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A SATELLITE-BASED DIGITAL DATA SYSTEM FOR LOW-FREQUENCY GEOPHYSICAL DATA

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ABSTRACT

A reliable method for collection, display, and analysis of low-frequency geophysical data from isolated sites, which can be throughout North and South America and the Pacific Rim, has been developed for use with the Geostationary Operational Environmental Satellite (GOES) system. Geophysical data primarily intended for earthquake hazard and crustal deformation monitoring are digitized with either 12-bit or 16-bit resolution and transmitted every 10 min through a satellite link to a bank of UNIX-based computers in Menlo Park, California. There the data are available for analysis and display within a few seconds of their transmit time. This system provides real-time monitoring of crustal deformation parameters such as tilt, strain, fault displacement, local magnetic field, crustal geochemistry, and water levels, as well as meteorological and other parameters, along faults in California and Alaska, and in volcanic regions in the western United States, Rabaul, and other locations in the New Britain region of the South Pacific. Various mathematical, statistical, and graphical algorithms process the incoming data to detect changes in crustal deformation and fault slip that may indicate the first stages of catastrophic fault failure. Alert trigger levels based on physical models, signal resolution, and previous history have been defined for particular instrument types. Computer-driven remote paging and mail systems are used to notify appropriate personnel when alarm status is reached. The system supports continuous historical records of low-frequency geophysical data, software for extensive analysis of these data, and programs for modeling fault rupture with and without seismic radiation, as well as providing an environment for real-time attempts at earthquake prediction.

INTRODUCTION

Automated data collection and analysis systems of many kinds have been developed for the retrieval and display of various types of data. Somewhat unique design problems are encountered with large-scale data collection systems intended for earthquake and volcano hazard monitoring. These systems must be capable of operating reliably under emergency conditions during high ground acceleration, power and telephone outages, and heavy telephone access load after a large earthquake or volcanic eruption. The U.S. Geological Survey (USGS) has developed a digital system for low-frequency geophysical data collection based primarily on the Geostationary Operational Environmental Satellite (GOES) system operated by the National Environmental Satellite Data and Information Service (NESDIS). The USGS system has been in operation since 1985. The data network currently handles about 100 satellite Data Collection Platforms (DCP's) including all field instrumentation involved in the unique earthquake prediction experiment near Parkfield, California (Bakun *et al.*, 1987). This note briefly describes the system.

In order to develop a viable earthquake and volcano hazard reduction program, we require continuous on-line collection, analysis, and interpretation of crustal deformation observations. The most useful data include direct observations of crustal stress, strain, tilt, crustal displacement, fault creep, and indirect measurements of crustal deformation such as differential magnetic field, water level in wells, and soil gas emissions. In general, these low-frequency measurements cover the frequency band that exists between seismic and geodetic monitoring. These types of data are the focus of integrated observational programs in many countries (Japan, U.S.S.R, China, United States, etc.) where there are severe earthquake and volcano hazards (Rikitake, 1976).

Important criteria in the design of systems to collect these data are low power, wide dynamic range, reliability, robustness, real-time data accessibility, and independence from commercial power and telephone line connections. Typically, power and telephone lines are the first casualties of a volcanic eruption or a major earthquake. With battery/solar-powered, independent monitoring points, the unexpected loss of a few transmitters due to serious ground collapse, falling objects, etc., will not seriously impair the data collection network. The requirement for real-time operation with high data density places severe constraints on the accuracy of Data Collection Platform timing. Also, since most instruments must operate unattended for long periods, provide continuous low-noise data, remain unaffected by changes in hostile environmental conditions, and remain intact and functionally independent during and immediately following damaging earthquakes, there is a clear need for reliability.

Criteria for the recognition and determination of significant signals in each type of data vary widely. Some of the sensors have sensitivities exceeding 1 part in 10^8. Most are susceptible to various sources of earth noise in different frequency bands (Agnew, 1986). At very low frequencies ($<10^{-6}$ Hz) ground noise can exceed the resolution of the sensors by several orders of magnitude. Signal processing techniques, from simple differencing to sophisticated time series analysis, are used to improve the signal-to-noise ratios within the frequency ranges of interest.

When monitoring specific seismic and volcanic hazards, individual data sets are rarely considered in isolation. Rather, the combination of several data sets are used to evaluate quickly the status of the hazard. The satellite-based digital data system allows near real-time observations and comparisons of multiple data sets that are required to provide this rapid response. As the level of knowledge of how these measurements relate to physical models of particular earthquake or volcano increases this need for timeliness is expected to become increasingly important.

Telemetry System

The telemetry system consists of three main subsystems: (1) solar-powered Data Collection Platforms (DCPs) in the field that digitize and transmit information from geophysical field sites, which can be anywhere in the United States or the Pacific region, through the GOES West satellite; (2) a downlink or Direct Readout Ground Station (DRGS) in Menlo Park, California; and (3) a network of computers used to control the downlink and to transfer data to the Low-Frequency Data Base. The GOES Data Collection System is operated under the National Oceanic and Atmospheric Administration by NESDIS (MacCallum and Nestlebush, 1983). The satellite-based network replaces a USGS digital telemetry system (Rogers *et al.*, 1977) that used telephone lines and radio links to transmit data from low-frequency geophysical instrumentation in remote locations to the USGS in Menlo Park, California.

Figure 1 is a schematic of the system showing the flow of data from sites in the field to computer systems in Menlo Park. Data from each sensor are sampled and stored in a DCP, which then transmits the data to the GOES satellite at a predetermined time. As shown, multiple sensors may use the same DCP. Furthermore, multiple parameters, such as barometric pressure, battery voltage, and tem-

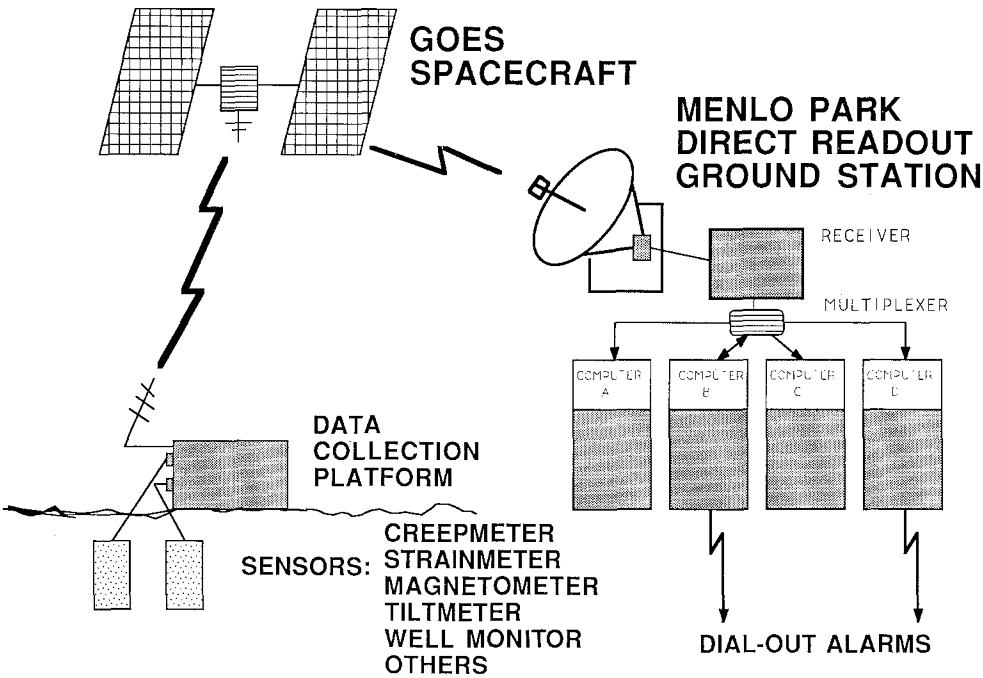

FIG. 1. Schematic diagram of the USGS satellite-based digital data system.

perature readings, are often transmitted in addition to the geophysical data. The data are received from the satellite by the ground station in Menlo Park over various channels on the satellite system. Arrangements were made with NESDIS to use a dedicated channel for many of these data because of the unique reporting requirements compared to normal GOES satellite data operations. Specialized software running on one of the computers in Menlo Park controls the ground station. Other backup computers receive the data stream from the ground station but do not control its operation unless directed to do so.

The 5-meter dish antenna of the downlink is stationary but must occasionally be manually repositioned to maintain peak signal strength from the satellite. The receiver system locks onto a reference signal sent by NESDIS from its Wallops Station in Virginia. Demodulators process received signals, converting the modulated carrier signal to digital data. Each demodulator can accommodate one channel under manual control or multiple channels under computer control. The multiplexer scans all demodulators for received messages. When it detects a message in one of the demodulators, it time-stamps that message using a satellite time code receiver. When receipt of the message is complete, the data are retrieved from the demodulator and stored in a buffer of the multiplexer along with demodulator number, time information, and transmission quality parameters. The buffer retains the message until it is retrieved by the host computer or until the buffer becomes full and the message is overwritten. The multiplexer responds to computer communications over a standard RS-232 port. Firmware running on the multiplexer's processor recognizes control commands from the host computer and sends data over the serial line to the host computer upon request.

Because expected anomalous signals from field sites range from the order of minutes, to days, or longer, transmissions must be fairly frequent. Ten-min samples have been selected for the majority of the instrumentation as a compromise between desired density of data and that which is practical to transmit, process, and store. Normal usage of the GOES satellite involves transmission intervals of 3 or 4 hours, or random transmissions at more frequent intervals triggered when some particular type of physical event occurs at a field site. Unfortunately, since there is no universal signal in earthquake premonitory data and since earthquake energy release may involve thousands of kilometers of active faults, continuous transmission from one monitoring point at the expense of others using adaptive random reporting techniques (McCallum and Nestlebush, 1983) is not generally advantageous.

DCPs used by the USGS in Menlo Park are manufactured by Handar Corporation of Sunnyvale, California, LaBarge Electronics of Tulsa, Oklahoma, and Sutron Corporation of Herndon, Virginia. (Note that use of trade names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.) The DRGS is also manufactured by Sutron. Because the Sutron units have a "short" message preamble format, they are used exclusively for data sampled and transmitted every 10 min. (The short message preamble takes 1.52 sec compared to 7.84 sec for the standard format.)

Two slightly modified versions of the Sutron Model 8004 DCP are employed. One version has a 12-bit analog-to-digital (A-to-D) converter plus a sign bit for a range of 13 bits (8192 counts). Input impedance is on the order of 10 Megohms and inputs are sampled through field effect transistors. The second version of the DCP employs a 16-bit A-to-D converter (65536 counts). Input impedance is 1 Megohm, and inputs are sampled through relays. Both versions will accept a maximum of 16 analog or digital (serial or parallel) inputs (parameters) in any combination. The range of input voltages for both versions is −10 to +10 V. The DCPs are programmed via an RS-232 port integral to the unit. This feature enables some applications, including the use of remote programming and utilization of the NESDIS adaptive random reporting procedures. Both of these capabilities are under study for future implementation.

Each data sample is formatted into 3 coded bytes and the message length is the same for DCPs having either 12-bit or 16-bit analog-to-digital converters. Since the transmission rate through the GOES data collection system is restricted to 100 bits/sec typical message transmission duration for data collected at most sites is on the order of 3 to 5 sec.

Using a 3-sec guardband around the message to avoid interfering with adjacent transmission "windows" results in a maximum of 60 DCPs, each with more than eight data inputs (including redundancy), which can transmit every 10 min on a single GOES channel. Maintaining a 10-min sampling interval, but changing the transmission interval to 20 min permits 100 DCPs to operate on a single channel. Similarly, changing to 30 or 60 min transmission intervals results in channel capacities of 129 and 180 DCPs, respectively.

To stay within the 3-sec transmission guardband, the relative stability of the reference oscillator in the DCPs is maintained to better than 3 sec/yr. Experience with temperature-compensated crystal oscillators (TCXOs) used in an experiment involving synchronized measurements of the earth's magnetic field in remote field sites indicates that this level of drift can be achieved (Mueller *et al.*, 1981). The measures taken to achieve the same level of stability with the DCP clocks required: (1) preselection and testing of the TCXOs to ensure that the best lowdrift crystals were used, (2) extra burn-in and testing of the DCPs after manufacture, (3) precision adjustment of the TXCOs with an accurate (one part in 10^{10} or better) reference oscillator prior to DCP deployment, (4) insulation and installation of the DCP in a vault at a depth of 1.5 meters below the earth's surface to minimize thermal effects, (5) routine tracking of the transmission time by computer, and (6) periodic adjustment of the TCXOs in the field to correct for drift.

To provide a more reliable data collection system, redundant data samples from previous transmissions are sent from almost all sites. In most cases this provides up to 6 hr of insurance to cover times of power outages in Menlo Park, semi-annual periods when the satellite is out of operation for short intervals during eclipse periods (i.e., when the spacecraft is shaded from the sun by the earth and spacecraft power is reduced), signal loss due to spacecraft orbit irregularities, and computer down time at the receiver site. The redundancy feature has proven invaluable for maintaining complete data sets, and has resulted in transmission efficiencies greater than 99 per cent for data sampled every ten min.

RETRIEVAL SYSTEM

Software developed at the USGS interfaces the data multiplexer at the receiver site with the host computer. Programs were designed to process data upon receipt at the ground station so that instrumental readings are immediately available for automatic processing and display. Data are stored in the data base format used for all telemetered low-frequency data. As such, data from the field are available in Menlo Park, or by telephone from anywhere in the world, seconds after they have been recorded at the remote site. The software was implemented originally on a Digital Equipment Corporation PDP-11/44 minicomputer running under the Berkeley UNIX 2.9 operating system (UNIX is a trademark of Bell Laboratories). By the beginning of 1986 it was also running on an AT&T PC7300 under AT&T UNIX Version 3.0. All software was written in the C programming language. Currently, two Integrated Solutions V24S computer systems operating under BSD UNIX are the main and primary backup systems. The PDP 11/44 and PC7300 still receive data from the satellite telemetry system.

Normally, software on the V24S interacts with the multiplexer to control the flow of data over an RS232 serial line. In this mode, software on the backup machines is in a passive state, listening to output being sent from the multiplexer and processing any incoming messages. The V24S in active mode sends the appropriate commands to the multiplexer to perform startup initialization, real-time demodulator channel selection, and scheduled data retrieval. Any of the computers is capable of running in active or passive mode. The selection of whether the software runs in the active or the passive mode is controlled by an input parameter when the program is started. Thus, during down time for the V24S, such as preventive maintenance or system development, the passive mode software on an alternate system is halted and the active mode is initiated. Eventually, the machines will interact so that as the passive process recognizes that an active process may no longer be operative, it will change to the active mode and attempt to continue data collection. In times of normal operation, identical data files of the latest information (at least several weeks) are stored on all machines.

Processing these satellite data requires interactive status checking, data requests between computers and the multiplexer, error checking of received transmissions, data storage in a standard format by field instrument component and DCP identification number, and computation and storage of Sutron transmission quality parameters. Other programs are available for producing reports concerning number and quality of transmissions received. Identical software (implemented with conditional compilation statements) is used on all computer systems.

The system currently monitors about 50 DCPs on the USGS dedicated channel and approximately 50 DCPs on various other channels. This accounts for over 6500 transmissions daily, containing over 40,000 data samples (including redundant samples). A subset of these instruments showing the locations of several different instrument types in the Parkfield region of California is shown in Figure 2. The instrument locations are listed in Table 1. All processed data samples are stored in files identified by field instrument component. The original transmissions for each platform are also stored in separate files by DCP identification code. Data samples are kept online for at least 1 yr on the primary computer system, while the transmission files are removed as disk space becomes needed for other purposes (usually each month). Software exists to transfer data between computers should it be necessary to fill in data gaps.

Since going online at the beginning of 1985, the GOES low-frequency data system has had only brief periods of downtime. The few short interruptions in operations have resulted from hardware failures, loss of signal due to satellite drift and antennae mispointing (mostly beyond the control of the current hardware configuration), and software/computer system failures which have been corrected within hours. With redundant data transmissions, the total amount of data loss has been minimal. Other problems have arisen from failures of DCPs in the field. Overall, however, the satellite system has provided a highly reliable means for collecting data and monitoring fault activity. It is presently used as a key tool in attempts at real-time earthquake prediction.

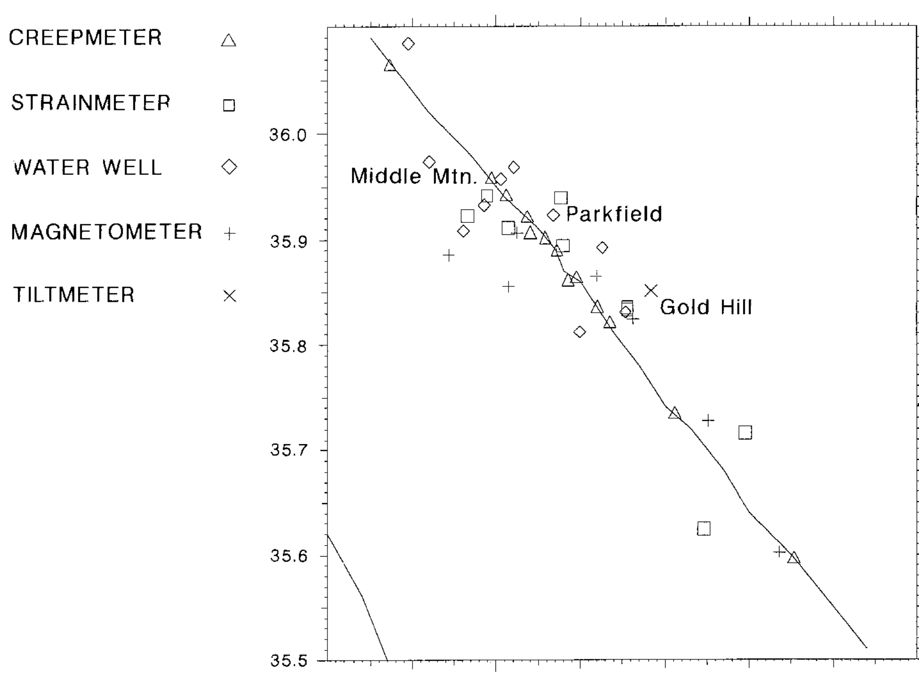

FIG. 2. Locations of several low-frequency instrument types monitored via satellite from the Parkfield, California, region.

TABLE 1

LOCATIONS (IN DECIMAL DEGREES) AND SITE NAMES FOR CREEPMETERS, MAGNETOMETERS, STRAINMETERS, AND WATERWELLS IN THE PARKFIELD REGION OF CALIFORNIA

Latitude	Longitude	Site Name
		Creepmeter Δ
35.597	−120.147	Twisselman (TWR1)
35.735	−120.288	Highway 46 (X461)
35.820	−120.348	Gold Hill (XGH1)
35.835	−120.363	Carr Ranch (CRR1)
35.862	−120.415	Hearst Southwest (XHSW)
35.858	−120.392	Work Ranch (WKR1)
35.890	−120.427	Taylor Ranch (XTA1)
35.902	−120.442	Parkfield (XPK1)
35.907	−120.460	Roberson Southwest (XRSW)
35.922	−120.462	Varian Ranch (XVA1)
35.942	−120.485	Middle Ridge (XMD1)
35.958	−120.502	Middle Mtn. (XMM1)
36.065	−120.628	Slack Canyon (XSC1)
		Magnetometer +
35.602	−120.164	Grant Ranch (GRA)
35.727	−120.249	Antelope Grade (AGD)
35.824	−120.338	Gold Hill (GDH)
35.855	−120.486	Hog Canyon (HGC)
35.865	−120.382	Turkey Flat (TFL)
35.885	−120.557	Varian (VRR)
35.906	−120.476	Lang Canyon (LGC)
		Tiltmeter ×
35.851	−120.317	Gold Hill (GOA)
		Strainmeter □
35.624	−120.254	Red Hills (RH0)
35.716	−120.205	Jack Canyon (JC0)
35.833	−120.345	Gold Hill (GH1)
35.835	−120.344	Gold Hill (GH2)
35.894	−120.421	Eades (EDT)
35.907	−120.485	Froelich (FR0)
35.911	−120.486	Froelich (FLT)
35.922	−120.534	Vineyard Canyon (VC0)
35.939	−120.424	Donna Lee (DL0)
35.940	−120.423	Donna Lee (DLT)
35.941	−120.511	Claussen (CLS)
		Water Well ◇
35.812	−120.402	Cholame Hills (WCH)
35.831	−120.347	Gold Hill (WGH)
35.892	−120.374	Turkey Flat (WTF)
35.908	−120.539	Vineyard Canyon (WVC)
35.923	−120.433	Joaquin Canyon (WJC)
35.932	−120.514	Flinge Flat (WFF)
35.957	−120.495	Middle Mtn. (WMM)
35.969	−120.478	Pine Canyon (WPC)
35.973	−120.580	Stockdale Mtn. (WSM)
36.085	−120.604	Bourdieu Valley (WBV)

Data Display and Analysis System

Most of the routine requirements for display and analysis of these data have been automated such that, for example, one-word commands will produce plots of individual instruments or stacked by instrument type as shown in Figure 3. In this case a plot was produced of 21 days of strainmeter and differential magnetic field data. Although data are always available for display, in order to provide 24-hr monitoring of data from various instrumentation, automated means of data analysis have been developed.

Perhaps the most important function of a system of hazard monitoring is to provide automatic notification, or "alerts," when unusual fault or eruptive activity occurs. Such an alert system has been set up and has been in operation for several years for these low-frequency data (Bakun *et al.*, 1986). This system is of particular importance for the current earthquake prediction experiment in the Parkfield region of the San Andreas fault (Bakun *et al.*, 1987). The alert system consists of software which periodically processes telemetered data and checks for signals of particular form or amplitude which exceed specified thresholds.

Figure 4 displays data from the Middle Mountain and Middle Ridge creepmeters for 1987. The vertical lines indicate times at which amplitude thresholds were exceeded and automated alarms were issued by the computer system. For the Middle Mountain instrument, the alarm criteria consisted of differencing the average value of the last hour of data received with the average data value of the previous 23 hours of data received. For the Middle Ridge instrument, the vertical bars indicate alarms issued for times at which the average rate of fault displacement over a 7-day period exceeded the threshold value. In all cases a vertical bar reflects a time at which the computer automatically dialed a paging system which produced beeper

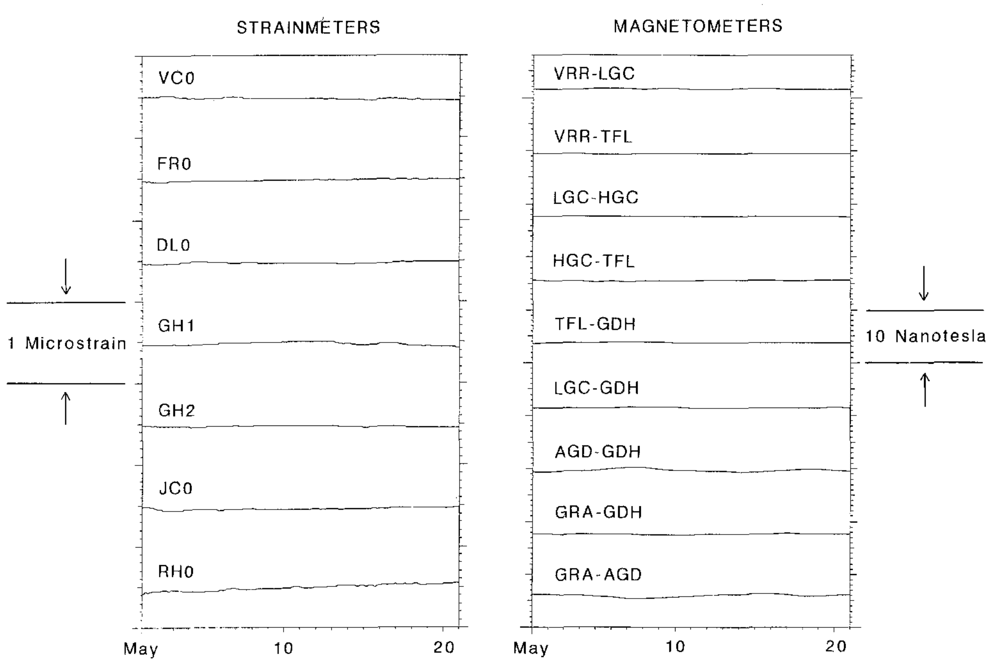

FIG. 3. Composite data time history of strain and differential magnetic field for a 60-day period in the spring of 1988.

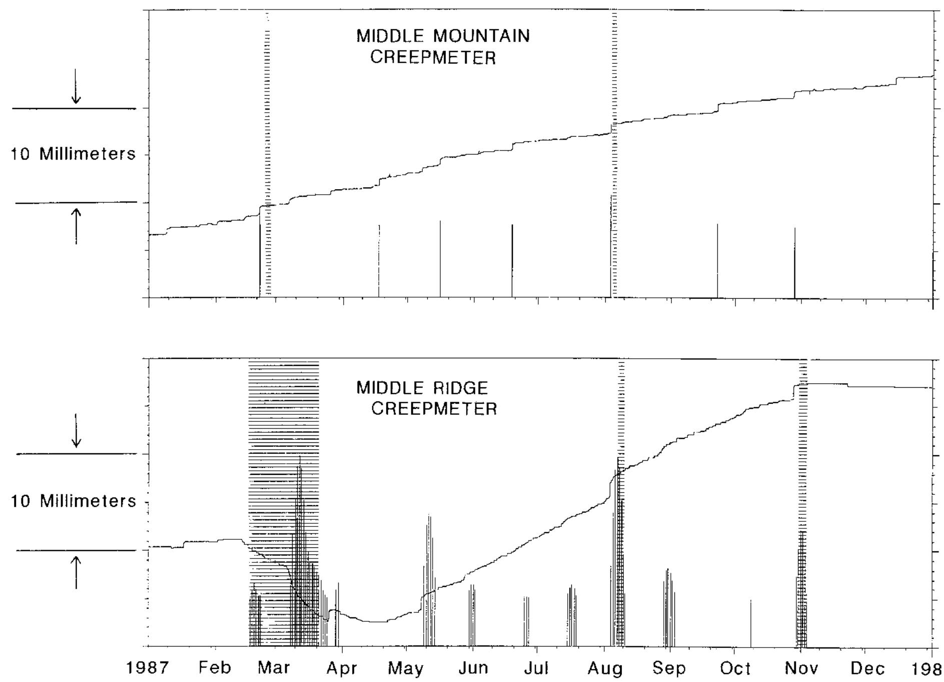

FIG. 4. Fault creep data during 1987 from the instruments at Middle Mountain (XMM1) and Middle Ridge (XMD1) which span the San Andreas fault at Middle Mountain, near Parkfield, California. The vertical lines indicate times at which amplitude thresholds were exceeded and automated alarms were issued by the computer system. The shaded region in the plots shows times at which an actual alert was declared for the Parkfield region.

notification within minutes. Computer mail is also sent to others monitoring these phenomenon. The shaded region in the plots shows times at which an actual alert was declared for the Parkfield region (Bakun *et al.*, 1987).

In addition to the creepmeters, there are automated alarm systems for volumetric strainmeters and magnetometers. Figure 5 shows the stages of automatic processing of strain data prior to automated testing for anomalous behavior at the Gold Hill deep-borehole volumetric strainmeter. First, telemetry errors, calibration, and maintenance offsets are removed from the raw data record. The system then removes tidal signals from the data, detrends the data, and attempts to remove the effects of barometric pressure loading. Finally, the processed data set is run through a differencing program to compare recent data with previous data. Notification of data exceeding thresholds causes automated paging and computer mail.

In the case of magnetometers, an automated computer algorithm produces output indicating possible anomalous signals. The processing involves differencing data between selected sites and constructing data sets of smoothed hourly means. The data sets are then checked for long-term magnetic field changes larger than predetermined 95 per cent confidence levels.

Other automated monitoring and alarm systems are under various stages of development and implementation. Among these are alarms for (1) activity at multiple sites detected with similar or different instrument types; (2) changes in 2-color laser data; (3) status of on-site digital recorders (GOES) systems with regard to number of events detected, amount of tape used, and other parameters for remote access to instrument status; and (4) automated alarms for failure of hardware in the satellite receiver and interruption of the monitoring system.

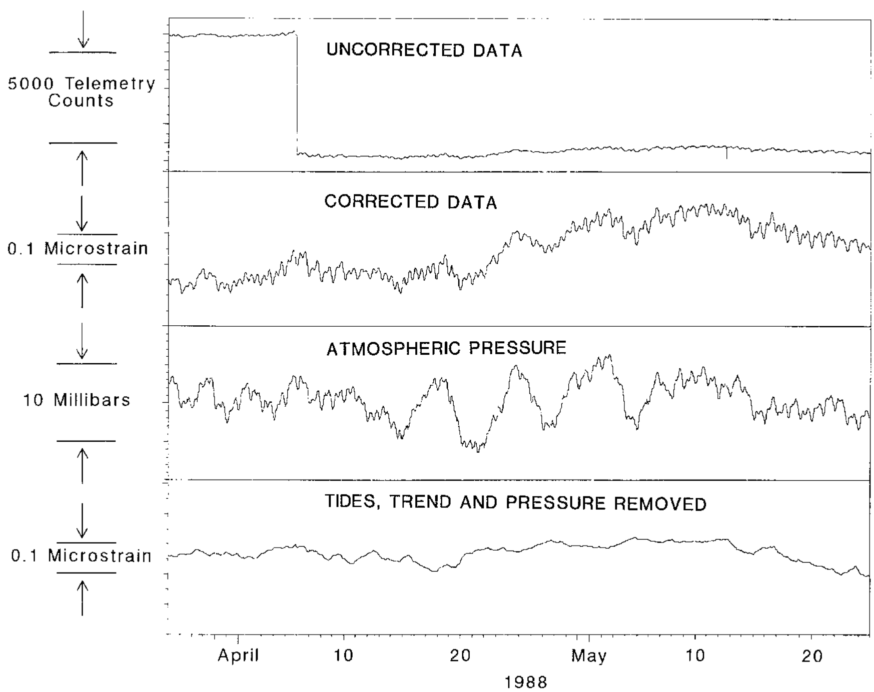

FIG. 5. Time history plots showing the stages of automated processing of volumetric strain data from the borehole dilatometer GH1A near Gold Hill, California. Data displayed in the bottom plot are passed through the alarm algorithm which checks for changes in strain rate and amplitude greater than some predetermined value.

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