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# Near Real-Time Monitoring of Seismic Events and Status of Portable Digital Recorders Using Satellite Telemetry

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**Abstract** Near real-time monitoring of seismic events and status of portable 16-bit digital recorders has been established for arrays near Parkfield, Mammoth Lakes, and San Francisco, California. This monitoring system provides near real-time seismic event identification (rough location and magnitude) and a cost-effective means to maintain arrays at near 100% operational level. Principal objectives in the design of this system have been portability and low-cost telemetry. The system has been developed to use portable digital seismic recorders (GEOS—General Earthquake Observation System) and portable data collection platforms (DCP's) for the Geostationary Operational Environmental Satellite (GOES) telemetry system. Data are transferred asynchronously from the GEOS seismic system through a microprocessor-controlled interface every 10 min. The interface stores, determines priority, converts, and synchronously transfers these data to a Sutron Corp. model 8004 DCP for transmission through the GOES satellite telemetry system. Event parameters include trigger time, peak amplitude, time of peak amplitude, and event duration. Instrument configuration parameters, transmitted at system start-up time and every 24 hr, include recording parameters, trigger parameters, GEOS software version, clock reference, and location parameter. Instrument status includes battery voltage, number of events, and percentage of tape usage. These data are transmitted as appropriate to the U.S. Geological Survey satellite downlink and computers located in Menlo Park, California, where they are processed and displayed.

## Introduction

Monitoring seismicity associated with pending eruptions of volcanoes and aftershock activity immediately following large damaging earthquakes often demands rapid deployment of portable digital recording equipment (Boatwright, 1985; Borcherdt, 1989; Mueller and Glassmoyer, 1990; Pinatubo Volcano Observatory Team, 1991). In addition, various mid-term and long-term experiments also are using portable digital recorders with increasing frequency to provide on-site recording capabilities. The maintenance logistics and scientific objectives associated with such applications are substantially improved with the addition of remote monitoring capabilities at each of the sites using satellite telemetry. Such capabilities can provide near real-time monitoring of event time, location, and size, plus instrument status including power or battery voltage, data storage capacity, timing accuracy, and instrument programming selections.

A monitoring capability for portable digital recorders using the Geostationary Observational Environmental System (GOES) has been developed. The GOES (Nelson, 1975), together with Meteosat operated by the European Meteorological Satellite organization and the Japanese Geostationary Meteorological Satellite system, provides worldwide coverage between latitudes 55° north and south (Harris, 1987). The GOES telemetry system provides a cost-effective method for data transmission for a rapidly deployed portable system or in a base-station-type application. The telemetry system for portable recorders has been developed and applied with the General Earthquake Observation System (GEOS) recorders (Borcherdt *et al.*, 1985). The system could be modified to operate with other microprocessor-based digital recording systems with programmable RS-232 output capabilities.

Our research concerns data from borehole strain and seismic instrumentation that has been installed along the San Andreas fault system to monitor crustal deformation and seismic processes. The network of borehole strainmeters and 3-component seismometers operated by the U.S. Geological Survey in California is located in seismically active areas of interest such as the San Francisco Bay area, Mammoth Lakes, Parkfield, and in southern California (Johnston *et al.*, 1987, 1992) (Fig. 1). The data from strainmeters and other instruments are transmitted at a slow rate (10-min interval) through the GOES satellite telemetry system (Silverman *et al.*, 1989). Crustal strain plus 3-component seismic velocity and acceleration are recorded on-site at 200 samples per second with 16-bit GEOS digital recorders using the self-triggering mode. The recorders are programmed to trigger on local earthquakes with magnitudes greater than ≈*M* 2.5. Together the two recording systems cover frequencies from $10^{-8}$ Hz (1000 days) to about 100 Hz (Borcherdt *et al.*, 1989).

A microprocessor-controlled interface was developed to transfer data from the GEOS recorder to a Sutron Corporation model 8004 satellite data collection platform (DCP) for transmission through the GOES system to USGS headquarters in Menlo Park, California (Fig. 2). With this system we can

1. monitor the status of remotely deployed GEOS for maintenance purposes, and
2. provide near real-time retrieval of seismic event data.

Although the 100 baud data rate through the GOES system prevents the transmission of digitized seismograms, the system is used to send summarized seismic event parameters, system configuration information, internal clock time corrections, and system status data. These data are transmitted asynchronously every 10 min by the GEOS recorder to the GEOS-DCP interface. The interface stores, determines priority, compacts, and synchronously transmits the reformatted data to the DCP where they are stored until transmitted at an assigned 10-min transmission interval. The data are received through a satellite downlink

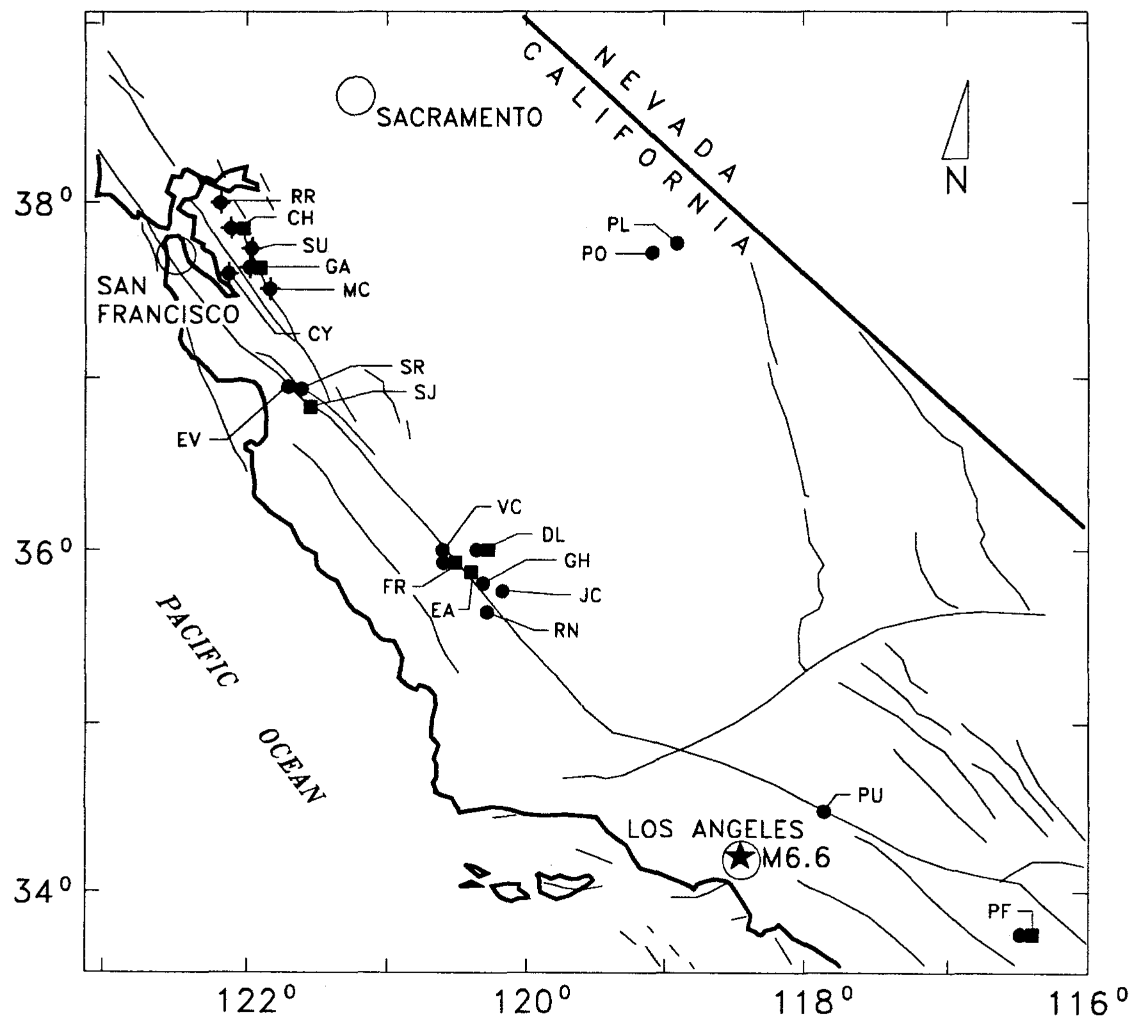


Figure 1. Borehole strain network in California showing the location of dilatometers with 3-component seismic velocity (●), plus 3-component seismic acceleration (◆), tensor strainmeters (■), and the 17 January 1994 Northridge earthquake epicenter (★). All strain-monitoring sites retrieve data through the GOES satellite telemetry system.

and transferred to computers where they are stored, processed, and displayed (Fig. 2).

With GEOS digital recorders previously deployed at all the borehole strainmeter locations with existing GOES telemetry, the addition of the GEOS-DCP interface provided a low-cost solution for retrieval of GEOS data. With the additional cost of a DCP, this system can be used to retrieve data from any remotely deployed GEOS recorder. Recorders with this capability are currently transmitting strong-motion data from sites located in San Francisco, California.

## Data from the GEOS Seismic Recorder

The GEOS recorder transfers data to the GEOS-DCP interface once every 10 min via an RS-232 port with selectable baud rate. Four types of information are transmitted: (1) status information, (2) instrument timing parameters, (3) instrument configuration parameters, and (4) seismic event parameters. These four types of information are transferred at preselected time intervals depending on priority.

One of four status parameters is transmitted every 10 min. Time correction parameters are transmitted at a software selectable interval, typically 12 hr. The configuration parameters are transmitted every 24 hr commencing with initial instrument setup. All event parameters recorded in the previous 10-min interval will be transferred from the GEOS to the GEOS-DCP interface for sequential transmission at 100 baud through the GOES telemetry system.

The parameters describing instrument status are as follows: percentage of tape usage, power supply battery voltage, number of triggered event records, and the instrumental or seismic background noise level plus software version number.

The time correction parameters report the time of day of the internal time standard in the GEOS and the millisecond difference between the internal time and an external WWVB time reference. The internal time of day is represented by day of year, hour, minute, second, and millisecond. Millisecond readings from eight consecutive seconds represent differences between the internal clock and the external reference and are used to correct any internal clock drift.

The configuration parameters indicate the options programmed on initial setup of the GEOS recorder. They include information on site location number, experiment number, input channels that are activated (1 through 6), input channel used to trigger the recorder, sample rate, type of clock reference, triggering ratio, postevent recording time, and each active channel's instrument type, gain, and filter setting. This information is used to determine and confirm that remotely deployed recorders are operating properly.

The event parameters were chosen to minimize required transmission bandwidth, but provide sufficient information for approximated event location and magnitude assessment. They include the following: trigger time

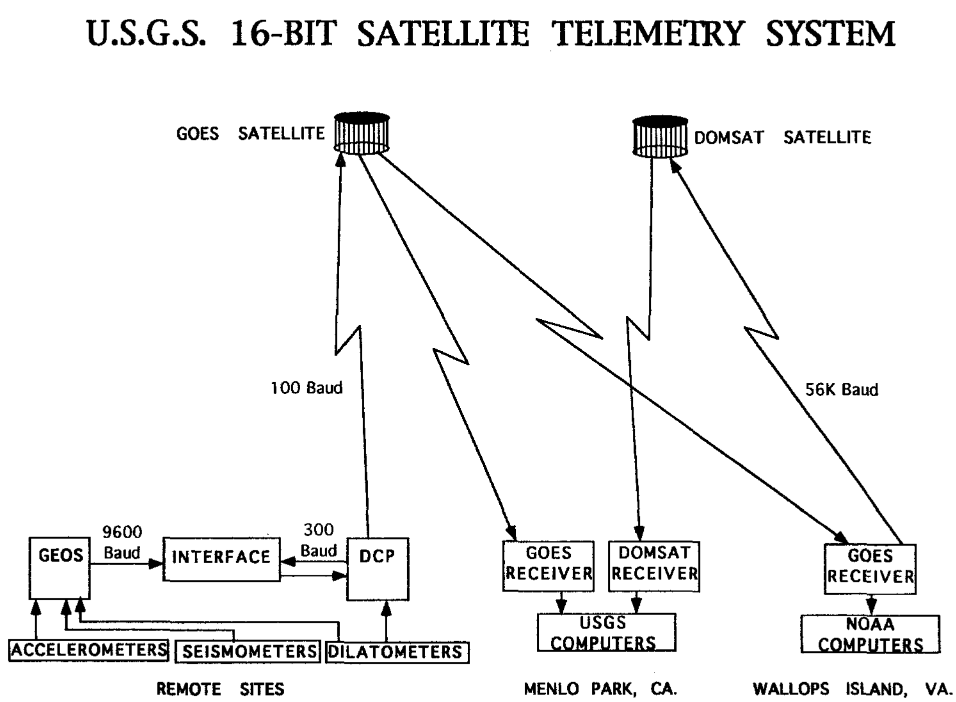


Figure 2. Illustration of the 16-bit satellite telemetry system used to retrieve strain and seismic data from the strain sites located in California.

of the event (day, hour, minute, second, and millisecond), time duration of the event, peak amplitude during the event, and the time to the peak amplitude. Although these summarized data do not allow precise determination of event magnitude and location, they do allow rapid determination of approximate earthquake magnitudes and locations which are useful in remotely deployed arrays or as a backup under emergency situations to existing telephone or microwave telemetry systems (Table 1).

Any of the above parameters that occur during the previous 10-min period will be transferred to the GEOS-DCP interface where these data are received, converted, and transmitted through the satellite telemetry system as the baud rate permits.

## GEOS-DCP Interface

The GEOS-DCP interface is designed to transfer the parameter data received from the GEOS recorder to the DCP where the data are stored and then transmitted at assigned intervals. The various parameter data packets are asynchronously received by the interface, priority is determined, and these data are reformatted and stored as five 16-bit data words (one message). The reformatted data are synchronously transferred to the DCP every 10 min using the serial digital data input mode and five analog input channels for each message. From one to three messages can be transmitted through the satellite telemetry system every 10 min.

Each message is made up of two parts, the GEOS status portion and the GEOS data portion. With the exception of an event parameter, the status part of a message occurs in the first word of the five-word message and may be one of five forms: (1) number of records, (2) battery voltage, (3) tape usage, (4) software version and background noise level, and (5) missing data. A missing data message is created by the interface when

Table 1
List of Aftershocks ($M \geqq 3.7$) from the 17 January 1994 Northridge Earthquake*

| Time (UT) | | | | | | Magnitudes | | | | Differences | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Yr | Mo | D | Hr | Min | Sec | *M* | *M*(du) | *M*(am) | *M*(av) | *M-M*(du) | *M-M*(am) | *M-M*(av) |
| 94 | 1 | 17 | 14 | 14 | 30.31 | 4.4 | 4.0 | 4.7 | 4.3 | 0.4 | −0.3 | 0.1 |
| 94 | 1 | 17 | 14 | 26 | 51.82 | 3.8 | 3.5 | 3.6 | 3.6 | 0.3 | 0.2 | 0.2 |
| 94 | 1 | 17 | 15 | 07 | 02.93 | 4.2 | 4.6 | 4.1 | 4.3 | 0.4 | 0.1 | −0.1 |
| 94 | 1 | 17 | 15 | 42 | 12.43 | 3.9 | 3.6 | 3.6 | 3.6 | 0.3 | 0.3 | 0.3 |
| 94 | 1 | 17 | 15 | 54 | 10.75 | 4.8 | 4.4 | 4.6 | 4.5 | 0.4 | 0.2 | 0.3 |
| 94 | 1 | 17 | 16 | 16 | 01.64 | 3.8 | 3.6 | 3.7 | 3.6 | 0.2 | 0.1 | 0.2 |
| 94 | 1 | 17 | 19 | 35 | 34.33 | 4.0 | 3.8 | 4.2 | 4.0 | 0.2 | −0.2 | 0.0 |
| 94 | 1 | 17 | 20 | 38 | 24.21 | 3.4 | 4.7 | 3.6 | 3.6 | −0.3 | −0.2 | −0.2 |
| 94 | 1 | 17 | 20 | 46 | 01.93 | 4.9 | 4.6 | 4.6 | 4.6 | 0.3 | 0.3 | 0.3 |
| 94 | 1 | 17 | 23 | 33 | 30.31 | 5.6 | 5.4 | 5.5 | 5.4 | 0.2 | 0.1 | 0.2 |
| 94 | 1 | 18 | 00 | 36 | 20.76 | 3.9 | 4.4 | 3.8 | 4.1 | −0.5 | 0.1 | −0.2 |
| 94 | 1 | 18 | 00 | 39 | 34.87 | 4.4 | 3.6 | 4.3 | 4.4 | 0.2 | 0.1 | 0.0 |
| 94 | 1 | 18 | 00 | 43 | 08.80 | 5.3 | 4.0 | 5.1 | 5.0 | 0.3 | 0.2 | 0.3 |
| 94 | 1 | 18 | 06 | 29 | 02.14 | 3.7 | 4.9 | 3.8 | 3.8 | −0.2 | −0.1 | −0.1 |
| 94 | 1 | 18 | 07 | 23 | 56.14 | 4.0 | 4.2 | 3.6 | 3.9 | −0.2 | 0.4 | 0.1 |
| 94 | 1 | 18 | 09 | 41 | 48.46 | 3.7 | 3.8 | 3.9 | 3.9 | −0.1 | −0.2 | −0.2 |
| 94 | 1 | 18 | 15 | 23 | 46.88 | 4.8 | 4.5 | 4.7 | 4.6 | 0.3 | 0.1 | 0.2 |
| 94 | 1 | 18 | 15 | 51 | 44.89 | 4.0 | 4.0 | 3.8 | 3.9 | 0.0 | 0.2 | 0.1 |
| 94 | 1 | 19 | 14 | 09 | 14.83 | 4.4 | 4.5 | 4.9 | 4.7 | −0.1 | −0.5 | −0.3 |
| 94 | 1 | 19 | 14 | 46 | 35.03 | 3.9 | 3.8 | 3.6 | 3.7 | 0.1 | 0.3 | 0.2 |
| 94 | 1 | 19 | 19 | 50 | 09.11 | 3.7 | 3.9 | 4.1 | 4.0 | −0.2 | −0.4 | −0.3 |
| 94 | 1 | 21 | 18 | 39 | 15.39 | 4.6 | 4.7 | 4.7 | 4.7 | −0.1 | −0.1 | −0.1 |
| 94 | 1 | 21 | 18 | 42 | 28.76 | 4.1 | 3.8 | 4.1 | 4.0 | 0.3 | 0.0 | 0.1 |
| 94 | 1 | 21 | 18 | 52 | 44.16 | 4.1 | 4.2 | 3.8 | 4.0 | −0.1 | 0.3 | 0.1 |
| 94 | 1 | 21 | 18 | 53 | 44.49 | 4.2 | 4.0 | 4.2 | 4.1 | 0.2 | 0.0 | 0.1 |
| | | | | | Differences | | | | | *M-M*(du) | *M-M*(am) | *M-M*(av) |
| | | | | | Average magnitude difference | | | | | 0.044 | 0.040 | 0.052 |
| | | | | | Standard deviation | | | | | ±0.26 | ±0.23 | ±0.20 |

*Preliminary magnitudes (*M*) are from the Southern California seismic catalog (USGS-Pasadena). These magnitudes are compared with magnitudes determined from GEOS event data using duration ($M_{du}$), amplitude ($M_{am}$) and the average of the two ($M_{av}$). Magnitudes calculated using the GEOS event data are within ±0.2 of those in the seismic catalog.

no data is received from the GEOS during the previous 10-min interval. If an event has triggered the GEOS recorder and the event data are received by the GEOS-DCP interface, the status portion is preempted.

The data portion of a message may be one of six different forms: (1) null data, (2) time-correction data type I, (3) time-correction data type II, (4) event data, (5) configuration data type I, and (6) configuration data type II. While event data are transferred in a single message (80 bits), configuration and time correction require two messages for transfer to the DCP. The highest priority is given to time correction data, second highest to event data, and lowest priority is given to configuration data. The null data is transmitted when none of the three GEOS parameters (time correction, event, or configuration) has been received by the interface during the previous 10-min interval.

The GEOS-DCP interface can store a total of 1750 five-word messages and transmits one every 10 min (single-message mode) until it has cleared the memory. In the event of a memory overflow, a simple wrap-around algorithm is used to throw out the oldest information while observing the priorities between the different data parameters mentioned above. A maximum of three five-word messages may be transferred to the DCP every 10 min (three-message mode).

## Data Processing and Display

After reception by the satellite telemetry downlink in Menlo Park, California (Fig. 2), the various data are stored in computer files where programs allow users to access and display data. All software is written in the C language on Sun Microsystems workstations. A menu mode display lets users select currently active sites and the time period for display. The basic output shows various recorder parameters such as battery voltage, tape usage, number of events, time corrections, time of events, peak amplitude of events, and missing satellite transmissions for the time period selected (Fig. 3). Configuration parameters indicating the GEOS program choices are also displayed and the system allows easy monitoring of the remotely deployed units and any recorded seismic events.

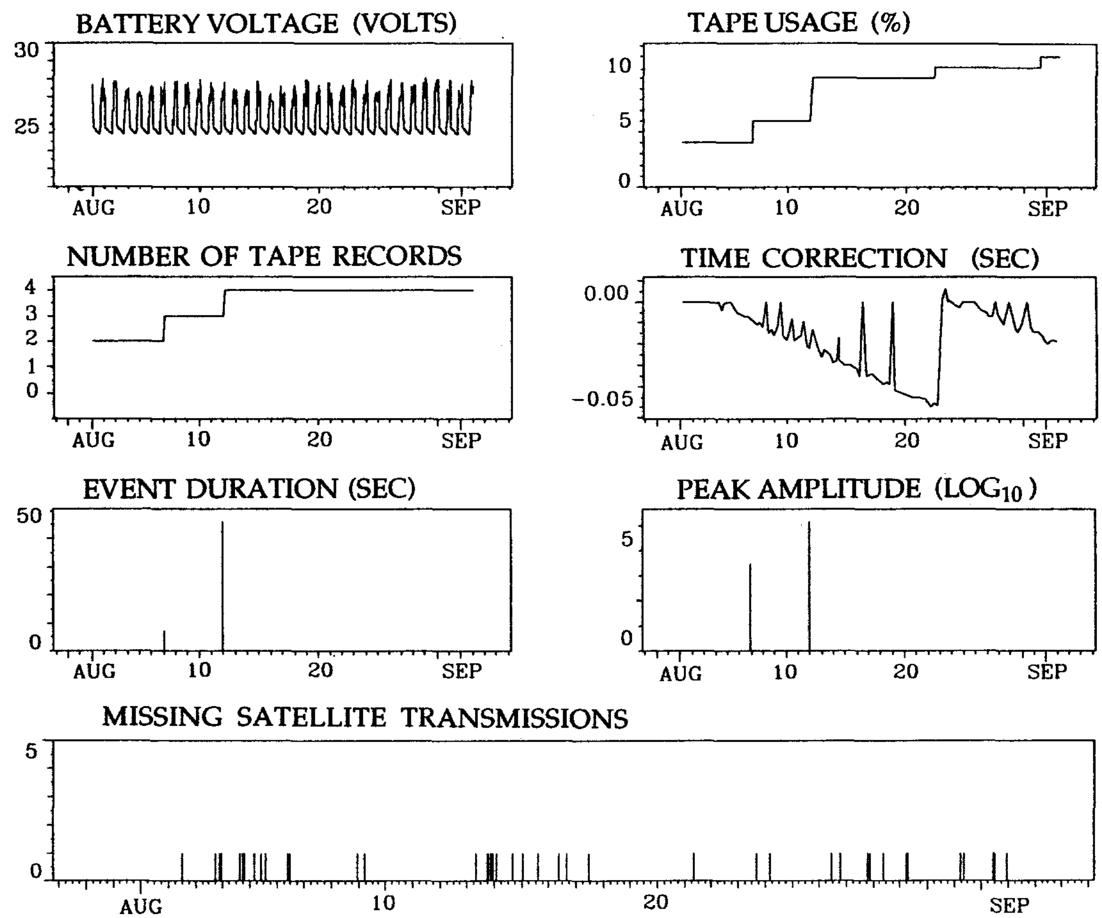


Figure 3. Example of software-produced time-series plots to display the various GEOS parameters from active strain sites.

## Operational Example: The Northridge Earthquake

The recent *M* 6.7 Northridge earthquake on 17 January 1994 provided an excellent example of the advantages of telemetering recorder data with this system. Strainmeter PUB is located 74 km from the epicenter of the Northridge earthquake (Fig. 1) and has a GEOS recorder, DCP-GEOS interface, and a DCP to transmit data to Menlo Park, California. The GEOS at this site recorded the main event and many aftershocks with magnitudes greater than about *M* 3.7. After the mainshock at 12:30:55 UT, 57 events with $M > 3.7$ occurred during the next 24-hr period and 71 events occurred during the 5-day period following the mainshock. The on-site tape in the GEOS recorder was filled 21.5 hr after the mainshock.

It was not possible to change the tape in the GEOS unit at the PUB site until 28 hr after the main event. During the 7.5-hr period when events were not recorded by the on-site recorder, event data were still transferred to the GEOS-DCP interface from the GEOS and transmitted through the satellite system. This provided a record of the activity both during this period and during the entire aftershock sequence. The occurrence time and estimated magnitudes of events monitored through the satellite system during the postseismic period were collected and have been compared with events from the regional seismic catalog. The duration *D* and peak amplitude *A*, from the event parameter, were used to calculate the earthquake magnitudes with the following empirical equations:

$$M_{(\text{duration})} = 2[\log_{10}(D + 10)] + 1$$

$$M_{(\text{amplitude})} = \sqrt{2}\,[\log_{10}A] - 0.86$$

$$M_{(\text{average})} = \frac{M_{(\text{duration})} + M_{(\text{amplitude})}}{2}.$$

A comparison of magnitudes from the event data telemetered by satellite and magnitudes from the seismic catalog recorded by the USGS in Pasadena (Table 1) indicates agreement in estimated magnitude for events in the range *M* 3.7 and *M* 5.4 to within ±0.2. In addition to providing backup data, the system also provided information on the recorder status, allowing visits for tape changes to be minimized without risking data loss.

The use of satellite monitoring of digital event recorders provides a cost-effective method for monitoring seismic activity and the status of these recorders at remote locations in near real time. While identification of event times and magnitudes are less accurate then those obtained with normal seismic network operation, the information can be useful following large events when local network operations based on telephone telemetry and normal grid power may be inoperative, or access to the on-site data is prevented or delayed. Furthermore, since the satellite data can be received anywhere in North or South America, rapid decision making based on these data can occur at great distances from a major earthquake and/or volcanic event. Finally, the optimization of maintenance and remote diagnosis of recorder and data problems using this system maximize operational efficiency.

## Acknowledgment

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