitter provided by NASA.

TABLE 7.3 LIST OF DCP TRANSMITTER IDENTIFICATION NUMBERS AND THE LOCATIONS AND PERIOD OF OPERATION OF THE TRANSMITTERS.

| PLATFORM ID | TYPE | LOCATION | TIME ON YDAY | TIME OFF YDAY | LATITUDE DEG | LATITUDE MIN | LONGITUDE DEG | LONGITUDE MIN | ELEVATION FEET |
|---|---|---|---|---|---|---|---|---|---|
| 6004 | 1 | REPAIR | 3255 | 3331 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6004 | 2 | PACAYA TILT | 3331 | 0 | 14 | 23.85 | 90 | 33.65 | 5500 |
| 6005 | 1 | TEST WASH | 2286 | 2286 | 47 | 45.00 | 122 | 24.00 | 0 |
| 6005 | 1 | ST HELENS | 2287 | 0 | 46 | 11.58 | 122 | 14.20 | 4670 |
| 6011 | 1 | REPAIR | 3016 | 3168 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6011 | 1 | HAWAII AHUA | 3168 | 3203 | 19 | 23.75 | 155 | 16.53 | 3500 |
| 6011 | 1 | REPAIR | 3203 | 3331 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6011 | 1 | PACAYA | 3331 | 0 | 14 | 23.85 | 90 | 33.65 | 5500 |
| 6034 | 1 | IZALCO | 3066 | 3201 | 13 | 49.25 | 89 | 37.80 | 5250 |
| 6034 | 1 | REPAIR | 3201 | 3230 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6034 | 1 | MT BAKER | 3231 | 0 | 48 | 47.00 | 121 | 54.20 | 5500 |
| 6036 | 1 | CERRO NEGRO | 3093 | 0 | 12 | 31.35 | 86 | 42.08 | 1150 |
| 6043 | 1 | AGUA | 3077 | 3186 | 14 | 26.55 | 90 | 41.55 | 5250 |
| 6043 | 1 | REPAIR | 3203 | 3233 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6043 | 1 | MT RAINIER | 3234 | 0 | 46 | 56.49 | 121 | 40.38 | 6200 |
| 6057 | 2 | MT LASSEN | 2275 | 0 | 40 | 28.52 | 121 | 30.50 | 8720 |
| 6066 | 1 | MT BAKER | 2283 | 3027 | 48 | 47.00 | 121 | 54.20 | 5500 |
| 6066 | 1 | REPAIR | 3231 | 0 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6103 | 1 | PACAYA GUATE | 3046 | 3320 | 14 | 23.85 | 90 | 33.65 | 5500 |
| 6103 | 1 | REPAIR | 3320 | 0 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6117 | 2 | HAWAII TILT | 3005 | 0 | 19 | 25.40 | 155 | 17.60 | 4075 |
| 6132 | 1 | BUENA VISTA | 3052 | 0 | 14 | 40.00 | 90 | 38.45 | 7400 |
| 6154 | 1 | SAN CRISTOBAL | 3092 | 3151 | 12 | 40.88 | 87 | 01.43 | 2460 |
| 6154 | 1 | REPAIR | 3203 | 3220 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6154 | 1 | MT RAINIER | 3221 | 3234 | 46 | 56.49 | 121 | 40.38 | 6200 |
| 6154 | 1 | REPAIR | 3234 | 3312 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6154 | 1 | AGUA | 3312 | 0 | 14 | 26.55 | 90 | 41.55 | 5250 |
| 6162 | 1 | TEST MENLO | 2206 | 2258 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6162 | 1 | SANTIAGUITO | 3076 | 0 | 14 | 46.60 | 91 | 33.75 | 8900 |
| 6163 | 1 | MT LASSEN | 2287 | 0 | 40 | 28.52 | 121 | 30.50 | 8720 |
| 6176 | 1 | TEST SEATT 2 | 2266 | 2276 | 47 | 45.00 | 122 | 24.00 | 10 |
| 6176 | 1 | STANFORD TES | 2342 | 3027 | 37 | 24.31 | 122 | 10.55 | 100 |
| 6176 | 1 | MINA LIMON | 3098 | 3341 | 12 | 45.95 | 86 | 44.18 | 980 |
| 6176 | 1 | REPAIR | 3341 | 0 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6213 | 1 | TEST EP | 2273 | 2364 | 38 | 30.00 | 121 | 30.00 | 200 |
| 6213 | 1 | REPAIR | 3106 | 3222 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6213 | 1 | TELICA | 3223 | 0 | 12 | 36.20 | 86 | 51.55 | 200 |

| PLATFORM ID | TYPE | LOCATION | TIME ON YDAY | TIME OFF YDAY | LATITUDE DEG | LATITUDE MIN | LONGITUDE DEG | LONGITUDE MIN | ELEVATION FEET |
|---|---|---|---|---|---|---|---|---|---|
| 6240 | 1 | FUEGO GUATE | 3048 | 3203 | 14 | 26.65 | 90 | 50.62 | 4600 |
| 6240 | 1 | REPAIR | 3203 | 0 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6247 | 2 | REPAIR | 3041 | 3047 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6247 | 2 | FUEGO TILT | 3074 | 3084 | 14 | 26.65 | 90 | 50.62 | 4600 |
| 6247 | 2 | REPAIR | 3106 | 3169 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6247 | 1 | AGUA | 3187 | 3312 | 14 | 26.55 | 90 | 41.55 | 5250 |
| 6247 | 1 | REPAIR | 3328 | 3335 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6247 | 1 | MINA LIMON | 3342 | 0 | 12 | 45.95 | 86 | 44.18 | 980 |
| 6252 | 1 | AGUA | 3044 | 3057 | 14 | 26.55 | 90 | 41.55 | 5250 |
| 6262 | 1 | HAWAII AHUA | 3094 | 3157 | 19 | 23.75 | 155 | 16.53 | 3500 |
| 6262 | 1 | REPAIR | 3157 | 3347 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6262 | 1 | SAN CRISTOBAL | 3347 | 0 | 12 | 40.88 | 87 | 01.43 | 2460 |
| 6274 | 1 | MINA LIMON | 3094 | 3097 | 12 | 45.95 | 86 | 44.18 | 980 |
| 6274 | 1 | REPAIR | 3106 | 3169 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6274 | 1 | SAN CRISTOBAL | 3196 | 3347 | 12 | 43.88 | 87 | 01.43 | 2460 |
| 6274 | 1 | REPAIR | 4010 | 0 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6276 | 2 | TEST MENLO | 3055 | 3057 | 37 | 24.31 | 122 | 10.55 | 69 |
| 6276 | 2 | PACAYA TILT | 3081 | 0 | 14 | 23.05 | 90 | 37.35 | 5450 |
| 6311 | 1 | REPAIR | 3095 | 3201 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6311 | 1 | IZALCO | 3201 | 0 | 13 | 49.25 | 89 | 37.80 | 5250 |
| 6315 | 1 | TEST SFD 1 | 2260 | 2263 | 37 | 24.31 | 122 | 10.55 | 100 |
| 6315 | 1 | ICELAND | 2354 | 0 | 64 | 01.30 | 21 | 51.00 | 0 |
| 6320 | 1 | REPAIR | 3046 | 3047 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6320 | 2 | FUEGO TILT | 3103 | 0 | 14 | 26.65 | 90 | 50.62 | 4600 |
| 6334 | 1 | TEST WASH 1 | 2284 | 2284 | 47 | 45.00 | 122 | 24.00 | 10 |
| 6334 | 1 | MT RAINIER | 2286 | 3206 | 47 | 56.49 | 121 | 40.38 | 6200 |
| 6334 | 1 | REPAIR | 3192 | 0 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6342 | 1 | TEST SFD 2 | 2261 | 2262 | 37 | 24.31 | 122 | 10.55 | 100 |
| 6342 | 1 | MT ILIAMNA | 2275 | 0 | 60 | 10.92 | 152 | 48.97 | 1800 |
| 6365 | 1 | TEST SFD 3 | 2260 | 2262 | 37 | 24.31 | 122 | 10.55 | 100 |
| 6365 | 1 | ST AUGUSTINE | 2269 | 0 | 59 | 22.55 | 153 | 22.25 | 348 |
| 6370 | 1 | TEST SEATT 1 | 2267 | 2278 | 47 | 45.00 | 122 | 24.00 | 10 |
| 6370 | 1 | HAWAII NPIT | 3069 | 0 | 19 | 20.20 | 155 | 17.00 | 3600 |
| 6372 | 2 | HAWAII TILT | 2341 | 2341 | 19 | 25.40 | 155 | 17.60 | 3750 |
| 6372 | 1 | TELICA | 3106 | 3203 | 12 | 36.20 | 86 | 51.55 | 200 |
| 6372 | 1 | REPAIR | 3203 | 3312 | 37 | 24.31 | 122 | 10.55 | 0 |
| 6372 | 1 | FUEGO GUATE | 3312 | 0 | 14 | 26.65 | 90 | 50.62 | 4600 |

Alaska and winter snows had made it impossible to update this equipment. Thus the most sensitive event counter channel, and in some cases the second most sensitive channel were not useable from October, 1972, until the equipment was overhauled in the summer of 1973.

A light emitting diode was built into the event counter to indicate during installation when channel 1 was being triggered. This light was used to set the proper attenuation of the amplifier. Initially we enabled the light and set the attenuation to a level where the light came on only once in a while. After operating the counters in the Cascades and Alaska for a few weeks, it became clear that the gain was too high. More experimentation showed that the attenuation should be 18 db greater than the setting where the light flickers on once in a while. By this time, in early November, it was impossible to reach the stations in the Cascades and Alaska because of heavy snow storms. Thus the most sensitive channel on all these stations was constantly inhibited by high ground noise until the summer of 1973 when the stations were serviced.

These few design and adjustment problems were certainly the minimum that could be hoped for in a system of this complexity that was designed and built in three months and rushed into the field to be installed before winter set in. During the spring of 1972, we repeatedly warned persons at NASA that continued delay of the funding would seriously jeopardize the program. Without the loan from the EROS program none of the Alaska or Cascade stations would have been installed before the summer of 1973.

By December, 1972, it was found that sometimes the printer would print after every transmission of the DCP. This problem was traced to the fact that sometimes the "data gate" signal, provided by the DCP to signify when the DCP programmer is turned on, ended prior to the "enable" signal which is provided by the DCP to signify when data is being processed and transmitted. These two signals are used to reset different parts of the event counter printer circuit in order to be sure that a print and a transmit do not occur simultaneously. A reversal of the order causes the printer to respond after every transmission. This problem is a DCP problem discussed in Section 7.4. By late fall of 1973, it was decided to disable all printers since the satellite system was working so reliably.

A few event counters have failed after operating in the field for many months. In each case the failures seem to be linked to large local lightning storms where the induced electro-magnetic field has been high enough to damage the digital logic. In some of these cases a large percentage of the integrated circuits were damaged. In a couple of cases only the logic gates that interface to the DCP were damaged and the DCPs were also inoperative. We do not know which unit failed first or whether some chance sequence in the interface caused the failure of both units.

Generally the event counters have worked far better than could be reasonably expected considering the haste of putting such a circuit together. This excellent record occurred to a large extent because the contractor, Electra-Physics Laboratories, Inc., Folsom, California, took great care in the design and shielding of all circuits and worked very closely with us during the design and construction process to improve the specifications as more experience with the counter was available.

### 7.3 Tiltmeters

The first year of operation of tiltmeters in the ERTS project was plagued by several serious problems. The most serious of these and one with which we had no previous experience was lightning damage of the instruments.

The first tiltmeter installed under the ERTS program was at Lassen Peak in northern California. As previously mentioned this was a "non-standard" installation in that there was no steel-cased pit. The tiltmeter was emplaced in a diamond-drilled hole in solid rock. The installation was completed in late September of 1972 and after 3 days of operation the tiltmeter failed during a severe electrical storm. At the same site a seismic event counter and a standard seismic station also failed during the same storm.

The tiltmeter was removed and returned to Autonetics for failure analysis and repair. Detailed analysis revealed that several integrated circuits had suffered catastrophic damage due to voltage transients and that the bubble sensor itself had also been severely damaged by transients severe enough to partially vaporize some of the deposited platinum electrodes. The examination of damaged integrated circuits included opening of the packages and microscopic examination of the chips themselves to determine exact location of damage. As a result of this detailed study, Autonetics concluded that the transient voltages were the result of an electromagnetic pulse (EMP) produced by a nearby lightning strike. They recommended that the cables connecting the sensor with the electronics box be enclosed in flexible steel conduit to provide some ferromagnetic shielding against EMP. This electromagnetic pulse effect should not be confused with a direct strike on the equipment by a lightning bolt. The

EMP is produced by the extremely high currents and short rise-times characteristic of lightning strikes ($10^5$ to $10^6$ amperes in $10^{-7}$ to $10^{-6}$ seconds) and can induce high voltage transients in a nearby conductor without the lightning actually striking the conductor.

During this period three other tiltmeters had been installed around Kilauea Volcano in Hawaii. In these installations the tiltmeter results were telemetered via frequency modulated carrier on cables lying on the ground to the Observatory over 4 km away for local recording and also for transmission via the ERTS transmitter. The Kilauea sites were similar to our "standard" installation except that batteries and FM telemetry equipment also shared the steel-lined pit with the tiltmeter sensor electronics.

After three weeks of operation all three Hawaiian tiltmeters failed during an exceptionally severe electrical storm. The same storm also damaged 18 telemetering seismic stations in the area. In this case not only the tiltmeters were damaged, but also all of their associated DC-DC converters and telemetry transmitters were also rendered inoperative. All of the equipment was repaired and reinstalled in early December. The tiltmeters were fitted with the flexible conduit suggested by the EMP Group at Autonetics, and an improved lightning arrestor was installed on the cables at each tiltmeter. The telemetry at Summer Camp was not operational until January 1973, due to delays in completing the repairs.

Tilt measurements at all three sites were satisfactory through mid-February, when another electrical storm damaged the Ahua and Uwekahuna equipment. Damage in this case was not catastrophic and the meters continued to operate but produced erratic results, with the extent of the damage not being confirmed for several months. During the three months before damage all three meters operated stably, and those on telemetry produced records of excellent quality.

The instrument at Summer Camp survived the February storm and operated continuously until late May, when it too was damaged by lightning-induced transients on the long cables to the observatory.

By this time it was apparent that lightning protection of tiltmeters was a major problem, especially in applications requiring the use of long cables for telemetry. Replacement of the Kilauea tiltmeters was therefore delayed until a dependable scheme could be developed for isolating the tiltmeters from lightning-induced transients. The system we adopted makes use of recently available opto-electronic devices to couple the output of the voltage-controlled oscillators to the telephone line via a modulated light beam directed through a small hole in the steel casing. This completely eliminates any electrical connection between the long cables outside the steel casing of the tiltmeter pit and the tiltmeter with its power supply and telemetry equipment inside the pit.

The photo-coupler schematic is shown in fig. 7.1. The photo-emitting diode is biased into its linear region by current through $R_B$ connected to the unregulated 5 volt supply. The two Voltage Controlled Oscillators are connected to the anode of the diode through 680 Ω resistors. When operating in the linear region, the diode provides a constant voltage drop and the anode becomes a current summing junction, with the diode's photo output proportional to the current sum. This diode emits radiation in a 4 degree beam along the axis of symmetry. The beam is directed down a 5 cm glass tube at the other end of which is a photo-sensitive transistor. An inexpensive low-power operational amplifier amplifies the photo-transistc signal and drives the telephone line through a lightning arrestor. In the

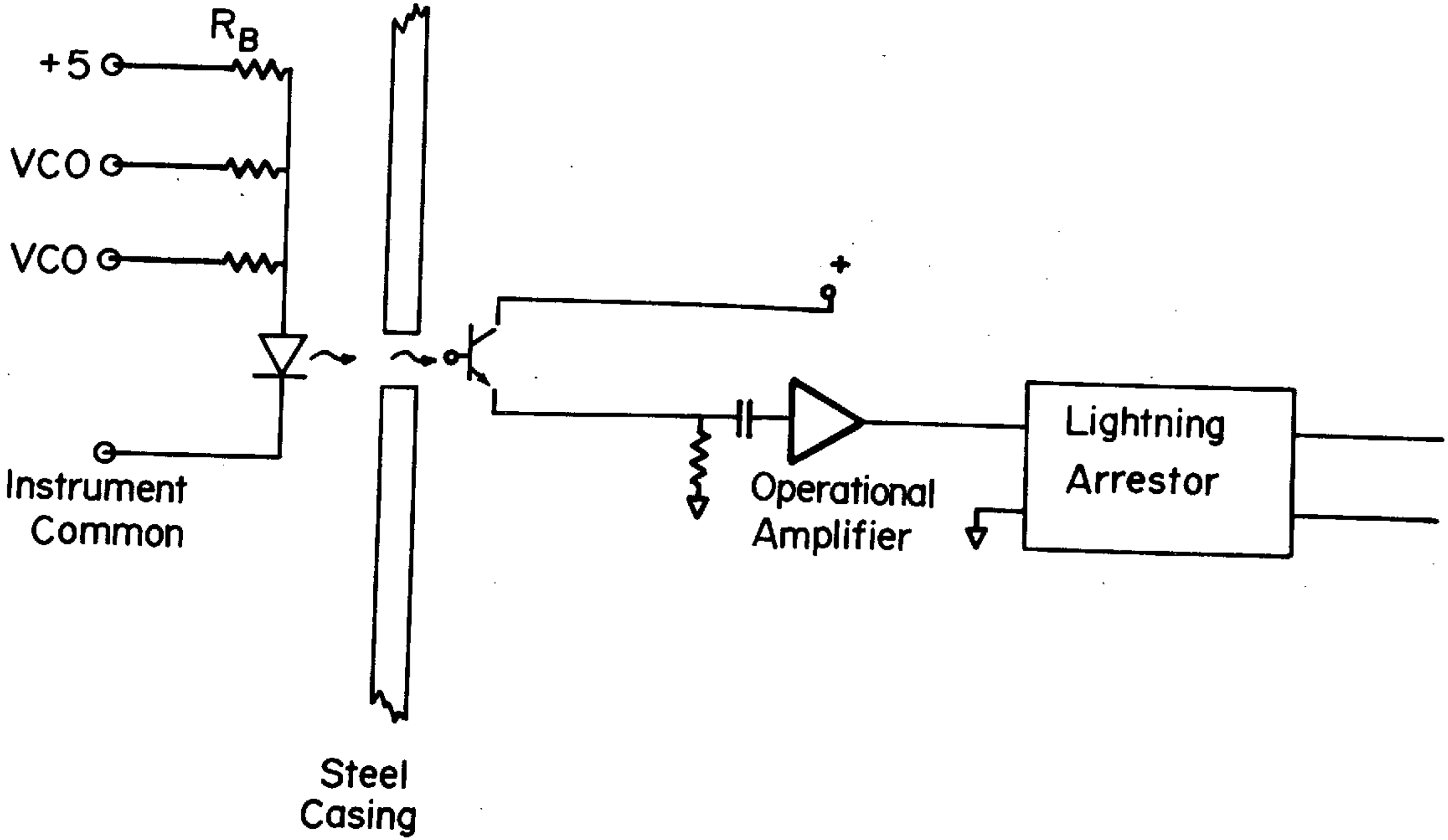


FIGURE 7.1. Schematic of the photo-coupler used for lightning protection in Hawaii.

event of minor lightning-induced surges on the telephone line the lightning arrestor will protect the amplifier and photo-transistor. The arrestor has been lab-tested with 2000 volt pulses from a dynamite cap firing box and performs adequately at these levels, but surges in the field may be expected to exceed this from time to time. The amplifier and photo-transistor are easily replaced and cost only a few dollars so that they are considered expendable.

In operation the photo emitting diode and the photo-transistor are mounted at opposite ends of the 5 cm glass tube which is protected from damage by a larger polystyrene tube. This tube passes through a hole in the steel tiltmeter pit casing, with the photo-transistor on the outside. A short two-conductor cable leads to the box enclosing the amplifier and lightning arrestor together with small batteries for the amplifier, and another pair of output terminals provides for connection to the telephone line.

Tiltmeters were reinstalled at all three Kilauea sites using this technique in early October 1973. On two later occasions electrical storms have damaged (in one case almost destroyed) the photo-demodulator outside the pit with no effect on the tiltmeter and VCOs inside the pit. The photo-demodulator is cheap and easily repaired so it is functioning as a rather elaborate fuse in this application (80 cents each).

The two tiltmeters in Guatemala were installed in March 1973 on the active volcanoes Fuego and Pacaya. Within a month these instruments began reporting erratic tilt values which in effect produced about a 15 micro-radian uncertainty in the telemetered values. The exact nature of the observed data would require too lengthy a description to include here, but the trouble was very elusive and steps suggested to local personnel in Guatemala did not fully solve the problem. In September we finally succeeded in duplicating the malfunction in a test setup at the lab in Menlo Park. The problem was RF coupling from the DCP transmitter antenna into the DCP analog inputs through the analog lines from the tiltmeter pit to the DCP enclosure. Low-pass filters were installed in these analog inputs in early November and seem to have solved the problem.

The Lassen Peak tiltmeter operated very satisfactorily through the winter of 1972-73 until the antennas were crushed by settling of the melting snow pack in the spring. During the interval between telemetry loss and the first visit to the site after the snow melted, the meter drifted badly. Part of this drift was due to poor electrical connections in the meter electronics, which were isolated and corrected on site by Autonetics. They changed fabrication procedures to ensure against a repetition of this problem. We believe that most of the remainder of the drift was due to shifting of the bedding sand as meltwater invaded the hole through joint systems in the rock. On-site measurements suggested that a very small amount of moisture might have penetrated the seals of the steel tube housing the bubble and bridge resistors. With field equipment available at the site it was not possible to ascertain this unambiguously, however, and we elected not to remove the meter from the hole since this would have disturbed the cumulative settling of the packing sand by meltwater. We considered the advantages of continued observation of a novel type of installation justified the risk that the meter might fail entirely. We lost this gamble, as the meter failed entirely shortly after the onset of the heavy snowfalls of winter.

Generally the tiltmeters have worked better than we anticipated considering the difficulties of measuring tilt, the near lack of anyone's previous experience with shallow borehole installations, and the newness of the instrument. The staff of Autonetics Division of North American Rockwell has worked very closely with us in improving the tiltmeter design whenever any field experience suggested the presence of a weakness in design. These tiltmeters appear well suited for use as part of a volcano surveillance system and appear to be the only instrument available at a price as low as $1850 that can reliably measure tilt in the environments of this experiment with modest field installations.

### 7.4 Data Collection Platforms

The data collection platforms (DCP) for processing and transmitting data to the satellite were produced by Radiation Systems Division, Melborne, Florida for General Electric Company Space Division on contract to NASA Goddard Spaceflight Center, Greenbelt, Maryland. They were provided to us between July and October 1972, together with two Field Test Sets designed to test out the operation of the DCPs. Repairs of these units have been done by the DCP Repair Depot at NASA, Wallops Station, Wallops Island, Virginia.

The DCPs have been the most unreliable part of this volcano surveillance network. More than 50 percent have been repaired and while 29 were supplied, we have rarely had more than 23 operating at one time. We have had 4 chassis sitting on the shelf for nearly five months simply waiting for programmer boards to be repaired and returned. Several times spare units have not been available to replace defective units in the field and thus we have deleted several planned site installations and limited the number of sites with DCPs to 24 even though we have all the other hardware, equipment, and cables necessary to install three more event counter installations.

The DCP contains four cards of electronics:

a. Transmitter

b. Programmer and serial input

c. Analog input

d. Parallel digital input

Only two transmitter cards have failed and both cases were caused by lightning damaging one of the output transistors. Such failures are to be expected in the regions where these instruments are placed but may be reduced in the future (section 7.6). We have observed no failures with the analog input card used only for the tiltmeters and we have not used the parallel digital input card. Thus, nearly all of the failures have been with the programmer and serial input card. Analysis of these failures has been difficult because the repairs have been made in a laboratory on the other side of the country with which we have had no communication and the repairs are often made months after the failures for a variety of reasons. Furthermore, in the frenzied rush to get this network installed, we did not keep careful logs of failure occurrence.

There have been three basic types of failures:

a. New or repaired DCPs when received have been plugged in and do not work.

b. DCPs fail after operating successfully for a few days to a few weeks.

c. DCPs fail after operating successfully for months.

Failure type "a" suggests either that the units were not properly checked out before shipment or were damaged by vibration during shipment. A few of these units appeared okay when tested with the field test set but could not be received through the satellite. In these cases we assume the unit was never checked out adequately. In at least one case the data gate was shutting off too early and causing truncation of the message.

Failure type "c" can usually be traced to damage by lightning. In these cases the transmitter is usually totally unresponsive to any tests.

Most failures are of type "b" and these are the most disturbing since they suggest either a basic flaw in the design or a basic flaw in the way we are using the DCPs. Thus far we have been unable to find any systematic pattern to the types of failures or the times of failure. These failures are exceedingly mystifying since other DCPs installed in exactly the same manner have now operated for 15 months without any failure. The results of a failure in most cases is that no data are received through the satellite. The individual symptoms vary and include the following:

a. DCP totally unresponsive to any tests.

b. DCP does not turn on by itself.

c. Transmitter shuts off before the message is completed.

We are unable to adequately document all the symptoms or give the number of DCPs with each symptom simply because in most cases the DCPs were returned for repair without a detailed description of the failure.

Very often the Field Test Set would show a programmer failure and the data would be random. Nevertheless the DCP would operate properly transmitting the correct data through the satellite. The test set would show that the DCP operated properly in the analog and parallel digital mode and often in the serial digital mode if the transmitter was disabled. This problem seemed to come from the power supply for the DCP and could be eliminated if a variable power supply was used for the DCP and the voltage varied until the test set functioned properly. As a result, however, no DCP was assumed to have failed until it had operated unsuccessfully for several satellite passes on an antenna that was known to be working properly and on a power supply or batteries known to work well. Often we simply replaced an operating DCP with one to be tested so that we were sure the power supply and antenna were functioning properly.

As a magnitude of the problem with the DCPs became clear, we began to look for possible causes of the failures. Two problems were noted that help explain why some failures cause burning of a "land" on the printed circuit board. These will be described here and the reader will have to refer to the DCP manuals for the codes used.

a. An analysis of the grounding shows that electronic ground for the transmitter, parallel digital, and analog boards passes through one small "land" on the printed circuit board next to IC number U24. This was clearly an oversight since this same ground goes through several pins at each connector to allow for momentary high currents but then passes through a land that is about the size of a 1 or 2 amp fuse on the way to the battery input. The repair depot at Wallops reports several instances of this land being burned and of U24 having failed catastrophically.

b. U24 is a dual 4-input positive NAND buffer (S5400) that buffers the output of the enable and clock signals for the serial mode interface. This gate is built with a cascade output and can be damaged by holding the output at logic high when the gate wants to be at logic zero. This condition could not occur when the DCP is connected to the event counter unless there was a component failure or a short-circuit.

These two observations do not explain why the DCPs fail but they explain why any failure involving moderate current drains might result in burning of the land near U24 and they explain one way that U24 could be damaged. The causes of the DCP failures are not well understood by anyone involved (Personal communication, Earl Painter, Goddard, 1974). We strongly suspect some problem with the design or with some components, however, since some DCPs work well and others fail under the same circumstances. One major potential source of problems in our particular application with the event counters, is that we are not only interfacing two different types of digital logic but we are using two different logic power supplies at voltages of 4.2 and 4.8 volts DC. Furthermore, both the transmitter and the event counter have momentary decreases in logic voltages during transmit and print cycles, respectively. These digital logic power considerations have often caused problems in the past. We found, for example, that if the event counter and transmitter are interconnected but the event counter is not powered, some of the interface logic gates in the event counter can be damaged. Ideally in the future the event counter and transmitter should be designed as one unit. This was not possible in this experiment because of the time schedule.

The inverted dipole antennas have also been a problem. The ground plane on these antennas is 1.2 m. (46 in.) in diameter so that the antenna as supplied and boxed is too large (by only a few inches) to be shipped by air freight on most airplanes. The antenna can barely fit in the rear cabin of a Bell Jet Ranger helicopter. The second problem is that the connector in the ground plane contains no mechanical clamp to hold the central terminal in place. This terminal can be pulled out accidentally when removing a cable and it can also come unsoldered. When the terminal is pulled out, the connector must be removed from the antenna, epoxy chipped off, and the whole connector taken apart and rebuilt. Also the terminal can become unscrewed easily and in one case it was lost in the cracks of an old lava flow when the protective cap was unscrewed. We learned to unscrew this cap after shipment with the antenna upside down.

A plexiglass dome (Photo 5 and 19) was fabricated to fit over the antennas and bolt to the four antenna guy wire holes (built to our specifications by Econo Manufacturing Co., Redwood City, California). This dome was initially intended to keep snow off the elements in the Cascades and Alaska but was also used in Central America to protect the elements from vandals. The antennas with domes seem to work well under at least 10 feet of snow but were crushed by the snow in the spring at several locations as the snow pack settled (Photo 17). Also, some antennas warped when the guy wires were tightened during installation. This large antenna did survive winds in excess of 100 km/hr on St. Augustine volcano. Nevertheless from our experience, we prefer the use of the CHU antenna (Section 6.3.1, Photo 6).

## 7.5 Standard Seismic System

The standard seismic system was originally considered to be a proven system that could easily be deployed with the new event counters. Several problems emerged in the design, however, that needed to be corrected.

When installing the first seismic systems in the Cascades we found that if the amplifier-VCO was near the VHF transmitter, the RF signal modulated the FM signal. Initially the transmitters were mounted on the antenna masts in order to avoid this problem. By November, however, with the help of Electra-Physics Co. we were able to eliminate the RF interference by putting blocking capacitors on all signal and power leads to the amplifier and transmitter.

The second problem was that the preamplifiers in Central America were being damaged by lightning within one or two months of installation and this often led to losing several months of data before qualified technicians could repair the amplifiers. Apparently electric currents were being induced by local lightning in the 15 meter cable between the geophone and the preamplifier. Two diodes in parallel but reversed in direction were added across the differential input and from each input to ground.

These have substantially reduced the failure rate. The geophone cables were placed in steel flexible conduit in February 1974 for further protection.

### 7.6 Lightning

The primary cause of failure of equipment for this program in the field is lightning. In only one case at Mt. Lassen just after the initial installation was any equipment burned. Usually integrated circuits, operational amplifiers, and transistors were simply damaged by induced currents rather than electric currents from a direct lightning strike. Because of the many equipment failures, we talked at some length to researchers at North American Rockwell who have studied ways to protect missle installations from lightning. We also talked to other persons in the USGS and in private industry who have worked on protecting field equipment from such induced currents. While lightning protection seems to be at best a black art, certain principles seem to emerge that will reduce the vulnerability of instruments such as those used in this project:

a. Avoid cables between equipment. Try to put all equipment together in one box.

b. Surround all equipment and cables by iron to shield them from electric and magnetic fields.

c. Isolate the whole system from earth.

d. Isolate the system from power lines or, if impossible, install protective circuits on the power input.

e. Design protective diodes, zener diodes, crowbar clamps, neon discharge tubes, etc. into the system particularly at the ends of all long cables and at the inputs or outputs of antennas. These protective devices should be designed to short out ultra-high frequency, high current-induced voltages above any voltage that would damage the components being protected.

f. In some cases a well grounded diversionary lightning rod might help when placed higher than the equipment being protected and at a distance greater than a few hundred meters.

We are currently modifying our equipment where possible to conform to these general principles.

7.7 Security

Security was anticipated as a major problem but has turned out not so significant. In Central America, for example, it is customary to hire watchmen to guard anything worth very much. Watchmen are inexpensive and many of our collaborators thought it highly unlikely that unguarded equipment could be installed in the countryside and not damaged or pilfered by curious people or by thieves. A number of principles were adopted that worked well. The only problems to arise as of January 1974, were that a box was broken into and batteries stolen at the Telica station in Nicaragua and antenna guy wires were cut at the Cerro Negro station. The principles adopted are as follows:

a. Place equipment on private land, preferably a large "finca" or ranch were the owner can let it be known that this equipment is to be respected and left alone.

b. Make the field installation look simple, not very valuable, and inconspicuous.

c. Bury as much of the equipment as practical.

d. Put the equipment in a securely locked steel box anchored to the ground.

e. Put a notice on the equipment saying what it is and who to call for information. Place the seal of a respected local organization on the equipment.

f. Pay local helpers adequately during installation of the equipment and interest them and the landowners in the project.

7.8 Maintenance

Maintenance of a network spread over several different countries can be a major problem and expense. A global network must require minimal maintenance by untrained personnel if the network is to work and be truly economical. In this program it has been hard to find local personnel with enough training to do minor repairs on the equipment. Even where good personnel exists, it is difficult to interchange parts for repair with them in foreign countries because of the large delays in communication, shipment and particularly in clearing customs. As a result the equipment requiring the least maintenance has worked most reliably. Thus the new event counters and tiltmeters have worked far more reliably than the standard seismic stations whose design was based on several years of experience but which require daily maintenance.

This observation suggests that satellite telemetry could be more reliable and effective than conventional seismic data collection techniques applied over a large area because of the following reasons:

a. Scientists in a central station will know nearly instantaneously when any instrument fails.

b. Each instrument can be small, compact, and selfcontained. This reduces the vulnerability to lightning and pilferage.

c. The equipment can be placed in many more locations than possible when line-of-sight to a local office is required for FM radio telemetry. This means that the equipment can often be made more accessible for maintenance.

d. Daily or monthly maintenance is not required to change records or batteries.

## 8.0 DATA ANALYSIS METHODS

### 8.1 Data Transmittal

The basic source of data transmission from Goddard Spaceflight Center to Menlo Park is by mailing computer cards with each card containing a hexadecimal representation of the 64 data bits and the platform identification number, time of reception and error codes (Figure 8.1). Initially only the cards with no detected transmission errors were sent. By fall of 1973 we convinced the group at Goddard that they should send all messages received so that we could determine the error rate and in some cases correct the errors (Section 8.4).

Since the cards typically arrive one to two weeks after reception of the data, we requested a teletype, which NASA provided by April 23, 1973, over which the data is sent usually within 90 minutes of each satellite pass (Figure 8.2). The data are both printed on paper and punched on five-level paper tape. These data are abbreviated and do not contain the data for which transmission errors are detected. Receipt of the data on such a timely basis is extremely valuable for verifying that field installations are working and particularly for responding to large changes in numbers of earthquakes or ground tilt. For example, the teletype had not been installed in February 1973 when Volcán Fuego erupted in Guatemala

FIGURE 8.1 TYPICAL ERTS DATA AS SENT FROM GODDARD ON COMPUTER CARDS.

| ID YDAYHRMNSC | | DATA BITS | QUALITY BITS |
|---|---|---|---|
| SCI384603413351165342N | 07H | DCC66E4C80DA03FE | FFFFFFFFFFFFFFFF |
| SCI384604313351165403N | 07H | 306AE183003AA209 | FFFFFFFFFFFFFFFF |
| SCI384603413351165523G | 07H | DCC66E4C80DA03FE | FFFFFFFFFFFFFFFF |
| SCI384603413351165523N | 07H | DCC66E4C80DA03FE | FFFFFFFFFFFFFFFF |
| SCI384603413351165704G | 07H | DCC66E4C80DA03FE | FFFFFFFFFFFFFFFF |
| SCI384603413351165704N | 07H | DCC66E4C80DA03FE | FFFFFFFFFFFFFFFF |
| SCI384616313351165720G | 07H | 003EFFA4000008FD | FFFFFFFFFFFFFFFF |
| SCI384616313351165720N | 07H | 003EFFA4000008FD | FFFFFFFFFFFFFFFF |
| SCI384604313351165736N | 07H | 306AE183003AA209 | FFFFFFFFFFFFFFFF |
| SCI384604313351165736G | 07H | 306AE183003AA209 | FFFFFFFFFFFFFFFF |
| SCI384603413351165844G | 07H | DCC66E4C80DA03FE | FFFFFFFFFFFFFFFF |
| SCI384603413351165844N | 07H | DCC66E4C80DA03FE | FFFFFFFFFFFFFFFF |
| SCI384610313351165949G | 07H | 0000000000000000 | FFFFFFFFFFFFFFFF |
| SCI384610313351165949N | 07H | 0000000000000000 | FFFFFFFFFFFFFFFF |
| SCI384613213351170004G | 07H | 0A340400005D4000 | FFFFFFFFFFFFFFFF |
| SCI384613213351170004N | 80H | 01456360580EE340 | F6FDFFEFFFFFFFBE |
| SCI384601113351170030G | 07H | EE02040000482008 | FFFFFFFFFFFFFFFF |
| SCI384600513351170044G | 07H | 02B706C200A07100 | FFFFFFFFFFFFFFFF |
| SCI384600513351170044N | 07H | 02B706C200A07100 | FFFFFFFFFFFFFFFF |
| SCI384616313351170053G | 07H | 003EFFA4000008FD | FFFFFFFFFFFFFFFF |
| SCI384616313351170053N | 07H | 003EFFA4000008FD | FFFFFFFFFFFFFFFF |
| SCI384605713351170102G | 07H | 000000000000A17F | FFFFFFFFFFFFFFFF |
| SCI384604313351170109G | 07H | 306AE183003AA209 | FFFFFFFFFFFFFFFF |
| SCI384604313351170109N | 07H | 306AE183003AA209 | FFFFFFFFFFFFFFF[illegible] |
| SCI384613213351170131G | 07H | 0A340400005D4000 | FFFFFFFFFFFFFFFF |
| SCI384613213351170131N | 80H | 00000F0000596F00 | F17F74DEFFFD86DE |
| SCI384601113351170202G | 07H | EE02040000482008 | FFFFFFFFFFFFFFFF |
| SCI384631113351170209G | 07H | 290658532035A14D | FFFFFFFFFFFFFFFF |
| SCI384610313351170246G | 07H | 0000000000000000 | FFFFFFFFFFFFFFFF |

FIGURE 8.2 Typical ERTS data as sent from Goddard by teletype.

B#VU Z
DTZMVTEDOX
GZDOO7A
PP GZDA
DE GERS 0660
15/163 6Z
REF ERTS DCS

ATT D HARLOW US GEOLOGICAL SURVEY PHONE 415 323 8111

| S | Y | DDDHHMM | SS | PID | C | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | CS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | 4 | 151621 | 53 | 6004 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| G | 4 | 151621 | 53 | 6004 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| N | 4 | 151623 | 24 | 6004 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| G | 4 | 151623 | 24 | 6004 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| G | 4 | 151624 | 56 | 6004 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| NO MESSAGES | | | | 6005 | | | | | | | | | | |
| N | 4 | 151620 | 21 | 6011 | 7 | 372 | 210 | 0 | 143 | 4 | 0 | 0 | 0 | 2 |
| G | 4 | 151620 | 21 | 6011 | 7 | 372 | 210 | 0 | 143 | 4 | 0 | 0 | 0 | 2 |
| N | 4 | 151621 | 52 | 6011 | 7 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 7 |
| G | 4 | 151621 | 52 | 6011 | 7 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 7 |
| N | 4 | 151623 | 23 | 6011 | 7 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 7 |
| G | 4 | 151623 | 23 | 6011 | 7 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 7 |
| G | 4 | 151624 | 53 | 6011 | 7 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 377 | 7 |
| HN | 4 | 151612 | 41 | 6034 | 7 | 334 | 303 | 4 | 314 | 200 | 332 | 57 | 376 | 1 |
| N | 4 | 151614 | 21 | 6034 | 7 | 334 | 303 | 4 | 314 | 200 | 332 | 57 | 376 | 1 |
| N | 4 | 151616 | 02 | 6034 | 7 | 334 | 303 | 4 | 314 | 200 | 332 | 57 | 376 | 1 |
| N | 4 | 151623 | 20 | 6036 | 7 | 116 | 77 | 113 | 0 | 0 | 203 | 0 | 7 | 6 |
| G | 4 | 151623 | 20 | 6036 | 7 | 116 | 77 | 113 | 0 | 0 | 203 | 0 | 7 | 6 |
| G | 4 | 151624 | 47 | 6036 | 7 | 116 | 77 | 113 | 0 | 0 | 203 | 0 | 7 | 6 |
| N | 4 | 151611 | 54 | 6043 | 7 | 60 | 155 | 347 | 203 | 0 | 72 | 222 | 10 | 3 |
| N | 4 | 151615 | 27 | 6043 | 7 | 60 | 155 | 347 | 203 | 0 | 72 | 222 | 10 | 3 |
| G | 4 | 151615 | 27 | 6043 | 7 | 60 | 155 | 347 | 203 | 0 | 72 | 222 | 10 | 3 |
| N | 4 | 151619 | 00 | 6043 | 7 | 60 | 155 | 347 | 203 | 0 | 72 | 222 | 10 | 3 |
| G | 4 | 151619 | 00 | 6043 | 7 | 60 | 155 | 347 | 203 | 0 | 72 | 222 | 10 | 3 |
| NO MESSAGES | | | | 6057 | | | | | | | | | | |
| NO MESSAGES | | | | 6066 | | | | | | | | | | |
| NO MESSAGES | | | | 6103 | | | | | | | | | | |
| NO MESSAGES | | | | 6117 | | | | | | | | | | |
| N | 4 | 151621 | 04 | 6132 | 7 | 201 | 2 | 4 | 0 | 0 | 123 | 300 | 0 | 1 |
| G | 4 | 151621 | 04 | 6132 | 7 | 201 | 2 | 4 | 0 | 0 | 123 | 300 | 0 | 1 |
| N | 4 | 151622 | 31 | 6132 | 7 | 201 | 2 | 4 | 0 | 0 | 123 | 300 | 0 | 1 |
| G | 4 | 151622 | 31 | 6132 | 7 | 201 | 2# | 4 | 0 | 0 | 123 | 300 | 0 | 1 |
| G | 4 | 151623 | 58 | 6132 | 7 | 201 | 2 | 4 | 0 | 0 | 123 | 300 | 0 | 1 |
| G | 4 | 151625 | 24 | 6132 | 7 | 201 | 2 | 4 | 0 | 0 | 123 | 300 | 0 | 1 |

(Section 9.1). We did not find out about the increase in activity prior to the eruption until several weeks after the eruption.

Deletion of the data that contain transmission errors seems inadvisable as long as these data are properly identified. For example, in November 1973 we were trying to determine why data from DCP 6262 were not being received. The transmitter checked out perfectly on the Field Test Set provided by NASA and we could find no indication as to why no messages were coming through the satellite. Two months later when the data on cards were being analyzed, we found that transmissions were being received for this platform but some of the data bits between bit 45 and 56 were not being received properly and were flagged as being in error. We strongly urge that all data received through the satellite be sent to the user to allow him to determine whether the data should be thrown away.

## 8.2 Computer Program Used for Analysis

By the end of 1973, nearly 72,400 messages had been received through the satellite and processed and data continues to be collected at an average rate of 10 messages per day from each operating transmitter. To handle this data flow a computer program was developed to operate on the CDC 1700 available in our office in Menlo Park, California. A generalized block diagram of this 1,760 line Fortran program is shown in figure 8.3.

Routine processing is done every day at noon after data from the morning satellite passes are received. The paper tape punched by the teletype is read directly by the CDC1700 and data for up to the previous 30 days are read into the computer from magnetic tape. This tape is updated with the new data. Listings and plots are then made of these data as shown in figures 8.4 to 8.8 and described in the following section.

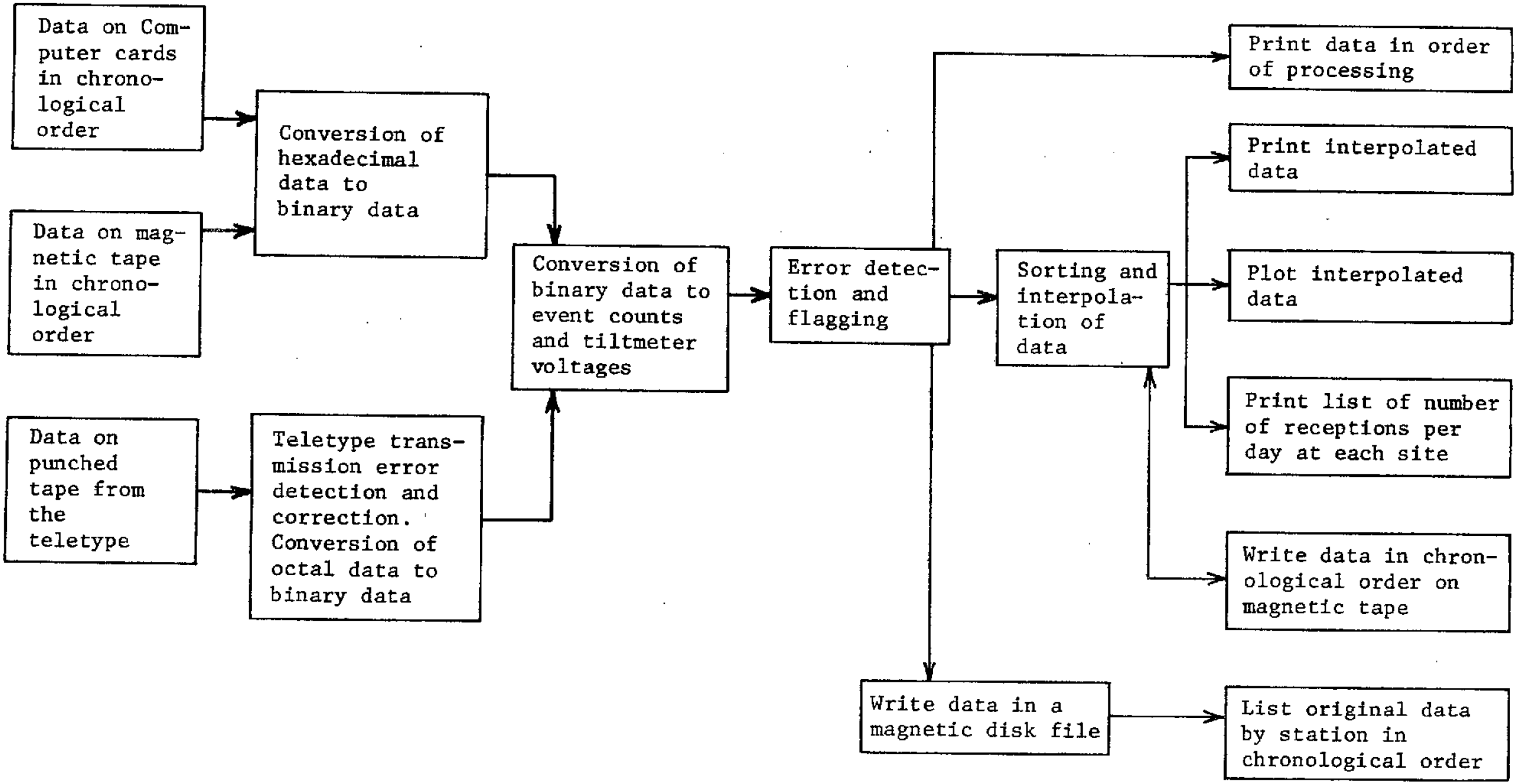


FIGURE 8.3. Simplified block diagram of the computer program used to process ERTS data.

FIGURE 8.4. Typical typewriter output of the ERTS data processing program showing computer prompts and operator corrections of data containing teletype transmission errors.

```
GZD003A
 DE GERS 0260
 15/0235Z

 ERROR  3.  I  TO  IGNOR, - FOR BLANK.
 -S--Y-DDDHRMN-SS--PLAT--Q--DA1--DA2--DA3--DA4--DA5--DA6--DA7--DA8---C-
   N  4  150201 23  6004  7    0    0    0    0   00000    0    0   7
                                                ----0----0    0    0   7

 ERROR  1.  I  TO  IGNOR, - FOR BLANK.
 -S--Y-DDDHRMN-SS--PLAT--Q--DA1--DA2--DA3--DA4--DA5--DA6--DA7--DA8---C-
   N  4  150200 35  6011  7    0 #  0    0    0    0    0    0    0   7
 15/0236Z JAN GERS

   2
GZD004A
 DE GERS 0360
 15/0415Z
 15/0416Z JAN GERS

   3
GZD005A
 DE GERS 0460
 15/0545Z
 15/0546Z JAN GERS

   4
GZD006A
 DE GERS 0560
 15/1449Z
 15/1449Z JAN GERS

   5
GZD007A
 DE GERS 0660
 15/1636Z

 ERROR  1.  I  TO  IGNOR, - FOR BLANK.
 -S--Y-DDDHRMN-SS--PLAT--Q--DA1--DA2--DA3--DA4--DA5--DA6--DA7--DA8---C-
 HN  4  151612 41  6034  7  334  303    4  314  200  332   57  376   1
 -

 ERROR  1.  I  TO  IGNOR, - FOR BLANK.
 -S--Y-DDDHRMN-SS--PLAT--Q--DA1--DA2--DA3--DA4--DA5--DA6--DA7--DA8---C-
   G  4  151622 31  6132  7  201   2#    4    0    0  123  300    0   1

DE GERS 0661
15/1636Z
6276 SEQUENCE
```

ERTS DATA ANALYSIS 01/16/74

| PLATFORM | TYPE | DESCRIPTION | YDAY | HRMN | SEC | ERROR CODE | DATA 1 | DATA 2 | DATA 3 | DATA 4 | DATA 5 | DATA 6 | DATA 7 | DATA 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6176 | 1 | SPARE | 4015 | 529 | 15 | 128 | 1023 | 1023 | 1023 | 1023 | 1023 | 1023 | 7 | 0 |
| 6176 | 1 | SPARE | 4015 | 532 | 13 | 128 | 1023 | 1023 | 1023 | 1023 | 1023 | 1023 | 7 | 0 |
| 6342 | 1 | MT ILIAMNA | 4015 | 533 | 7 | 128 | 672 | 564 | 304 | 1 | 212 | 647 | 1 | 0 |
| 6342 | 1 | MT ILIAMNA | 4015 | 536 | 31 | 128 | 672 | 564 | 304 | 1 | 212 | 647 | 1 | 0 |
| 6365 | 1 | ST AUGUSTINE | 4015 | 532 | 45 | 128 | 728 | 175 | 14 | 0 | 509 | 6 | 0 | 0 |
| 6365 | 1 | ST AUGUSTINE | 4015 | 536 | 16 | 128 | 728 | 175 | 14 | 0 | 509 | 6 | 0 | 0 |
| 6004 | 2 | PACAYA TILT | 4015 | 1438 | 42 | 64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6004 | 2 | PACAYA TILT | 4015 | 1440 | 15 | 64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1439 | 25 | 64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1439 | 57 | 64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6036 | 1 | CERRO NEGRO | 4015 | 1438 | 9 | 64 | 113 | 191 | 11 | 0 | 193 | 0 | 6 | 0 |
| 6036 | 1 | CERRO NEGRO | 4015 | 1439 | 37 | 64 | 113 | 191 | 11 | 0 | 193 | 0 | 6 | 0 |
| 6132 | 1 | BUENA VISTA | 4015 | 1438 | 10 | 64 | 129 | 16 | 2 | 0 | 970 | 0 | 0 | 0 |
| 6132 | 1 | BUENA VISTA | 4015 | 1439 | 37 | 64 | 129 | 16 | 2 | 0 | 970 | 0 | 0 | 0 |
| 6154 | 1 | AGUA | 4015 | 1439 | 49 | 64 | 803 | 896 | 0 | 0 | 523 | 257 | 0 | 0 |
| 6162 | 1 | SANTIAGUITO | 4015 | 1440 | 53 | 64 | 912 | 519 | 36 | 3 | 299 | 24 | 3 | 0 |
| 6247 | 1 | MINA LIMON | 4015 | 1439 | 0 | 64 | 757 | 5 | 0 | 0 | 37 | 0 | 0 | 0 |
| 6247 | 1 | MINA LIMON | 4015 | 1440 | 31 | 64 | 757 | 5 | 0 | 0 | 37 | 0 | 0 | 0 |
| 6311 | 1 | IZALCO | 4015 | 1440 | 58 | 64 | 236 | 686 | 164 | 19 | 435 | 163 | 3 | 0 |
| 6315 | 1 | ICELAND | 4015 | 1430 | 3 | 64 | 723 | 76 | 18 | 0 | 39 | 0 | 0 | 0 |
| 6320 | 2 | FUEGO TILT | 4015 | 1439 | 10 | 64 | 131 | 129 | 131 | 128 | 131 | 178 | 167 | 134 |
| 6320 | 2 | FUEGO TILT | 4015 | 1440 | 44 | 64 | 130 | 129 | 131 | 129 | 131 | 178 | 167 | 134 |
| 6372 | 1 | FUEGO GUATE | 4015 | 1439 | 16 | 64 | 604 | 147 | 15 | 2 | 39 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4015 | 1440 | 44 | 64 | 604 | 147 | 15 | 2 | 39 | 9 | 2 | 0 |
| 6004 | 2 | PACAYA TILT | 4015 | 1621 | 53 | 64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6004 | 2 | PACAYA TILT | 4015 | 1621 | 53 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6004 | 2 | PACAYA TILT | 4015 | 1623 | 24 | 64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6004 | 2 | PACAYA TILT | 4015 | 1623 | 24 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6004 | 2 | PACAYA TILT | 4015 | 1624 | 56 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1620 | 21 | -64 | 351 | 4 | 96 | 131 | 0 | 0 | 0 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1620 | 21 | -128 | 351 | 4 | 96 | 131 | 0 | 0 | 0 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1621 | 52 | 64 | 1023 | 1023 | 1023 | 1023 | 1023 | 1023 | 7 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1621 | 52 | 128 | 1023 | 1023 | 1023 | 1023 | 1023 | 1023 | 7 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1623 | 23 | 64 | 1023 | 1023 | 1023 | 1023 | 1023 | 1023 | 7 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1623 | 23 | 128 | 1023 | 1023 | 1023 | 1023 | 1023 | 1023 | 7 | 0 |
| 6011 | 1 | PACAYA | 4015 | 1624 | 53 | 128 | 1023 | 1023 | 1023 | 1023 | 1023 | 1023 | 7 | 0 |
| 6034 | 1 | MT BAKER | 4015 | 1612 | 41 | 64 | 827 | 48 | 818 | 4 | 91 | 1021 | 7 | 0 |
| 6034 | 1 | MT BAKER | 4015 | 1614 | 21 | 64 | 827 | 48 | 818 | 4 | 91 | 1021 | 7 | 0 |
| 6034 | 1 | MT BAKER | 4015 | 1616 | 2 | 64 | 827 | 48 | 818 | 4 | 91 | 1021 | 7 | 0 |
| 6036 | 1 | CERRO NEGRO | 4015 | 1623 | 20 | 64 | 114 | 191 | 13 | 0 | 193 | 0 | 6 | 0 |
| 6036 | 1 | CERRO NEGRO | 4015 | 1623 | 20 | 128 | 114 | 191 | 13 | 0 | 193 | 0 | 6 | 0 |

FIGURE 8.5. Typical output of data in chronological order from the ERTS data analysis program.

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| PLATFORM | TYPE | DESCRIPTION | YDAY | HRMN | SEC | ERROR CODE | DATA 1 | DATA 2 | DATA 3 | DATA 4 | DATA 5 | DATA 6 | DATA 7 | DATA 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6372 | 1 | FUEGO GUATE | 4007 | 1537 | 24 | 64 | 141 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4008 | 302 | 17 | 64 | 156 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4008 | 303 | 44 | 64 | 155 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4008 | 305 | 11 | 64 | 156 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4008 | 443 | 2 | 128 | 157 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4008 | 1540 | 52 | 64 | 166 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4008 | 1542 | 20 | 64 | 166 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4008 | 1543 | 47 | 64 | 166 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4009 | 307 | 23 | 64 | 168 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4009 | 310 | 18 | 64 | 168 | 131 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4009 | 448 | 7 | 128 | 170 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4009 | 1546 | 27 | 64 | 173 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4009 | 1547 | 54 | 64 | 173 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4009 | 1549 | 22 | 64 | 173 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4010 | 313 | 44 | 64 | 174 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4010 | 315 | 11 | 64 | 174 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4010 | 316 | 39 | 64 | 174 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4010 | 454 | 19 | 128 | 174 | 132 | 12 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4010 | 1552 | 40 | 64 | 175 | 133 | 13 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4010 | 1554 | 7 | 64 | 175 | 133 | 13 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4011 | 319 | 25 | 64 | 177 | 133 | 13 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4011 | 320 | 52 | 64 | 177 | 133 | 13 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4011 | 322 | 20 | 64 | 177 | 133 | 13 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4011 | 1557 | 36 | 64 | 179 | 133 | 13 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4012 | 325 | 38 | 64 | 186 | 134 | 13 | 2 | 37 | 8 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4012 | 1603 | 54 | 64 | 196 | 135 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 148 | 53 | 64 | 203 | 135 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 150 | 20 | 64 | 203 | 135 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 332 | 1 | 128 | 207 | 135 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 1427 | 58 | 64 | 277 | 136 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 1429 | 26 | 64 | 277 | 136 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 1609 | 56 | 64 | 302 | 136 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 1611 | 22 | 128 | 303 | 136 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4013 | 1611 | 22 | 64 | 303 | 136 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4014 | 155 | 12 | 64 | 344 | 139 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4014 | 155 | 12 | 64 | 344 | 139 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4014 | 156 | 39 | 64 | 344 | 139 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4014 | 156 | 39 | 64 | 344 | 139 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4014 | 337 | 6 | 128 | 361 | 139 | 14 | 2 | 38 | 9 | 2 | 0 |
| 6372 | 1 | FUEGO GUATE | 4014 | 338 | 34 | 128 | 361 | 139 | 14 | 2 | 38 | 9 | 2 | 0 |

FIGURE 8.6. Typical output of data listed by station from the ERTS data analysis program.

| STATION | YDAY HR | DATA1 | DATA2 | DATA3 | DATA4 | DATA5 | DATA6 | DATA7 | DATA8 | HRBE | HRAF | NUMB | DAT1 | DAT2 | DAT3 | DAT4 | DAT5 | DAT6 | DAT7 | DAT8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6372 FUEGO GUATE | 4001 500 | 73 | 121 | 11 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 6 | 73 | 121 | 11 | 2 | 37 | 8 | 2 | 0 |
| 6372 FUEGO GUATE | 40011700 | 76 | 121 | 11 | 2 | 37 | 8 | 2 | 0 | 0 | 9 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4002 500 | 76 | 121 | 11 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40021700 | 77 | 121 | 11 | 2 | 37 | 8 | 2 | 0 | 0 | 10 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4003 500 | 80 | 122 | 11 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 6 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40031700 | 84 | 123 | 11 | 2 | 37 | 8 | 2 | 0 | 2 | 9 | 1 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4004 500 | 87 | 123 | 11 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 7 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40041700 | 89 | 123 | 11 | 2 | 37 | 8 | 2 | 0 | 2 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4005 500 | 106 | 124 | 11 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 7 | 17 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40051700 | 113 | 125 | 11 | 2 | 37 | 8 | 2 | 0 | 2 | 10 | 1 | 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4006 500 | 124 | 128 | 12 | 2 | 37 | 8 | 2 | 0 | 0 | 10 | 5 | 11 | 3 | 1 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40061700 | 131 | 128 | 12 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 3 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4007 500 | 137 | 130 | 12 | 2 | 37 | 8 | 2 | 0 | 0 | 11 | 5 | 6 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40071700 | 143 | 131 | 12 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 3 | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4008 500 | 157 | 131 | 12 | 2 | 37 | 8 | 2 | 0 | 0 | 11 | 4 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40081700 | 166 | 131 | 12 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 3 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4009 500 | 170 | 132 | 12 | 2 | 37 | 8 | 2 | 0 | 0 | 11 | 3 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40091700 | 173 | 132 | 12 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4010 500 | 174 | 132 | 12 | 2 | 37 | 8 | 2 | 0 | 0 | 11 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40101700 | 175 | 133 | 13 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4011 500 | 177 | 133 | 13 | 2 | 37 | 8 | 2 | 0 | 2 | 11 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40111700 | 180 | 133 | 13 | 2 | 37 | 8 | 2 | 0 | 1 | 10 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4012 500 | 187 | 134 | 13 | 2 | 37 | 8 | 2 | 0 | 2 | 11 | 1 | 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40121700 | 197 | 135 | 14 | 2 | 38 | 9 | 2 | 0 | 1 | 9 | 1 | 10 | 1 | 1 | 0 | 1 | 1 | 0 | 0 |
| 6372 FUEGO GUATE | 4013 500 | 216 | 135 | 14 | 2 | 38 | 9 | 2 | 0 | 1 | 9 | 3 | 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40131700 | 306 | 136 | 14 | 2 | 38 | 9 | 2 | 0 | 1 | 9 | 4 | 90 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4014 500 | 375 | 139 | 14 | 2 | 38 | 9 | 2 | 0 | 1 | 11 | 4 | 69 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40141700 | 492 | 143 | 14 | 2 | 39 | 9 | 2 | 0 | 1 | 9 | 3 | 117 | 4 | 0 | 0 | 1 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4015 500 | 549 | 145 | 15 | 2 | 39 | 9 | 2 | 0 | 1 | 10 | 4 | 57 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 40151700 | 615 | 147 | 15 | 2 | 39 | 9 | 2 | 0 | 1 | 9 | 4 | 66 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6372 FUEGO GUATE | 4016 500 | 647 | 150 | 15 | 2 | 39 | 9 | 2 | 0 | 1 | 10 | 5 | 32 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |

FIGURE 8.7. Typical output of interpolated data from the ERTS data analysis program. HRBE is the hours between the interpolation time and the most recent previous data message. HRAF is the hours between the interpolation time and the next data message. NUMB is the number of messages received in the previous 12 hours. The right-hand columns are the changes in the data in the preceding 12 hours.

```
PLATFORM 6372       FUEGO GUATE
YDAY  EC1 EC2 EC3 EC4 0123456789A123456789B123456789C123456789D123456789E123456 1234  IC1 IC2 IC3 0123456789A123456789B12345678 123
4001A 450 9951020   0I4         I         I         I         I         I       1/3 110221023   0I3         I         I         12
4001B   3   0   0   0I*  1      I         I         I         I         I           I   0   0   0I*         I         I
4002A   0   0   0   0I*         I         I         I         I         I           I   0   0   0I*         I         I
4002B   1   0   0   0I*1        I         I         I         I         I           I   0   0   0I*         I         I
4003A   3   1   0   0I*2 1      I         I         I         I         I           I   0   0   0I*         I         I
4003B   4   1   0   0I*2  1     I         I         I         I         I           I   0   0   0I*         I         I
4004A   3   0   0   0I*  1      I         I         I         I         I           I   0   0   0I*         I         I
4004B   2   0   0   0I* 1       I         I         I         I         I           I   0   0   0I*         I         I
4005A  17   1   0   0I*2        I      1  I         I         I         I           I   0   0   0I*         I         I
4005B   7   1   0   0I*2     1  I         I         I         I         I           I   0   0   0I*         I         I
4006A  11   3   1   0I43 2      I1        I         I         I         I           I   0   0   0I*         I         I
4006B   7   0   0   0I*      1  I         I         I         I         I           I   0   0   0I*         I         I
4007A   6   2   0   0I* 2   1   I         I         I         I         I           I   0   0   0I*         I         I
4007B   6   1   0   0I*2    1   I         I         I         I         I           I   0   0   0I*         I         I
4008A  14   0   0   0I*         I   1     I         I         I         I           I   0   0   0I*         I         I
4008B   9   0   0   0I*        1I         I         I         I         I           I   0   0   0I*         I         I
4009A   4   1   0   0I*2  1     I         I         I         I         I           I   0   0   0I*         I         I
4009B   3   0   0   0I*  1      I         I         I         I         I           I   0   0   0I*         I         I
4010A   1   0   0   0I*1        I         I         I         I         I           I   0   0   0I*         I         I
4010B   1   1   1   0I4*        I         I         I         I         I           I   0   0   0I*         I         I
4011A   2   0   0   0I* 1       I         I         I         I         I           I   0   0   0I*         I         I
4011B   3   0   0   0I*  1      I         I         I         I         I           I   0   0   0I*         I         I
4012A   7   1   0   0I*2     1  I         I         I         I         I           I   0   0   0I*         I         I
4012B  10   1   1   0I4*        I         I         I         I         I           I   1   1   0I3*        I         I
4013A  19   0   0   0I*         I        1I         I         I         I           I   0   0   0I*         I         I
4013B  90   1   0   0I*2        I         I         I         I         I       1   I   0   0   0I*         I         I
4014A  69   3   0   0I*  2      I         I         I         I         I       1   I   0   0   0I*         I         I
4014B 117   4   0   0I*   2     I         I         I         I         I       1   I   1   0   0I*1        I         I
4015A  57   2   1   0I432       I         I         I         I         I       1   I   0   0   0I*         I         I
4015B  66   2   0   0I* 2       I         I         I         I         I       1   I   0   0   0I*         I         I
4016A  32   3   0   0I*  2      I         I         I 1       I         I           I   0   0   0I*         I         I
```

FIGURE 8.8. Typical plot of the interpolated data. The event counter data (1 to 4) are plotted on the left and the inhibit-time counts (1 to 3) are plotted on the right. YDAY 4001A is January 1, 1974 at time 0500Z. B is time 1700Z.

By daily processing old as well as new data, the interpolated listings and plots can be readily updated with each new page showing the trends over a period of time. When the data on computer cards are received they are sorted chronologically. At regular intervals a large batch is processed with appropriate files of data and printed output generated.

Numerous transmission errors occur in the teletype data. These range from the year or day being incorrectly generated or simply left out of the message, to characters being added, garbled, or deleted (Figure 8.2). For this reason a reasonably detailed error detection and correction sub-program was written for routine processing of the teletype data. When teletype lines containing data are found to contain errors, the computer prompts the operator by typing the bad line on the computer's teletype and allowing the operator to correct the line (Figure 8.4). Now that the various patterns of errors have been observed, this process could be automated but we still prefer direct control over any changes made to the actual data. Copies of the teletype tape reading subroutine and the error detection and correction subroutine may be of interest to other ERTS users and can be provided upon request.

## 8.3 Different Types of Data Displays

The basic displays of data used in the project are shown in figure 8.5 through 8.8. In each of these displays the binary bits have been converted to the 7 decimal counts (0 to 1023) from the event counters and 8 decimal voltages (0 to 255) from the tiltmeters. A descriptor for each platform number has been added. The error code is 64 for data received at Goddard and 128 for data received at Goldstone. Any other value signifies a flagged error according to a code. The data are routinely displayed by message in order of reception (Figure 8.5), by message for a given station in chronological order (Figure 8.6), by station but with the data interpolated to give one line every 12 hours (Figure 8.7), and by plotting the interpolated data (Figure 8.8). In addition daily summaries of messages received at each station are printed.

These few data displays are adequate to show clearly what is happening at each station. Special displays such as the plots of daily receptions shown in section 9.3 are generated occasionally from the reduced data stored on magnetic tape. The data are not analyzed routinely in any statistical manner since detailed statistical tests are not necessary to show the trends in the data.

# 9.0 RESULTS

## 9.1 Seismic Event Counters

### 9.1.1 Reliability of detecting earthquakes

Standard seismometers were operated next to nearly all event counters in this preliminary experiment. A typical comparison of events counted electronically with earthquakes counted by a seismologist studying typical seismograms is shown in figure 9.1. 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 inhibit-time counts. These comparisons of data together with the detailed analysis of the event counter operation in Hawaii (section 6.1.3) provide the basis for the following conclusions about the reliability of the 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

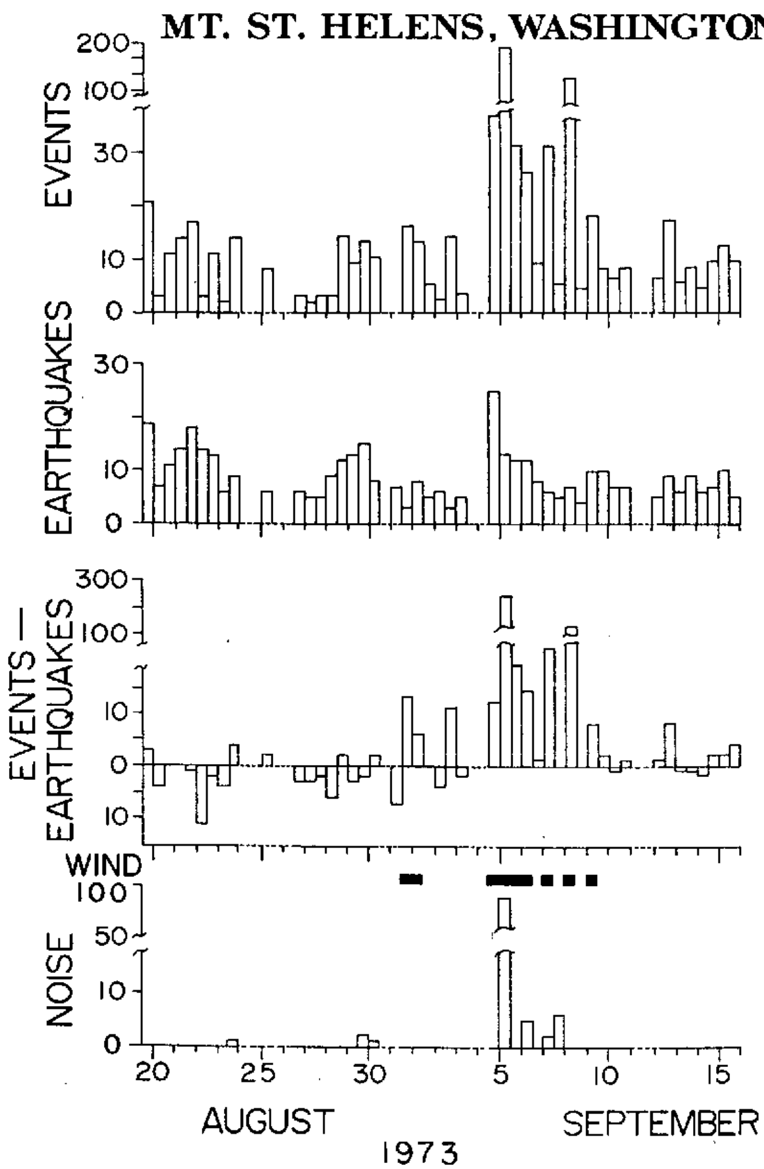



FIGURE 9.1. Seismic events counted by the event counter on Mt. St. Helens in Washington compared to earthquakes detected by a seismologist from a seismograph operated nearby.

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 Photo 21 where the square tic marks are clock pulses that occur once every minute. Failure to detect some earthquakes during periods of high background noise is normally not serious since the noise will inevitable cause some spurious counts and the high noise counts will flag the number of event counts as being suspect anyway. Failing to detect earthquakes that occur rapidly in succession is also not necessarily serious since such events will very rarely occur except during swarms of earthquakes when the percentage of such undetected earthquakes is likely to be very 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 Photo 22. 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 from being counted but it turns out that at some volcanoes, particularly Pacaya and San Cristobal 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, and St. Augustine (Mauk and Kienle, 1973). These events are not counted because they begin with small ground amplitudes that build up to a maximum in about 5 seconds. In many cases 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 could 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 cultural sources of ground noise but predominantly are wind-induced. Such spurious counts, however, are either infrequent or are usually accompanied by significant noise or in other words inhibit-time counts. Cultural noise is successfully avoided at most sites by placing the instrument in an area remote from frequently traveled roads or trails. Wind noise is reduced by placing the sensors at low elevation, in spots sheltered from high winds, away from trees, at 25 or 30 meters from the large antennas (Photo 19), and by using smaller types of antennas (Photo 6). Major changes in background noise level caused by wind cannot be totally avoided. Spurious event 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 noise counts. Such cases can usually be identified, however, since of a large number of event counts triggered by earthquakes recorded on one channel, approximately 15 to 30 percent should be counted on the next most sensitive channel. This relationship occurs because earthquakes are well-known to be distributed in size according to the Gutenberg and Richter (1949) relationship modified by Suzuki (1953)

$$\log N = -b \log A + C$$

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 many inhibit-time counts 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, 1969; 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 constants. 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 earthquakes as periods of noise.

The results from these new seismic event counters are very encouraging and show that significant processing of the seismic data can be done by relatively simple electronic circuits. We think 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 field data processing and are thus continuing to experiment with other types of counters.

### 9.1.2 Changes in seismicity observed

A microearthquake swarm occurred near St. Augustine Volcano in Alaska between January 11 and 23, 1973. There is an excellent correlation (Figure 9.2) between the numbers of microearthquakes observed on a standard seismograph (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 (see section 7.2). Since the third channel is 16 times less sensitive than the most sensitive channel, the numbers 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 b-value 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. St. 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

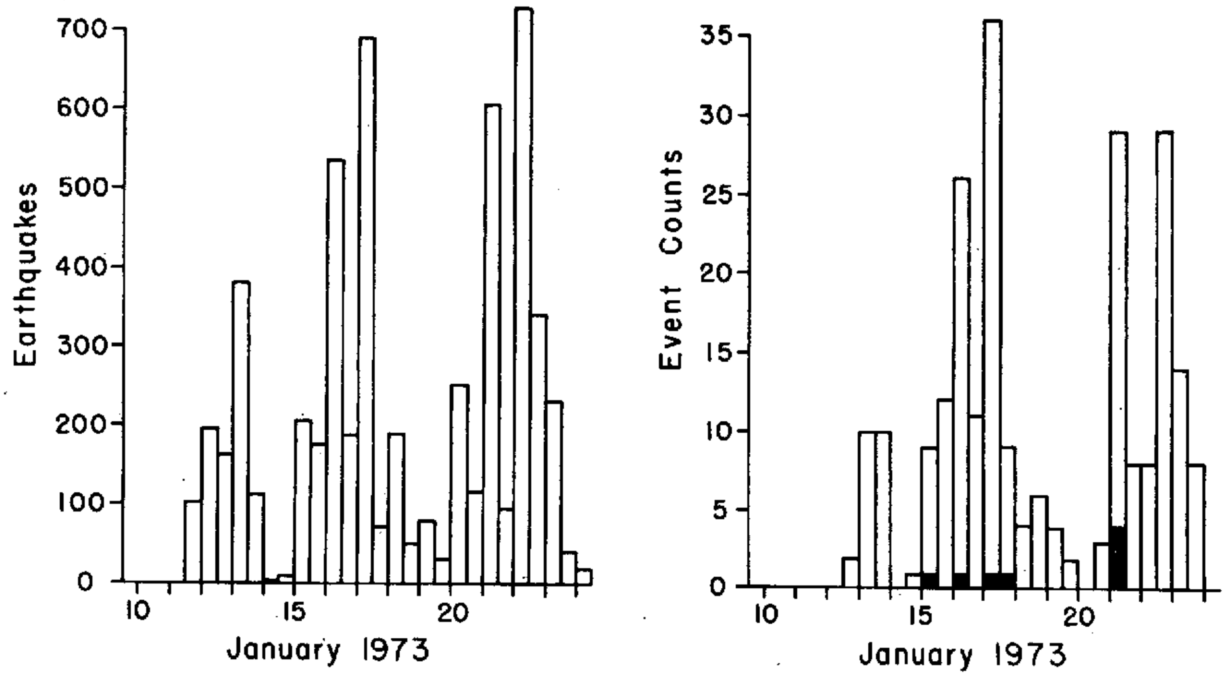



FIGURE 9.2. Earthquakes counted from a standard seismometer on St. Augustine in Alaska (left) compared to events counted by the event counter located nearby (right) on Channel 3 (open bars) and Channel 4 (open bars).

85 meters since 1957. This swarm clearly illustrates why a change of two or even three orders of magnitude in seismicity does not necessarily allow one to predict a specific eruption. Such a change does indicate, however, when these swarms occur regularly, that this volcano is very active and has a relatively high potential for eruption.

The number of seismic event counts recorded at Santiaguito Volcano in Guatemala from March through September, 1973, are shown in Figure 9.3. There are three times when the number of events increase by about an order of magnitude but each of these periods are accompanied by a significant number of inhibit-time counts. Thus there are no changes in the event counts in the figure that would stand out as designating changes in seismicity. The seismicity in this region does stand out, however, as generally high.

Rose (1974) described an eruption on April 19, 1973, that was the largest nuée ardente eruption of Santiaguito 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 deposits appeared to originate from the Caliente vent area of Santiaguito. A second nuée occurred on September 16, 1973, that was smaller and originated at the toe of a lava flow coming off of the dome. Rose and Bonis suggest the possibility that both of these nuées may have originated at or 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 figure 9.4. 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 thus creating no serious threat to the farms and towns on its flanks. The

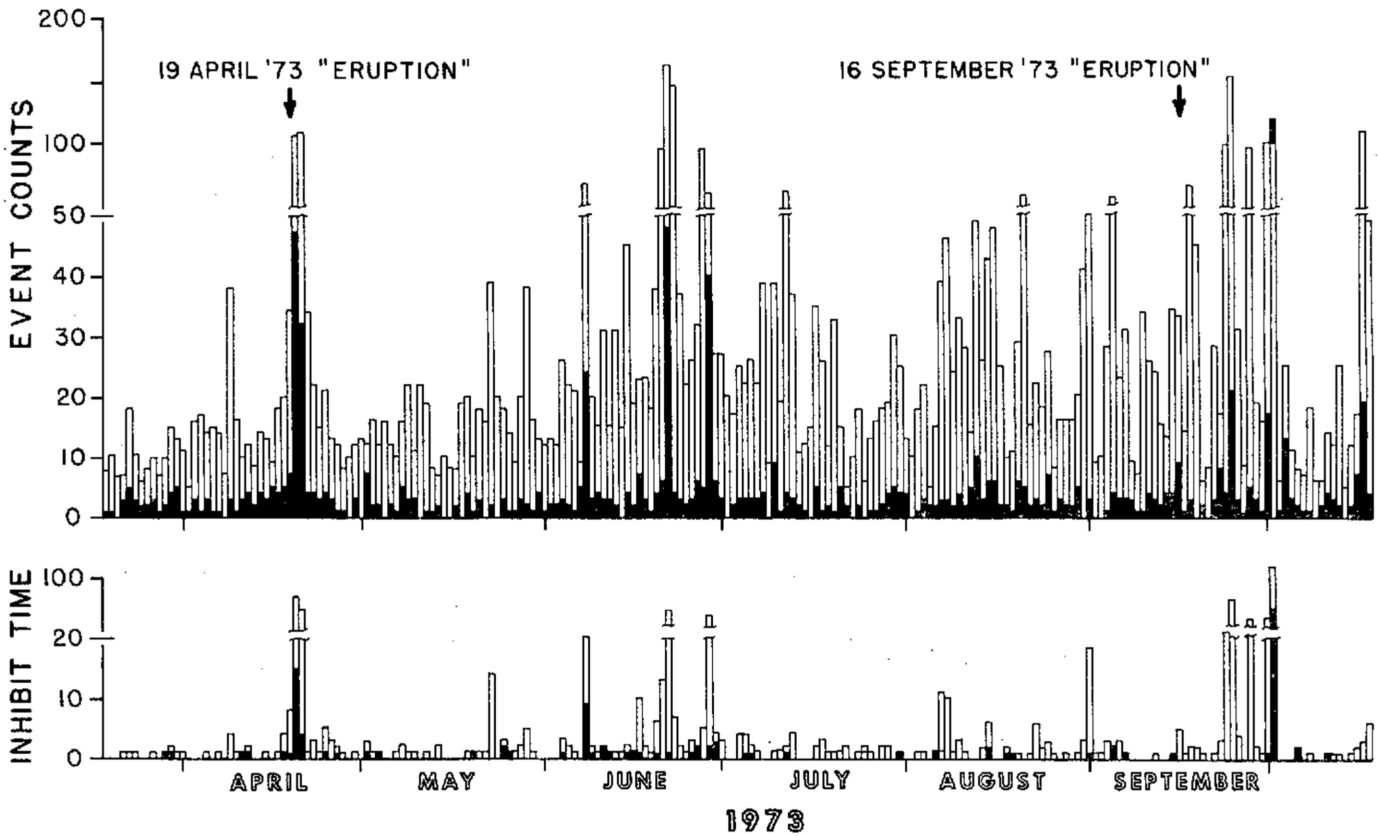



FIGURE 9.3. Seismic event counts and inhibit-time counts per day recorded near Volcán Santiaguito in Guatemala.

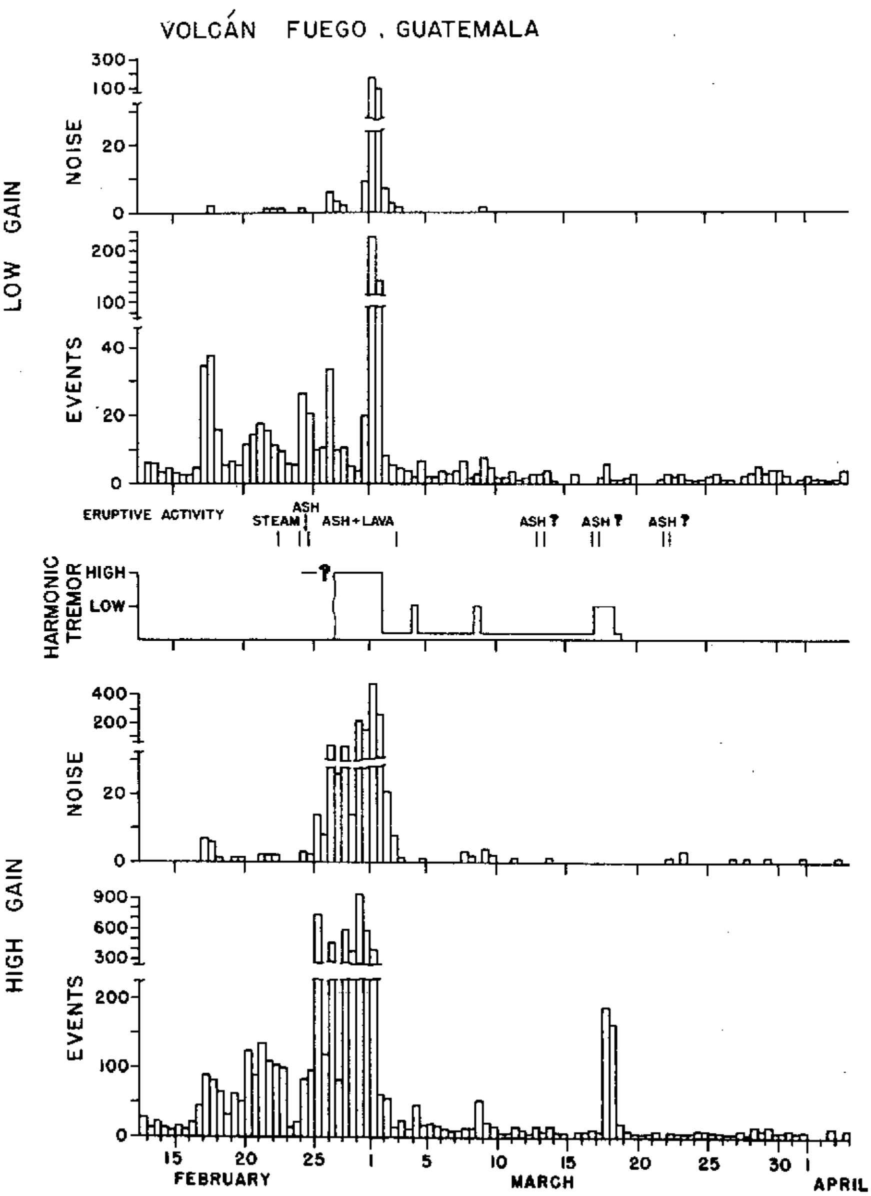



FIGURE 9.4. Seismic events and noise counted near Volcán Fuego in Guatemala in early 1973. Note the increase in seismic activity during the eruption in February.

chronology of the eruption as best can be constructed is as follows (S. Bonis, personal communication, 1973):

| | |
|---|---|
| September 1971 | Last previous eruption. Heavy ash fall for 12 hours. |
| 13 November 1972 | Small ash eruption in nearby Acatenango volcano. |
| 22 February 1973 | New eruption starts with strong steam emission for a day or two previous. |
| 23 February | Light ash falls and voluminous ash flows from crater begin. |
| 25 February | Probably period of strongest eruption. |
| 1 March | Last day of appreciable ash fall. |
| 3 March | End of eruption, although some glow still reported from crater. |
| 2 to 12 March | No activity reported. |
| 13 March | Approximate initiation of explosions and slight ash fall on upper western slope. |
| 17 March | Explosions louder and shaking huts. |
| 19 March | Loud explosions. |
| 22 March | 00:30 to 01:30 hours. Strong explosions waking up everyone and shaking ground in vicinity of cone. 12:00. Ash starts falling on lower west slopes of cone. Last reported activity. |

An order of magnitude increase in 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 most sensitive channel. These 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 probably 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 of this.

A seismograph installed next to the event counter on Fuego began operating four days after the eruption began. The level of harmonic tremor or ground noise 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 peaks in event counts can be readily identified as spurious because there are not sufficient corresponding counts on the next most sensitive channel, as discussed in section 9.1.1.

This example from Fuego is one type of increase in seismic activity prior to eruptions that we hope to monitor except that the time between the increase in seismicity and the eruption can be expected to increase as the size of the eruption and thus the volcanic hazard increases. We are just as interested, however, in looking for long term changes from year to year at different volcanoes. Such changes may be more significant and we are looking forward to analyzing those data as they become available.

9.2 Tiltmeters

The three tiltmeters situated around Kilauea Caldera in Hawaii operated satisfactorily in the intervals between lightning damage (section 7.3), but unfortunately the data recovery was about 50 percent in the past year before the photo-coupler described in section 7.3 was installed. Nevertheless several significant records of interest were collected.

A plot in figure 9.5 shows data from the east-west component of the level-bubble meter near Uwekahuna vault compared to simultaneous records from a mercury tube tiltmeter and a water tube tiltmeter operated in the vault. During this three-month period there was almost no tilt activity at Kilauea, and data from all three instruments agreed within a few microradians. The rather noisy record from the water-tube tiltmeter reflects the relatively low precision of reading to be expected from this type of instrument.

Also shown in figure 9.5 is a plot of both components of tilt at the Summer Camp site before the instrument was damaged by lightning on May 28. The record shows no appreciable 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. A histogram of rainfall at Kilauea for this same period of time is shown in figure 9.6. Note that there is no noticeable tilt response to the very heavy rains in March.

The detailed tilt response of the three level-bubble meters to the collapse of the summit of Kilauea on May 5, 1973, are shown in figure 9.5. At this time only the Summer Camp tiltmeter was fully operational. The Uwekahuna and Ahua meters were operating somewhat eratically after damage by lightning in February. These meters do, however, provide coherent short term records. The instantaneous cummulative tilt vectors from the three instruments are superimposed on a map of the summit area in

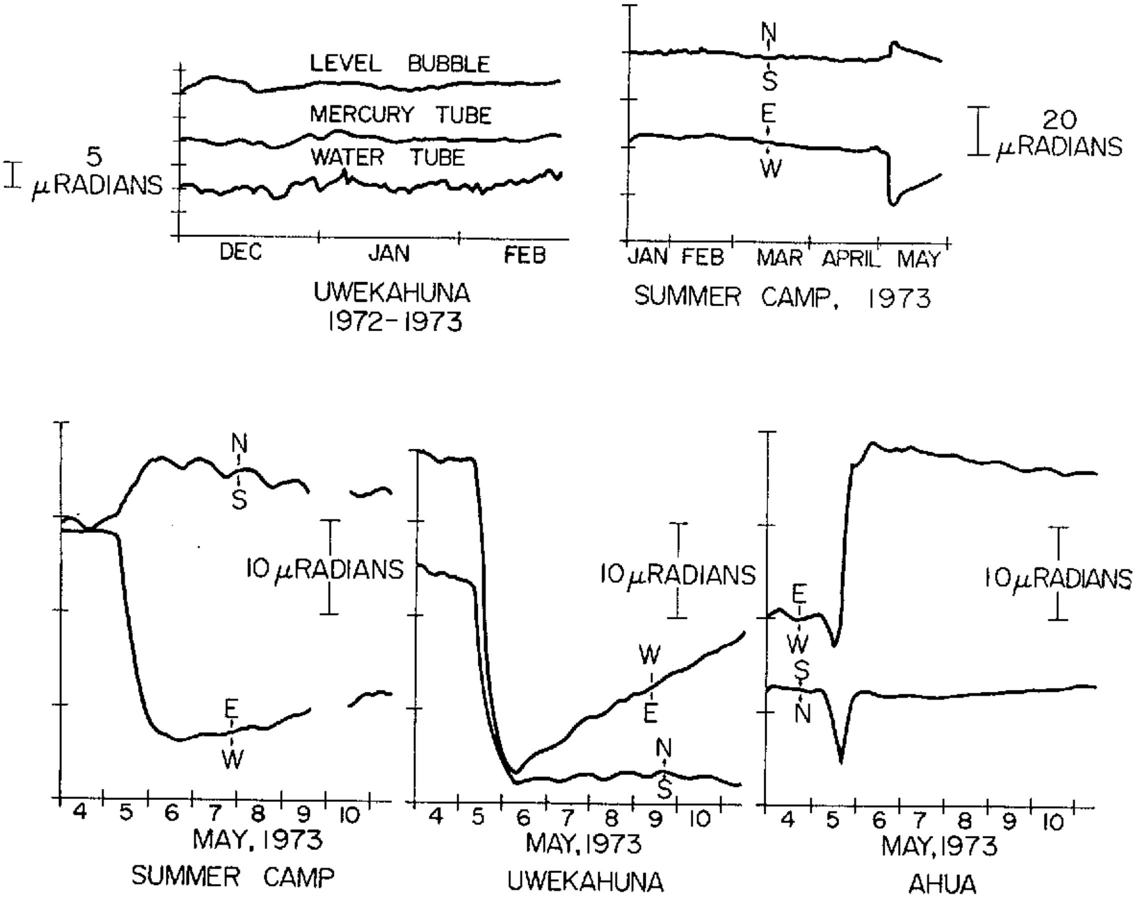



FIGURE 9.5. Typical data from three tiltmeters located around the central caldera of Kilauea Volcano during a collapse of the caldera area. The data in the upper left shows a comparison of the new level bubble tiltmeter with two other types of tiltmeters operated in Hawaii for several years.

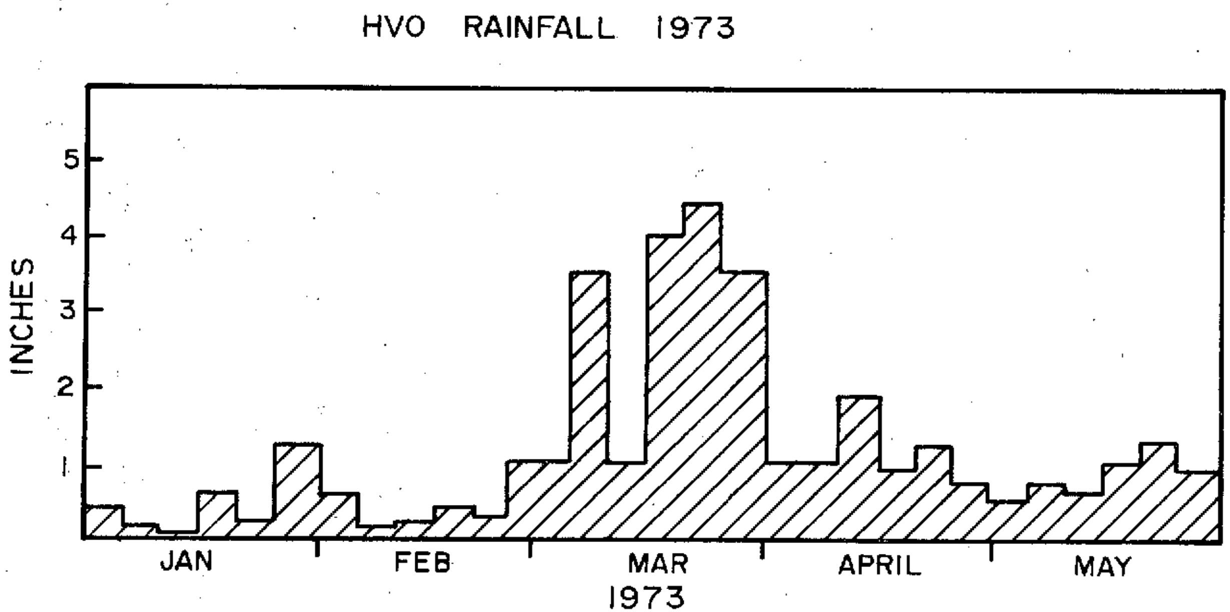



FIGURE 9.6. Rainfall in Hawaii at the Hawaiian Volcano Observatory plotted in 5-day intervals for January through May, 1973.

figure 9.7. 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 and Heake Craters. A comparison of these data with a chronology of the eruption provided by the staff of the Hawaiian Volcano Observatory shows an interesting correlation. The eruption of lava began in Pauahi at about 1025 and ended by 1200 with all but about 20,000 $m^3$ of lava draining back down the vent by 1230. Note the tilt at Ahua at this point was inward toward Kilauea Caldera and Halemaumau. At about 1255 a new lava outbreak was spotted near Heake Crater. Lava erupted from many fissures increasing until about 1500 and ending around 1700 leaving about 440,000 $m^3$ of new lava in Heake Crater and about 500,000 $m^3$ of new lava flows outside the crater. During this phase of the eruption, the meter at Ahua showed rapid tilt down toward the eruptive center until about 2000 when the tilt rate decreased but the tilt continued for at least 16 hours to move in the same direction. These three tiltmeters showed more details of a summit collapse than ever available before. A more detailed analysis of these data will be done later since it is not directly related to the evaluation of the volcano surveillance network.

Tilt recorded at Volcán Fuego in Guatemala is shown in figures 9.8 and 9.9. Fuego had erupted in February (see section 9.1) about two months before the meter was installed and has been very quiet since then. The original data are shown as dots in figure 9.8. The stepped nature of the dotted curve was caused by the RF interference problem discussed in section 7.3. Thus we believe the solid line more truly represents the tilt that occurred. Note that there is no correlation between the tilt and the heavy rainfall between May and October (figure 9.10). These tilt data

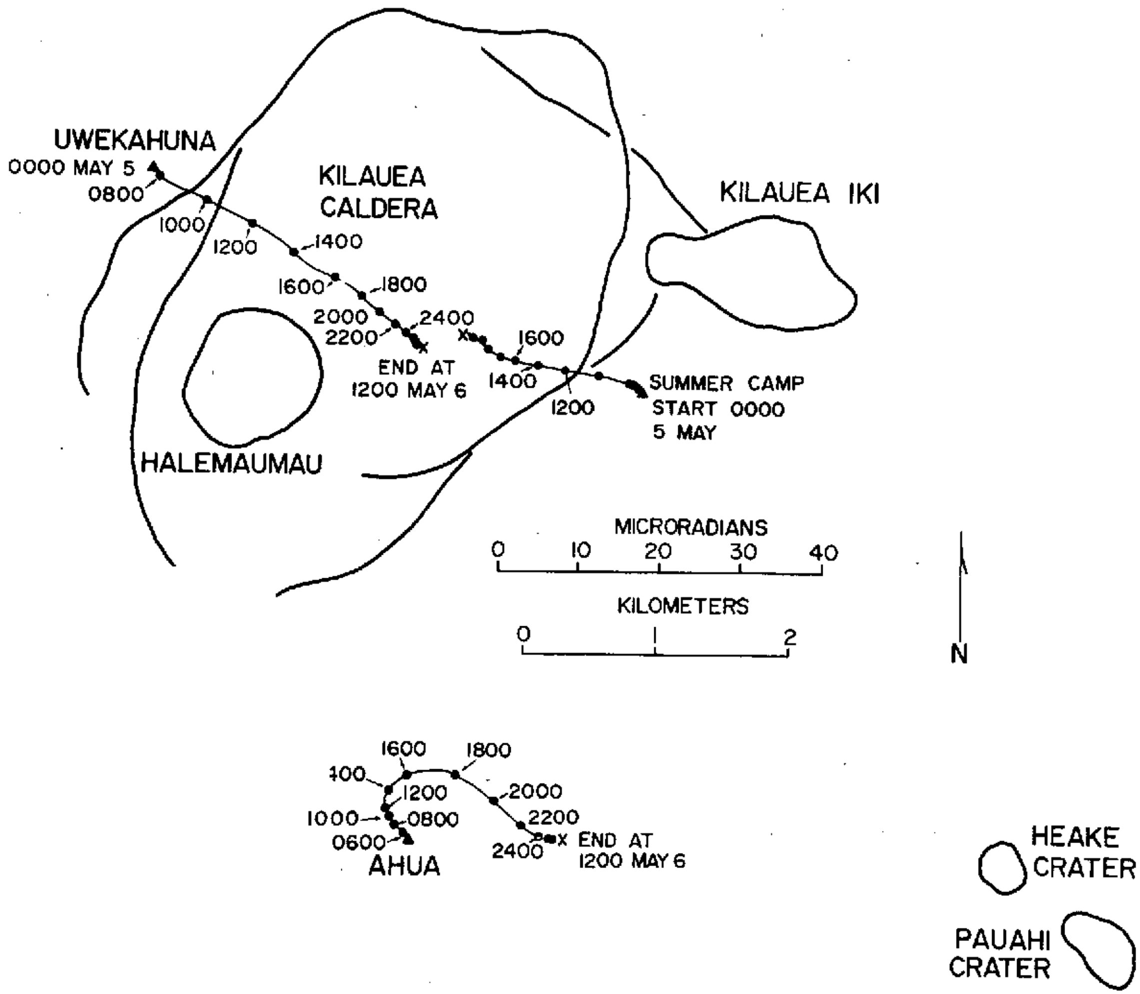



FIGURE 9.7. Sketch map of the summit area of Kilauea Volcano in Hawaii showing the tilt recorded at three different stations on May 5 and 6, 1973.

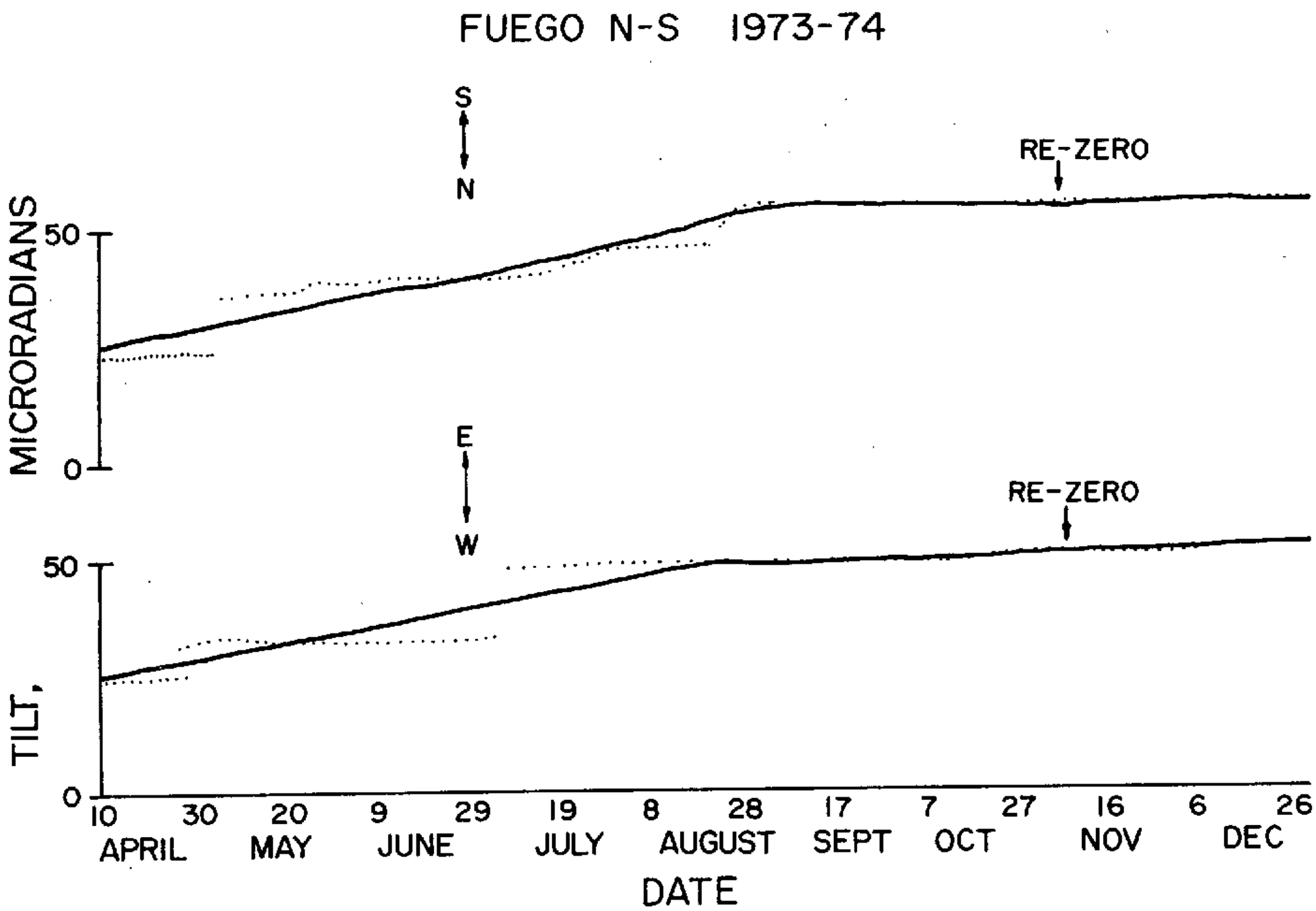



FIGURE 9.8. Tilt recorded on the southeast flank of Volcán Fuego in Guatemala in 1973. Dots show the recorded data. The solid line represents the assumed tilt after correcting for R. F. interference.

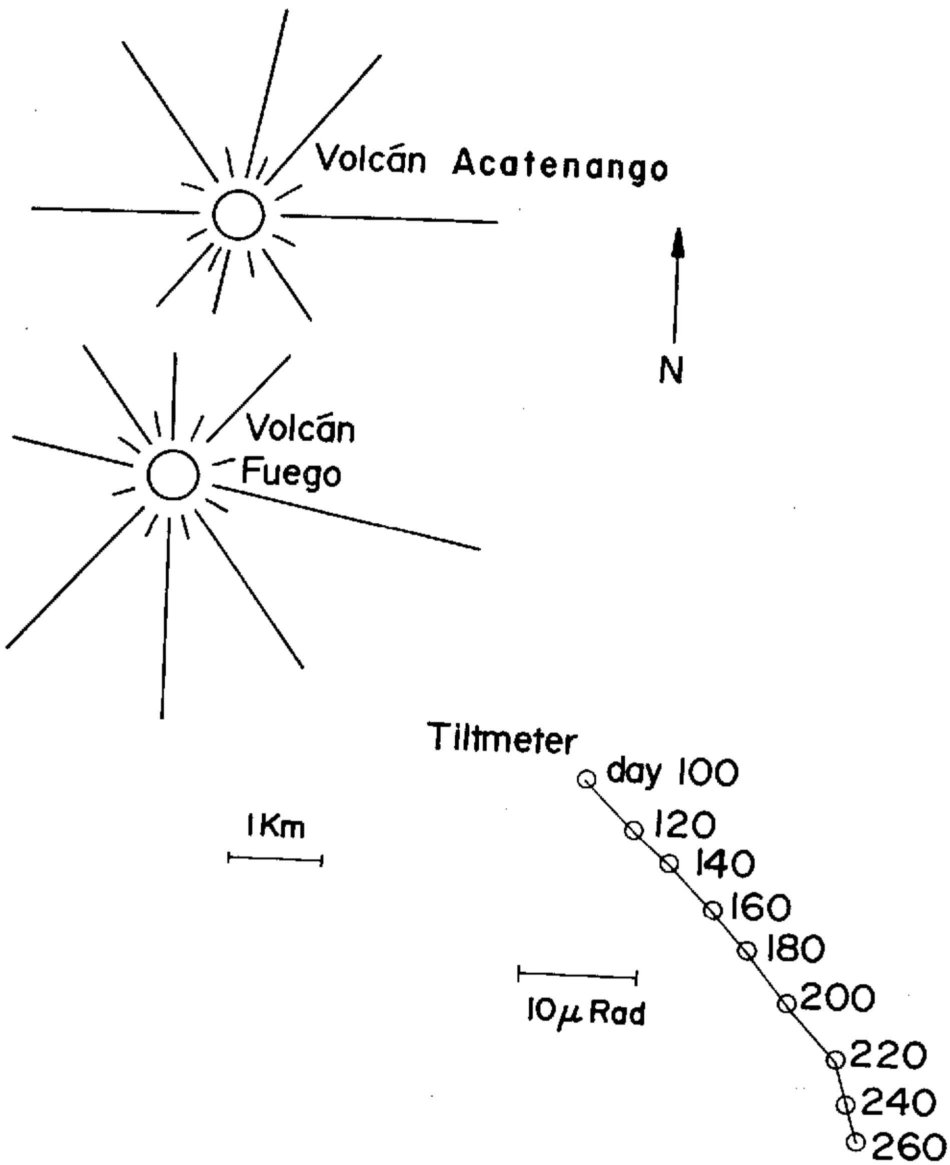



FIGURE 9.9. Sketch map of the area around Volcán Fuego in Guatemala showing the tilt vectors recorded from day 100 to day 260, 1973.

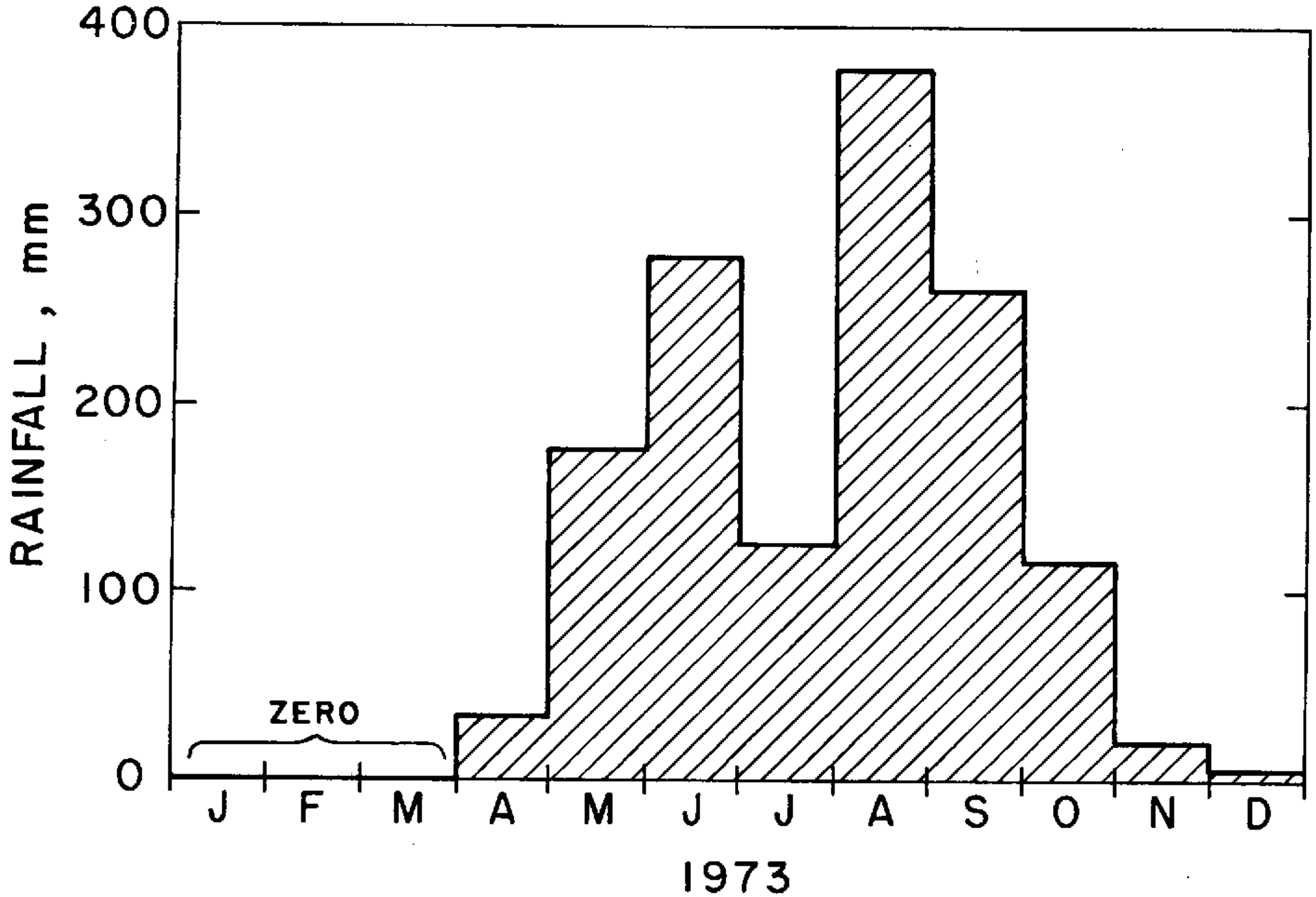



FIGURE 9.10. Monthly rainfall in Guatemala City. November and December are typical values. (Records not yet available).

show 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.

Tilt data from Volcán Pacaya are plotted in figure 9.11 and 9.12. These tilts are large but we believe they generally represent real tilts of the ground. Any question of their quality centers around the effects of the RF interference which undoubtedly causes some of the stepped appearance of the curves. Nevertheless we know that the overall tilt was registered by the instrument since the meter was checked in the field in October. The meter is situated in a block-faulted region of the volcano so that some doubt can be raised about whether the measured local tilt is representative of the overall tilt of the volcano.

Keeping these qualifications of the data in mind, we still conclude that the gross tilts represent a swelling of the volcano until October followed by a nearly equal subsidence. Volcán Pacaya has been active nearly continuously during this period. When project personnel have been in the area, intermittent explosion clouds have been observed at the vent on most clear days and lava was observed erupting from the flank vent area in June and July. Pacaya began erupting more lava in late January or early February 1974.

Tilt recorded at Mt. Lassen in California is shown in figure 9.13. No significant changes in tilt are observed. We believe the tilts measured are related to freezing and thawing of water in the joints in the rock outcrop containing the tiltmeter. This is part of the reason why we think that shallow installations in volcanic ash or sand are probably better than shallow installations in solid rock.

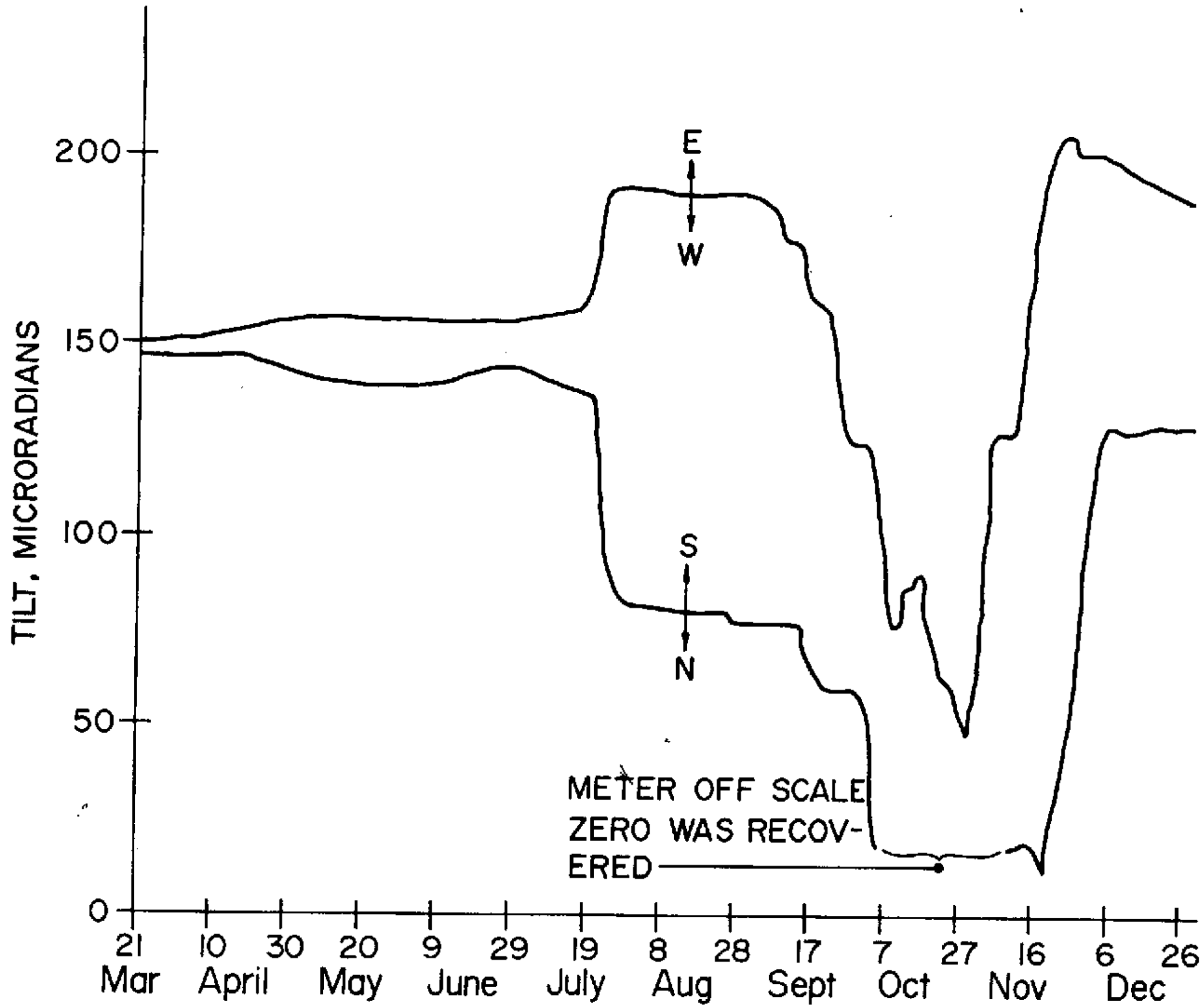



FIGURE 9.11. Tilt recorded on the west flank of Volcán Pacaya in Guatemala during 1973.

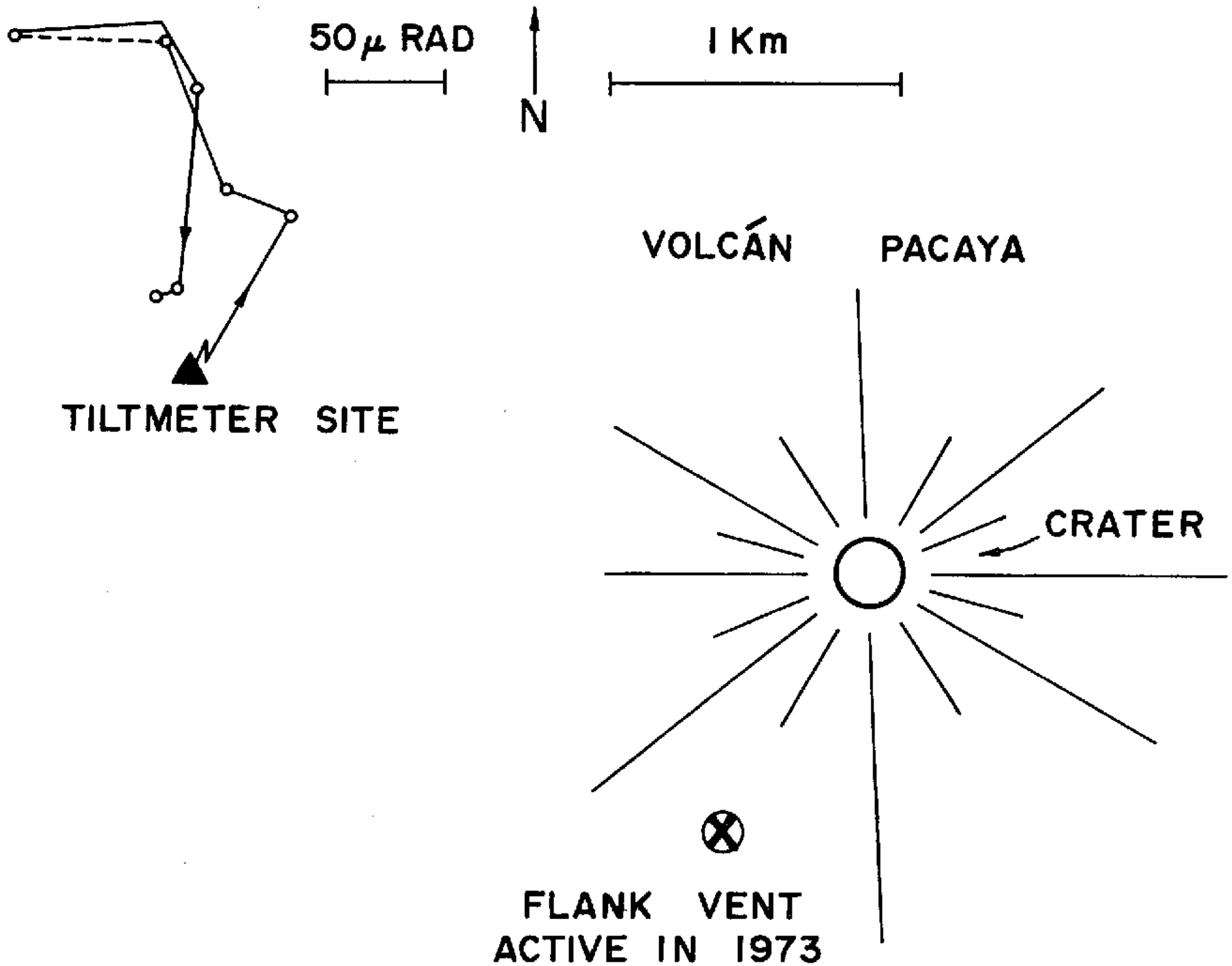



FIGURE 9.12. Schematic map of the tiltmeter site on Volcan Pacaya in Guatemala showing the instantaneous tilt vectors from the data in Figure 9.11.

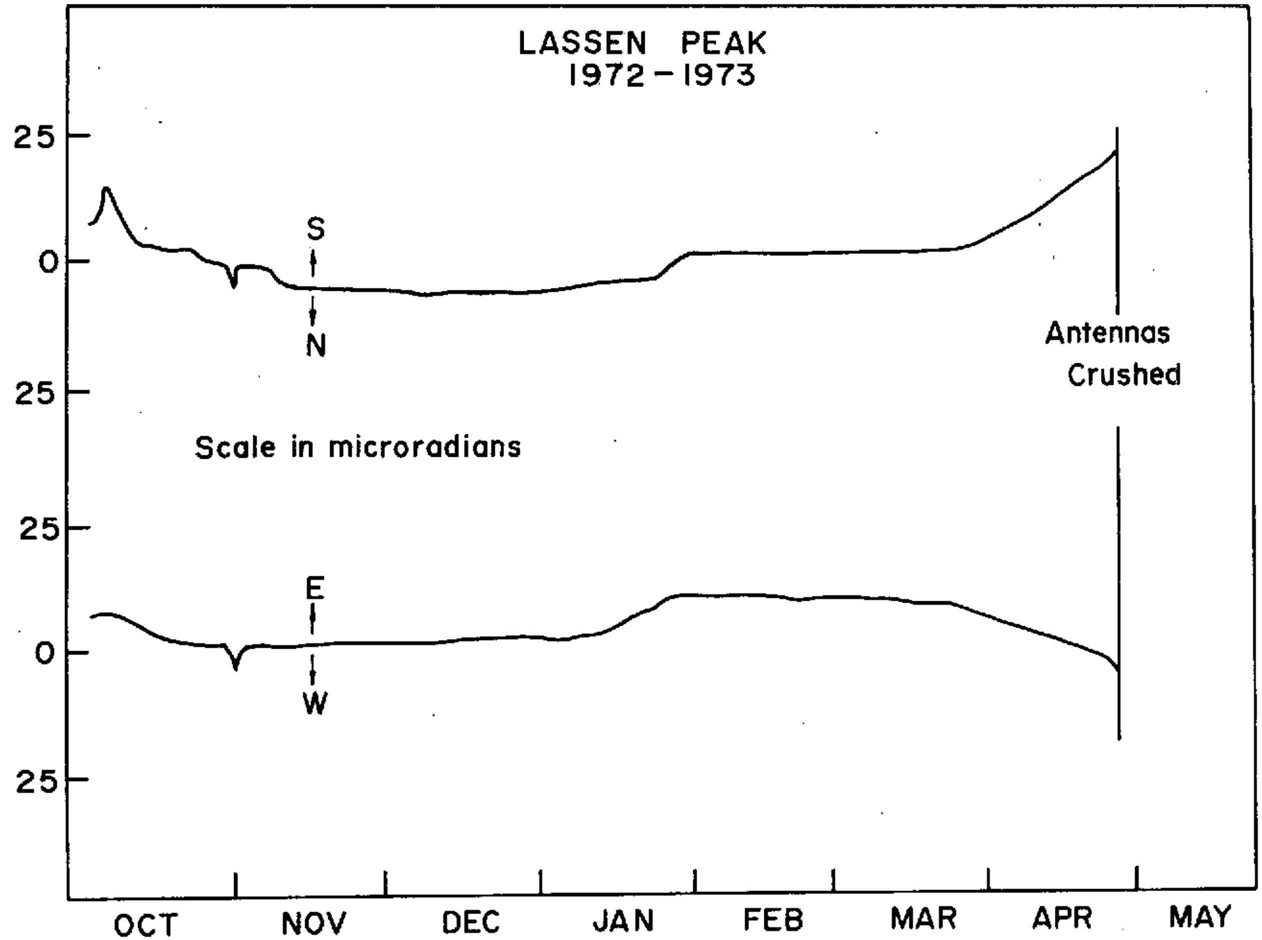



FIGURE 9.13. Lassen Peak tilt record through winter of 1972-73 before snow melt settling crushed the telemetry antennas.

These results from the different tiltmeters convince us that the meters are working quite stably in the field and that they are recording real tilts associated with volcanic activity. Continued recording for a much longer period of time will be needed before we can clearly assess the usefulness of these tilt data in providing early warning of eruptions. At this point the most important observation along this line is that large tilts from 30 to 150 microradians have been observed on three volcanoes related with eruptive periods whereas no significant tilt has been noted prior to spring melt on Mt. Lassen, the one volcano where tilt is being monitored that has had no observed volcanic activity for more than 50 years.

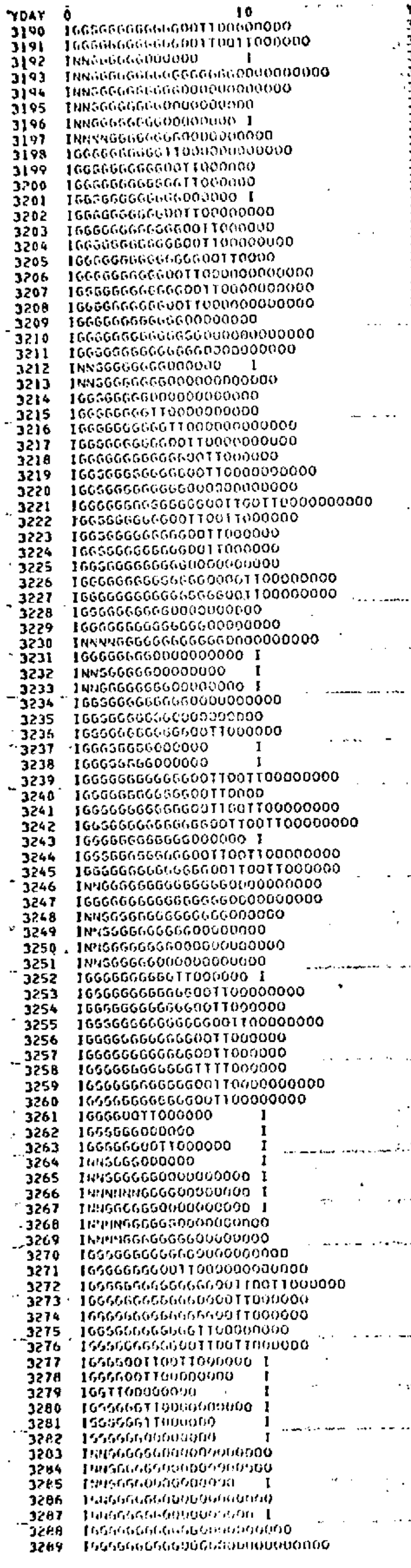
### 9.3 Satellite Message Transmission and Errors as a Function of Distance and Site Location

Although this research program is not aimed at evaluating the satellite relay system performance, the geographical distribution of DCPs is so wide that some comments on the effects of distance and site location seem desirable.

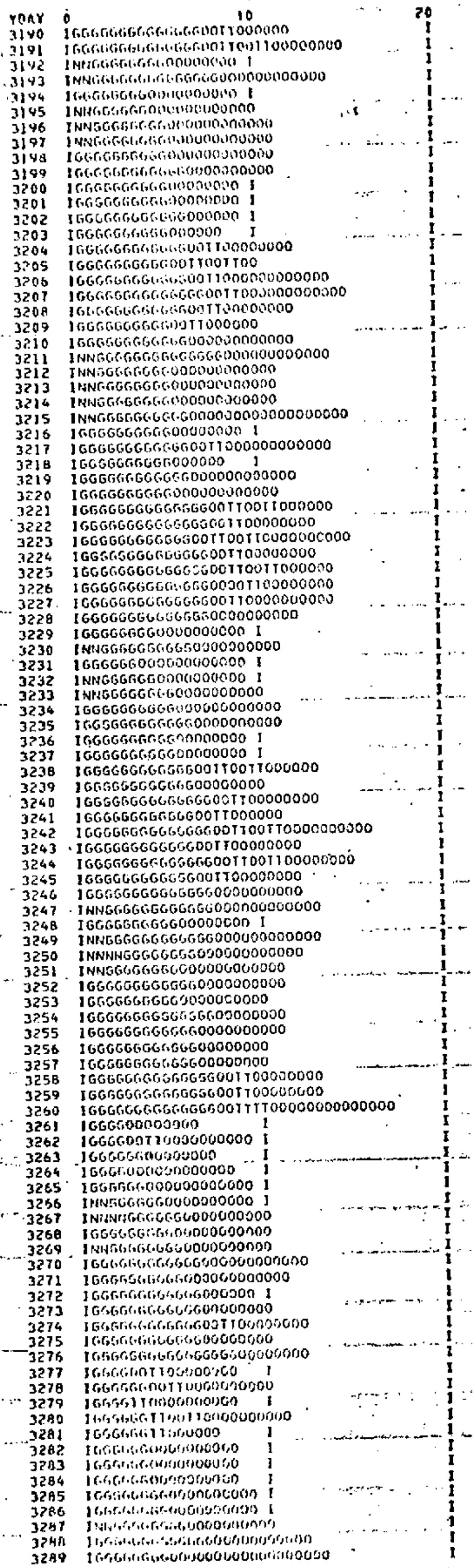
Typical plots of number of receptions per day for 100-day periods are shown in Figures 9.14 and 9.16 through 9.19. In these plots two 'N's represent one morning reception (0 to 1200Z) and two 'T's one afternoon reception at Goddard Tracking Station and two 'G's represent one morning reception and two 'O's one afternoon reception at Goldstone Tracking Station. The DCPs at Mt. Lassen (6057 and 6133), Mt. Rainier (6334), and St. Helens (6005) are set to transmit once every three minutes while the other DCPs shown transmit once every 1 1/2 minutes. In a few cases the same transmission is received at both Goddard and Goldstone and most of these cases are designated by two 'O's alternating with two 'T's or two 'G's alternating with two 'N's. The days of the year are preceded by the units of years.

## FIGURE 9.14

Platform 6163
Receptions per day




Platform 6057
Receptions per day



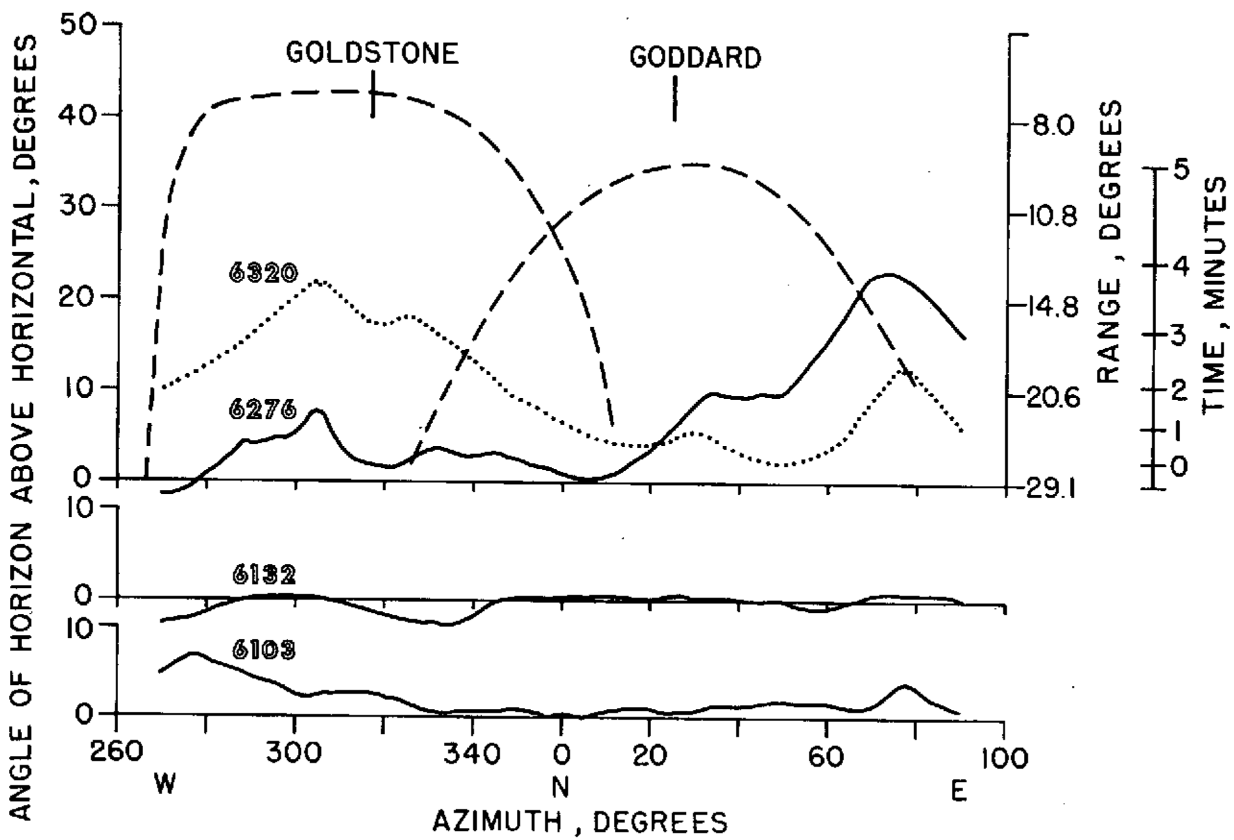
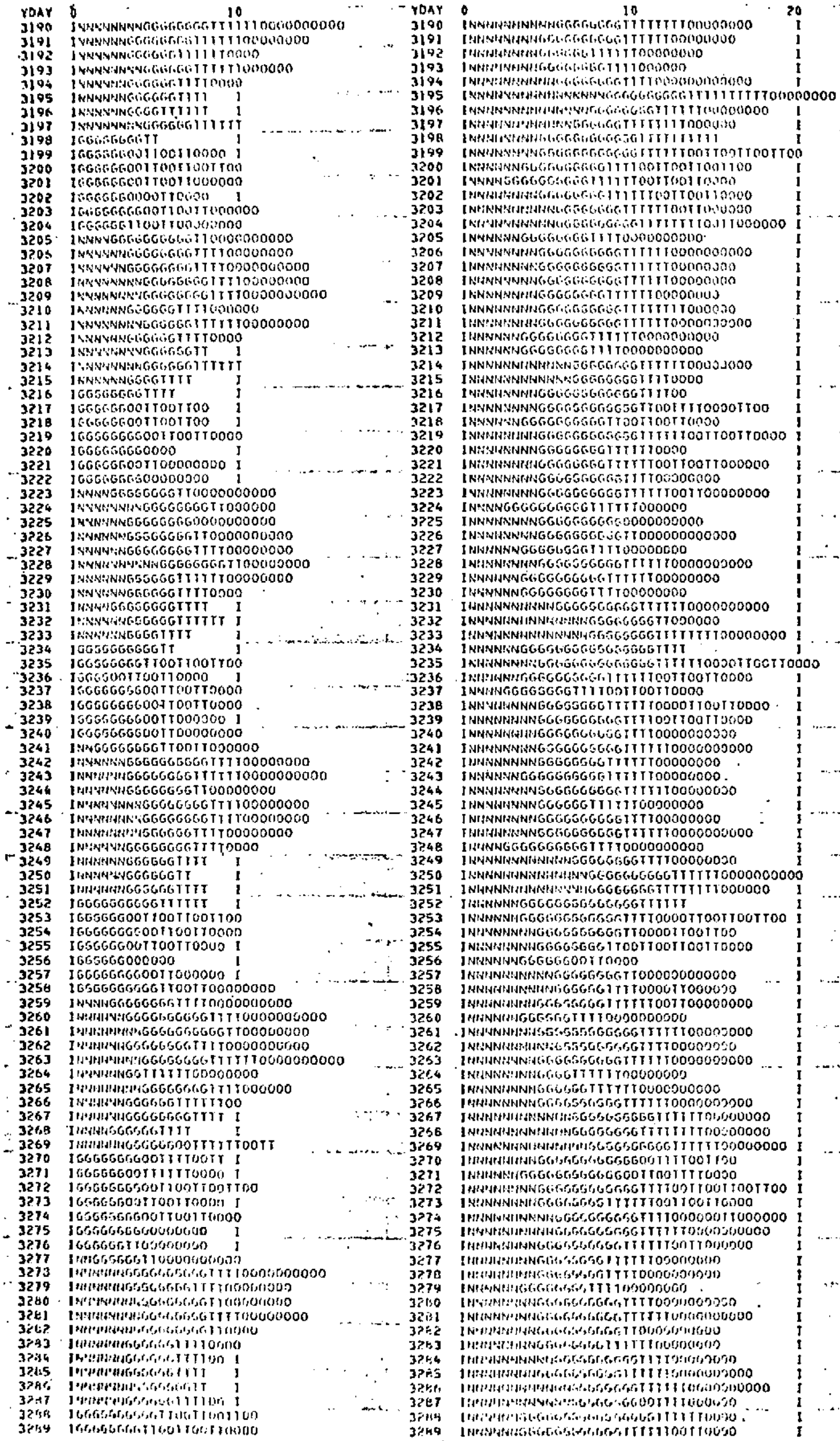



FIGURE 9.15. Angle to the horizon plotted as a function of azimuth at four transmitter sites in Guatemala. The dashed lines show the approximate regions in the sky where the satellite will be mutually visible to both the transmitters and either Goldstone or Goddard tracking stations.

FIGURE 9.16

Platform 6276 Receptions per day

Platform 6132 Receptions per day

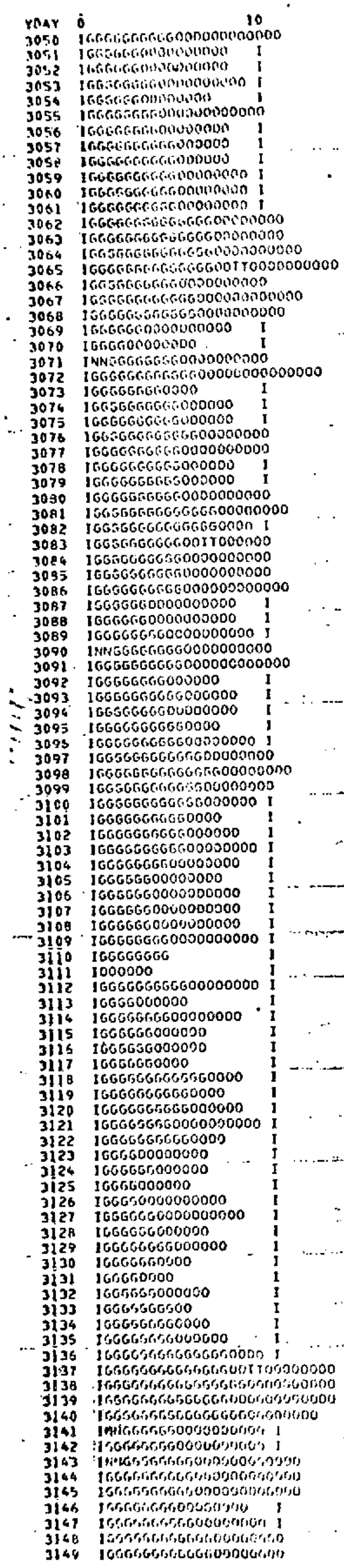


## FIGURE 9.17

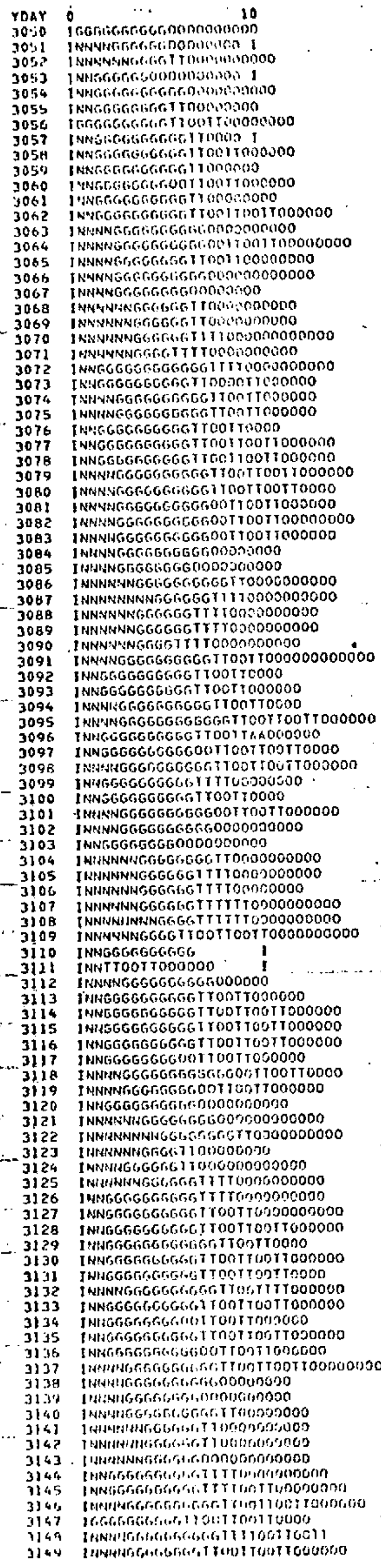
| YDAY | Platform 6311 Receptions per day (0 … 10) | Platform 6320 Receptions per day (0 … 10) | Platform 6103 Receptions per day (0 … 10) |
|---|---|---|---|
| 3190 | I | INNNNNNTTTTTT00 | INNNNNNNNNGGGGGGGTTTTTTT0000000000 |
| 3191 | I | INNNNNNGGTTTTTT | INNNNNNNNGGGGGGGTTTTT0000000000 |
| 3192 | I | INNNNNNNNTTTTTT | INNNNNNNNNNGGTTTTTTTT000000 |
| 3193 | I | INNNNNNNGGGGTT | INNNNNNNNGGGGTTTT000000 |
| 3194 | I | INNNNNNGGTTTT | INNNNNNNGGGGGTTTTT00 |
| 3195 | I | INNNNNNNTTTT | INNNNNNNNGGGGGGTTTTTT |
| 3196 | I | INNNNNNNGGTT | INNNNNNNNGGGGTTTTTT |
| 3197 | I | INNNNNNNTTTT | INNNNNNNNNNNNNTTTTTT |
| 3198 | I | IGGGGTTTTTT | INNNNNNGGGGGGGGTTTT |
| 3199 | I | INNGGGGTTOOTTOOTT00 | INNNNNNGGGGTT0000TT00TT |
| 3200 | I | INNNNGGGGTT00TT00TT00 | INNNNNNGGGGGGGGOOTTOOTT0000 |
| 3201 | I00TT00TT0000 | INNNNNNGGGGTTTT00TT0000 | INNNNNNNNGGGGGGGTTTOOTTOOTTOOTT0000 |
| 3202 | IGGGGGG00TT0000 | INNNNGGGGTT000000 | INNNNNNNNGGGGGGTTTTTT0000TT000000 |
| 3203 | INNGGGGGGTT00TT000000 | INNNNNNGGTTTTTT0000 | INNNNNNNNGGGGGGGTTTTTOOTTOOTT000000 |
| 3204 | INNNNGGGGGG00TT000000 | INNNNNNGGGGTTTT00 | INNNNNNNNGGGGGGGGGGTTTTTOOTTOOTT0000 |
| 3205 | INNGGGGGGGG00000000 | INNNNGGTTTT0000 | INNNNNNNNGGGGGGGTTT00000000 |
| 3206 | INNGGGGGGTT0000000 | INNNNNNNNNGGGTTTTTT00 | INNNNNNGGGGGGGGGGTTTTT000000000 |
| 3207 | INNNNGGGGGGGG00000000 | INNNNNNNNNGGGTTTTTT00 | INNNNNNNNGGGGGGGTTTTT000000000 |
| 3208 | INNGGGGGGTT0000 | INNNNNNGGGGTT | INNNNNNNNNNGGGGGGGTTTTT0000000000 |
| 3209 | INNNNGGGGGGGGTT000000 | INNNNNNGGTTTT | INNNNNNNNNNGGGGTTTTTT000000000 |
| 3210 | INNNNNNGGGGGGGGTTTT00 | INNNNNNNNNGGTTTTTT | INNNNNNGGGGTTTTTT00000000 |
| 3211 | INNNNNNGGGGGGGGTTTT0000 | INNNNNNNNGGTTTT | INNNNNNNNGGGGGGTTTTTT0000 |
| 3212 | INNNNNNGGTTTT00 | INNNNGGTT | INNNNNNGGGGGGTTTTTT00 |
| 3213 | INNNNTT00 | INNNNGGTTTT | INNNNNNGGGGGGTT |
| 3214 | INNNNTTTT | INNNNTTTT | INNNNNNNNNNNNGGGGTT |
| 3215 | INNNNTT | INNNNNNTT | INNNNNNNNNNNNGGTTTT |
| 3216 | IGGGGTT | IGGTT | INNNNNNGGGGGGTTTT |
| 3217 | IGGGG00TT0000 | INNGGGGGGTT0000TT00 | INNNNNNGGGGGGTTOOTTOOTTOOTT00 |
| 3218 | IGGGGGG00TT00TT00 | INNNNGGGGTT00TT00TT0000 | INNNNNNGGGGGGGGTTT0000TT0000 |
| 3219 | IGGGG00TT0000 | INNNNGGGGTT00TT0000 | INNNNNNGGGGGGGGTTTOOTTOOTT0000 |
| 3220 | INNGGGG0000 | INNNNNNGGGGTTTT0000 | INNNNNNNNGGGGGGGTT0000 |
| 3221 | INNGGGGGG00TT000000 | INNNNNNGGTTTT0000 | INNNNNNNNNNGGGGGGGGTTTOOTTOOTT000000 |
| 3222 | INNNNGGGGGG00TT000000 | INNNNGGGGTTTT00 | INNNNNNNNGGGGGGGGGTTTTT00000000 |
| 3223 | INNNNGGGGGGGGTT000000 | INNNNNNGGTT00 | INNNNNNNNGGGGGGGGTTTTT0000000000 |
| 3224 | INNGGGGGGGGTT00000000 | INNNNNNGGGGTTTT0000 | INNNNNNNNGGGGGGGGTTT00000000 |
| 3225 | INNGGGGGGGG00000000 | INNNNNNGGGG00 | INNNNNNNNGGGGGGGTT00000000 |
| 3226 | INNGGGGGGGG000000 | INNNNNNGGTT | INNNNNNGGGGGGGG000000000 |
| 3227 | INNNNGGGGGGGGTT000000 | INNNNNNGGTTTTTT | INNNNNNNNGGGGGGTTT0000000000 |
| 3228 | INNNNNNGGGGGG00 | INNNNGGTTTT | INNNNNNGGGGGGTTTTT00000000 |
| 3229 | INNNNNNGGGGGGGGTTTT0000 | INNNNNNNNGGTTTT | INNNNNNNNGGGGGGTTTT0000 |
| 3230 | INNNNNNGGGG00 | INNNNNNGGTTTT | INNNNNNNNGGGGGGTT0000 |
| 3231 | INNNNTTTT | INNNNGGTT | INNNNNNNNGGGGGGTTTT |
| 3232 | INNNNTTTT | INNNNGGTTTT | INNNNNNNNNNGGGGTTTTTTT |
| 3233 | INNTTTT | INNNNTT | INNNNNNNNNNNNNNNNGGTTTTTT |
| 3234 | IGGGGTT | INNGGGGGGTT | INNNNNNGGGGTTTT |
| 3235 | IGGGGTTOOTTOOTT00 | INNGGGGTTTTOOTTOOTT00 | INNNNNNGGGGGGGGTTTTTTTTOOTTOOTT00 |
| 3236 | IGGGGGGTTOOTTOOTT00 | INNNNNNGGGGTTTTOOTTOOTT00 | INNNNNNGGGGGGTTTTTTTTOOTTOOTT0000 |
| 3237 | IGGGGGG00TT0000 | INNNNNNGGGGTTOOTTOOTT00 | INNNNNNGGGGGGTTTTOOTTOOTT0000 |
| 3238 | INNGGGG00TT0000 | INNNNNNGGGGTT0000 | INNNNNNNNGGGGGGGGTTTT0000TT000000 |
| 3239 | INNNNGGGGGG00TT0000 | INNNNNNGGGGTTTT0000 | INNNNNNNNGGGGGGGGTTTTTTOOTTOOTT0000 |
| 3240 | INNGGGGGGTT00000000 | INNNNNNNNNGGGGTTTT0000 | INNNNNNNNNNGGGGGGGGGGTTTTTTOOTT000000 |
| 3241 | INNGGGGGGTT0000 | INNNNNNGGGGTTTT00 | INNNNNNNNGGGGGGGGTTTTOOTT000000 |
| 3242 | INNGGGGGGTT000000000 | INNNNNNGGGGTTTT00 | INNNNNNNNGGGGGGGGTTTTT0000000000 |
| 3243 | INNNNGGGGGGGGTT000000 | INNNNNNGGTTTT00 | INNNNNNNNGGGGGGGGTTT00000000 |
| 3244 | INNGGGGGGGGTT0000 | INNNNNNGGTTTT | INNNNNNNNNNGGGGGGGGTTTT00000000 |
| 3245 | INNGGGGGGGGTT0000 | INNNNNNGGTTTT | INNNNNNNNNNGGGGGGGGTT000000 |
| 3246 | INNNNNNGGGGGGGGTT0000 | INNNNNNNNNGGGGTTTT | INNNNNNNNGGGGGGTTTT00000000 |
| 3247 | INNNNNNGGGGGGTT0000 | INNNNNNGGTTTT | INNNNNNGGGGGGTTTTT0000 |
| 3248 | INNNNGGGGGGTTTT00 | INNNNGGTT | INNNNNNNNGGGGGGTTTTTT00 |
| 3249 | INNNNNNTTTT | INNNNNNTTTT | INNNNNNNNGGGGGGTTTT00 |
| 3250 | INNNNTT | INNNNNNTT | INNNNNNGGGGGGTTTTTTTT |
| 3251 | INNNNTT | INNNNNNTT | INNNNNNNNNNNNNGGTTTTTTTTTT |
| 3252 | IGGGGTT | INNGGGGTT | INNNNNNGGGGGGGGTTTTTT |
| 3253 | IGGGGGG00TT00TT00 | INNGGGGTTTTOOTTOOTT00 | INNNNGGGGGGGGTT0000TTOOTTTT0000 |
| 3254 | IGGGG00TT0000 | INNNNGGGGTTOOTTOOTT0000 | INNNNNNGGGGGGTT0000TT0000 |
| 3255 | IGGGG00TT0000 | INNNNNNGGGGTTOOTT0000 | INNNNNNNNGGGGGGGGTTTT0000TT0000 |
| 3256 | IGGGGGGTT000000 | INNNNNNGGGGTT0000 | INNNNNNNNGGGGGG0000 |
| 3257 | INNNNGGGGGG000000 | INNNNNNNNNGGGGTT0000 | INNNNNNNNGGGGGGGGTTTOOTT000000 |
| 3258 | INNNNGGGGGG00TT0000 | INNNNNNNNGGGGTTTT0000 | INNNNNNNNGGGGGGTTOOTTOOTT000000 |
| 3259 | INNGGGGGGTT00000000 | INNNNNNGGGGTTTT00 | INNNNNNNNNGGGGGGGGGGTTTTTTTT00000000 |
| 3260 | INNGGGGGGGGTT00000000 | INNNNNNGGGGTTTTTT0000 | INNNNNNNNNNNGGGGGGGGGGTTTTTT0000000000 |
| 3261 | INNNNGGGGGGGGTT00000000 | INNNNNNGGTTTT0000 | INNNNNNNNGGGGGGGGGGTT000000000000 |
| 3262 | INNGGGGGGTT000000 | INNNNNNGGTTTT | INNNNNNNNGGGGGGGGTT00000000 |
| 3263 | INNNNGGGGGGTT000000 | INNNNNNGGGGTTTT | INNNNNNGGGGGGTTTTT000000000000 |
| 3264 | INNNNTT0000 | INNNNTTTT | INNNNNNNNTTTTTT000000 |
| 3265 | INNNNNNGGGGGGGGTT0000 | INNNNNNNNNGGTTTTTT | INNNNNNNNGGGGGGTTTTTT00 |
| 3266 | INNNNGGGGTT00 | INNNNNNGGTTTTTT | INNNNNNNNGGGGGGTTTT00 |
| 3267 | INNNNGGTT | INNNNTTTT | INNNNNNNNGGGGTTTT |
| 3268 | INNNNTT | INNNNNNGGTTTT | INNNNNNNNNNNGGGGTTTT |
| 3269 | INNNNTTOOTT | INNGGTTOOTT | INNNNNNNNNNNGGTTTTOOTTOOTT |
| 3270 | IGGGGTTTT00 | IGGGGTTOOTT | INNNNNNGGGGGGGGTTOOTTTTOOTT00 |
| 3271 | IGGGGGGTT00 | INNGGGGTT0000TT0000 | INNNNNNNNGGGGGGGGOOTTTTOOTT00 |
| 3272 | IGGGGGG00TT0000 | INNNNGGGGTTOOTTOOTT0000 | INNNNNNGGGGGGGGTTTTOOTTOOTT0000 |
| 3273 | IGGGGTTOOTT0000 | INNNNNNGGGGTTTTOOTT0000 | INNNNNNNNNGGGGGGGGTTTTOOTTOOTTOOTT00 |
| 3274 | INNGGGGGGTTOOTT0000 | INNNNNNGGTTTTOOTT0000 | INNNNNNNNNGGGGGGTTTTOOTTOOTTOOTT0000 |
| 3275 | INNGGGG000000 | INNNNNNNNNGGTTTT0000 | INNNNNNNNNGGGGGGTTTT000000000 |
| 3276 | INNGGGGGG000000 | INNNNNNGGGGTTTT00 | INNNNNNNNNNNGGGGGGGGTTTTTTOOTT000000 |
| 3277 | INNGGGGGG00000000 | INNNNNNGGGGTT0000 | INNNNNNNNGGGGGGGGGGTTT000000 |
| 3278 | INNGGGGGGTT000000 | INNNNNNGGTTTTTT00 | INNNNNNGGGGGGGGTTTTTT00000000 |
| 3279 | INNGGGGGG00000000 | INNNNNNGGTTTT00 | INNNNNNNNNNGGGGGGTTTT00000000 |
| 3280 | INNNNGGGGGG000000 | INNNNNNNNNGGGGTTTT | INNNNNNNNNNNGGGGGGGGTTTT000000000 |
| 3281 | INNNNGGGGGG0000 | INNNNNNGGTT | INNNNNNNNNGGGGGGTTTT00000000 |
| 3282 | INNNNNNGGGGGGGGTT | INNNNNNGGTTTTTT | INNNNNNNNNNNGGGGTT |
| 3283 | INNNNNNGGGGTT00 | INNNNGGTTTT | INNNNNNGGGGGGTTTT0000 |
| 3284 | INNNNNNGGGGTTTT | INNNNNNGGTTTTTT | INNNNNNGGGGGGGGTTTT0000 |
| 3285 | INNNNTT | INNNNNNGGTT | INNNNNNNNNGGGGGGTTTT |
| 3286 | INNNNTT | INNNNTT | INNNNNNNNNNNGGGGGGGTTTTTT |
| 3287 | INNNNTTTT | INNNNOOTTTT00 | INNNNNNNNNNNNNNGGTTTTTT00 |
| 3288 | IGGTTTT0000 | INNGGGGTTTT0000 | INNNNGGGGGGGGTTOOTTOOTTOOTT00 |
| 3289 | IGGGGGGTT0000 | INNGGGGTTOOTT0000 | INNNNNNGGGGGGTTOOTTOOTT0000 |

## FIGURE 9.18.

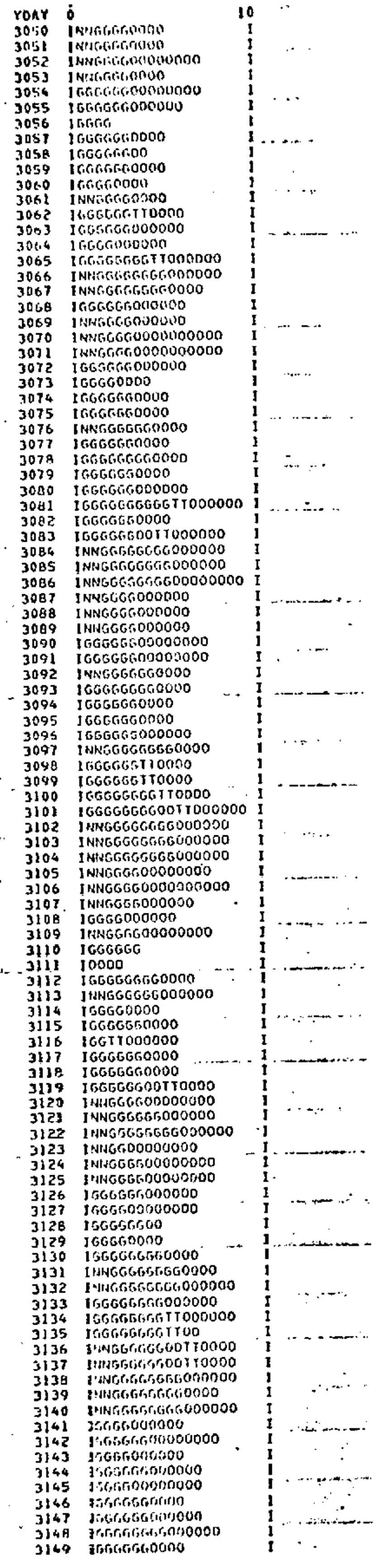
Platform 6005
Receptions per day




Platform 6334
Receptions per day




Platform 6365
Receptions per day

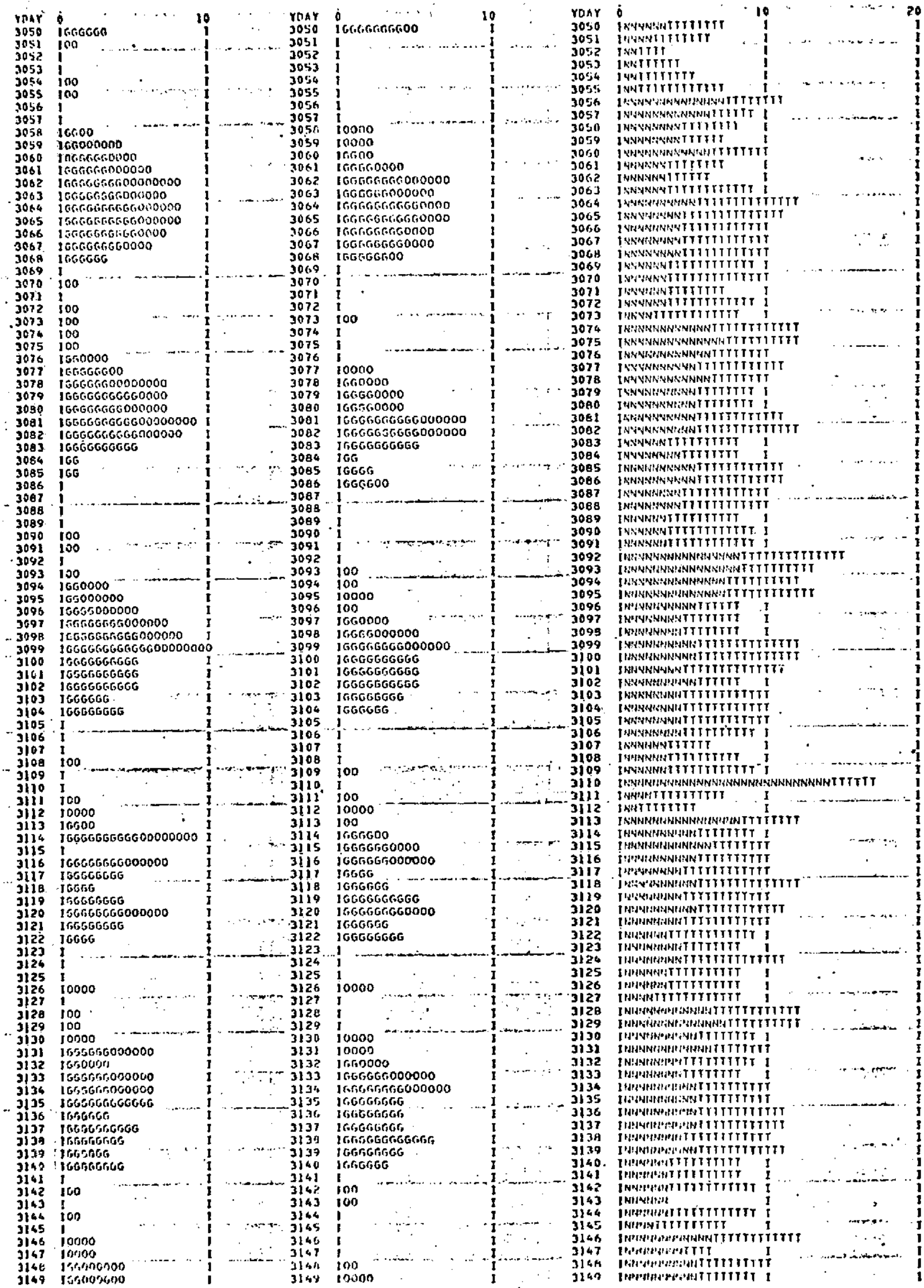


## FIGURE 9.19.

Platform 6117 — Receptions per day

Platform 6370 — Receptions per day

Platform 6315 — Receptions per day



Thus 3050 is day 50, 1973, which is February 19, 1973; day 3149 is May 29, 1973; day 3190 is July 9, 1973; and day 3289 is October 16, 1973. Platform locations and distances from the receiver sites are given in table 9.1.

Generally 3 to 5 transmissions are received in the morning and 3 to 5 in the afternoon for each platform. These receptions usually are grouped in two consecutive satellite passes separated by about 1 hour and 43 minutes in the morning and two consecutive passes separated by about 1 hour and 43 minutes in the afternoon. This pattern is altered substantially by hills and mountains near the transmitters raising the angle to the horizon in the general direction of the receiving stations. The distance between transmitter and receiver and the reception pattern of the receiving antenna also significantly affect the number of receptions.

Figure 9.14 shows the reception pattern for two transmitters (6163 and 6057) placed next to each other on Mt. Lassen in California. These two plots demonstrate that the exact number of receptions will vary because of the randomness of the clock at each transmitter but that the overall pattern will be the same for different transmitters at the same site or for different periods of the year. This repeatability of the overall pattern is also shown in each plot since the satellite retraces the same orbit every 18 days.

The effect of topography is shown by the plots in figure 9.15 through 9.17. Locations of platforms in these figures are given in table 9.1. Figure 9.15 shows topographic profiles at four different sites, two with mountains nearby and two with few hills or mountains obscuring the horizon. The dashed lines represent the approximate regions in the sky where the satellite will be mutually visible to both the transmitters and either Goldstone or Goddard tracking stations. The approximate angular distance to the satellite is shown as the range R in degrees where $R = \sin^{-1}$

Table 9.1 Location of platforms transmitting to the satellite and used for studies of message transmissions

| Platform ID | Name | Latitude | Longitude | Elevation feet | Distance in degrees to: Goddard | Distance in degrees to: Goldstone | Azimuth to: Goddard | Azimuth to: Goldstone |
|---|---|---|---|---|---|---|---|---|
| 6163 | Mt. Lassen, California | 40° 28.52' | 121° 30.50' | 8720 | 35° | 7° | 75° | 140° |
| 6057 | Mt. Lassen, California | 40° 28.52' | 121° 30.50' | 8720 | 35° | 7° | 75° | 140° |
| 6276 | Pacaya tilt, Guatemala | 14° 23.05' | 90° 37.35' | 5450 | 28° | 32° | 25° | 317° |
| 6132 | Buena Vista, Guatemala | 14° 40.00' | 90° 38.45' | 7400 | 28° | 32° | 25° | 317° |
| 6311 | Izalco, El Salvador | 13° 49.25' | 89° 37.80' | 5250 | 28° | 33° | 22° | 317° |
| 6320 | Fuego, Guatemala | 14° 26.65' | 90° 50.62' | 4600 | 28° | 32° | 25° | 317° |
| 6103 | Pacaya, Guatemala | 14° 23.85' | 90° 33.65' | 5500 | 28° | 32° | 25° | 317° |
| 6117 | Uwekahuna, Hawaii | 19° 25.40' | 155° 17.60' | 3750 | 70° | 37° | 56° | 60° |
| 6370 | North Pit, Hawaii | 19° 20.20' | 155° 17.00' | 3658 | 70° | 37° | 56° | 60° |
| 6365 | St. Augustine, Alaska | 59° 22.55' | 153° 22.25' | 348 | 51° | 34° | 81° | 123° |
| 6315 | Reykjavik, Iceland | 64° 01.30' | 21° 51.00' | 20 | 40° | 62° | 251° | 283° |
| 6005 | Mt. St. Helens, Washington | 46° 11.58' | 122° 14.20' | 4620 | 35° | 13° | 290° | 158° |
| 6334 | Mt. Rainier, Washington | 47° 6.49' | 121° 40.38' | 6200 | 35° | 13° | 290° | 158° |

($180-Z-\sin^{-1}$ [0.874 sinZ]) and Z is equal to 90 degrees plus the angle to the satellite above the horizontal at the transmitter. The constant 0.874 is the radius of the earth divided by the radius of the satellite's orbit.

Note in figure 9.16 that adequate receptions are received at both Goldstone and Goddard every day from platform 6132 and that only one tracking station is necessary and indeed the transmission rate could be changed to once every three minutes. This reception begins to degrade for platform 6103 where the horizon is only slightly raised by local hills. In the case of platform 6320, however, reception at Goldstone is totally inadequate and for platform 6276 reception at Goddard is marginal with no receptions on a few days and no morning receptions on many days. The masking of the zone of reception by local topography shows in figure 9.15 that there is a significant portion of the zone of mutual visibility above the local mountains. The satellite, however, moves through this upper zone more rapidly and is visible most of the time near the horizon. This effect is shown in figure 9.15 by the time axis. These times were calculated assuming the satellite is passing directly over Goddard and Guatemala and are meant to show only approximately the elevation of the satellite above the horizon during the 5 to 6 minutes that it would be mutually visible in such an orbit. On other orbits not passing directly over the station the percent of time close to the horizon would be even greater than shown here.

Similar effects on receptions can be seen by comparing receptions from platforms at St. Helens (6005) and Rainier (6334) in Washington (Fig. 9.18). Platform 6005 is on the west side of the volcano and is hardly ever received at Goddard. Thus good reception of data from stations at a distance of about 25 to 40 degrees from the receiving site depends critically on the local skylines of both transmitter and receiver being relatively close to the horizontal at the azimuth toward the other site and to about 60 degrees on either side of this azimuth.

Receptions from platforms in Hawaii and Iceland are shown in figure 9.19. The reception rate from Iceland at Goddard (distance of 40 degrees) is excellent with several morning and evening receptions every day. The reception at Goldstone from Hawaii (distance 37 degrees), however, is quite poor with no reception on some days and only morning or only afternoon receptions on most days. The primary reason for this difference is that the antenna reception at Goldstone is degraded by interference at an azimuth of 250 to 290 degrees as shown in figure 9.20. The location of the satellite at the times of many receptions in an 18-day cycle are shown in figure 9.21. The satellite locations and antenna reception patterns in figures 9.20 and 9.21 were provided by K. S. Rizk of the General Electric Company, Space Division in Beltsville, Maryland. Note how much of the zone of potential mutual visibility between Hawaii and Goldstone is covered by the lobe in the antenna pattern.

The following conclusions seem justified:

1. DCP data can be received well at distances of up to 40 degrees from the tracking station if the effective horizon is not more than 5 degrees above the horizontal as limited by local topography or radio interference.

2. Reception of data over a distance of 51 degrees was observed once a day for 8 to 10 days during an 18-day cycle (platform 6365). Regular receptions might be expected at a distance of 45 degrees if there were good horizon visibility. The range of the system might be extended to 50 degrees by transmitting more often than once every 90 to 180 seconds.

3. Local hills and mountains that raise the skyline to 5 or 10 degrees above the horizontal significantly reduce the number of receptions at distances of more than 25 degrees.

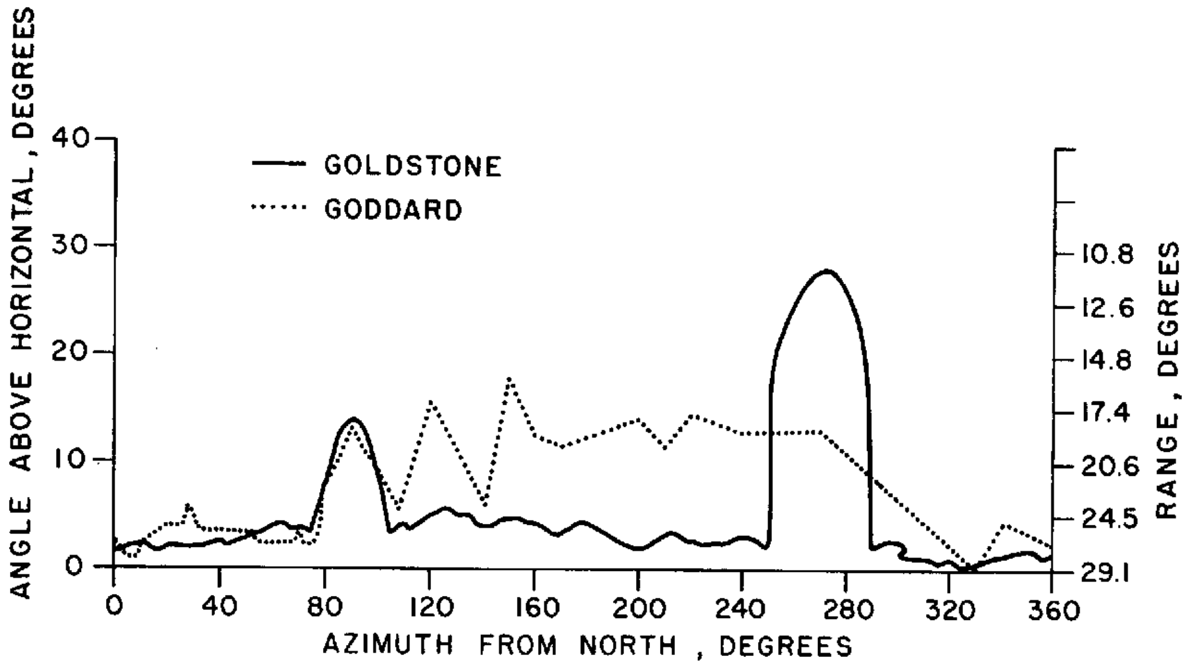



FIGURE 9.20. Reception pattern of the tracking stations at Goddard and Goldstone showing the angle above the horizontal of the ERTS satellite at the most distant point of reception for each azimuth.

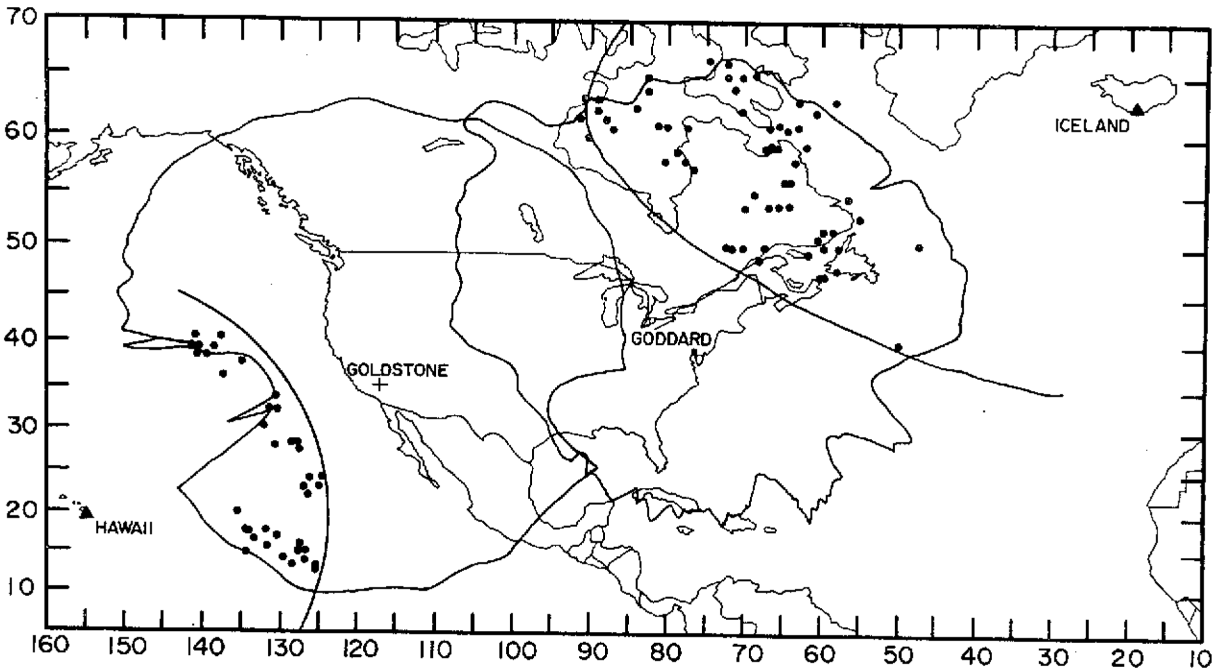



FIGURE 9.21. Map showing the limits of reception of the tracking stations at Goldstone and Goddard. The dots represent the latitude and longitude of the ERTS satellite at times when data were successfully relayed.

4. If the range of adequate reception around each tracking station is assumed to be 35 to 40 degrees in radius with no significant lobes in coverage, then at least four tracking stations would be needed to collect data with an ERTS-type satellite from most volcanoes around the world. For example, the following stations might work:

| Tracking Station | Region Covered |
|---|---|
| Peru | South America, Central America, Caribbean, Easter Island |
| Philippines | Indonesia, New Guinea, Marianas, Japan |
| Alaska | Cascades, Alaska, Kamchatka |
| Spain | Mediterranean, Azores, Iceland |

Regions not covered include Hawaii, the New Hebrides, and New Zealand. Furthermore existing tracking stations might be utilized and since they do not occur at these sites, five to six existing stations would be needed to give about the same coverage.

There are two kinds of errors that can occur in the data transmission: those that are detected as errors by NASA and those that are not. The principal method used by NASA to detect errors stems from the use of convolutional encoding which results in transmitting two bits for each message bit. These two bits can then be compared after reception and an error flag generated if the two bits do not agree. An examination of these flagged errors shows that they normally constitute up to about 2 percent of the received data for transmitters in the mainland United States and Alaska, up to 5 percent of the data received from Hawaii, and 8 percent of the data received from Iceland. Thus these errors increase with distance of transmission and very likely occur because of radio interference. The data shown in figures 9.14 through 9.19 do not include messages with errors flagged.

The number of unflagged errors can be estimated from the event counter data. The event counters count consecutively and the status of these counter is read during each transmission. Thus any errors in transmission of the actual data would in many cases show up as a sudden change in the event counts or as a decrease in the counts. No such change has been noted. Furthermore a parity bit is generated by the event counter on 63 data bits and transmitted as the 64th bit. Only twice has the parity bit been in error and these instances can be attributed to a defective component in the data interface between the transmitter and the event counter. Thus we have detected no unflagged errors that can be attributed to transmission errors.

## 9.4 Publications and Talks Concerning the Prototype Volcano Surveillance System


Eaton, J. P., and P. L. Ward, 1972, Satellite relay telemetry in the surveillance of active volcanoes and major faults zones, Oral and written presentation for the Fourth Annual Earth Resources Program Review in Houston, Texas in January 17-19, 1972.

Ward, P. L., J. P. Eaton, E. Endo, D. Harlow, D. Marquez and R. Allen, 1973, Establishment, test, and evaluation of a prototype volcano-surveillance system, in _Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1,_ Volume 1, Technical Presentations 305-315.

Endo, E., P. L. Ward, D. Harlow, D. Marquez, and J. P. Eaton, 1973, A prototype volcano surveillance system with data collection using the ERTS-A Satellite, _Trans. Amer. Geophys. Union_, _54_ (4), 511.

Ward, P. L., 1973, Performance of the ERTS-1 DCS in a prototype volcano surveillance system, oral and written presentation for the ERTS-1 Data Collection Workshop, Wallops Island, Virginia, May 30-31, 1973.

Ward, P. L., 1973, A prototype global volcano surveillance system and identification of a volcano-tectonic fault in Central America, talk, Amer. Assoc. for Adv. of Science Meeting, Science and Man in the Americas, Mexico City, Mexico, June 20-July 4, 1973.

Ward, P. L., 1974, A prototype global volcano surveillance system and identification of a volcano-tectonic fault in Central America, _Bull. Volcanologique_, in press.

Endo, E. T., P. L. Ward, D. Marquez, R. V. Allen, and D. Harlow, 1973, A prototype global volcano surveillance system monitoring seismic activity and tilt: Part I Implementation, Trans. Amer. Geophys. Union, 54 (11), 1143.

Harlow, D. H., P. L. Ward, and E. T. Endo, 1973, A prototype global volcano surveillance system: Part 2 Preliminary Results, Trans. Amer. Geophys. Union, 54 (11), 1143.

Ward, P. L., E. T. Endo, D. H. Harlow, R. Allen, and J. P. Eaton, 1973, A new method for monitoring global volcanic activity, oral and written presentation for the ERTS-1 Symposium, Washington, D.C., December 10-13, 1973.

Ward, P. L., 1974, Results from a prototype network for monitoring global volcanic activity using satellite telemetry, Talk to the Washington (D.C.) Geological Society, January 23, 1974.

Endo, E. T., P. L. Ward, D. H. Harlow and R. V. Allen, 1974, A prototype global volcano surveillance system monitoring seismic activity and tilt, Bull. Volcanologique, in review.

Ward, P. L., E. T. Endo, D. H. Harlow, and R. V. Allen, 1974, A new method for monitoring global volcano activity, Trans. Amer. Geophys, Union, 55 (4), in press [abstract].

## 10.0 COST OF A GLOBAL VOLCANO SURVEILLANCE SYSTEM

### 10.1 Sensors

The sensors as currently built and installed cost as follows (not including development costs):

| | |
|---|---|
| Event Counters | $2,000.00 |
| Tiltmeters | 1,850.00 |
| Tiltmeter interface (proposed) | 480.00 |
| Transmitters | 2,140.00 |
| Installation hardware | 250.00 |
| | $6,720.00 |

Each unit in this system was built and packaged separately. By building all the electronics in one box and avoiding duplicate timers, power supplies, etc., an event counter, tiltmeter and transmitter package could probably be build in a quantity of 100 for about $5,000 each, including development. A substantially lower cost may be possible in the future with the current trends in miniaturizing electronics.

With the new developments in electronic components and antennas a more efficient design and packaging can now be envisaged. For example, Ball Brothers Research Corporation, Boulder, Colorado has introduced a printed circuit board antenna that could be mounted on the lid of the electronics container. Since there would be no wind loading on such an antenna mounted flush with the ground surface, the seismometer and tiltmeter could be mounted in the container or directly next to it. Thus a single small package containing all necessary components and no external cables could be built and easily deployed by local scientists in each country. A cost of $5,000 each for such a system still seems a reasonable estimate and this unit cost might be reduced at least 30 percent in a quantity of 1000. Installation could be only a few hundred dollars per site if local personnel in each country did the work. In any case an average installation cost of $1,000 would more than cover the expenses.

Maintenance would be required only every three years to change batteries unless the data being received clearly indicated a malfunction. In this case, maintenance could be by replacement of the whole unit shipped from one central repair depot.

10-2 Spacecraft

The following costs are based on rough estimates provided by Earl Painter at Goddard Spaceflight Center, Greenbelt, Maryland. To build and implement an ERTS-type data collection system would cost as follows:

| | |
|---|---|
| Develop and build satellite | $1.0 million |
| Launch satellite | $1.8 million |
| Build one receive site with an S-band radio link | $0.15 million |
| Build one receive site if a UHF radio link was used | $0.05 million |
| Operate the satellite | $0.1 million/year |

Thus it would cost on the order of $3.5 million to build and launch a satellite with an ERTS-type data collection system and four ground stations and to operate it for five years, which is considered as a typical design life. The yearly cost is then $0.7 million. If this satellite were shared by 10,000 sensor stations collecting not only data on volcanos but data on stream flow, flooding conditions, ecological monitoring, etc., then the cost per year per ground station is $70.

The current ERTS system has a capacity of only 1000 transmitters in view at any one time but multiple channels could be used and different data rates to increase this capability.

These costs could be reduced by launching the satellite together with other satellites. Such piggy-back rides are often available. Two satellites might be launched 180 degrees out of phase to double the temporal coverage.

Recording of the data on the satellite might be added using solid state memories for about $0.5 million. (Tape recorders have not been used successfully for a five-year period in space.) Such on-board recording would mean that only one ground station would be required and no ground data links to get the data back to one office. This addition would increase by a few hours the delay in receiving the data, but such a delay is not important for the volcano monitoring use.

An alternative-type system would be to use a stationary satellite similar to the GOES system being launched by the Department of Commerce in 1974. This type of satellite with a data collection system would cost about $12 million to build, launch and operate, or $2.5 million per year. It might be shared by 40,000 ground stations at a cost of about $610 per station. This system would relay the data instantaneously and could provide for emergency transmissions at any time necessary. However at least three such satellites would be necessary to cover most of the volcanoes in the world.

10.3 Analysis

The data relayed by satellite could be sent to one international office or a few offices each with a central computer processing the data upon receipt. Warnings could be issued by this office(s) if abnormal activity were noted. Such an office might be staffed by scientists, technicians, and a group to maintain the equipment sent from the field for repair for about $500,000 or $500 per site for 100 remote sites.

10.4 Comparison to Recording of Similar Data Near the Volcanoes

Thus a volcano surveillance system could be installed covering 1000 volcanoes or 1000 remote sites on a fewer number of volcanoes for an initial one-time cost of about $6000 per site and a yearly cost of about $1000 per site provided the satellite was shared by other programs. This adds up to about $2.2 million per year for 5 years which could be paid for by participating countries.

The cost of installing a seismometer and a tiltmeter at one site and recording within 100 kilometers would be as follows:

| | |
|---|---|
| Seismometer and amplifier and packaging | $ 600.00 |
| Radio telemetry | 600.00 |
| Seismic recorder and clock | 3,000.00 |
| Tiltmeter | 1,850.00 |
| Tiltmeter recorder | 350.00 |
| | $6,400.00 |

Installation and maintenance could not be done by untrained personnel although daily records changing could. Installation would cost on the average of at least $1000 per site and maintenance and analysis would cost at least $2000 per year. These instruments would collect more data when operating than those connected to the satellite because of the low data rate for transmission through the satellite. The equipment probably would not work continuously based on our experience so far because of the problems of routine maintenance and the need for skilled operators as well as the higher vulnerability to lightning damage and vandalism. The data return would probably be about 50 percent as an average over all of the stations. Furthermore the data would not be rapidly available for analysis by skilled scientists although it would be readily available to people near the volcano.

Thus the satellite surveillance system would have an initial cost comparable to the standard methods used but a yearly maintenance cost probably of less than half the standard methods. The satellite system would provide for rapid data collection and analysis by specialists. The standard local recording techniques would provide more data when the sites functioned properly but the equipment can be expected not to function during large parts of the time.

A satellite volcano surveillance system would have two principal purposes: basic research and early warning of increased hazard. The purpose of basic research ultimately is aimed at providing more reliable early warning and even specific predictions of eruptions. The early warning purpose would probably best be served by a satellite system with rapid data relay. The basic research need might best be served by on-site recording or by spending the same dollars on more intensive studies of fewer volcanoes. Weighing the various tradeoffs and considerations responsibly, depends first on demonstrating the types and reliability of data collected by the different approaches, and secondly on determining how complete the data, for example on seismicity, could be made by further development of on-site data processing schemes. This is the direction of our continuing research.

## 10.5 Cost Benefit Considerations

The possibility of global volcano surveillance has been of interest to several domestic and foreign potential "users". For example, the emergency services coordinator for Portland, Oregon, is looking for an economical way to monitor the nearby and relatively young volcano Mt. Hood to warn the residents of a possible reawakening of activity. Safety specialists at an atomic power plant on the Columbia River are worried about monitoring the young volcano St. Helens to obtain early warning of a reawakening of volcanic activity in order to shut down the reactor during periods of high risk. A group of researchers in Paris have asked about using these instruments in the French West Indies to monitor potentially dangerous volcanoes that they might not be able to afford to monitor in any other way. These examples illustrate the types of interests that have been expressed to us for immediate uses of a volcano surveillance system. Many different volcanologists have expressed an interest in this system. One leading volcanologist said at the American Geophysical Union meetings in Washington, D.C., in the public discussion after a talk concerning this work, that he thought development of this volcano surveillance system was the most exciting thing now being done in volcanology.

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 early warning of the reawakening of volcanoes and criterea for judging the degree of unrest of each volcano. Such information would aid in minimizing the disruption caused by a volcanic eruption to the local economy. Life-loss 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 volcano hazard continues to increase.

The value of human life is difficult to establish in economic terms but figures near $300,000 have been estimated in reasonable analyses (Sagan, 1972; Some values range from $50,000 to $9 million). Loss of life from eruptions is rather irregular in the course of time. Individual eruptions have killed 50,000 to 100,000 people. An average of several hundred people per year has been killed by volcanoes during the last 500 (Van Bemmeln, 1949) and 1000 (Decker, personal communication, 1974) years. Allowing for the increase in world population, it is not unreasonable to assume that the yearly loss of life in the near future could be on the order of 500 and the corresponding yearly "economic loss" could be on the order of $150 million. While 500 lives may not seem like a large number in comparison to other hazards, it must be remembered that this is a long-term average. Specific eruptions may kill many times this number of people in one small area, causing extremely large and concentrated economic loss. These figures suggest that even a few percent reduction in the rate of life loss from volcanic eruptions would "pay" the cost of a global volcano surveillance system.

By providing direct criteria for judging the degree of unrest of various volcanoes, such a surveillance system would aid in development planning of regions around volcanoes. When a choice is possible, clearly more construction and development should proceed on those volcanoes showing absolutely no signs of unrest over several years than on those volcanoes showing some signs of unrest. Naturally development should be avoided around those volcanoes showing the greatest amount of activity or showing rapid changes in activity.

Another major benefit of a global volcano surveillance system is that it would focus use of available resources on detailed studies of volcanoes that have the highest probability of erupting. Such focussing would 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 focussing use of the research funds and talents of many different countries.

## 11.0 Conclusions

The principal conclusion from this project to develop and evaluate a prototype global volcano surveillance system is that a global volcano surveillance system is now technologically and economically feasible but that 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 has been designed, deployed at 19 locations, and thoroughly tested that reliably indicates order of magnitude changes in seismicity. This event counter is significantly more reliable than any such system previously available.

b. A tiltmeter adapted from a defense application has been successfully deployed at 6 remote locations and shown to operate reliably and stabily for at least a year. This meter can be installed quickly and easily in remote locations.

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

c. 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. Lightning has caused the most problems with field equipment and it must be considered carefully in designing future systems.

f. Over 70,000 messages relayed through the ERTS satellite have been processed, tabulated, and plotted in different ways. These data show that the data collection system accurately relays at least 95 percent of the data and correctly identifies the other 5 percent of the messages containing transmission errors.

g. Local earthquakes were observed on all volcanoes monitored in this study, suggesting that even the Cascade Volcanoes are not extinct.

h. An order of magnitude increase in seismicity was observed several days pior to the eruption of Volcán Fuego in Guatemala in February 1973.

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

j. 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.

k. Continued evaluation and development of a prototype volcano surveillance system should include the following:

    1. Evaluation of seismic and tilt data collected through the system over a long period of time to evaluate long-term changes.

    2. Continued detailed analysis of the short-term data to clearly demonstrate the relation between these data and the level of activity of different volcanoes.

    3. Deployment of at least 15 more tiltmeters to adequately evaluate their performance in different regions, to further

develop installation techniques, and to determine how many tiltmeters are required on each volcano to show in the best manner the changes in tilt.

4. Investigation of other ways of compressing seismic data that would result in a less severe loss of information than simple earthquake counts.

5. Evaluation and testing of other methods to monitor the level of activity of volcanoes.

We find the results of this initial project extremely encouraging. It appears that a global volcano surveillance system utilizing satellite telemetry may be very practical and desirable. Considerable evaluation and development still needs to be done, however, to demonstrate to reasonable skeptics, including ourselves, just how valuable such a system would be and how soon it should be built.

## 12.0 Recommendations

The following recommendations are addressed to people at NASA and other organizations who are considering details in the continued operation of the ERTS Data Collection System and who are planning other similar research-oriented or operational data relay systems.

a. Present data collection system users should be encouraged in every way to participate in the design of future systems and new transmitters for the present system so that maximum benefit can be gained from their field experience. Seminars such as that held at Wallops Island, Virginia, in May 1973 are an excellent way to stimulate discussions on design details.

b. New transmitters should be designed to be delivered in or to be put by the user in waterproof, airtight cases with a desiccant.

This method has proved to work well with the event counters.

c. New transmitters especially for operational systems should be kept simple and inexpensive by including only the serial data input option in the basic unit. While the versatility of the present data collection platforms has made it easier for a wide variety of users to use the data collection system, this versatility costs money and, of far greater importance, it provides for a greater chance of component and operator failure. We question whether the ability to mix input options is in general really useful.

d. More care must be given to interfacing equipment to the transmitter and the need for different power supplies for the user's equipment. Interfacing might be much more reliable if the DCP provided continuous power to the user to operate his equipment. For large operational systems, the transmitter and user's equipment should be designed and built together.

e. The DCP might be easier to use if a lower voltage such as 6 or 12 volts were used rather than 24 volts. If 5 or 6.25 volts were used the DCP could easily and economically be run on Aircell or Carbonaire batteries (section 6.5) for periods of 3 years between battery changes.

f. A significant effort should be made to find small antennas that will operate reliably in extreme climates and that can be shipped easily. The CHU antenna (section 6.3) appears from our field work to be well suited for this use and the printed circuit antenna designed by Ball Brothers Research Corporation appears to be even better from the point of view of field installation, although this antenna has not yet been tested.

g. Considerable thought should be given to utilizing a UHF or other type of communication link rather than S-band from the satellite to the tracking station that might allow construction of inexpensive ground receiving sites. This experiment has demonstrated that the data link from the ground to the satellite and back to the ground is infinitely more reliable than the data link from the ground-receiving site to the user. Inexpensive receiving equipment would allow major users to have their own receiver site.

h. An operational system should require a minimum of data handling by personnel. For example, some computer cards have been lost between Goddard and Menlo.

i. Data sent to the user should always be sent in chronological order. Occasionally message order is reversed.

j. All data received and identified as belonging to a particular user should be sent to him with appropriate quality indicators even if the data has errors in it. Only the user should decide what data will be thrown away.

k. An internal error-checking scheme such as the convolutional encoding scheme for ERTS is necessary in a reliable data collection system (see section 9.3).

l. A field test set should be built that decodes and checks the total RF signal from the transmitter and also shows the RF power and the actual data supplied by the user. This test set should ideally not be connected to the transmitter but should operate only by receiving the RF signal. Economic considerations, however, may require connecting the clock of the transmitter to the test set to synchronize the two systems. The test sets provided for this experiment are unreliable in the serial mode and have showed nonfunctioning transmitters to be functioning.

m. Development of a solid state memory to record DCP data on the satellite while out of view of ground stations would be extremely valuable for a global volcano surveillance network.

n. An effort should be made to fund programs requiring instrument development and deployment soon enough prior to the launch of a new satellite system, that maximum use can be made of the satellite's lifetime.

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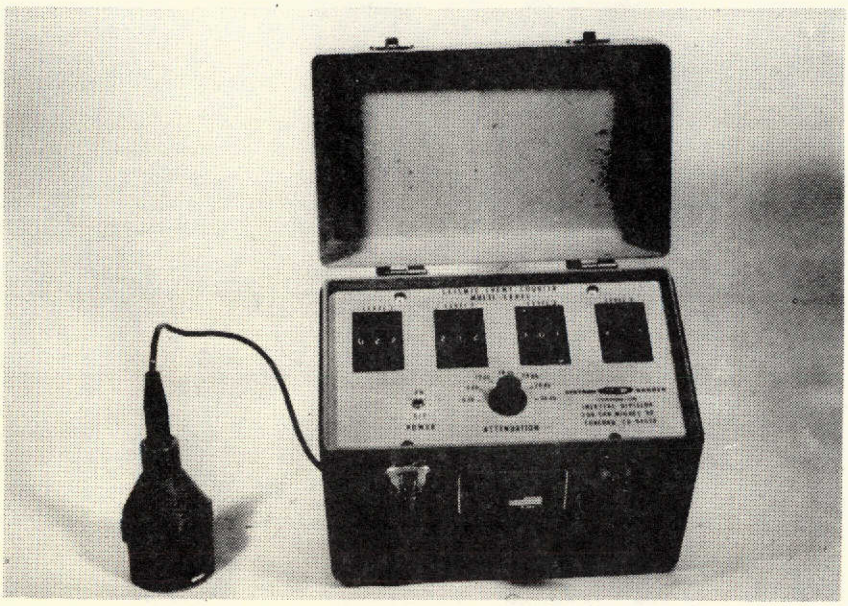

Photo 1: One of six prototype multilevel seismic event counters built in 1971 for the U.S.G.S. to develop event counting techniques. This instrument uses mechanical counters and analog circuitry and is designed to connect to the parallel digital input of the satellite transmitter.

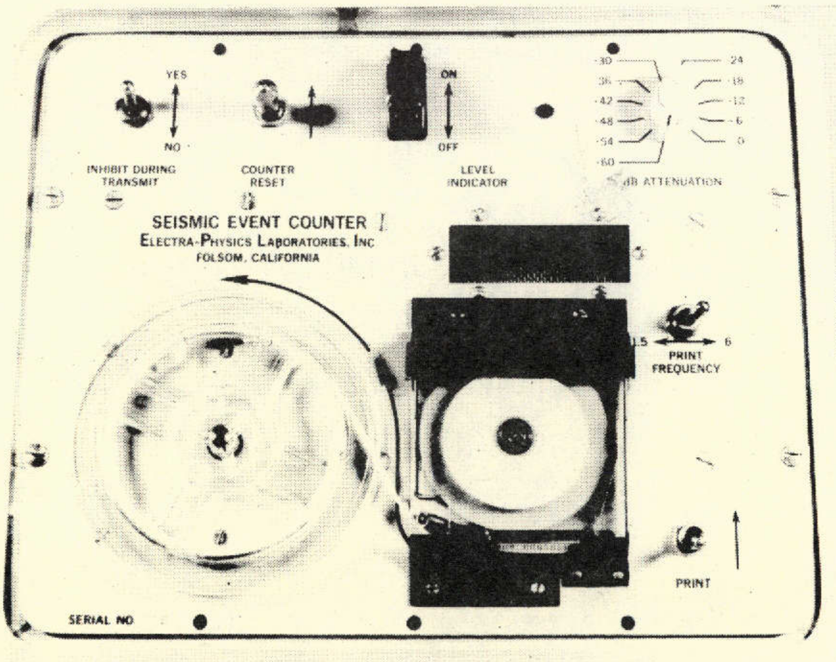


Photo 2: Control panel of one of 23 seismic event counters built in 1972 for use in the prototype volcano surveillance system. This counter uses digital techniques after the seismic signal is amplified and filtered. The level indicator is a light that shows when the most sensitive counter is on in order to set the gain during installation. The printer prints all data every 1.5 or 6 hours in a binary matrix format by a thermal process. The only moving part is the solenoid that turns the takeup spool. The paper supply is sufficient for one print sequence every 6 hours for two years.

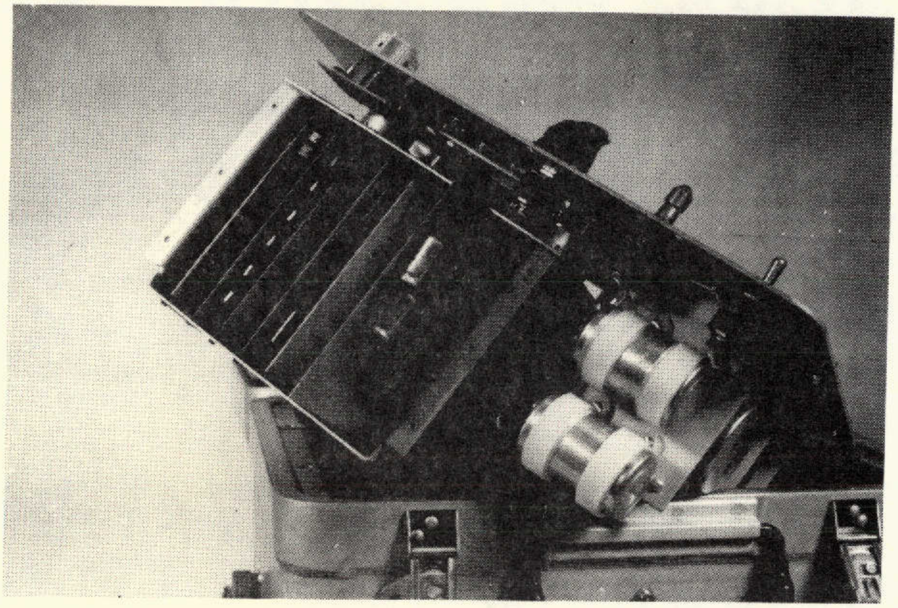

Photo 3: A view under the panel of a seismic event counter. There are 6 digital cards, one amplifier, filter, comparator card and one power supply and clock card. The system uses about 120 COSMOS integrated circuits. The large capacitors are for operation of the printer solenoid and filtering during solenoid operation.

Photo 4: Satellite transmitter (left), seismic sensors (left foreground), seismic event counter (center) and alkaline batteries sufficient for at least one year of operation (right) in any climate.

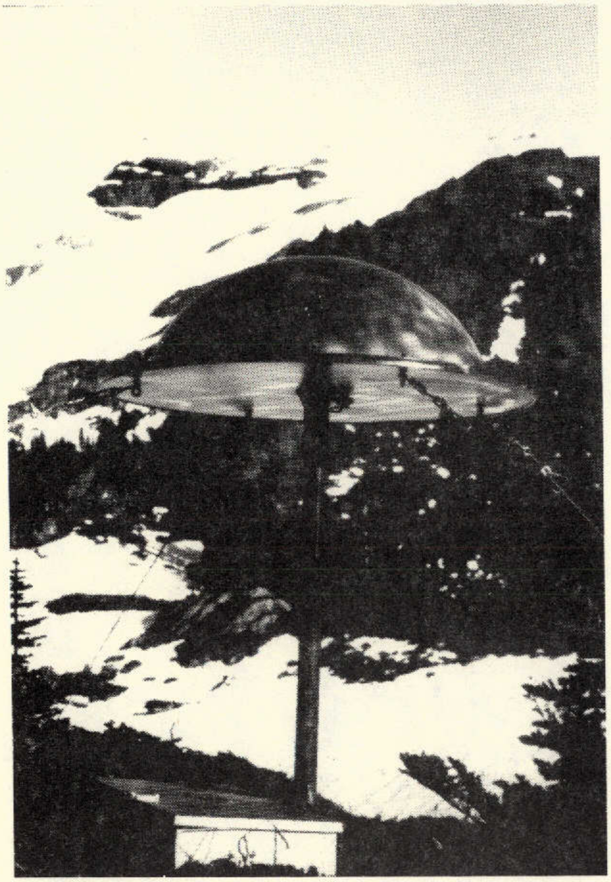

Photo 5: Typical installation of the seismic event counting system in the Cascades in Washington state. The antenna is about 1.2 meters (46 inches) in diameter. The inverted dipole elements are protected by a plexiglass dome.

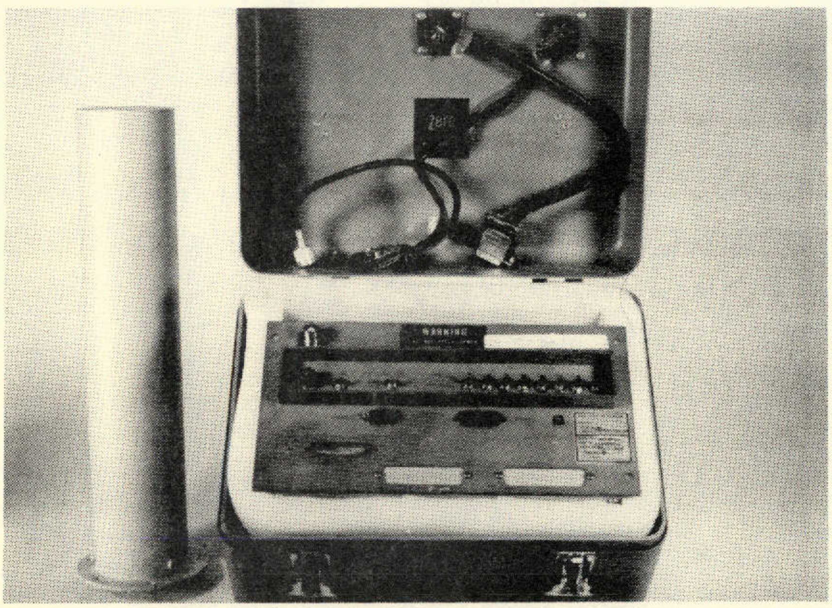

Photo 6: Transmitter for sending data every 90 or 180 seconds to the ERTS-1 polar orbiting satellite. Spiral antennas like the one on the left were used in 1973 to replace several inverted dipole antennas in the Cascades crushed by snow (Photo 17).

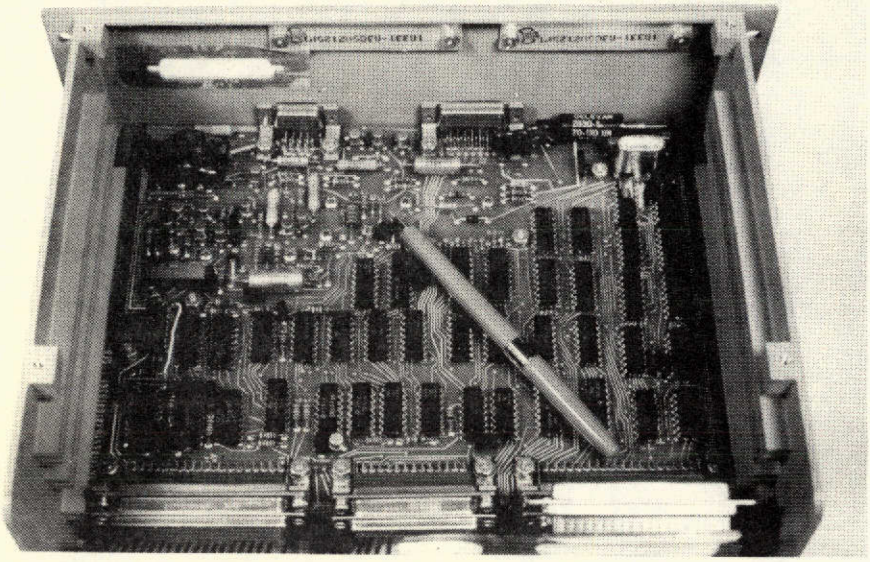

Photo 7: Programmer card in the satellite transmitter. This card turns the transmitter on and off, formats the data, and adds platform identity and preamble bits to the data. The ballpoint pen shows the scale.

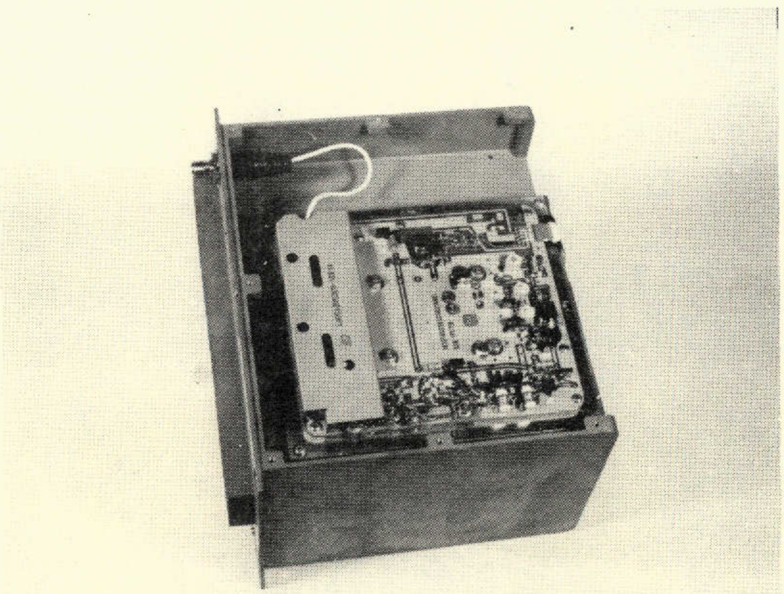

Photo 8: Transmitter card that modulates the formatted digital data and transmits it in a 38-millisecond, 10-watt minimum pulse.

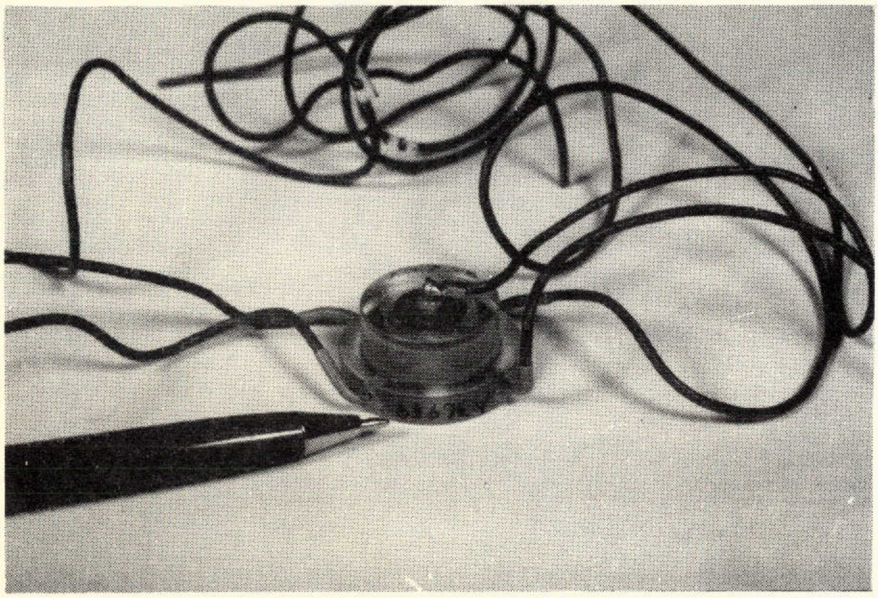

Photo 9: View of the underside of the level bubble used in the biaxial tiltmeter shown with a ballpoint pen for scale. Tilt is measured by accurately detecting the difference in resistance between the four poles with an AC signal attached to the central terminal.

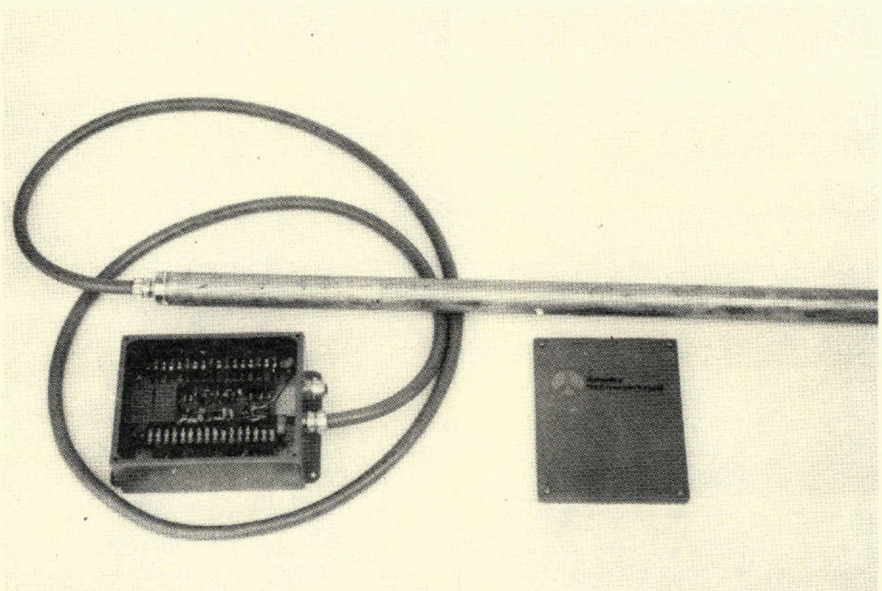

Photo 10: Biaxial tiltmeter and electronics. The pipe is about 5 cm (2 in) in diameter and 1.3 m (48 in) long.

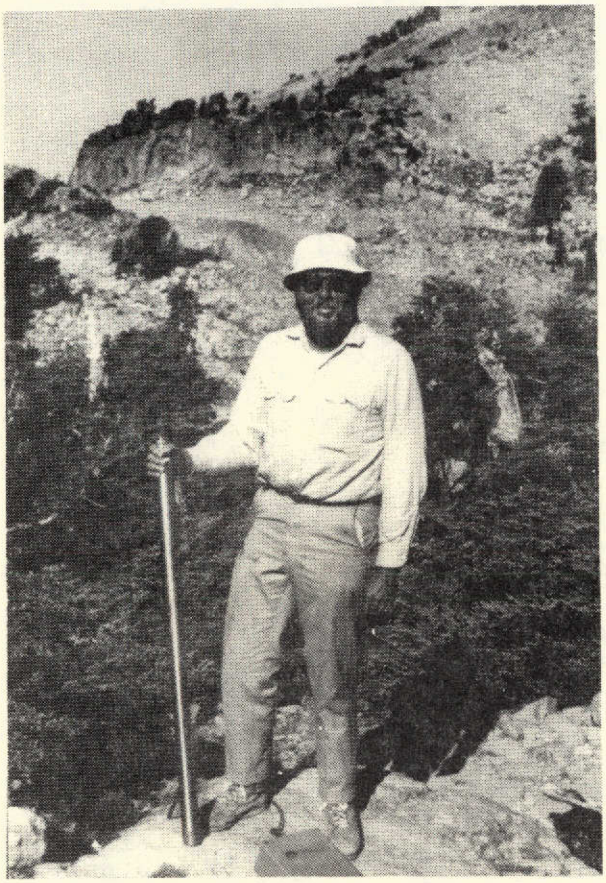

Photo 11. Biaxial tiltmeter and electronics ready for installation on Mt. Lassen in California.

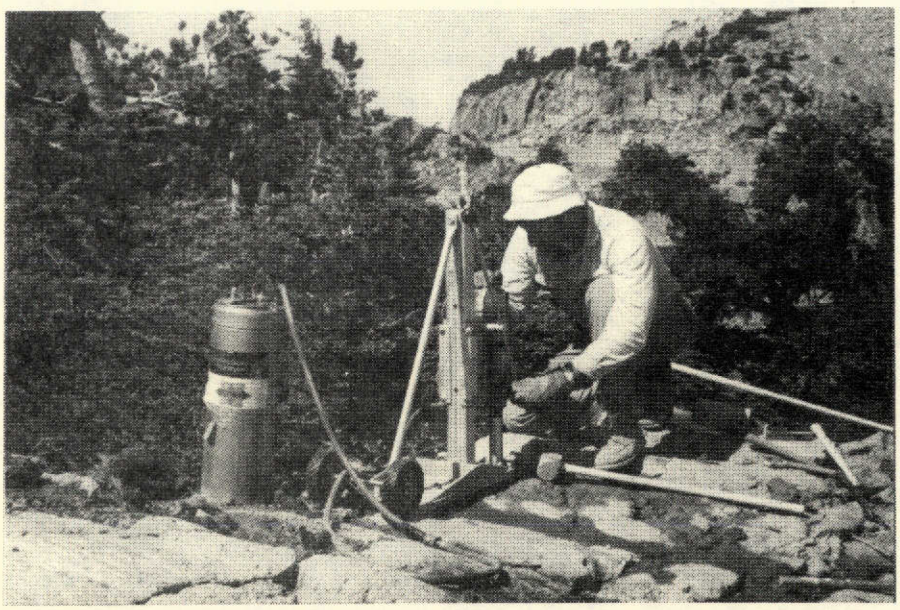

Photo 12: Portable electric drill used with a portable generator to drill a hole about 10 cm (4 in) in diameter and about 1.3 m (4 feet) deep for installation of the tiltmeter in rock on Mt. Lassen.

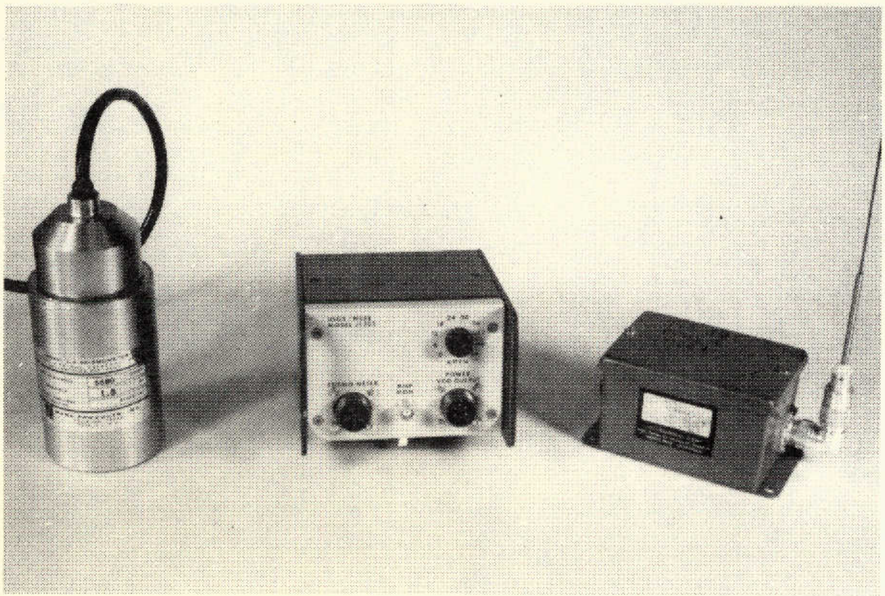

Photo 13: Geophone (left), amplifier and voltage-controlled oscillator (center) for FM modulation, and a low power VHF radio transmitter (right) used to detect seismic signals and send the data to a central office for recording. This type of equipment has been installed next to most seismic event counters to provide standard seismic data to compare with the seismic data compressed by the event counter. This equipment has been developed over many years by staff of the U.S. Geological Survey.

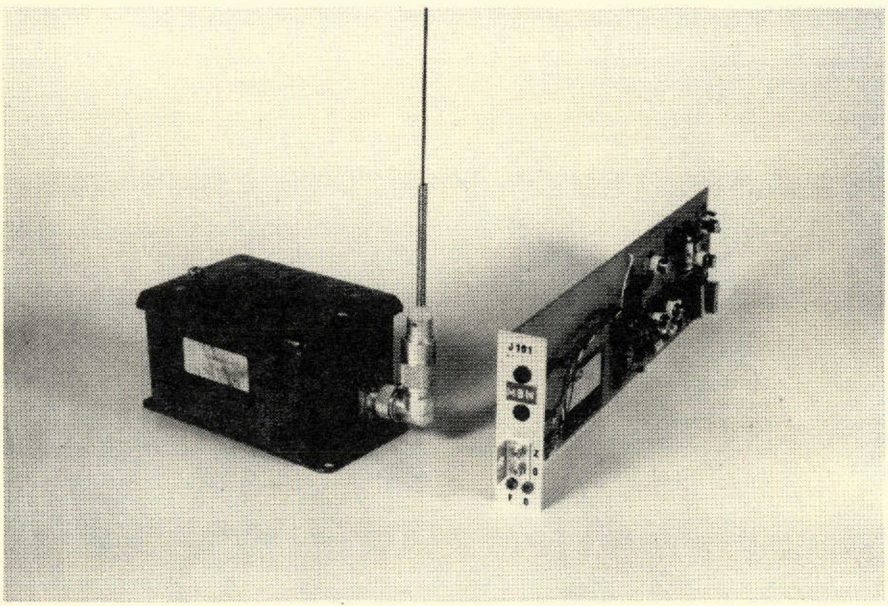

Photo 14: VHF radio receiver and FM demodulator used to receive the seismic data sent by the equipment in Photo 13.

Photo 15: Installation of the equipment in Photo 13 together with batteries and antenna on Volcan San Cristobal in Nicaragua. The double lid on the steel box prevents overheating of the equipment by the sun. The antenna of the event-counting system can be seen in the background.

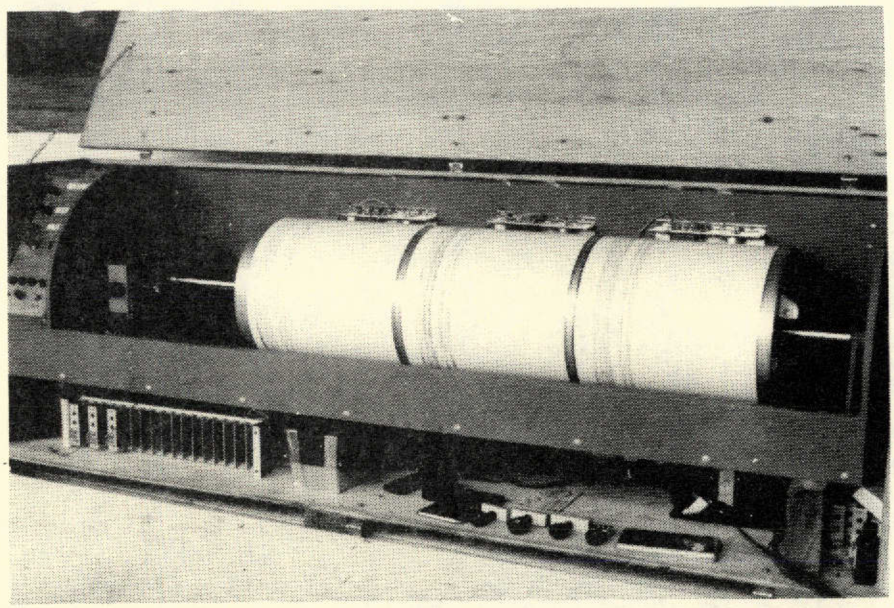

Photo 16: Recording system for three remote seismic stations as used in Nicaragua and Guatemala. The records are made by a hot pen on special paper. Under the recorder are the discriminators (left), time code receiver (left of center), standby power unit (right of center) and spare parts (right). Two automobile batteries power the unit during short local power failures. The clock is not shown.

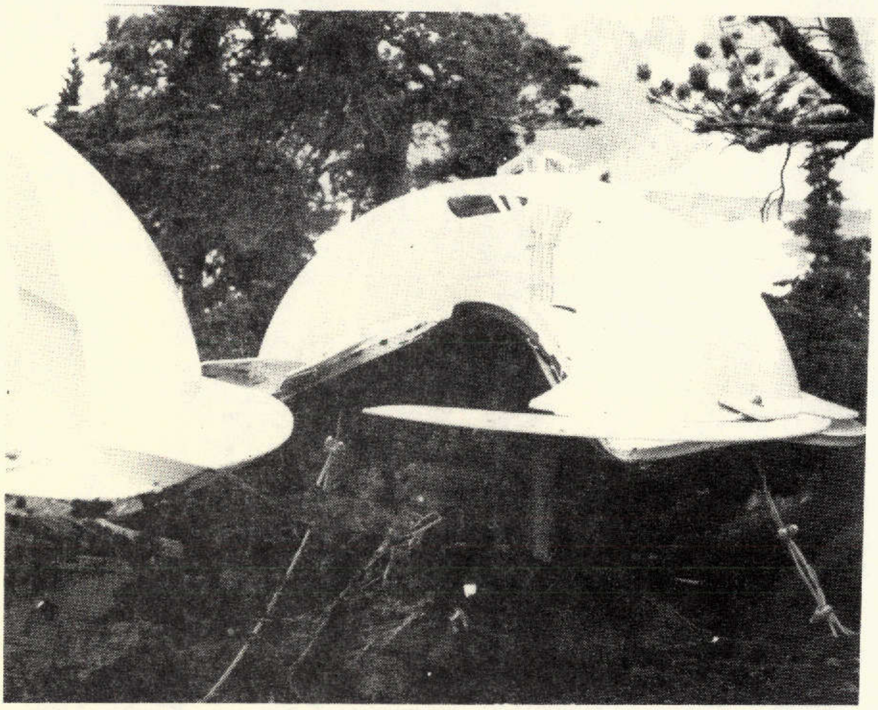

Photo 17: Inverted dipole antennas on Mt. Lassen in California as crushed by melting and settling snow in the spring of 1973. During the winter the snow covered the antennas by at least 10 feet but transmissions were received. Note how the ground plane and plexiglass dome are crushed and the dipole elements are folded in against the central mast.

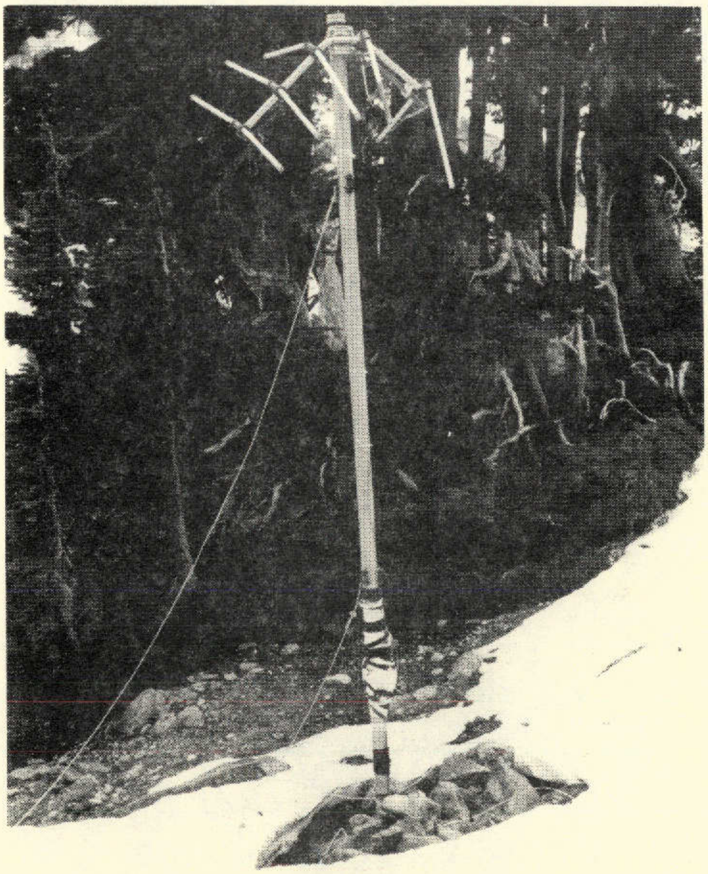

Photo 18: Yagi antenna for VHF radio transmission crushed by melting and settling snow on Mt. Lassen in the spring of 1973. These antennas are very sturdily built.

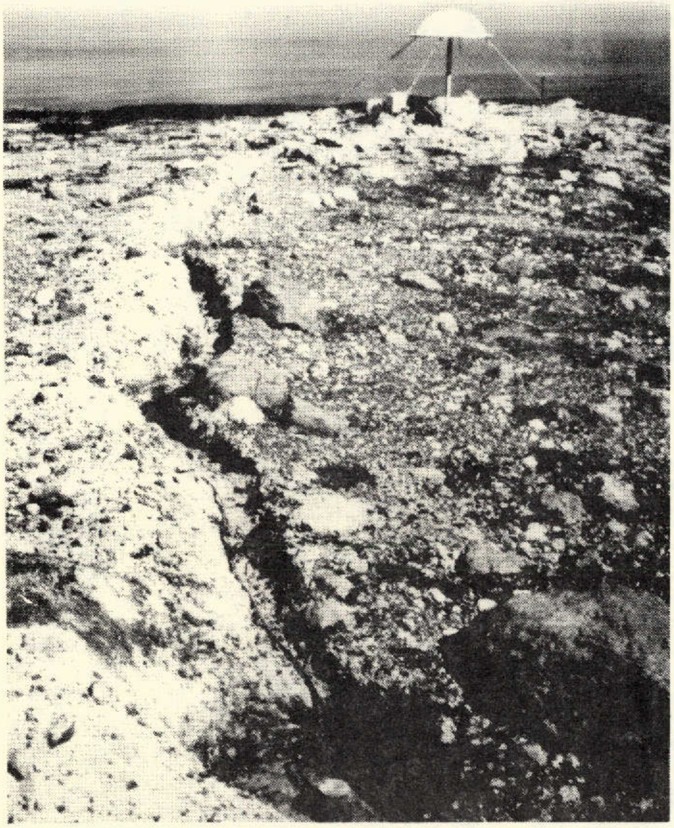

Photo 19: St. Augustine, Alaska event counter site. Geophone (foreground) is located approximately 25 meters from the event counter and satellite transmitter.

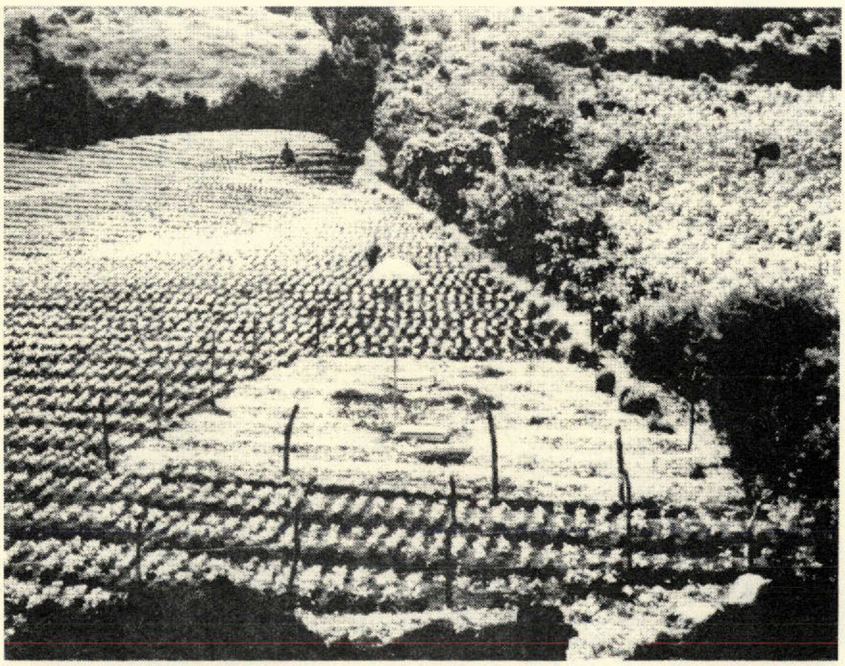

Photo 20: Pacaya Volcano tiltmeter site in Guatemala. The tiltmeter and tiltmeter electronics are located in the culvert behind the satellite transmitter.

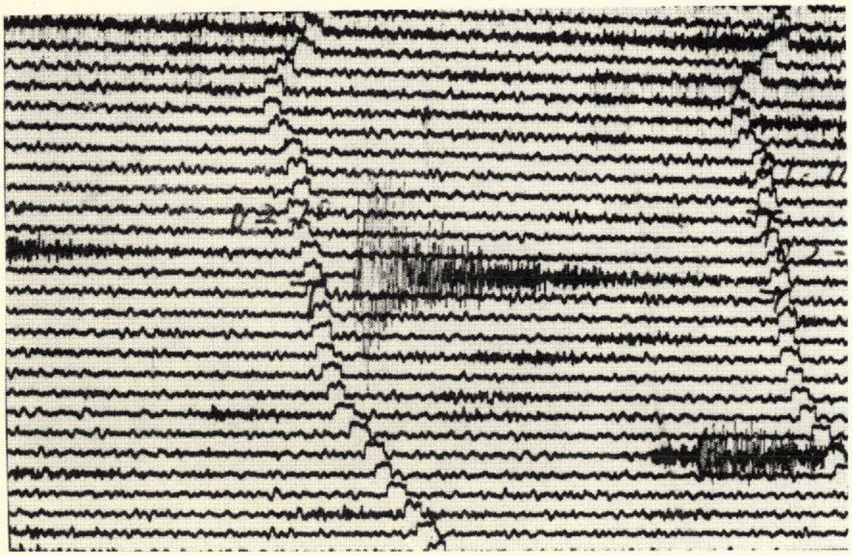

Photo 21: Example of an impulsive, high frequency microearthquake that the event counters normally count reliably.

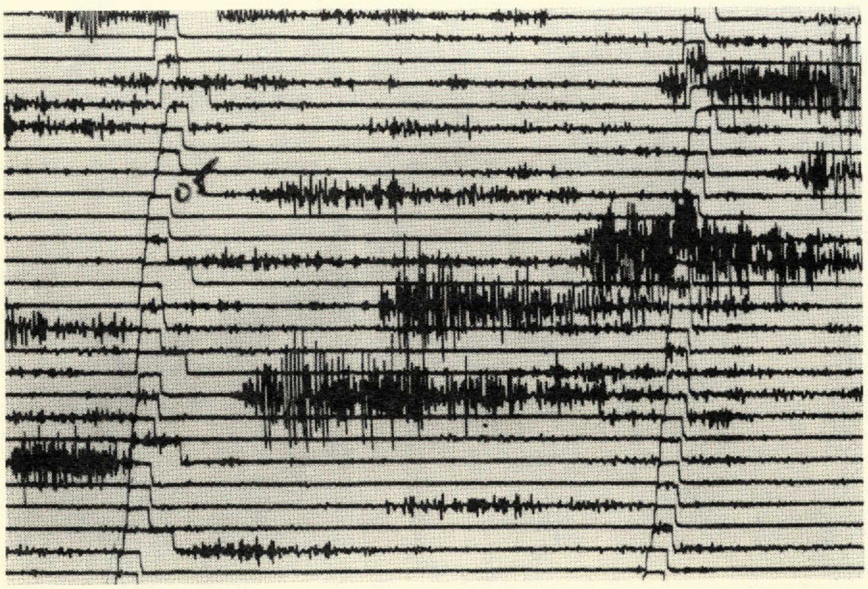

Photo 22: Example of emergent, low frequency microearthquakes recorded at Pacaya Volcano, Guatemala. These events are often not counted by the event counters.