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A GENERAL EARTHQUAKE-OBSERVATION SYSTEM (GEOS)

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Abstract

Microprocessor technology has permitted the development of a General Earthquake-Observation System (GEOS) useful for most seismic applications. Central-processing-unit control via robust software of system functions that are isolated on hardware modules permits field adaptability of the system to a wide variety of active and passive seismic experiments and straightforward modification for incorporation of improvements in technology. Various laboratory tests and numerous deployments of a set of the systems in the field have confirmed design goals, including: wide linear dynamic range (16 bit/96 dB); broad bandwidth (36 hr to 600 Hz; >36 hr available); selectable sensor-type (accelerometer, seismometer, dilatometer); selectable channels (1 to 6); selectable record mode (continuous, preset, trigger); large data capacity (1.4 to 60 Mbytes); selectable time standard (WWVB, master, manual); automatic self-calibration; simple field operation; full capability to adapt system in the field to a wide variety of experiments; low power; portability; and modest costs. System design goals for a microcomputer-controlled system with modular software and hardware components as implemented on the GEOS are presented. The systems have been deployed for 15 experiments, including: studies of near-source strong motion; high-frequency microearthquakes; crustal structure; down-hole wave propagation; teleseismicity; and earth-tidal strains. These studies have yielded recordings of near-source radiation fields in the frequency band of 1 to 300 Hz with signal resolution greater than 84 dB, documented seismic signals of 80 Hz at distances of 190 km with implications for nuclear detection, provided complete onscale high-resolution recording of several aftershock sequences with signal amplitudes ranging over 180 dB, and records of Earth dilational strain over the period band 0.1 sec to 28 hr, with superimosed radiation fields for nuclear explosions at regional distances and near-source earthquakes. Data sets recorded on the GEOS illustrate the importance of broad bandwidth, high resolution, and wide linear dynamic range for future earthquake studies. Field deployments of a minicomputer system compatible with the GEOS have emphasized the usefulness of portable field computers for experiments using microcomputer-controlled data-acquisition systems.

Introduction

Seismic signals of seismologic and engineering interest vary in period content from milliseconds to hours and days with corresponding amplitude variations from nanometers to meters. Such broad ranges in signal characteristics have resulted in the necessity to develop a variety of seismic detection and recording systems, each being best suited for a particular part of the frequency spectrum and amplitude range. However, recent advances in technology have made the construction of a single seismic recording system useful for a much larger number of applications feasible.

Rapid technological advances have led to system components that permit greater dynamic range and broader bandwidth. The advent of microcomputers has added degrees of flexibility in system design and recording capabilities that previously were unrealizable with hardwired units. The capability of the microcomputer to provide instructions to external hardware devices permits software control of the various system hardware components based on decisions provided either by online processing of incoming data or information provided by the operator. Utilization of these capabilities shifts the emphasis in system design from hardware to software, with corresponding advantages in capabilities to modify and reproduce system functions. Advantages in system flexibility can be obtained utilizing system designs based on maximizing software control of the required hardware components and by maximizing the number of tasks to be performed by the software. The purpose of this paper is to explore the design capabilities permitted for seismic data-acquisition systems by the microcomputer, to describe the General Earthquake-Observation System (GEOS) developed to implement these concepts, and to provide an evaluation of design features based on a variety of data sets collected on the GEOS.

The seed for development of microcomputer-controlled systems originated with the design of ocean-bottom seismographs, where the requirements for long periods of unattended operation, low power, large data-storage capacity, system self-reliance, and external communication are necessary attributes of a successful system. Prothero (1979, 1980) and, later, Moore *et al.* (1981) were among the first to utilize the capabilities of a microcomputer. Their efforts focused on developing intelligent ocean-bottom data-logging systems under control of an IM-6100 microcomputer based on the extensive PDP-8E instruction set of the Digital Equipment Corporation. The resulting systems (Prothero, 1980; Moore *et al.*, 1981) demonstrated the feasibility of low-power microprocessor-based systems and illustrated several advantages over traditional hardwired units, including reproducibility, reliability, data manipulation and access, internal system checking for self-reliance, and communication capabilities. Experience gained in development of the ocean-bottom seismographs was generously provided by W. A. Prothero, Jr. and R. D. Moore (personal communication, 1978) in review of the design specifications for the GEOS.

Recent advances in technology, especially those associated with microcomputers, have significant implications for improving seismic data-acquisition capabilities. These advances have been proposed recently to provide the basis for establishing a national instrumentation resource comprising as many as 1000 instruments and for expanding and improving the existing worldwide network for the detection of teleseismic signals (Committee on Opportunities for Research in the Geological Sciences, 1983). Given appropriate planning and establishment of suitable standards, the microcomputer and present technology offer the potential for development of modular system components (hardware and software) that can be configured to serve both long- and short-period data-acquisition needs. A principal motivation for using a microcomputer in the development of the GEOS was, as the name implies, the implementation of a *general* modular environment (software and hardware) useful for a variety of applications and one from which separate dedicated systems can be easily configured. Consequently, it is of interest to critically examine the design concepts for microcomputer-controlled systems, their justification, and the flexibility of the resulting GEOS in light of the data sets collected to date.

GENERAL DESIGN GOALS

Advances in seismology and engineering within the past two decades have generated increasing demands for improvements in data quality, implying more versatile and improved instrumentation. Demands for versatility in instrument application are readily apparent in several different fields of study; however, the demands are nowhere more apparent than in the recently established field of strong-motion seismology, concerned with the prediction of strong ground motions and with inferences regarding the physics of seismogenic failure. Strong motion seismology requires instrumentation capable of recording: strong motions generated by large events near the source; aftershocks with signals ranging from that of the seismic background noise to that of the main event, dense reflection and refraction profiles for near-surface, crust, and mantle structure; microearthquakes, and teleseismic events. This broad range in required applications establishes that major design goals of any system intended for general application must necessarily be adaptability and versatility with respect to a wide variety of potential seismologic and engineering experiments. In addition, rapid advances in technology require that the design be sufficiently versatile to readily permit incorporation of improvements as they become available. Because these general design goals were considered essential to the development of a general purpose, data-acquisition system, four different levels of potential system modifications were defined.

Level 1: System changes selectable under software control in the field.
Level 2: Routine system changes that may be accomplished in the field, including replacement of hardware modules and associated software.
Level 3: System changes requiring modification of software and (or) hardware modules more easily accomplished in the laboratory.
Level 4: System changes requiring redesign of the general system configuration.

Specification of these levels was useful in developing design specifications and in categorizing the complexity of potential system modifications.

Concepts, considered essential to optimizing adaptability and versatility of the system at the levels specified, included: modular hardware components with central-processing-unit (CPU) control of each; a general computer bus structure that is either standard or easily interfaced to a standard; and a general software architecture designed and implemented according to subtasks and hardware components.

The need to utilize the system in a wide variety of seismic studies imposed additional design requirements, including: broad frequency bandwidth; wide dynamic range; variable sensor inputs; selectable external time standard; various event-detection capabilities; large data capacity; self-calibration; portability; low power; ease of instrument setup by relatively untrained observers; ease of data recovery via standardized tape formats; and modest cost. The GEOS was developed to implement these general design goals. Figure 1 shows a model of the data-acquisition/retrieval system currently being produced, together with two sets of three-component sensors and antenna.

General System Functions, Configuration, and Operation

Major functions required of a digital seismic data-acquisition system designed to meet the above goals include: signal conditioning of analog sensor outputs; digital conversion of analog signals; temporary data storage for preprocessing and online external decision capability based on the incoming data stream; data storage, retrieval, and transmission; time reference; system calibration; and operator interface. Figure 2 illustrates the general system configuration, which was designed to isolate major system functions on corresponding hardware and interface modules with central control of each module produced by the microcomputer via the general computer bus. General segmented software developed to control the various modules and to perform system functions facilitates system debugging and replacement of various modules for the purpose of optimizing instrumental adaptability.

A data bus for rapid data transfer from preevent memory to an internal or external storage medium promotes the efficiency of the CPU. The digital-to-analog (D/A) conversion module in combination with the read capability of the data recorder permits playback of recorded data for inspection in analog form. This read capability also permits playback of data with a modem, via telecommunication systems such as telephone, microwave, or satellite. Monitor ports are useful for system evaluation and field checking.

FIG. 1. Side and front-panel view of the GEOS, together with a WWVB radio antenna and two sets of three-component sensors commonly used to provide more than 180 dB of linear dynamic range. System operation for routine applications requires only initiation of power. Full capability to reconfigure system in the field is facilitated by simple operator response to English-language prompts via keyboard.

In the operating mode, the general system configuration (Figure 2) permits the analog signals from a selectable number of sensor channels to be amplified, filtered for antialiasing, multiplexed, sampled and held, and converted to digital signals with the accuracy permitted by the analog-to-digital (A/D) converter. Digitization rates selectable under program control can then be further modified by using digital antialiasing filters. Temporary storage of digital data in preevent memory permits decisions by the CPU for data transfer via the data bus to internal storage media or transfer via telemetry to an external storage device. During temporary storage of the data in memory, considerable preprocessing and evaluation can be conducted if desired. Internal CPU capabilities are easily augmented by utilizing other CPU's with data access established via preevent memory.

Common modes of system operation under software control include: event detection based on conventional short-term average/long-term average algorithms; teleseismic detection algorithms; preset time; and continuous record, with each mode selectable under software control. Decisions based on independent or simultaneous execution of these modes to transfer data from preevent memory provide the stimulus for automatic transfer of desired header and time information. Calibration switches and corresponding signal generators operated under program control permit generation of either automatic or operator-induced calibration signals at both the sensor and preamplifier stages for recording on desired storage media.

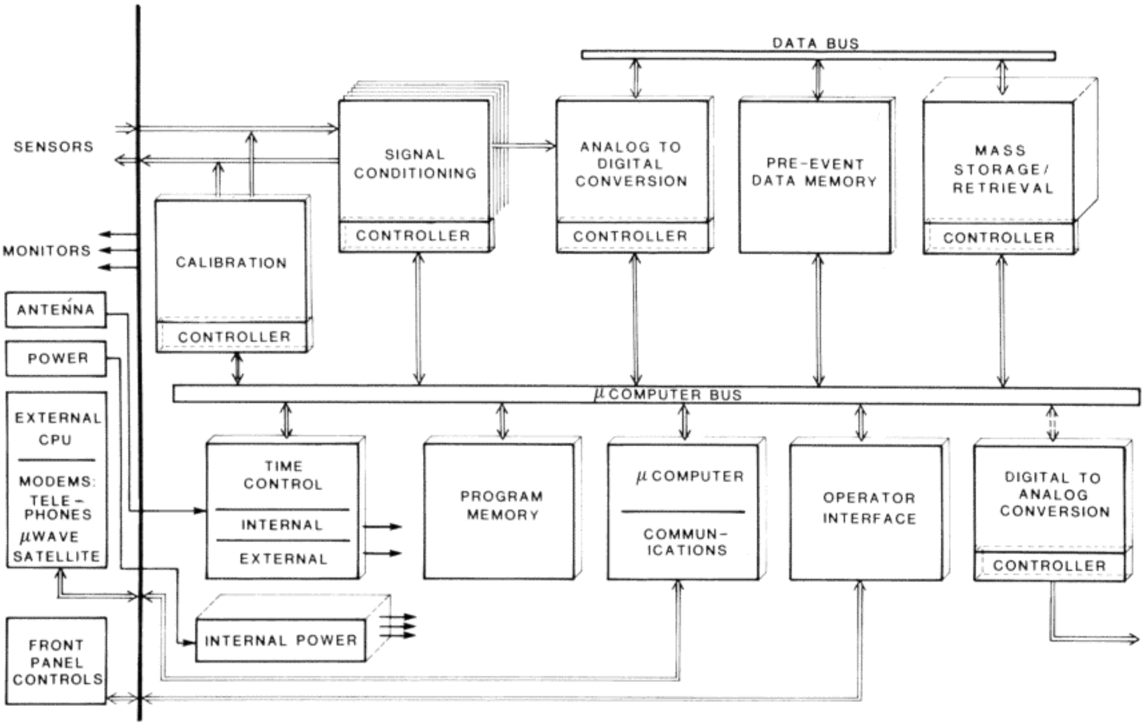

FIG. 2. General system configuration for the GEOS, showing required system functions isolated on separate hardware modules. Central CPU control of each module via general computer bus permits full capability to configure system for most field applications and facilitates incorporation of improvements in technology.

Because no single sensor currently has sufficient dynamic range to adequately detect the range of seismic signals required for all of the various applications, the most straightforward system configuration involves input for two sets of three-component sensors. Such a six-channel system, in combination with a 16-bit A/D converter, allows the GEOS to record all seismic signals on scale without a change in gain settings.

The number of channels—from one to six—can readily be selected under software control at level 1 and increased beyond six at levels 3 and 4. For some applications, such as multi-channel arrays with more than six channels, digital sampling can be readily synchronized at level 2 to provide an easy means of extending both the number of channels and the data capacity.

Data-storage capacity, beyond that of the internal device, can be easily extended at level 2 by the addition of slave storage devices or modification at level 3 to permit data transfer via modem to the external storage medium of choice. Data capacity can also be extended by replacement at level 3 of the internal storage device.

The design philosophy utilized for the GEOS emphasized the development of a general system configuration (Figure 2) to perform the desired system functions. Selection of particular hardware components to perform these various functions, although important, was considered secondary to development of the general system configuration. As technology improves, costs permit, and (or) applications require, the configuration discussed here (Figure 2) is intended to facilitate component interchange and replacement and to serve as a standard for the design of future microcomputer-based systems.

HARDWARE MODULES

The hardware modules required to perform the necessary system functions were designed to facilitate repair, to accommodate future replacements incorporating technological improvements, and to promote overall system compactness. Except for the data-storage device, the internal power source, and the display for operator interface, the hardware components are configured on cards of uniform size (5 × 7 in) in a sturdy card cage (6 × 9 × 13 in). Controllers required for some of the modules are configured on separate cards to facilitate repair and replacement. Module control is provided via a 100-pin general computer bus permitting slot or position independence of all cards except those necessary for analog signal conditioning. This bus can be interfaced to several other commercially available buses. Components selected for the required hardware modules in current GEOS production models are discussed below.

Microcomputer and data-input/output module. The microcomputer, in the context of the general configuration represented in Figure 2, serves as the central module of the system with two basic purposes. The primary purpose is to provide software control of the required hardware modules. The secondary purpose is to execute software algorithms for a variety of possible data-processing requirements. The control of required hardware modules is considered as the primary purpose, because elaborate algorithms beyond the capabilities of the selected CPU can be executed by another or external CPU dedicated to such tasks, with access to the incoming data stream provided via the preevent memory module (see Figure 2).

The general system configuration (Figure 2) is based on the philosophy that the principal purpose of the CPU is to control the hardware modules. This philosophy permits relatively straightforward upgrade of system computational capabilities by replacement of the external CPU as improvements in chip technology develop. Adoption of the philosophy that the internal system CPU should be replaced could require that major efforts be devoted to software and, possibly, hardware conversions in order to incorporate the computational advantages offered by more sophisticated chips. Such a philosophy would reduce the flexibility of the system unnecessarily.

Initially, two low-power microcomputer chips were commercially available for construction of the GEOS (RCA 1802 COSMAC, 8 bit; INTERSIL IM-6100, 12 bit). The general design goals of the system could have been achieved by using either chip. The main advantage of the IM-6100 is peripheral support for direct memory access (DMA), which permits achievement of high throughput rates and allows substantial efficiency in utilization of CPU cycles. Other advantages of the IM-6100 include compatibility with a 12-bit A/D converter that requires only card interchange and minor software modification to convert system resolution from 16 to 12 bit, less roundoff error in computing double-precision trigger algorithms for 16-bit data streams, compatibility with the extensive PDP-8 instruction set, and standardization with University systems developed by Prothero (1979, 1980) and Moore *et al.* (1981). Standardization on the IM-6100 for primarily hardware-control functions and utilization of more sophisticated CPU's (such as the CMOS 16-bit chips presently on the commercial horizon) provides a cost-effective means for upgrading system capabilities as the technology advances without sacrificing system flexibility.

The microcomputer module implemented in the GEOS contains the CPU and associated peripherals (Figure 2). Specifically, this module includes the CPU chip, a memory extension/DMA/interval timer, a mechanized design and integrated control (MEDIC) chip, a peripheral-interface element, and a bit-rate generator, with clock information provided by a 3-MHz timer. Detailed documentation describing chip performance is available from Intersil and Harris Semiconductor Corp. Internal data transfer to storage media is accomplished via the data bus, utilizing the simultaneous DMA feature of the MEDIC chip. Data communication is provided by an RS-232 driver chip and an RS-232 receiver chip for bidirectional information transfer either online or from storage media. A universal asynchronous receiver-transmitter (UART) is included for communication with external MODEMS and permits bidirectional information transfer via telephone, microwave, or satellite. Power-switching circuits for 12-V power are provided on this card to disconnect power to RS-232 devices when they are not in use in order to minimize power consumption.

Program-memory module. System software is stored in erasable-programmable read-only memory (EPROM) and executed from random-access memory (RAM) with transfer taking place via a buffered (direct-exchange) DX bus at the time of system startup (Figure 2). In present production models, two program-memory modules are included: an EPROM card with 16-K 12-Bit word capacity and a RAM card with 8-K 12-bit word capacity (Table 1). CMOS chips and power-control features are utilized to minimize power when the chips are not in use. Isolation of the memory chips on separate cards permits relatively simple memory upgrade and expansion as the technology improves and applications require.

Operator-interface module. Characteristics of the interface between the operator and the data-acquisition system play a significant role in reducing field-deployment errors, minimizing instrument setup time, and simplifying system debugging. Experience shows that instrumentation designed for simple and relatively straightforward field operation by relatively untrained observers contributes significantly to the success of field experiments.

The operator-interface module designed for the GEOS (Figure 2) contains circuitry for interface with the operator via the keyboard and the 32-character alphanumeric display, memory containing extensive software for instrument-debugging purposes, and circuitry for the selection of operational software from either system EPROM or the mass-storage/retrieval module.

Alphanumeric display and a keyboard with both function and numeric keys, in combination with appropriate software, afford the opportunity for especially simple system setup in the field, while optimizing flexibility to change operational parameters if desired. The alphanumeric display permits the system to provide English-language instructions to the field operator regarding the selection of operational parameters. This system capability greatly reduces instrument-deployment errors and training requirements for field operators.

GEOS software is designed such that the operator may select operational parameters in several ways. The operator may select either default parameters loaded into EPROM, parameters loaded from an internal data-storage/retrieval device, or parameters entered via keyboard upon English-language prompt from the CPU. Changes in operational parameters may also be initiated via telecommunication; however, this option has not yet been implemented.

TABLE 1

SPECIFICATIONS FOR CURRENT PRODUCTION MODELS OF THE GEOS*

Microcomputer and Communications

Internal CPU: CMOS, 12 bit.
External CPU: Optional.
Data transfer:
  Internal: Direct memory access
  I/O Port: RS-232-compatible baud rate, programmable to standard rates.
  Telecommunications: UART, modem optional.
  Analog playback via A/D converter.

Program Memory

Executable Memory: 8-K 12-bit-word CMOS RAM.
Program Storage: 16-K 12-bit-word CMOS PROM.
Alternate Program Storage: Programs may be stored on magnetic tape for loading directly into program RAM.

Sensor Inputs and Signal Conditioning

Input Channels: Six balanced differential inputs, program selectable.
Preamplifier Dynamic Range: Greater than 100 dB at 0-dB gain, programmable in 6-dB steps from 60 to 0 dB.
Filters: Low-pass Butterworth, 42 dB per octave; program selectable, 17, 33, 50, and 100 Hz; high pass 0.1-Hz, 6 dB per octave.
Calibration: Internal, automatic with or without sensors.
Transient Protection: ±15 V

Analog to Digital Conversion

Resolution: 16 bits (1 part in 65,536).
Stability and Linearity: ±1 count no missing codes over full temperature range -20°C to + 60°C.
Conversion Rate (Total samples per second for all active channels): max 1,200 sps min 0.29 sps; programmable as 1,200/N, where N may be through 4,096.

Pre-Event Data Memory

Size: 4,096 words, 16 bits per word.
Pretrigger Memory: Five 512-word blocks minimum-word at 1,200 sps (2.14 s), six 512-word blocks at 300 sps (10.24 seconds), program selectable.

Mass Data Storage/Retrieval

Cartridge: Read/Write, 3M type, 1,600 bpi.
Tape capacity: 3,680 512-word blocks (1.88 million samples) typical for 450-ft tape, 26 minutes continuous-record time at maximum sampling rate.
Tape Speed: 30 ips, write or read.
Slave Recorders: Two optional, separate housing.

Time Control

External:
  WWVB Receiver: Automatic synchronization of internal clock to WWVB receiver under program command.
  Master Clock: Synchronization of internal clock with external pulse and corresponding time corrections derivable at selectable times under program command.
  Manual: Time entered through keyboard and synchronized manually.
Internal:
  Frequency: 3 MHz.
  Temperature Stability: ±1x10^{-6}; -20°C to +70° C.
  Aging Rate: Less than 5x10^{-7} per year.

Operator Interface

Operating Environment: English-language commands under software control.
Display: 32-character alphanumeric display, 18 segment, character height 0.15 in. LED with optical filters.
Keyboard: Mechanical switch with dust cover and water seal, 20-button keyboard with numeric and function entry.
Status Checks: Time, battery voltage, number of events, percentage of tape used, elapsed time since power-up.
Debug: Single and subroutine stepping.

Operating Modes

Self-triggering:
  Near Field: Selectable short-term average (STA), long-term average (LTA), ratio.
  Teleseismic: Comparative ratios for two selectable frequency bands.
Preset Time: Record at selectable times and intervals.
Both: Operate in both preset-time and self-triggering modes.
Manual: Record under keyboard control for start-stop functions.

Power Requirements

Voltage, Current: +24 V dc nominal ±15 percent; 40 mA nominal in operating mode with display off, 300 mA nominal with display on, 600 mA with display on and recording.
Internal Batteries: ±24 V, 5 AH Gates type; will operate about 3 days on internal batteries. Connector provided for internal battery charging or external battery operation.

Physical and Environmental Requirements

Case Type: Waterproof aluminum case, 20-1/2 in. long, 9-7/8 in. wide, 13 3/4 in. high.
Weight: 47 lb. with internal batteries.
Operating Temperature Range: -20°C to +60°C, 15 to 95 percent relative humidity.

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* Patent pending.

System operation using default parameters or those entered via a data-retrieval device requires minimal setup time and affords minimal opportunity for error. Possibilities for operator-induced errors are further reduced by simultaneous display of English-language prompts and default parameters, as well as by "watchdog" software that permits only those parameters appropriate for system operation to be entered via keyboard. If the default parameters are most appropriate for the desired application, then system setup involves no more than turning the power on, connecting the sensors and antenna, and, with present software, answering "no" to six questions. The system then proceeds to record mode. For some routine applications, such as seismic refraction, operation can be reduced to simply turning on the power.

Software packages have been developed to both record and play back data via the GEOS. The record package was developed to permit simple reconfiguration of the system in the field for a wide range of possible applications. The playback package was developed to retrieve digital data via RS-232 device, via a D/A converter for visual display on a strip-chart recorder, and via digital playback for examination of the bit stream.

The flow diagram for a present version of the record software implemented on the GEOS is shown in Figure 3. The diagram shows the English-language prompts, the default parameters, and the layered structure of the prompts. This layered structure permits the operator to select specific sections of the operational parameters for change. This feature of the software has been found to be especially convenient and a significant factor in reducing the time for instrument setup. Record options for operator selection via keyboard include: station recording-environment parameters (experiment, location, event, and year); sensor parameters (active channels, type of sensor, gain settings, antialiasing filters, and sampling rate); record mode (event trigger, preset time, or both and continuous); clock synchronization (WWVB, master clock, or manual, with options to synchronize and determine time differences later for recording as desired); and options regarding examination and recording of calibration signals for sensors and the signal-conditioning unit. A wide variety of other operational parameters can be implemented at level 3. Selected parameters are stored and recorded in an event header to permit automatic data retrieval and calibration for the purpose of facilitating analysis of large amounts of data by a compatible minicomputer system located in the laboratory or field.

The flow diagram for a present version of the playback software implemented on the GEOS is shown in Figure 4. The diagram shows the English-language prompts, the default parameters, and the layered structure of the prompts. As with the record software, this layered structure permits the operator to select specific sections of the operational parameters for change. Playback options for operator selection via keyboard include: selectable output device (D/A, RS-232), including establishment of playback protocols, choice of appropriate playback rate, and selection of time-mark intervals; selectable search mode for event, with ability to select events based on time or file number; an option to playback individual or successive events; and an option to display header information for each file to inspect parameters used to record the data. Other desired playback options can be implemented easily at level 3.

Signal-conditioning module. The principal functions of the signal-conditioning module (Figure 2) are to provide appropriate analog signal amplification and filtering prior to digitization, with the amounts of amplification and filtering varying

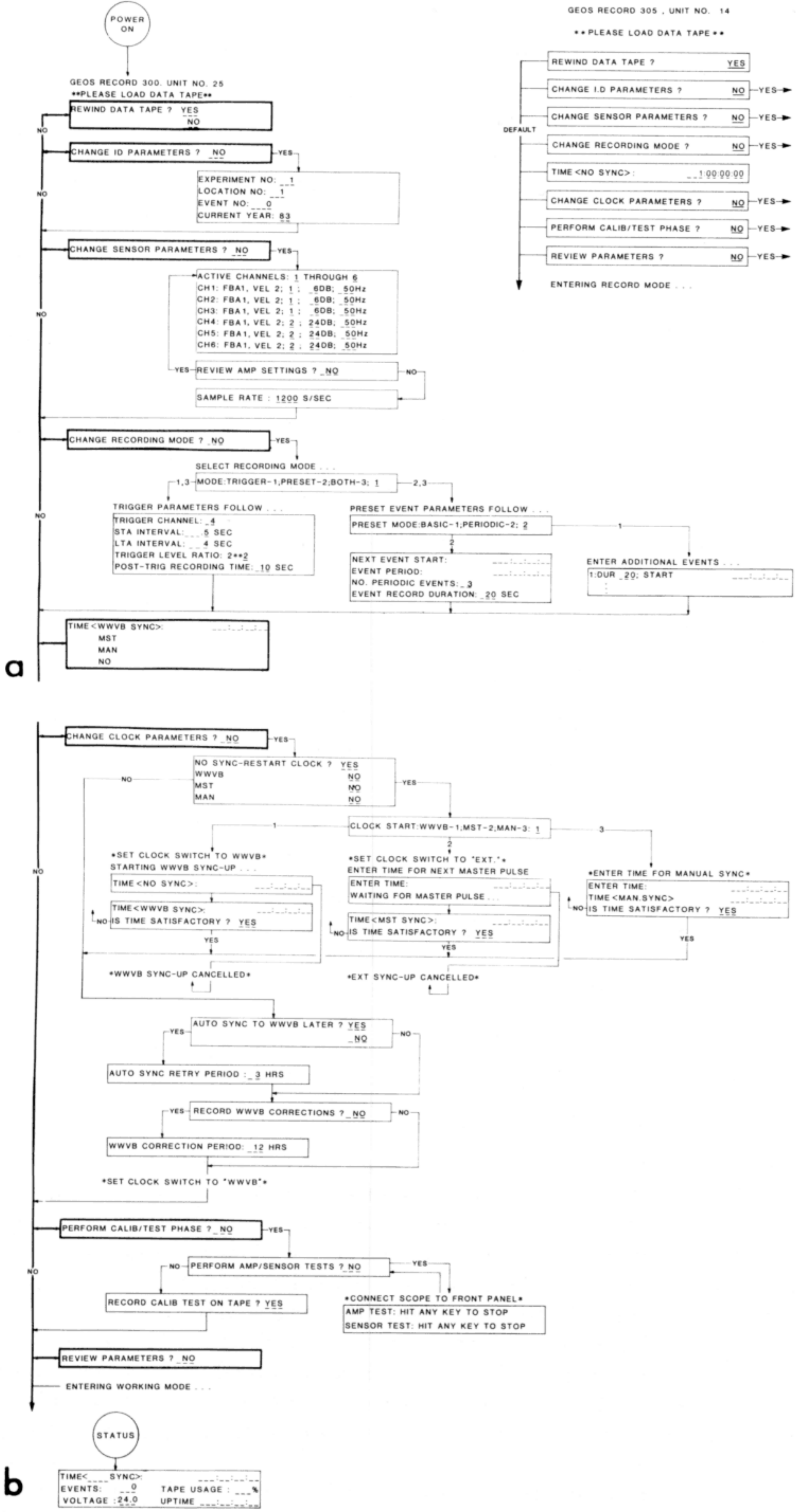

FIG. 3. English-language prompts to field operator, incorporated into a present version of data-acquisition software for the GEOS. Layered structure of prompts to field operator permits simple and rapid deployment of system in the field, as well as full capability to reconfigure system for desired application.

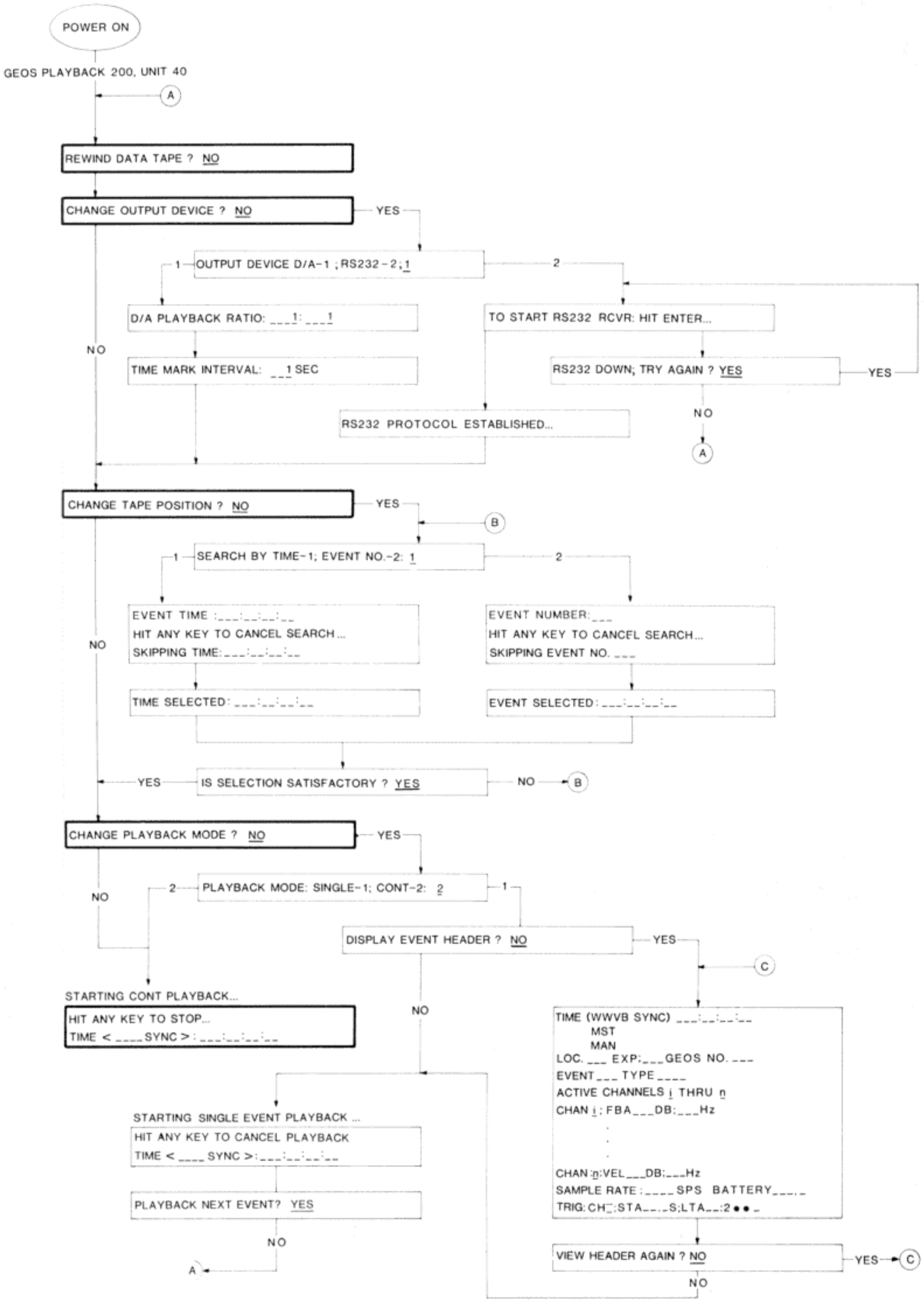

FIG. 4. English-language prompts to field operator incorporated into present version of data-playback software for the GEOS.

substantially, depending on the particular application and associated requirements concerning sensor type, bandwidth, and dynamic range.

The present configuration of the GEOS (Figure 2) includes inputs for six sensor channels. Six channels permit utilization of two sets of three-component sensors, so that all signals, from seismic background noise to the largest expected seismic signals, can be recorded on scale without change in preamplifier gain. This feature is especially useful for aftershock studies and provides a useful compromise for other studies, such as refraction, teleseismicity, and structural response. The number of input channels—from one to six—is selectable under program control at level 1. Applications beyond six channels can be achieved at level 3 by utilizing two additional channels of the present A/D converter and multiplexer and (or) by time synchronizing any number of additional GEOS units at level 1. Configurations of larger numbers of channels in a single carrying case reduces system portability, increases power consumption of individual units, and decreases system flexibility.

Selection of hardware components for preamplification was largely based on the design goal to achieve wide dynamic range. For compatibility with 16-bit A/D converters and 96-dB resolution, operational amplifiers were selected to provide dynamic range for the preamplifiers of greater than 100 db at 0-dB gain (Table 1). Program-selectable increments of 6 dB to a maximum of 60-dB gain are provided on internal signal conditioning module. Additional gain of 42 dB is provided by a separate set of preamplifier cards housed in a small waterproof container. Present amplifiers in the GEOS provide a compromise between system noise reduction and power consumption (Table 1). Other amplifiers can be added easily at level 2. Selection of preamplification components suitable for 16-bit resolution contributes to system flexibility because they permit simple conversion at level 2 or 3 to 12-bit resolution. Various types of gain ranging can also be added at level 3. Separate cards for each input channel contain circuitry for amplifier-transient protection and balanced input for reducing common-mode signals. An output buffer provides a low-impedance source to drive the multiplexer and A/D-converter card, with ac coupling to remove dc amplifier and filter offsets. A controller card with magnetically latched relays for reduced power consumption and reduced temperature effect on switching resistance provides microcomputer control of gain and filter settings.

A variety of analog and digital filtering options are available with a microcomputer-based data-logging system. Compromises are necessary between the extremes of performing all filtering via analog hardware filters and with the exception of one required analog filter, accomplishing all necessary antialiasing filtering options via digital filters. These compromises are imposed by achievable sample-throughput rates of other hardware modules, such as the CPU and A/D converter. To achieve throughput rates of 1200 samples per sec, needed to maintain system adaptability, signal-conditioning cards were selected for the GEOS to permit a choice of various analog filters for high sampling rates (e.g., 50 to 400 sps per channel). Filtering options for any desired lower digitization rate are easily accomplished by first digitizing the data from an appropriate analog filter, then digitally filtering and decimating the data to any desired reduction in sampling rate. Present analog filters utilized by the GEOS are seven-pole (42 dB per octave rolloff), low-pass Butterworth filters, with program-selectable corners at 17, 33, 50, and 100 Hz (Table 1). Selection of other filtering hardware for modification of the signal-conditioning module is straightforward at level 3 with module replacement at level 2.

A/D-conversion module. Digitization of the conditioned analog signals permits execution of software for online signal processing by the microcomputer. Utilization of this capability of the internal CPU or of an external one that may be added, permits online decisions with respect to signal disposition, definition and logging of various signal characteristics, and information for decisions with respect to the operational parameters for other hardware modules in the system. These software-based capabilities, permitted by the A/D-conversion module and the microcomputer, are responsible for the increased flexibility in system performance over that achievable with hardwired units. Performance characteristics of the A/D-conversion module play a significant role in determining the frequency bandwidth, dynamic range, and resolution of recorded signals, as well as the overall power consumption of the system.

Adaptability of the system to a wide variety of seismic studies requires considerable flexibility in the choice of frequency bandwidth with the high-frequency part of the spectrum (>200 Hz) requiring compromising decisions concerning data-storage capacity, data-transfer rates permitted by the hardware, and cost of hardware components. The present GEOS modules were designed for a maximum sample-throughput rate of 1200 sps. The sampling rate is selectable under software control via the A/D-conversion model in integer quotients of 1200 sps (i.e., 1200/n = 1200, 600, 400, . . . 0.293 sps) with additional reduction in sample rate permissible under software control using digital antialiasing filters and sample rejection. The corresponding bandwidth of the recording system ranges from 450 to 500 Hz on the upper end to that permitted by the performance characteristics of the selected sensors and the signal-conditioning module at the lower end. The selected sample-throughput rate is equally distributed over the number of selected data channels. Unequal sampling rates on various channels can be implemented at level 3. The flexibility achieved in selectability of the sampling rate for the GEOS at level 1 permits utilization of the system for seismic studies ranging from near-surface seismic exploration in which frequencies of 500 Hz are of interest to Earth-strain studies, in which periods of 24 hr are of interest. Simple replacement of the signal-conditioning module at level 2 permits bandwidth extension to essentially dc for long-term continuous monitoring of strainmeters and dilatometers.

Dynamic-range and signal-resolution requirements vary considerably for different applications. System adaptability is increased by maximizing these parameters. Two types of low-power (CMOS) A/D converters, available for construction of the present A/D-conversion module, were 12 bit (72 dB) and 16 bit (96 dB). Because various types of gain ranging can be added to increase dynamic range with either type of A/D converter, and costs of 16-bit (CMOS) A/D converters are significantly higher than those of 12 bit, a single type of A/D converter was not clearly preferable for all types of seismic studies. To increase system adaptability, the GEOS hardware components (bus structure, data RAM, etc.) were designed to accommodate both types of A/D converters with simple board or module replacement at level 1. Implementation of gain ranging is intended at levels 2 or 3, depending on the type desired.

A 16-bit CMOS A/D-conversion module (Phoenix Data, Inc.) was selected for initial implementation in the GEOS. Advantages of the 16-bit over a 12-bit A/D converter include: adaptability; increased signal resolution (96 versus 72 dB); and increased linear dynamic range (192 versus 144 dB with two types of sensors). For those applications requiring lower cost A/D-conversion modules, a 12-bit A/D-conversion module with/without gain ranging can be incorporated by simple board replacement at level 1. Specifications for 16-bit A/D-conversion module are summarized in Table 2. With two types of three-component sensors (e.g., force-balanced accelerometer and velocity transducers), the maximum system dynamic range is more than 180 dB without change in gain settings with signal resolution of 90 to 96 dB.

The design amplitude response of the GEOS is shown in Figure 5 together with the response of the complete system using two types of common sensors and Earth-noise levels (Aki and Richards, 1980). The GEOS is designed to have an essentially constant amplitude response to a constant-amplitude input voltage (constant-amplitude ground velocity). With the responses shown for the two types of sensors (force-balanced accelerometers and velocity transducers), the GEOS can record ground motions ranging in amplitude from that of Earth noise (2 nm at 10-Hz, 60-dB gain) to twice that of gravity with no gain.

Data-buffer module. The data buffer or preevent memory module provides interim data storage for online processing by the system CPU and (or) an additional CPU. Interim data storage permits software-based decisions regarding data transfer to the system mass-storage module or data transmission via telecommunication to another storage medium. Interim data storage also provides an opportunity for extensive processing of data prior to storage including digital filtering, sampling-rate decimation, and any number of other software-based operations that might be desired for a particular application. Software-execution capabilities of the system CPU can be augmented at level 3 by addition of external CPU. Configuration of the buffer on a separate module permits straightforward expansion or contraction of interim data storage capability at level 3.

TABLE 2

MEASURED POWER CONSUMPTION OF THE GEOS

	Analog (mA)	Digital (mA)	Total	
			(mA)	(W) (@24 V)
Menu Mode				
Tape-deck power on but not moving	26	664	690	16.6
Rewinding	26	724	750	18.0
Normal	26	279–334	305–360	7.3–8.6
Record Mode				
Quiescent	28	38	66	1.58
With WWVB receiver on	28	42	70	1.68
With status on	28	282–307	310–335	7.4–8.0
Recording	28	497 (avg.)	525 (avg.)	12.6
			1150 (peak)	27.6

The data-buffer module presently implemented in the GEOS includes 8 K of 16-bit data-storage capacity (RAM) and a multiplexor to provide addressing for bidirectional data transfer via the data bus. Data samples provided by the A/D-conversion module are stored in the buffer on a cycle-steal DMA basis; decisions for data transfer to the appropriate medium are provided under software control. Present software permits data transfer at preselected times and time intervals, upon detection of an event by software trigger algorithms and upon manual command from keyboard.

Time-control module. The time-control module provides accurate external time reference for the internal system clock with provision for synchronization of the internal clock under software control. Configuration of external time-code receiver and associated decoding hardware on a separate module permits straightforward interchange of time-code receivers at level 2. The GEOS may be deployed in different parts of the world either by utilization of an appropriate master clock or by replacement of the time-control module at levels 2 and 3.

The time-control module presently implemented in the GEOS includes a 3-MHz temperature-controlled crystal oscillator as an internal time standard, and a WWVB radio receiver and associated decoding electronics for automatic reference to external time using measured time differences. The 3-MHz internal time standard provides a reference for controlling the sampling rate of the A/D-conversion module, and a 1-kHz signal to a millisecond counter from which the CPU determines time to the nearest millisecond with a display showing days, hours, minutes, and seconds. This millisecond counter can be latched and interpreted by the CPU to determine the time of an event, or labeled by an external reference, including WWVB or master clock, to determine time differences between internal and external time. Digital filter and pulse-width discriminator circuits allow the CPU to easily and quickly decode the WWVB serial time code. The time-control module in present production models permits the system to synchronize, and derive time differences with respect to an external time reference (WWVB or master clock) upon operator or CPU command with the option to record time and time differences on a mass-storage device. Time-control modules that might utilize other external references,

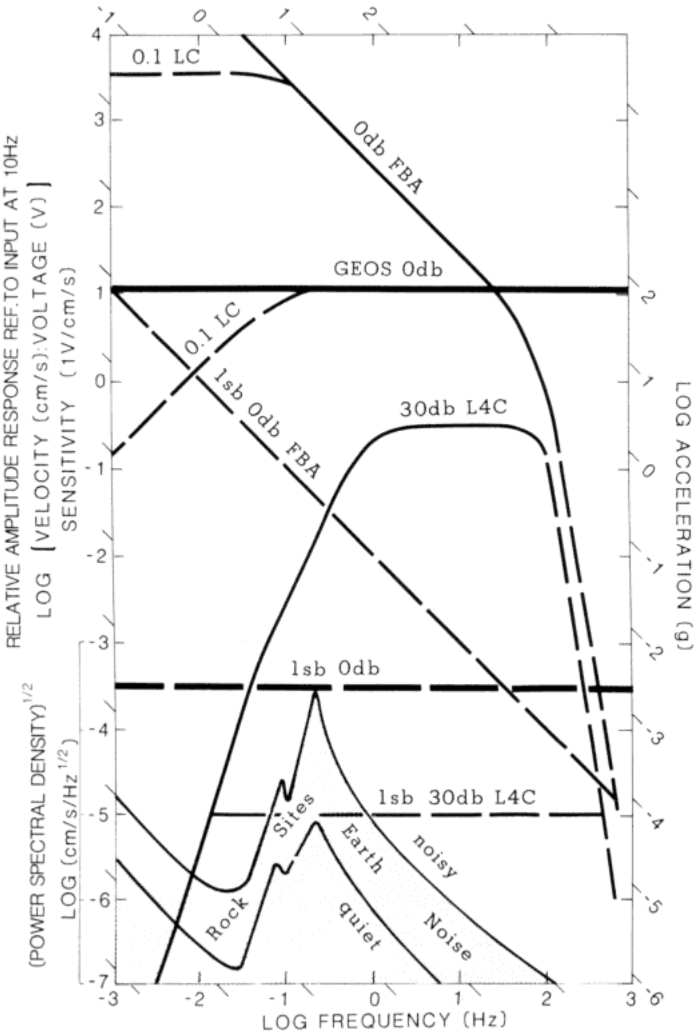

FIG. 5. Relative amplitude response of the GEOS recorder, GEOS with L4-C velocity transducer and force-balanced accelerometer, and square root of power spectral density for Earth noise (Aki and Richards, 1980). Amplitude responses were determined for recorder with constant input voltage of 10 V, for recorder with L4-C with constant input velocity of 10 cm/sec or 10 V at sensitivity of 1 V cm/sec at 10 Hz, and for recorder with force-balanced accelerometer with constant input acceleration of 2 g. Two sets of sensors operating simultaneously and linear dynamic range of 96 dB allow system to record 10-Hz signals with amplitudes ranging from 2 nm in displacement to 2 g in acceleration on scale without operator intervention.

such as satellite or Omega, can be implemented easily at level 3. Provision for synchronizing digitization rate and internal time between separate GEOS units is available at level 2 to allow expansion of the number of channels beyond six for dense array applications.

A minor amount of voltage-control circuitry has been appended to the time-control module to reduce space requirements. This circuitry converts source voltage of 24 to 5 V for digital components and to 12 V for analog sections using two dc-dc converters. Separate analog and digital grounds are maintained throughout the system with common power provided by the battery.

Mass-storage/retrieval module. The mass-storage/retrieval module plays a significant role in determining system characteristics. In addition to data-storage capacity, system portability, and power consumption, several more subtle system characteristics are determined by this module. Read as well as write capabilities of the module allow transmission of recorded data via telecommunication, and playback of data via RS-232 device to computer or strip-chart recorder. In addition, system software and operational parameters can be loaded into the system via system mass-storage/retrieval device. Data format [e.g., the American National Standards Institute (ANSI) standard] facilitates data accessibility via standardized readers either in the laboratory or the field and facilitates transportability of data and software between various minicomputer systems.

Such characteristics of data-storage devices are achievable in varying degrees by several available media, including magnetic-tape cartridge, solid-state memory, magnetic bubble memory, disk, and magnetic-tape cassette. The choice of storage medium depends on system application with certain media, such as tape cartridge, presently considered to provide the broadest range of system applicability. However, isolation of the internal mass-storage device and corresponding controller as a separate hardware module, as shown in Figure 2, permits interchange of media at level 3. In addition, rapid technological advances, stimulated by the disk backup requirements of the computer industry, are leading to considerable improvements in various media, especially cartridge-tape recorders, compact disks, and solid-state memory. Capability of the general system configuration (Figure 2) to permit replacement of the data-storage/retrieval module at level 3 with improved components contributes significantly to system flexibility as well as adaptability to various experiments.

The mass-storage/retrieval module presently implemented in the GEOS provides a controller for a master/slave configuration of magnetic-tape-cartridge recorders. The system includes capability for variable number (1 to 3) of slave recorders, each housed separately, to be utilized at level 1. Optional slave recorders increase data-storage capacity and permit data playback for telecommunication purposes during quiescent periods of data transfer from preevent memory. The cartridge recorder presently implemented in the GEOS has serpentine read-write capabilities on four tracks, in ANSI standard format, with a capacity of 1.25 Mbytes on a 300-ft tape. Recent increases in number of tracks and bit density has resulted in cartridge recorders with capacities ranging from 23 to 60 Mbytes, depending on the model of recorder, these recorders with larger capacity are being evaluated for implementation in future models of the GEOS.

Internal data storage on a tape cartridge, as opposed to other media, permits utilization of the system for a broad range of applications. Read capabilities of the device selected are utilized to load software during debugging stages before "burning" EPROM's for the program memory module, to play back data via RS-232 device, and with the D/A-conversion module to play back data for analog display. Utilization of the read capability in conjunction with slave recorders for telecommunication purposes is planned for future implementation. Tape cartridges with ANSI standard format are convenient for transporting data and software in a minicomputer-compatible format. Serpentine recording reduces tapehead alignment difficulties.

For some specific applications, storage media other than tape cartridge may be more appropriate. For example, in some strong-motion applications requiring only small amounts of data storage, solid-state memory may be preferred because of improved temperature specifications and increased reliability due to a reduction in the number of moving parts. For such applications, replacement of the tape-cartridge module at level 3 and implementation at level 2 are relatively straightforward.

Calibration module. Detailed interpretation of recorded signals requires accurate calibration of system components. Calibration of data acquisition systems may be accomplished in the laboratory; however, changes may occur in system response due to handling during instrument transport, changing environmental conditions, and sensor leveling. Relative system calibration conducted under field conditions at about the time that data sets of interest are recorded is important to ensure high-quality data.

The calibration module (Figure 2) developed for the GEOS permits calibration of sensors and the signal-conditioning module under software control of the CPU. Software control of the calibration module permits selection of calibration times corresponding to those of recorded data sets and those selected by the operator. In addition to system calibration, the generated signals are especially useful for evaluating sensor and system performance during deployment of instruments in the field. Monitoring the generated signals via oscilloscope and (or) CPU provides a convenient means of determining whether sensors and amplifiers are performing properly at the time of deployment; if not, the opportunity exists to replace and (or) repair sensors and amplifier cards before leaving the fieldsite. Software algorithms are planned to permit automatic internal system checkout at selected time intervals, with English-language diagnostics provided to the operator.

The calibration module presently implemented in the GEOS permits calibration of the signal-conditioning module and three types of sensors. Calibration capabilities for sensors include velocity transducers with and without calibration coils and force-balanced accelerometers. In the case of the velocity transducers, a dc voltage, derived under CPU control for appropriate gain setting from a D/A converter, is applied to either the main or calibration coil of the transducer for a software-selectable time interval. Voltage termination corresponds to an applied step function in acceleration to the sensor mass with the resultant signal determining relative calibration. In the case of force-balanced accelerometers, ±12 V are applied to the damped and undamped control lines.

The signal-conditioning module is calibrated using impulse of one samble duration and an alternating dc voltage derived and applied under software control to the amplifiers while the sensors are disconnected via appropriate relays. Separate calibration of sensors and the signal-conditioning module is convenient for diagnosing performance problems in the field, as well as for providing improved system calibration. Changes in input calibration signals and capabilities to calibrate other types of sensors can be accommodated at level 3 and implemented at level 1.

D/A-conversion module. The D/A-conversion module, together with the retrieval capabilities of the internal storage module, permits the GEOS to be used as an analog-data playback unit in the field or laboratory. Visual inspection of digitally recorded data in analog format can be especially useful during the initial stages of field deployment for some experiments.

Separate A/D- and D/A-conversion modules offer additional flexibility with respect to possible system configurations of the GEOS. The GEOS can be configured to include both modules or either module separately. With both modules the GEOS can be used as a data-acquisition/transmission system and as a system for analog-data playback. For many applications, however, it is more cost-effective and convenient to configure separate systems for the express purpose of analog-data playback.

Systems that are not configured with analog playback capability are easily converted by replacing the A/D-conversion module with the D/A-conversion module and replacing the corresponding software at levels 2 and 3. The present D/A-conversion module contains circuitry for microprocessor-interface logic, power control, D/A converter, and various low-pass filters. The interface logic receives digital data from the data bus and temporarily stores it in latches at the input to the D/A converter. The D/A converter, in turn, converts the digital samples into current which in turn is converted to an offset voltage proportional to the weighted value of digital samples. Because the D/A-conversion module may not be utilized during extended periods, current drain is minimized by switching power to the module upon command from the CPU. A prototype D/A-conversion module was developed that permitted selection of 17-, 33-, 50-, and 100-Hz three-pole Butterworth filters; however, because these filters were rarely used, the filtering circuitry and corresponding relays have been eliminated from the GEOS production models.

SOFTWARE ARCHITECTURE

Software design concepts are fundamental to the performance and future adaptability of microcomputer-based systems. The concepts employed determine the extent to which the system can be easily modified for future applications, the extent to which future improvements in hardware components can be readily incorporated, and the general versatility of the system. The development of the software architecture and its components is perhaps the most crucial and expensive aspect of system development.

General design goals established for the development of the GEOS software included

1. develop software components and architecture on the basis of required system functions, as indicated in Figure 2;
2. attempt to maximize software control of system functions and hardware modules;
3. develop software in a modular format to facilitate testing and future system changes;
4. attempt to maximize portability of the software;
5. develop diagnostic software to permit system self-evaluation and restart;
6. perform all system software development on host minicomputer system, and develop software tools to test, downline load, and debug GEOS micrcomputer;
7. develop extensive capability to configure the system in the field for a wide variety of scientific and engineering applications; and
8. develop provision for system self-calibration and self-testing.

These general design goals were pursued with emphasis on software integrity and redundancy to minimize and recover from system failures, as well as to minimize software overhead so as to improve CPU bandwidth. Pursuit of these goals for the

GEOS led to the development of a nested-ring software architecture (Figure 6) operated in a "watchdog" or self-diagnostic environment. The inner rings of the structure control the hardware environment, and the outer rings define the procedures for particular applications. This software structure is conducive to continued development of process software as indicated by future applications of the system.

Control panel and kernel. The inner ring, referred to as the control panel, contains procedures (Figure 7) stored and executed in EPROM upon CPU command by a hardware-induced signal or by one of three programmable signals. Upon initialization of power, the control panel is responsible for: execution of interactive system console functions via display and keyboard; application of system bootstrap mode, involving EPROM, power source, RAM, mass storage, and RS232 device; and initialization and management of "watchdog" functions to detect and recover from system failures. Figure 7 lists the processes currently exercisable from the control panel. Execution of standard system startup via control panel permits initialization of the GEOS kernel or the second ring in the software structure (Figures 6 and 8).

FIG. 6. Nested-ring structure of GEOS software architecture, showing inner ring containing system start-up and online debugging (see Figure 7), second ring containing GEOS operating system (see Figure 8), and third ring containing application software (see Figure 9), each of which is operated in a "watchdog" environment.

The kernel of the software is a fundamental part of the operating system developed for a microcomputer. The customized operating system, with both real-time and time-share attributes, performs the system functions that can be attributed to any seismic data-acquisition system centrally controlled by a microcomputer. The kernel contains procedures that implement hardware drivers, schedule process execution and communications, control clock functions, and manage memory utilization. Well-defined tools and procedures implemented within the GEOS kernel (Figure 8) facilitate development of application programs and provide the basis for an efficient real-time processing environment. Software drivers and interrupt routines to interface with commonly used devices (magnetic tape, display, keyboard, and clock) and a common interrupt-handling mechanism facilitate development of new device drivers at the applications level. The process scheduler provides the means for new process creation (spawning) and for interruptable postprocessing by device-interrupt routines. Clock queue routines allow processes to be scheduled for execution at a particular time. It should be noted that all GEOS processes share equal priority for the CPU and are interruptable only when a device requires attention. Memory-management routines implement primitive functions to provide the same transparency to the memory architecture. The GEOS kernel is linked with a particular application program and loaded by the control panel via the current bootstrap device. Sharing a single version of the kernel among all applications allows continued development of the real-time environment with benefits provided to previously developed subsystems.

Applications software (record and playback). The applications software in the third or outer ring of the software architecture is comprised of processes required for both recording (Figure 9) and playing back data in a variety of intended scientific and engineering applications of the system (e.g., near-source aftershock sequences, crustal structure, structural response, and long-term monitoring, including strong-motion regional seismicity, teleseismicity, and strain). Design of the applications software at the process level allows for modular and efficient implementation in which process interaction is initiated by procedure calls between processes, shared memory, or direct parameter modification.

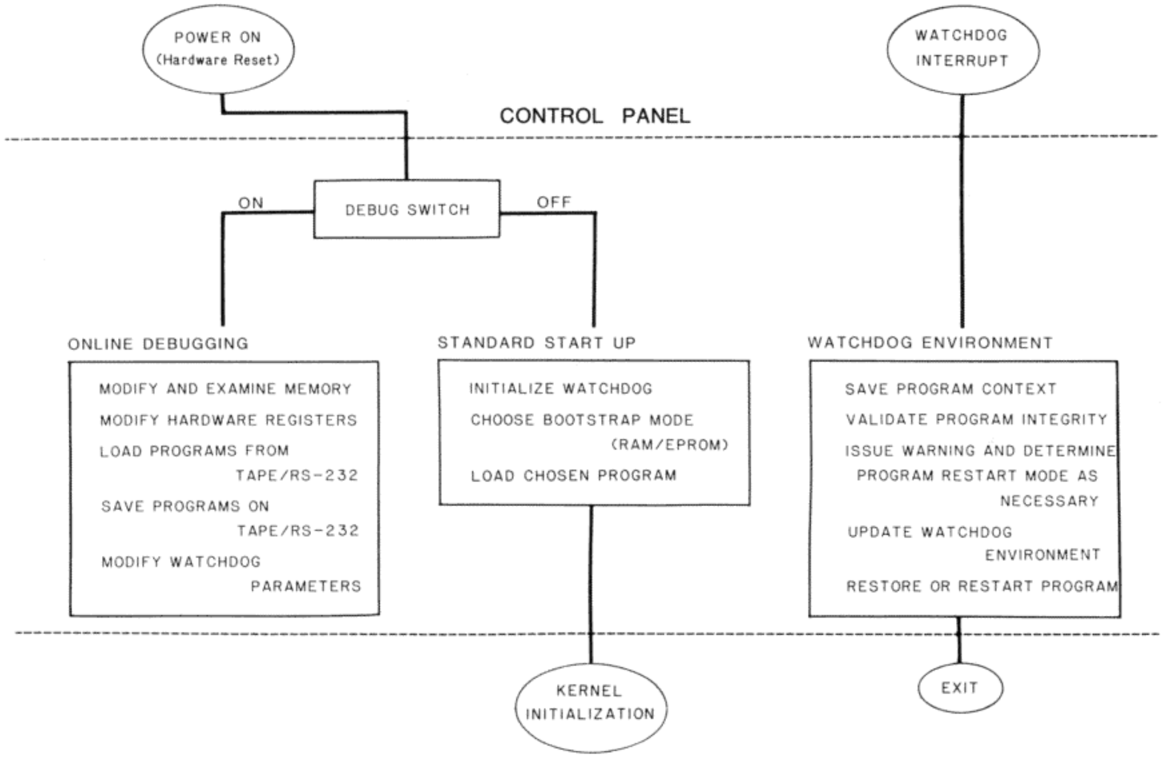

FIG. 7. Software processes constituting the control panel of the GEOS (inner ring of software architecture, Figure 6). Processes executed within control-panel environment include online debugging, with loading and transfer of software via RS-232 device or mass-storage medium, system start-up involving initialization of "watchdog" environment and selection of software from EPROM for execution in RAM, and execution of "watchdog" processes.

Record processes presently implemented in the GEOS (Figure 9) operate as a set of parallel processes, with some serialized ordering of process execution depending on the application. To the field operator, however, the GEOS system appears as a two-phase system, namely, setup or MENU mode and data-acquisition or RECORD mode. The menu mode is initiated upon turning on system power. In this mode, the keypad and display processes are called upon as prompted by the operator to permit changing of operational parameters for a desired application of the system. The clock process is executed in parallel. The trigger algorithm, presently implemented in the GEOS, is an adaptation of the short-term average/long-term average algorithm developed by Prothero (1980). The version in the GEOS has been revised to improve efficiency. The teleseismic algorithm developed by Evans and Allen (1983) has been tested and coded, but as of this writing has not yet been implemented on production models. When priorities permit, we plan to implement the teleseismic and digital filtering algorithms of W. A. Prothero, Jr. (personal communication, 1984). Implementation should be straightforward, because his algorithms have also been developed for the IM-6100.

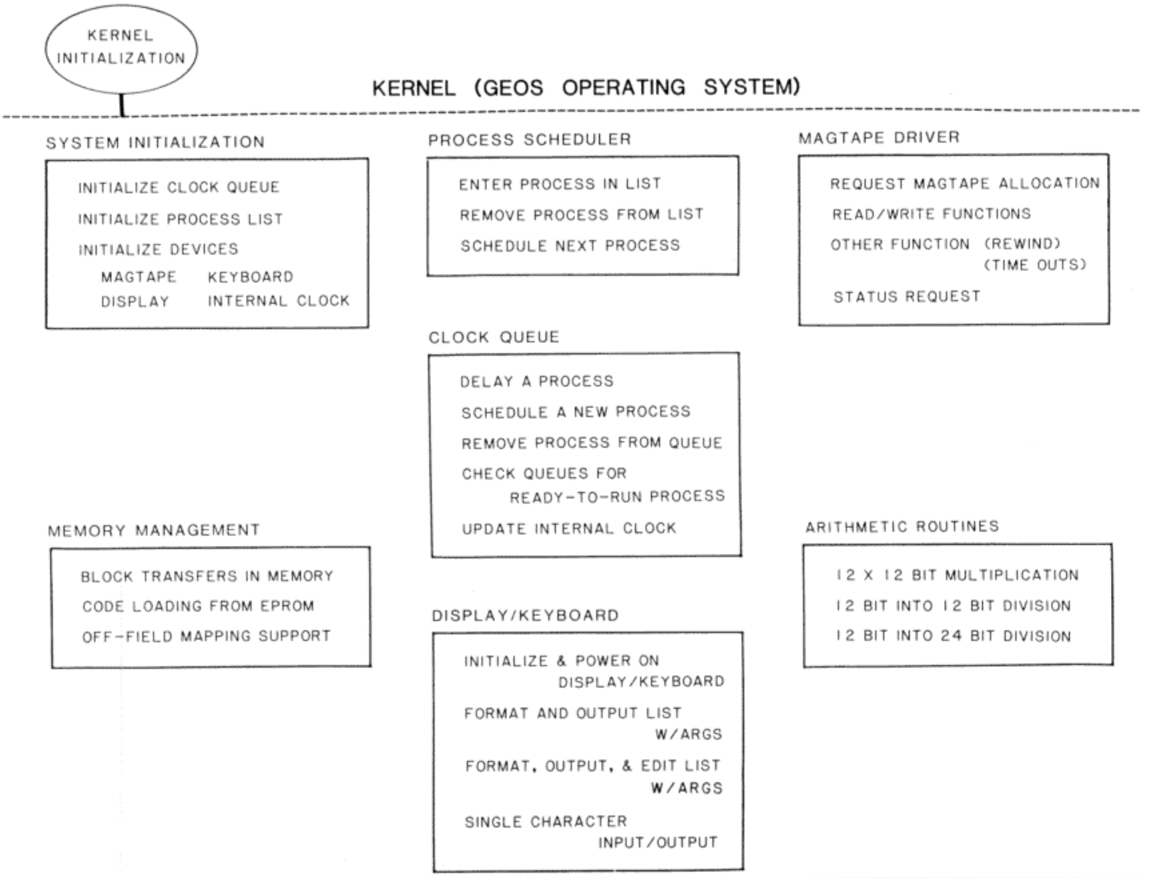

FIG. 8. Software processes constituting the GEOS kernel or operating system (second ring of architecture, Figure 6). Operating system, with both real-time and time-share attributes, contains processes for implementing hardware drivers, process scheduling, process communication, and management of clock and memory functions. Processes, in general, are characteristic of centrally controlled microcomputer data-acquisition systems.

The calibration process is channeled to the menu process for execution prior to entering the record mode. Upon operator determination to enter record mode, the calibration, clock, A/D-converter, record, and magnetic-tape processes (Figure 9) are executed as determined by operational parameters selected by the operator. The status-display process permits the operator to determine system status at any time after the system has entered record mode.

Execution of the various processes within a "watchdog" environment (Figure 6) containing extensive error-recovery routines decreases system vulnerability to hardware failures. Present operational software and recovery routines implemented in the GEOS have proved to be robust and reliable; however, we expect to implement further improvements with addition of more memory for the CPU.

The playback application software is comprised of several of the same processes developed for the record application software. Design considerations implemented in the playback software include double buffering of event data for accurate and selectable-speed data playback, diagnosis and recovery from hardware errors associated with mass-storage and RS-232 devices, and full recovery capability of both header and event data for error-detection purposes.

The present playback program permits the operator to optionally rewind the tape and select either analog or digital playback output. The analog output can be derived in real time or at selectable speeds (from 1/4095 to 4095 times the recorded sampling rate), and with selectable second markers with reference to recorded event time for playback on desired devices, such as strip chart or oscilloscope. The digital output via RS-232 device or UART permits data and header transmission with standard hardware protocols at a jumper-selectable baud rate. The present software (Figure 4) permits both sequential and selective playback of data files, as well as optional playout of header for selected files via alphanumeric display of the playback unit. Playback can be aborted at any time by depressing any of the numeric or function keys.

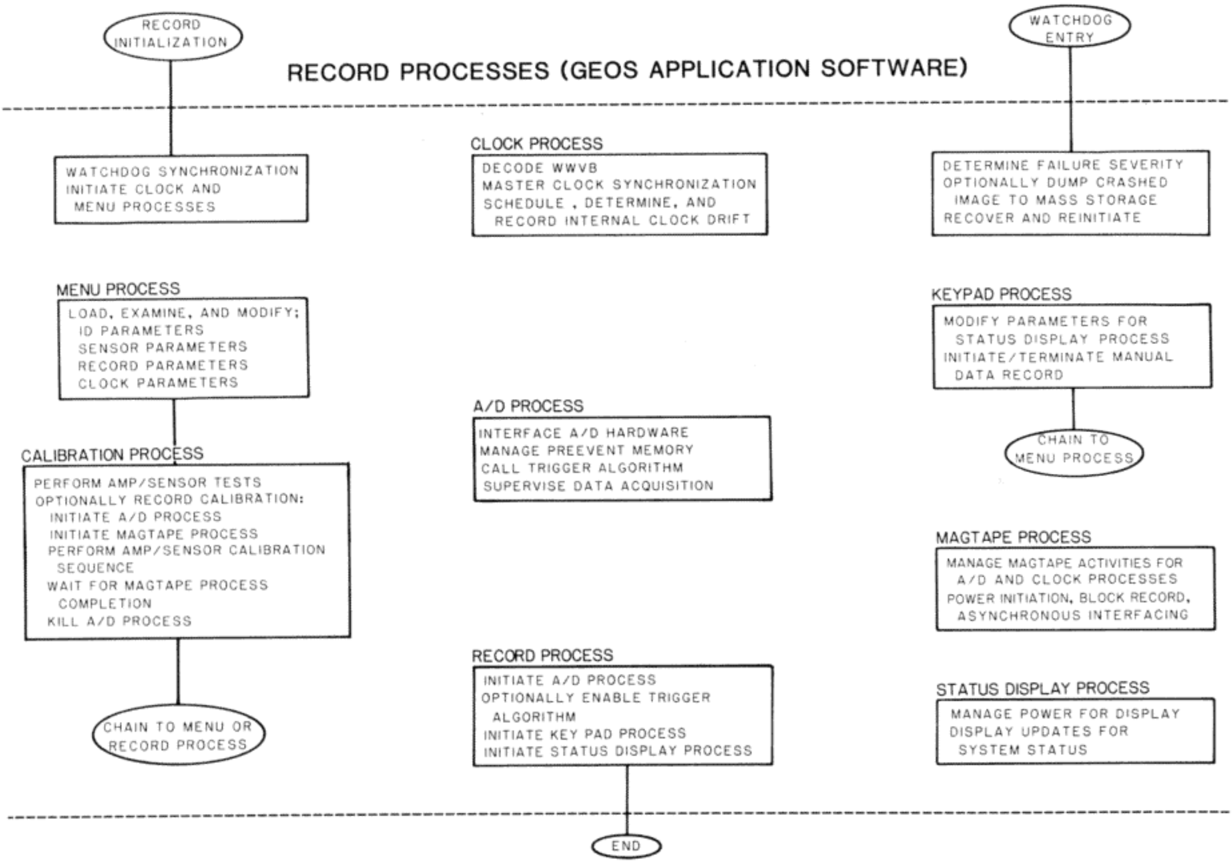

FIG. 9. Software record processes implemented in the GEOS for general application of system to a variety of seismic experiments (third ring of software architecture, Figure 6). Parameters for various applications can be chosen automatically be default or selectively by field operator via alphanumeric display and keyboard in menu mode. Selected parameters determine processes for execution in record mode.

LABORATORY EVALUATION AND CALIBRATION

A design objective given substantial emphasis during the development of the GEOS was the capability to record high-quality data. Extensions in both linear dynamic range and bandwidth were considered necessary to improve data quality over that of available recorders. To evaluate the resulting GEOS, noise tests and various calibration tests were conducted on the system.

The useful dynamic range of any recording system is determined by the resolution of the A/D converter and by the noise level of the input amplifiers. To utilize the full dyanamic range potential of the 16-bit A/D converter, special emphasis must be given to the design of low-noise input amplifiers with present technology requiring compromising decisions regarding noise level and power consumption.

A variety of operation amplifiers are selectable and easily implemented in the GEOS at level 2. Selection of the type of operational amplifier requires compromising decisions between desired system noise levels and power consumption. The noise level for the GEOS with presently implemented amplifiers that maintain total quiescent power consumption for the system at about 2.0 watts is shown in Figure 10. The noise level indicated in Figure 10 is the output of the GEOS to a shorted input with a resistor of impedance similar to that of geophones normally used in the field. The output trace (Figure 10) obtained at 60-dB gain (voltage amplification, about 1000) shows, at most, three transition levels with most transitions corresponding to that of the first least-significant bit (LSB). This behavior corresponds to that of random noise, with a standard deviation of about one LSB. These tests indicate that the A/D converter is operating over its full dynamic range of 90 to 96 dB. Because the LSB of the A/D converter is equivalent to 300 μV, the standard deviation indicated by Figure 10 is equivalent to about 0.3 μV (see Table 1). Other operational amplifiers can and have been used with GEOS to reduce power consumption to slightly more than 1 watt, but tests to date indicate an associated increase in the noise levels to the third LSB.

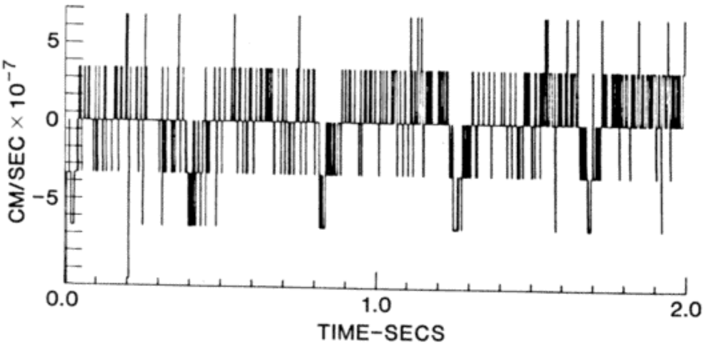

FIG. 10. Transition levels for output of the GEOS at 60-dB to an input shorted with a resistor of impedance similar to that of a common transducer (L4-C). Transition levels correspond to random noise of about one LSB, indicating that A/D converter is operating at full dynamic range.

Laboratory calibration for amplitude response of the GEOS was conducted using both steady-state and transient signals. Figure 11 summarizes the steady-state measurements conducted for each of the commonly used anti-aliasing filter selections. The sinusoidal measurements were made at 0-dB gain with input signals of 3.28 V rms. The sinusoidal input was recorded by the system at a maximum sampling rate of 200 sps per channel. All measured values were found to differ from the analytic prediction (not shown) by less than 0.6 percent. Characteristics of the signal generator did not permit measurement for lower order bits. (The 0.1-Hz single-pole low-cut filter and the 600-Hz single-pole high-cut filter implemented via hardware are commonly used for aftershock and seismic-refraction applications of the system. For other applications, other, more appropriate single-pole low- and high-cut filters can be implemented at level 3.)

Transient amplitude-response characteristics have been determined by using both steps and impulses in voltage applied to the input. Figure 11 plots the resulting time-domain output signals and corresponding calculated Fourier amplitudes for both types of input signals and each of the commonly used filter settings. Owing to input-frequency content, the step in applied voltage is most useful for determining the long-period response of the system and the impulse in applied voltage for determining the short-period response. The amplitude-response curves shown in Figure 11 for frequencies greater than 2 Hz correspond to those of impulse voltages of 1-msec duration and those for frequencies less than 2 Hz to a voltage step. The calculated curves (Figure 11) show less than 1 per cent deviation from the expected analytic results and the measured steady-state results over the bandwidth for which a good input signal-to-noise ratio was available.

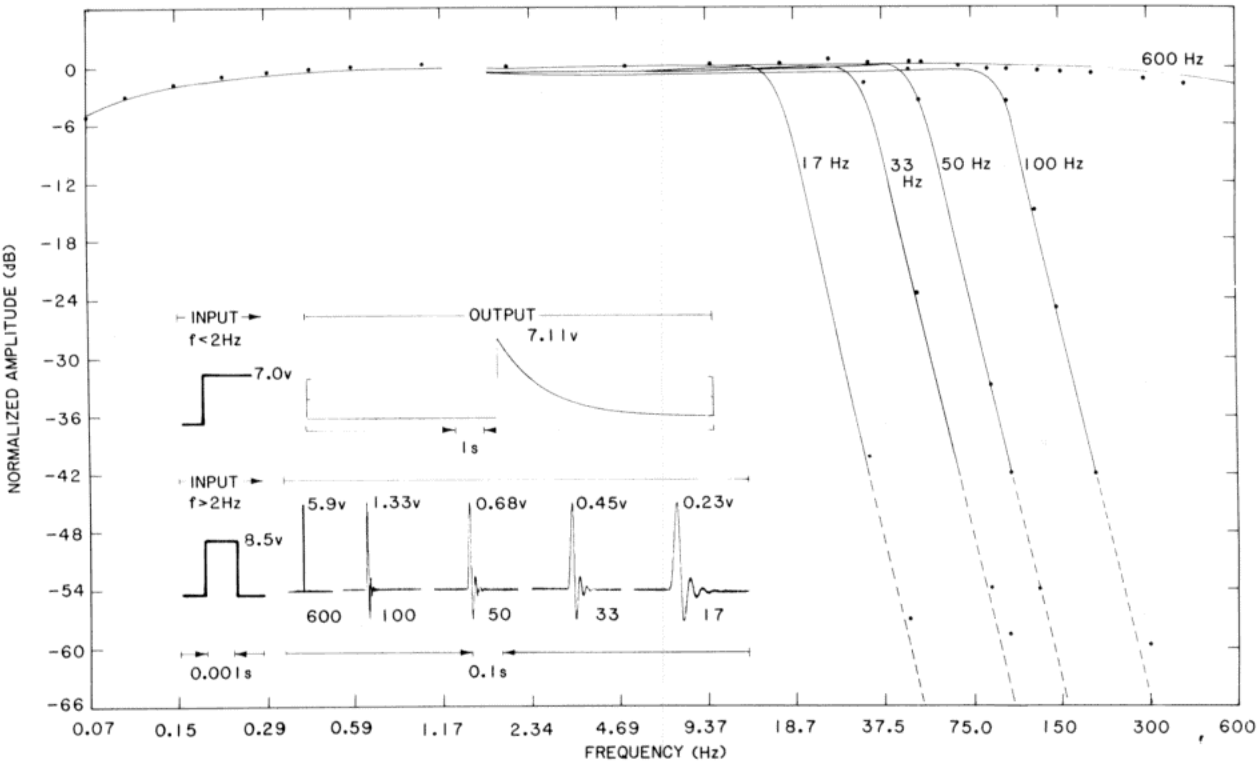

FIG. 11. Normalized amplitude response of the GEOS to steady-state (symbols) and transient input signals (curves) with software-selectable antialiasing filters of 17, 33, 50, 100 Hz, and a single 600-Hz high-cut Butterworth filter implemented in hardware but removable at level 2. Owing to frequency content of input signal, step in voltage was used to determine transient response for frequencies less than 2 Hz, and an impulse 1 msec in duration for frequencies greater than 2 Hz. Measured response deviates from predicted analytic design response (Figure 5) by less than 0.5 per cent. Dynamic range of measured response is limited by characteristics of input signals.

The phase response of the GEOS (Figure 12) was measured from Lissajous figures determined for the input and output signals at selected frequencies. The analog output was observed at the front-panel monitor jack, which samples the signal at the input of the A/D conversion module. The measured values of phase response show less than 1 per cent deviation from the expected analytic results over the frequency range 0.01 to 600 Hz. Results of laboratory measurements (Figures 10 to 12) suggest that the original design goals for system response have been achieved (see Figure 5).

Measurements of system power consumption are summarized in Table 2. The measurements were determined from the battery return current for both the analog and digital grounds. Thus, these mesurements include efficiency losses for the dc-dc power converters. The measurements were made with a configuration of signal conditioning components that yielded an intermediate level of power consumption. Choice of other dc-dc converters and operational amplifiers can yield quiesent power consumption values ranging from about 1 watt to over 2 watts with attendant variations in noise levels. The measurement of power consumption in quiescent record mode can be regarded as an approximate estimate of the average power consumption for several applications of the system. For example, for such applications as aftershock studies, the system is in an event-trigger mode for a majority of the time, and the amounts of power consumed in other modes (e.g., recording and menu) represent only a small percentage of the total power consumption. Present production models of the GEOS are intended to operate for about 3 days in event-trigger mode from the internal batteries (see Table 1) and for more than 1 month from two external car batteries. For applications involving permanent deployment or continuous-record mode at low sample rates, other sources of power such as solar panels are more appropriate.

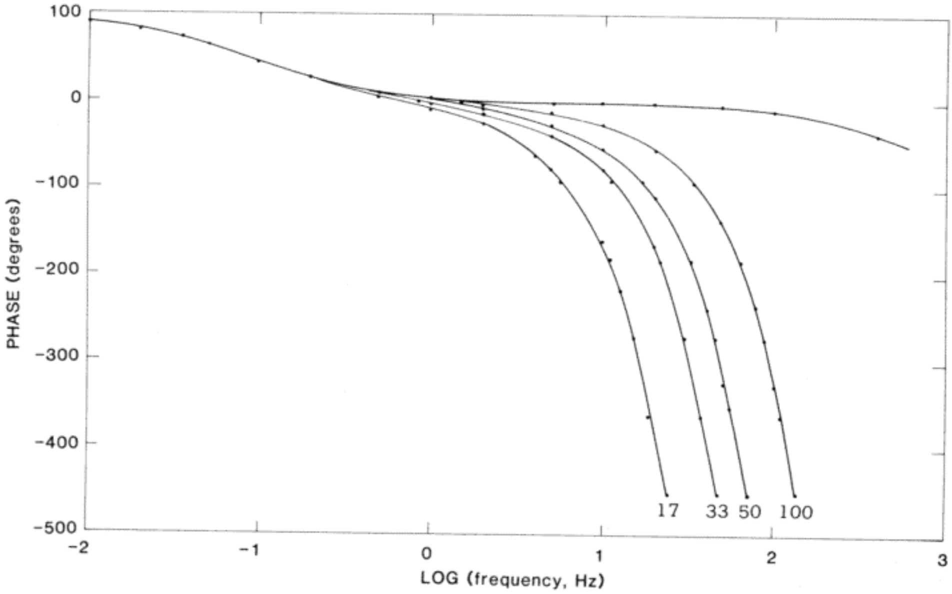

FIG. 12. Phase response of the GEOS, measured using Lissajous figures determined from a steady-state input and corresponding output measured at input to A/D-conversion module.

FIELD EVALUATION AND CALIBRATION

The ultimate test of system design concerns the reliability of the system to yield high-quality data for a variety of applications under a range of field conditions. To date, arrays of the GEOS units have been deployed for near-source, strong-motion studies (Borcherdt *et al.*, 1984; J. Boatwright, unpublished data, 1985; Archuleta *et* *al.*, 1985), high-frequency microearthquake studies (Cranswick *et al.*, 1984, E. Cranswick *et al.*, unpublished data, 1985), high-frequency air-gun experiments (H. Liu, personal communication, 1984), seismic-refraction shots (Mueller and Cranswick, 1985), downhole wave-propagation studies (Malin and Waller, 1985), teleseismic studies (Evernden *et al.*, 1985), high-frequency Earth-strain studies (Johnston and Borcherdt, 1984), volcanic studies of magma movement (B. Chouet, personal communication, 1984), and simulation of near-source earthquake ground motions using contained explosions (H. E. Lindberg and A. N. Lin, personal communication, 1984). In each of these applications, particular design features have been tested, and many general features, including self-calibration, data capacity, dynamic range, resolution, bandwidth, selectability of record modes, system versatility, and field reliability, have been used. In the following paragraphs, we examine the results of some of these experiments.

To test the self-calibration capability of the GEOS under field conditions, time-domain signals and their corresponding Fourier-amplitude spectrums have been obtained for most of the applications. Examples of these are shown for the recording system (Figure 13a) and the system with six types of sensors (Figure 13b). The time histories shown correspond to those presently utilized to calibrate the GEOS in the field without sensors (voltage pulse of one sample duration and alternating voltage applied to input amplifiers), the recording system with force-balanced accelerometers (±12 V), the recording system with velocity transducers without calibration coil (dc voltage applied to coil), and the recording system with transducers having a calibration coil (not shown). Calibration signals recorded from a force-balance accelerometer and five types of velocity transducers (L-1, L-22, L-4, HS-10, and S-13) are shown (Figure 13b). The background noise was recorded with the L-4 and HS-10 sensors within a few minutes of the recorded calibration signals at a site near Stanford University. The Fourier spectra computed from the output time histories for the various calibration signals and the background noise show that the response of the recording system and the various types of sensors can be determined independently under field conditions relative to the laboratory calibration of the input signals over the bandwidths permitted by the relative frequency content of input signals and the response characteristics of the chosen sensor.

Choice of calibration signals and procedures to account for variations in instrument response are dependent on the objectives of the experiment being performed. For many applications it is sufficient to utilize the self-calibration signals recorded in the field to verify the design system response as shown in Figure 5. For other applications requiring more accurate system calibration, the field-recorded signals can be utilized to determine the system response to the extent permitted by signal-to-noise characteristics of the input signal for the bandwidths of interest. Definition of input signal under software control allows user to develop other input signals at level 3 for implementation at level 2.

To date, the most extensive field evaluation of the GEOS has been provided by near-source studies in the epicentral areas of moderate earthquakes. At present, several thousand aftershocks have been recorded on three or more GEOS units in the epicentral area of moderate earthquakes near Mammoth Lakes, California (M_L 5.2; 7 January 1983), Coalinga, California (M 6.5; 2 May 1983), Miramachi, New Brunswick (M_L 5.7; 9 January 1982, field program July 1983), Goodnow, New York (M 5.2; 7 October 1983), Borah Peak, Idaho (M_S 7.3; 28 October 1983), and Morgan Hill, California (M_S 6.2, 29 April 1984). Except for the deployment near Miramachi,

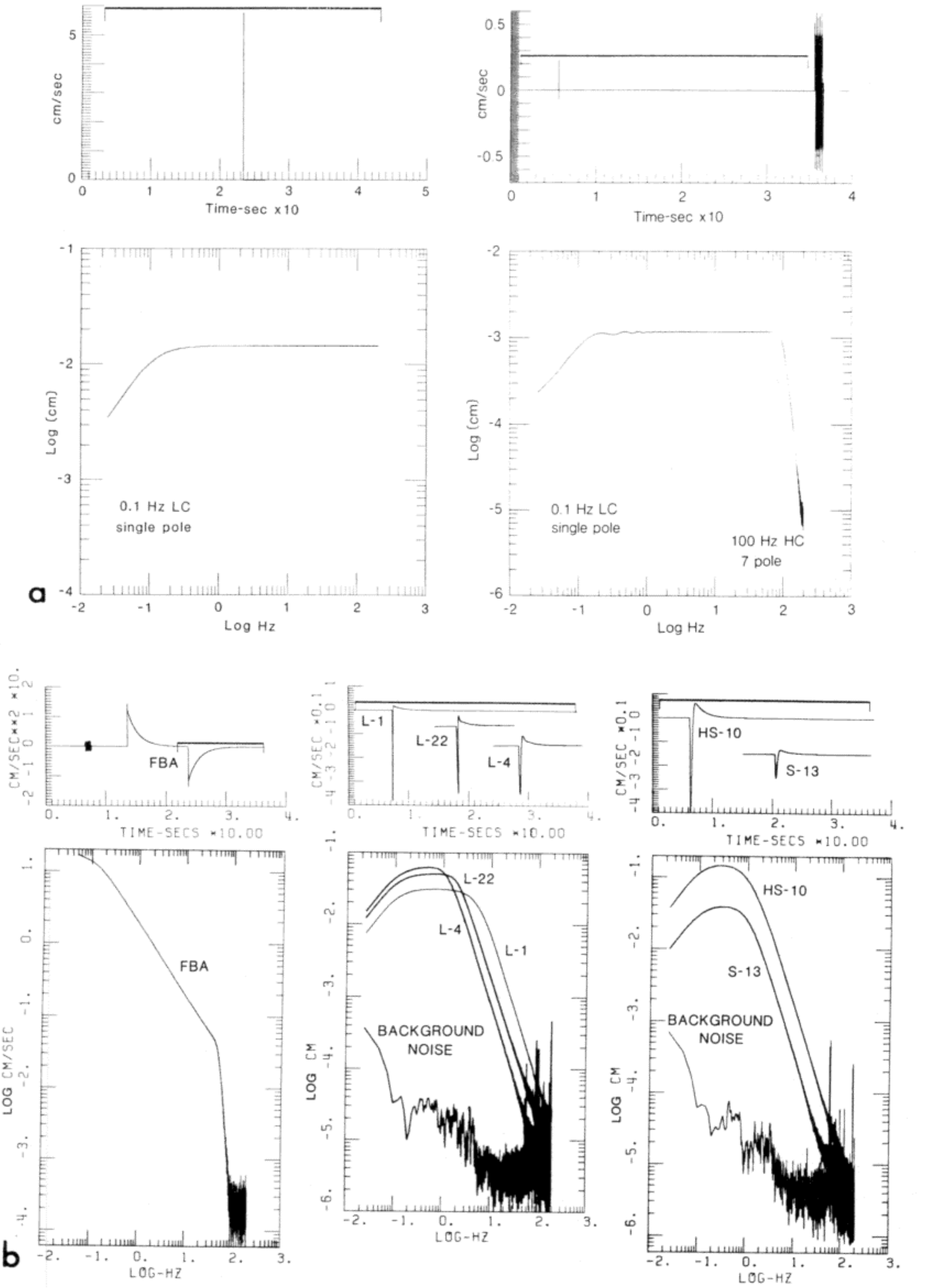

FIG. 13. (a) Self-calibration time history (impulse one sample duration) and computer amplitude response for the GEOS. The impulse on the *left* was generated by a high-quality external signal generator, and that on the *right* by a relatively low cost D/A internal to the GEOS. The amplitude response of the system determined from the impulse signals sampled at 400 sps meet design specifications (see Figure 5) and provide capability to obtain accurate relative calibration for the GEOS in the field during periods of data acquisition. (b) Self-calibration time histories generated by the GEOS for a force-balanced accelerometer (Kinemetrics) and five types of velocity transducers (L-1, L-22, L-4, HS-10, and S-13). The recordings of seismic background noise, using the L-4 and HS-10 sensors, were obtained within a few minutes of the time that the calibration signals for all of the sensors were recorded at a site near Stanford University. These calibration signals generated by the GEOS permit accurate relative calibration of sensors in the field over bandwidth for which input signal is above background noise.

about 10 stations were established in the epicentral area of each event and maintained for time intervals ranging from 2 to 8 weeks. None of these deployments has suggested any need for changes in the GEOS at level 4. The normal teething problems encountered with initial deployments have turned out to be relatively minor, with most being associated with some faulty hardware components (primarily integrated circuits), two with software, and one with signal timing between the CPU and mass-storage controller. By utilizing a couple of spare recorders, however, high-quality data have been obtainable on a more or less continuous basis at most of the stations established, including those of the initial deployment near Mammoth Lakes. Numerous deployments of newly constructed systems have demonstrated the importance of environmental testing in the laboratory before deployment. After thermal cycling in the laboratory, nine GEOS units were deployed in the epicentral area of the Morgan Hill earthquake with no failures reported during the 8-week deployment period.

The data sets collected near Coalinga, California, illustrate several GEOS design features extensively evaluated during the various near-source studies. Detailed descriptions of the data sets are provided by Borcherdt *et al.* (1983, 1984) and Mueller and Cranswick (1985). Ten GEOS units were deployed for a source-mechanism study over a 20 × 25 km area centered over the Kettleman Hills anticline within 48 hr of the main shock (Figure 14, *left*). Each GEOS unit was deployed in a six-channel trigger-record mode, with both three-component velocity transducers and force-balanced accelerometers. Gains on the velocity transducers were set at 24 and 30 dB, and on the force-balanced accelerometers at 6 dB. Digitization rate per channel and antialiasing filters were chosen at 200 sps and 50 Hz, respectively. The data set obtained for this experiment is unprecedented in its completeness and resolution of recorded signals. Figure 14 shows the locations of epicenters for the aftershocks recorded at three or more stations during the first 8 days of the sequence. Onscale three-component recordings of essentially all events ranging in magnitude from less than 1 to 5.1 were obtained with many of the events greater than magnitude 3.5 being recorded with a signal resolution greater than 40 dB. The largest aftershock of M 5.1 (9 May 1983) was well recorded on all 10 GEOS units; Figure 14 (*right*) shows the force-balanced accelerometers outputs for the north-south component observed at eight of these stations.

The capability of the GEOS to record the output from at least two types of three-component sensors with 16-bit resolution yielded an effective dynamic range of more than 180 dB for these experiments. This capability of the system is illustrated explicitly by an integrated force-balanced accelerometer recording of the magnitude 5.1 event (left trace, Figure 15) and a corresponding velocity-transducer recording, obtained on the same GEOS unit, of a magnitude 1 event which occurred about 40 min later (right trace, Figure 15). These two events, which occurred in about the same location at a distance of 10 km from the recorder, were obtained on the GEOS unit at station SUB (Figure 14, *left*) without operator intervention. The resolution of the signal recorded from the 5.1 event at station SUB is illustrated further by the displacement spectra computed for the S-wave pulse (Figure 16), which is uncontaminated by system noise over five orders of magnitude or 120 dB. The completeness and resolution of the Coalinga data set contributed to the studies by McGarr *et al.* (1985) regarding variations in high crustal strength within the seismogenic zone surrounded by zones of lower implied strength, by Andrews *et al.* (1984) regarding increases in stress drop with increasing moment, and by Borcherdt

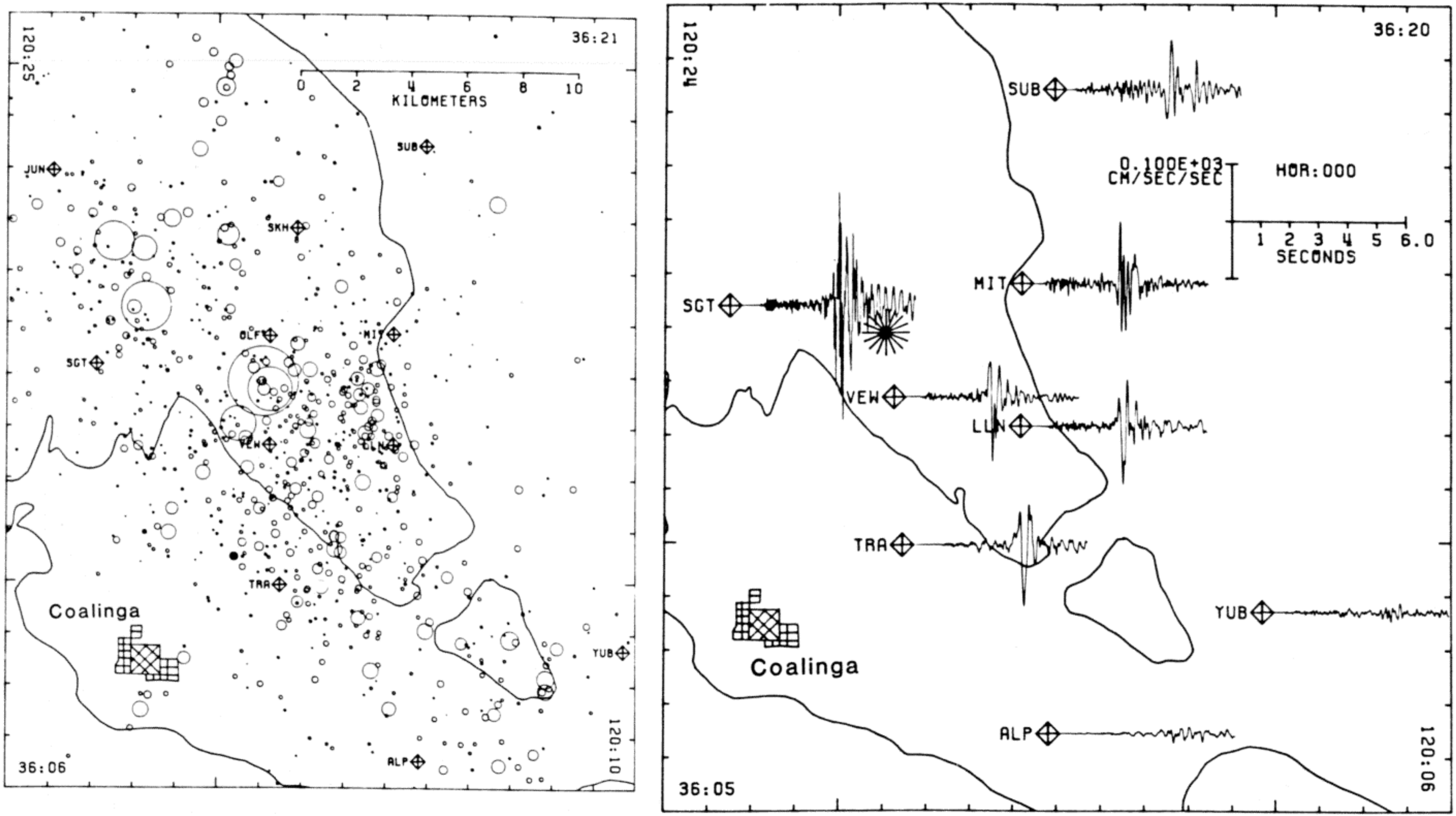

FIG. 14. Locations of epicenters (*left*) for events recorded at three or more GEOS stations (locations shown as three-letter code) during an 8-day time period following the Coalinga earthquake of 2 May 1983 and corresponding north-south component of horizontal ground acceleration (*right*) recorded at eight stations for a magnitude 5.1 aftershock. Events range in local magnitude from less than 1 to 5.1.

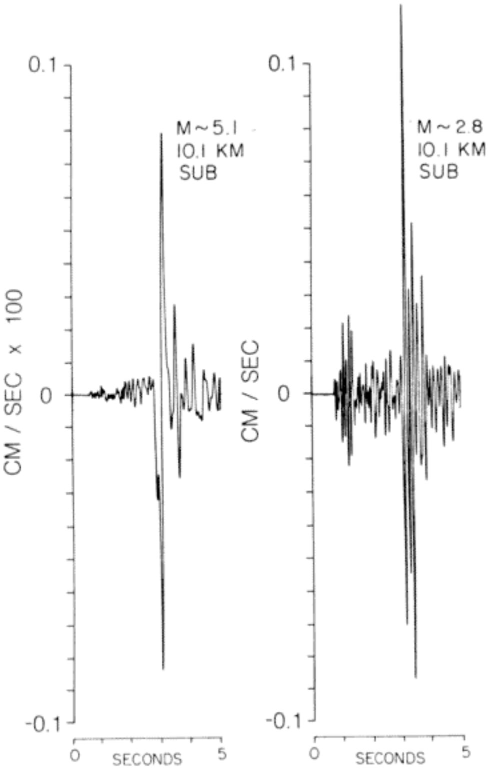

FIG. 15. Seismograms illustrating effective dynamic range and resolution of signals recorded on a GEOS unit at station SUB near Coalinga, California. The on-scale high-resolution recordings of the magnitude 5.1 and 1.0 collocated events were obtained on the same GEOS unit without operator intervention.

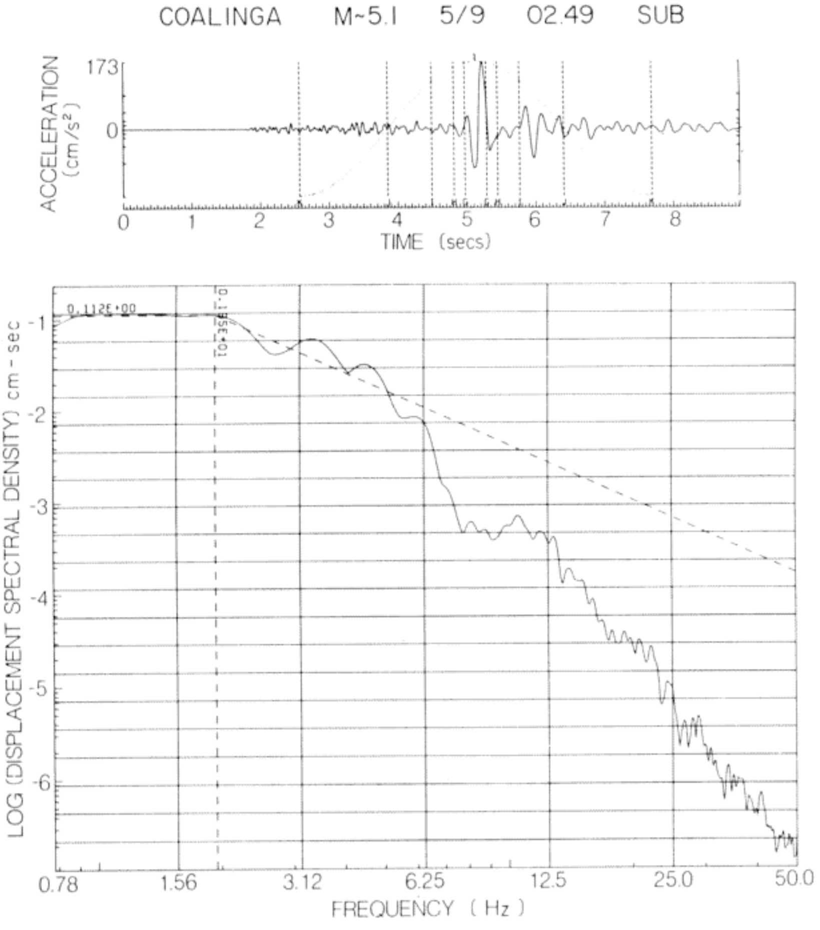

FIG. 16. Ground acceleration and inferred displacement spectrum for 135° horizontal component of *S* wave recorded at station SUB for a magnitude 5.1 aftershock (see Figure 17 for acceleration spectra). Discernible seismic energy is apparent in displacement spectrum over five orders of magnitude, or about 120 dB.

et al. (1983) regarding observed local site effects in the frequency band of 1 to 20 Hz in the city of Coalinga.

The opportunity to compare the signals recorded on the GEOS with those obtained on a standard strong-motion recorder (SMA-1, Kinemetrics) was provided by the magnitude 5.1 aftershock of 9 May 1983, near Coalinga. This event was simultaneously recorded on both an SMA-1 and a GEOS located about 30 m apart at station SUB (Figure 14, *left*). Figure 17 shows the time histories and spectra for the 135° horizontal component of strong motion recorded on both instruments. The SMA-1 signal was digitized at 600 sps and decimated to 200 sps. No correction for instrument response has been applied to either signal. The peak and rms values for the time histories differ by less than 2 per cent. Comparison of these spectra shows that they are nearly identical over the frequency band (0.4 to 25 Hz) for which the SMA-1 signal is above noise. The increased dynamic range and bandwidth of the GEOS in comparison with the SMA-1 is apparent in the acceleration spectra. Seismic signals associated with frequencies generated by the earthquake as high as 50 Hz are recoverable from the GEOS record (see Figure 17) but only as high as 25 Hz from the SMA-1.

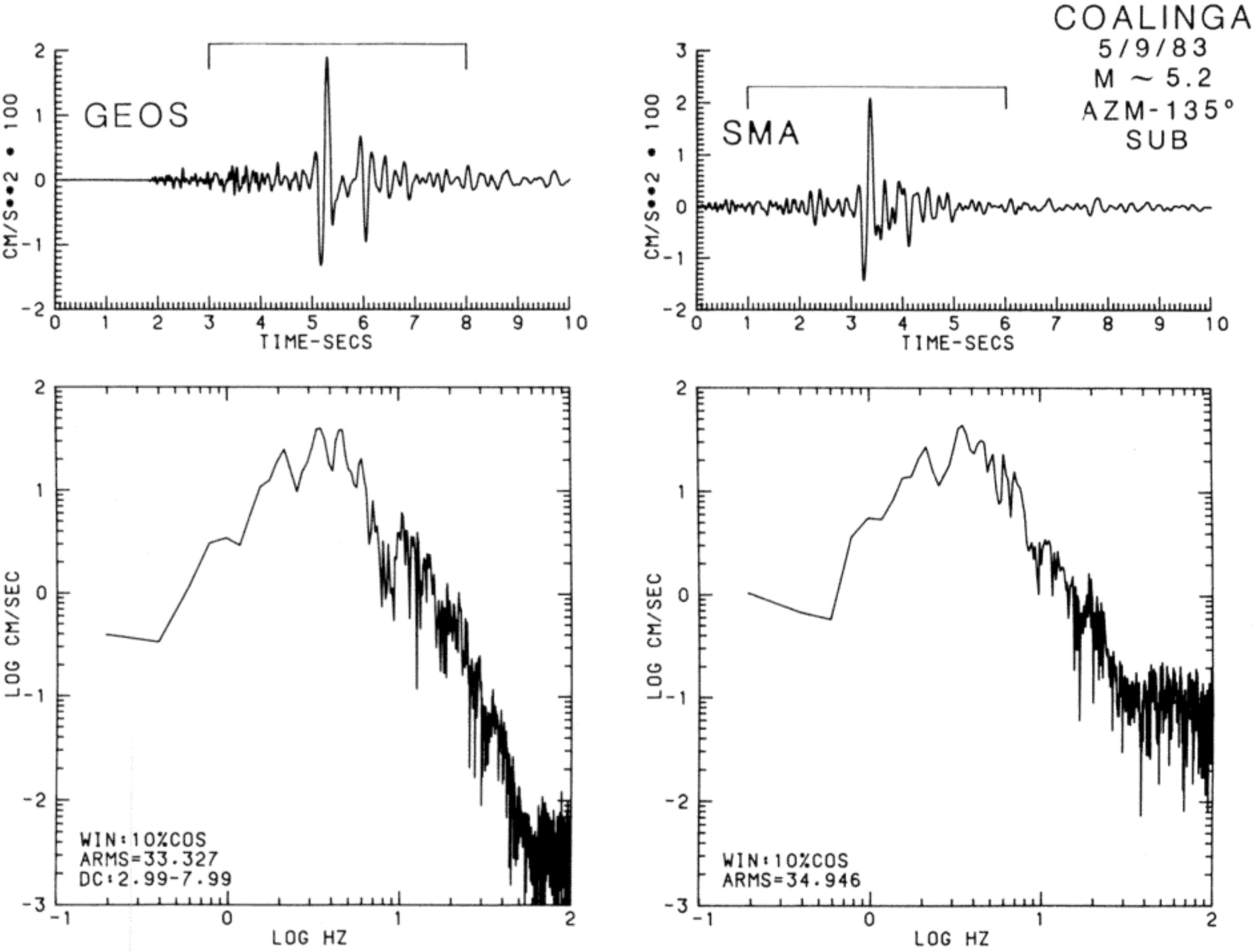

FIG. 17. Strong ground motions and spectra recorded on GEOS and SMA-1 units separated by a distance of about 25 m for 135° horizontal component of motion generated by a magnitude 5.1 aftershock near Coalinga. The time histories and spectra obtained on the two instruments are similar between 0.8 and 25 Hz. Seismic energy is discernible in the SMA-1 spectrum as high as 25 Hz, and in the GEOS spectrum as high as 50 Hz.

Applications of the GEOS requiring long-term and continuous deployment, as in an observatory-type setting for either short- or long-period data-acquisition purposes, have been partly tested. The GEOS units were utilized to record data from downhole arrays near Oroville and Parkfield, California, over 5- and 12-month intervals, respectively. Problems arose with battery voltage, untested hardware components, and electrical pickup in the sensory cables during the first few visits to the Oroville site but were subsequently corrected. The system deployed near Parkfield has been operating continuously without failure, using solar cells as a power source, for about 6 months (P. E. Malin, personal communication, 1984). Field-visit intervals to change tapes range from 2 to 4 weeks. Interpretation of 29 small ($M_b < 0.5$) earthquakes recorded on the GEOS from the array of three-component seismometers in a drill hole to 475 m near Oroville, California, shows marked reductions in S-wave energy above 30 Hz due to attenuation in the fault zone but no similar effect for P waves as high as 50 Hz (Waller and Malin, 1983). These data show that both S- and P-wave corner frequencies as observed at the surface were affected by attenuation in the fault zone (Malin and Waller, 1985). Similarly, data collected on the Parkfield array suggest that improved estimates of seismic-source characteristics can be derived from downhole observations (P. E. Malin, personal communication, 1984) with the implication that continuous deployment of high-resolution broad-bandwidth systems to record data from downhole arrays could improve inferences regarding local seismic-source characteristics. These applications of the GEOS emphasized the importance of the low-power design feature for permanent deployments in remote locations and have suggested that the GEOS is particularly well suited for long-term deployment applications where large amounts of backup power are not easily maintained.

Selectable digitization rates with a variable number of channels are important design features needed to achieve the flexibility in bandwidth required to utilize the GEOS in a wide variety of experiments. Experiments conducted in the Eastern United States recorded seismic frequencies as high as 300 Hz at 1200 sps. In contrast, experiments in California recorded Earth strain with periods of 24 hr at 10 sps. Figure 18 shows the horizontal component of ground velocity recorded at 1200 sps near Miramichi, New Brunswick. This time history was obtained by utilizing the GEOS as a single-channel recorder for a small ($M < 1.0$) earthquake at a distance of about 4 km (Cranswick *et al.*, 1984a, b). The displacement-time history (second trace, Figure 18) was derived with baseline removal, using the average of the first 512 samples, integration, and no filtering. The computed displacement spectrum, with a Nyquist frequency of 600 Hz and a dynamic range of 102 dB for inferred relative displacements, shows discernible seismic frequencies of 250 Hz (Figure 18). Cranswick *et al.* (1985) utilized similar data to infer moments ranging from 10^{13} to 10^{18} dyne-cm for 37 events, with evidence for an "$f_{\max}$" between 50 and 75 Hz. These data provided evidence for a velocity discontinuity at 0.5 km and for significant scattering effects in the near-surface (<0.5 km) materials for frequencies in the range of 50 to 150 Hz.

An earthquake ($M_b = 4.2$) at a regional distance of 190 km was also recorded near Miramichi, New Brunswick (Cranswick *et al.*, 1985). This event, located near Ottawa, Canada, was recorded by each of four GEOS units deployed for a microseismicity study. These units were operated as three-channel systems at 400 sps per channel, with a single-pole high-cut Butterworth filter of 600 Hz. Figure 19 shows the three-component time histories recorded for 160 sec at one of the sites. The recorded time histories and the slow decay of its coda emphasize the usefulness of

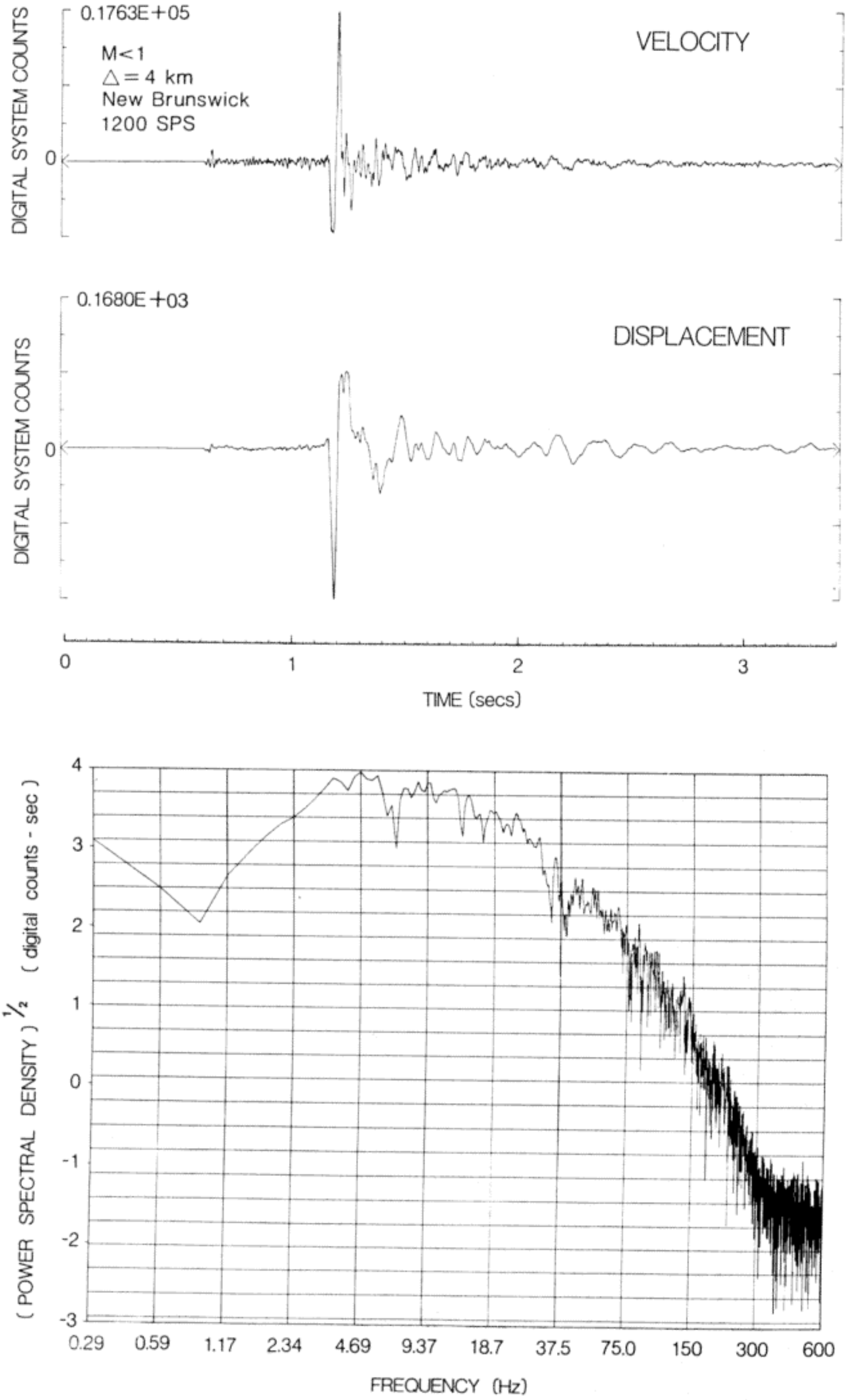

FIG. 18. Horizontal ground velocity, inferred displacement (integration, only dc removed), and displacement spectra determined from GEOS recording of a small earthquake ($M < 1$, $\Delta = 4$ km) near Miramichi, New Brunswick. The computer displacement spectra, with a Nyquist frequency of 600 Hz, shows a dynamic range of 102 dB and detectable seismic frequencies as high as 300 Hz.

wide bandwidth, as well as the robustness of the trigger algorithm, to determine the length of record time based on signal characteristics. The displacement time histories inferred by direct integration and no filtering for the initial P arrivals on the vertical component and the S arrivals on the transverse component (Figure 19) emphasize the significance of high-signal resolution. The displacement spectra computed from the inferred displacement time histories for the P and S arrivals

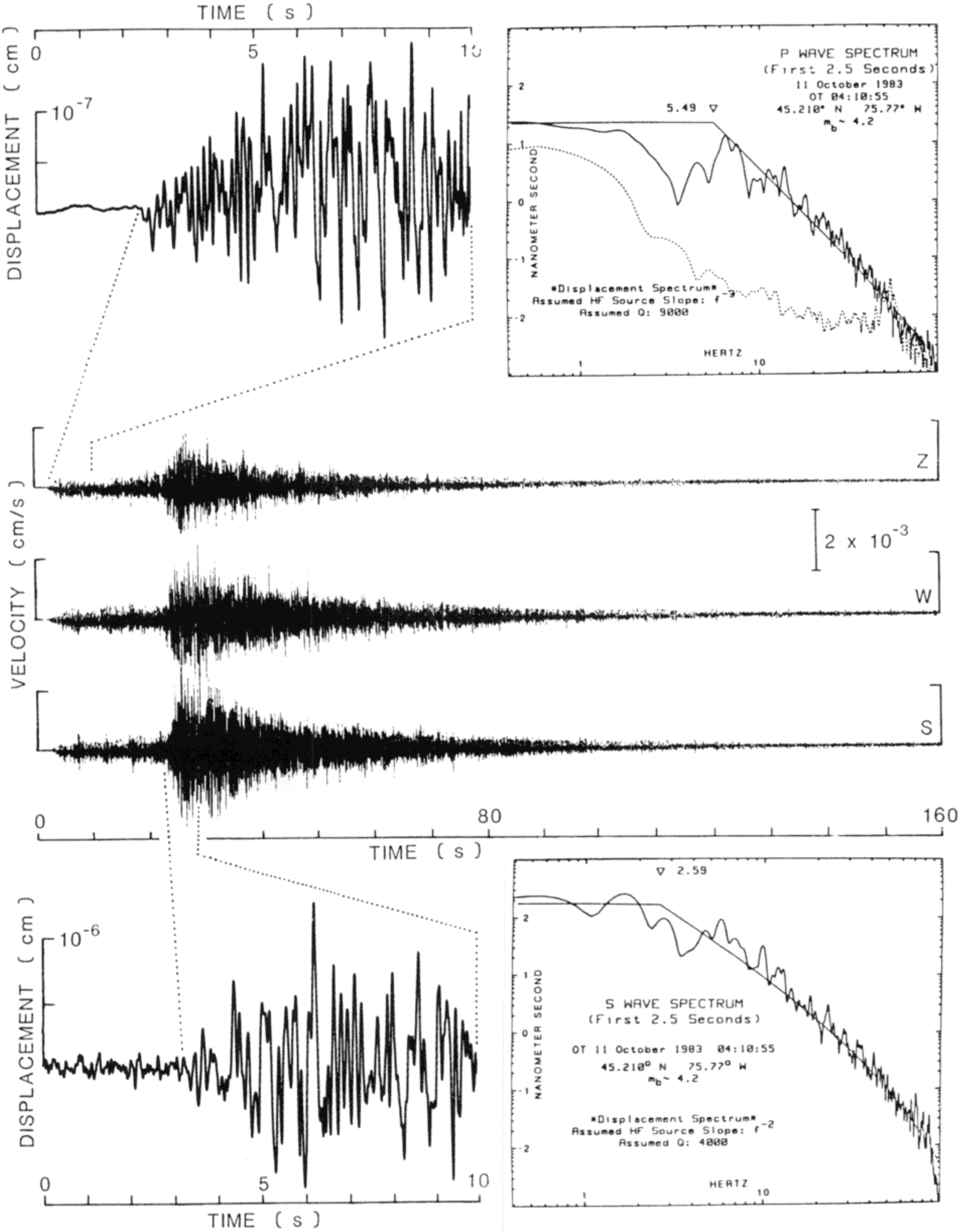

FIG. 19. Three components of ground motion (velocity) recorded for 160 sec at 400 sps on a GEOS sited in New York state at a distance of 192 km from an earthquake of magnitude 4.2 near Ottawa, Canada. Ground displacements inferred by direct integration are plotted at an expanded time scale for the initial P- and S-wave arrivals on the vertical and transverse components, respectively. Fourier spectra computed from the inferred displacements show discernible seismic energy at frequencies as high as 80 Hz and argue for extension of nuclear detection bandwidths to frequencies above 20 Hz.

show seismic signals discernible from the system noise as high as 80 Hz. Based in part on these and similar data [Evernden *et al.* (1985)] suggests that improvements in nuclear discrimination are possible with high-frequency seismic data collected at regional distances. In addition, the recordings argue for extending teleseismic recording capabilities for some worldwide stations to frequencies significantly higher than 20 Hz.

Crustal-strain, tilt, and displacement measurements contain important information on the physical properties of the Earth, the dynamic response of the crust, and, for near-field and active-fault monitoring, the details of preseismic and coseismic fault rupture. Much of this information lies in the period band 0.1 to 10,000 sec. At these periods, the dynamic range of the sensors (e.g., Sacks-Evertson dilatometer, Sacks *et al.*, 1971) typically exceeds 120 dB, and measurements are generally limited by the recording system used (McGarr *et al.*, 1982).

The GEOS is well suited to recording these data, and so experiments were designed to test this application in both continuous- and trigger-record modes. These experiments (Johnston and Borcherdt, 1984) included: (1) definition of Earth-strain noise at 10 deep-borehole dilatometer sites across California in the period band 0.1 sec to 24 hr; (2) simultaneous recording of three-component seismic and strain data during the detonation of a nuclear explosion in Nevada; and (3) near-field recording of strain and seismic data during local earthquakes. For these experiments, the GEOS units were operated as single- and three-channel systems at gains of 36 and 42 dB and sampling rates of 10, 50, 100, and 400 sps, with and without corresponding antialiasing filters.

Figure 20 shows an example of Earth strain recorded 31 May 1984 at a depth of 200 m near San Juan Bautista, California. The background sinusoidal variations are Earth tides with an amplitude of about 9×10^{-8} strain. Superimposed on these tidal variations is the decimated strain seismogram generated by a nuclear explosion in Nevada at a distance of about 400 km. The expanded time history of this signal is shown in the lower plot in Figure 20. The peak-to-peak strain variation is about 4×10^{-8} strain; smaller strain variations (down to about 5×10^{-11} strain) are superimposed on the strain-time history for the nuclear event. Spectral analysis of the strain seismogram (not shown) verifies that most of the energy is in the period band 0.5 to 20 sec, with a peak at about 3 sec. In contrast, the seismic energy simultaneously recorded on a Mark Products L4 sensor peaks between 1 and 2 Hz.

Average power spectra computed from the recordings of dilational strain indicate a 6-sec microseism peak at the quieter sites and provide an estimate of variations in Earth strain as low as 5×10^{-11} strain in the period band 0.1 sec to a few hours (Johnston and Borcherdt, 1984). Simultaneous recordings at seven dilatometer sites in California of a later nuclear explosion as detected by both seismometers and dilatometers have provided an opportunity to further investigate sensor-site characteristics of the dilatometer installations in the short-period range of 0.1 sec to 2 hr (Johnston and Borcherdt, 1984).

An earthquake of M 2.9 occurred at a hypocentral distance of 3.4 km from a GEOS recording site on 26 May 1984 (M. J. S. Johnston and R. D. Borcherdt, unpublished data, 1985). This earthquake was recorded by a GEOS unit operating as a three-channel system in trigger-record mode at 50 sps with antialiasing filters, using a dilatometer and two horizontal velocity transducers as sensors. The recorded dilatometer trace (Figure 21) suggests that the peak dilational strain associated with the earthquake occurred at about 1 Hz with significant energy in the band of

0.3 to 3.0 Hz. Comparison of the spectra computed for 1.5 min of the recordings from the dilatometer and the velocity transducer emphasizes the improved long-period response of the dilatometer, with the long-period level on the dilatometer spectra being consistent with the earth-strain noise levels for this period band established by Johnston and Borcherdt (1984). Of particular interest is the static or dc offset that is observed only in the dilatometer record. Analysis of this offset indicates that its origin is not instrumental. The most likely explanation of the offset appears to be coseismic-strain release associated with the nearby event. The offset corresponds to 1.86 nanostrain. Modeling of the earthquake with a simple dislocation-slip model for the event of dimension 250 m^2 at a depth of 2.6 km (Johnston and Borcherdt, 1985) with a moment of 6.3×10^{20} dyne-cm (Thatcher and Hanks, 1973) yields a static-dilational strain offset at the instrument location

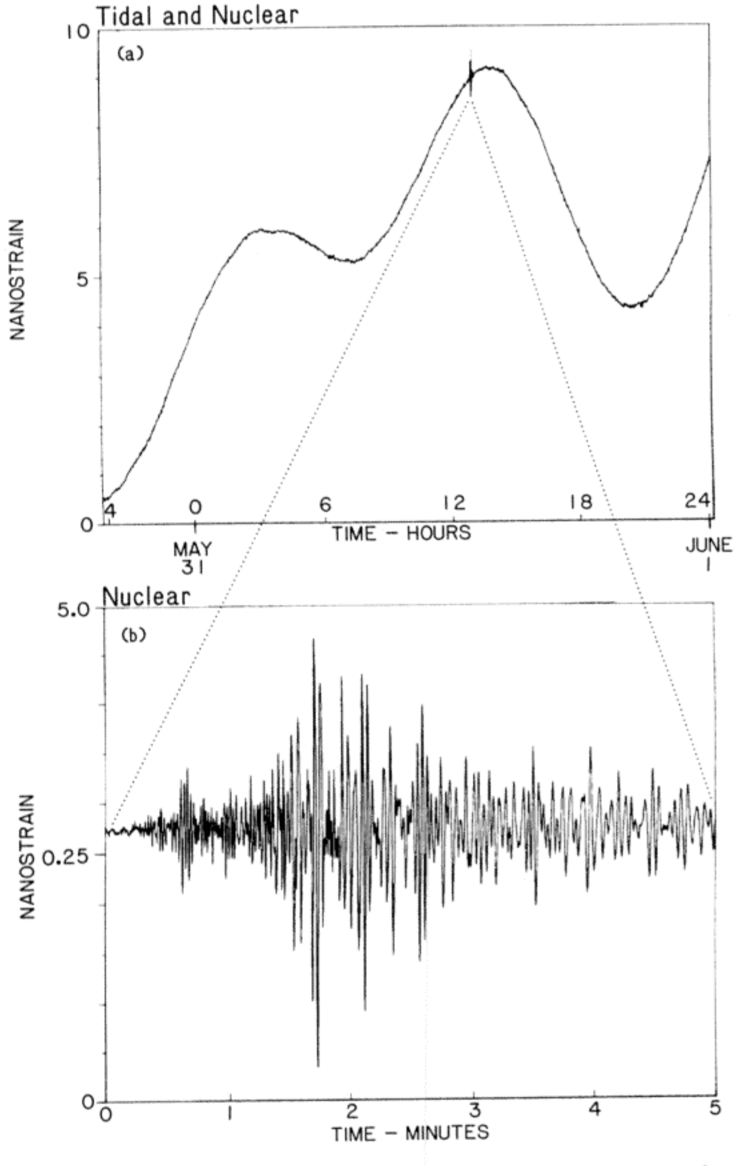

FIG. 20. Variations in Earth strain detected by Sacks-Evertson dilatometer and recorded on a GEOS unit at a site near San Juan Bautista, California. *Upper plot* shows tidal strains at 0.1 sps for a 28-hr interval and strains associated with detonation of a nuclear device in Nevada at a distance of 400 km. *Lower figure* shows strain variations recorded from nuclear explosion, plotted at an expanded scale and at 50 sps used to record the data.

of 2 nanostrain, for a crustal rigidity of 2.3×10^5 bars. Uncertainties in the various model parameters imply at least a factor of four uncertainty in the calculated value. Within this factor of uncertainty, the observed and calculated strain offsets are consistent.

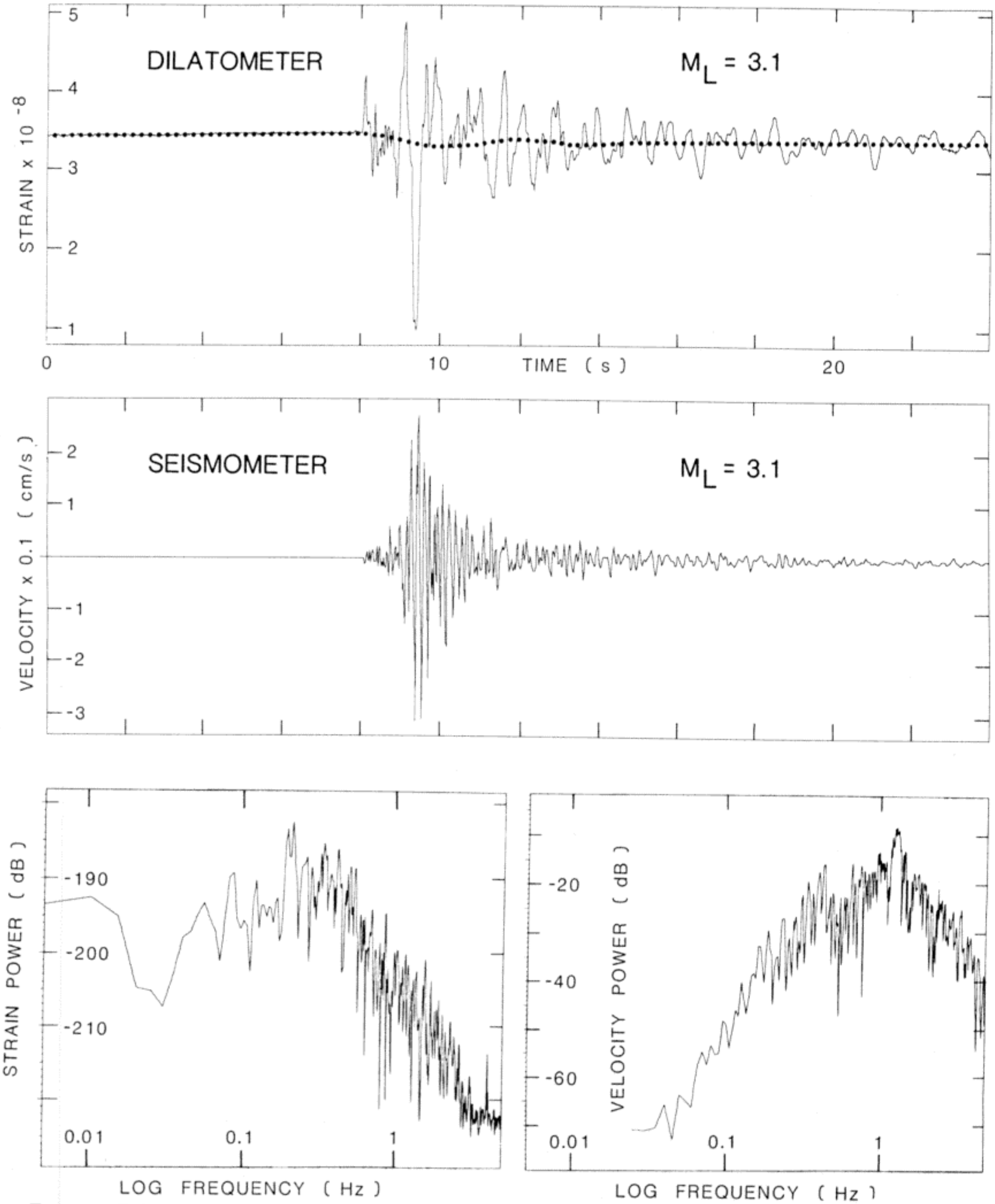

FIG. 21. Dilational Earth strain and ground velocity recorded on a GEOS unit operated with a Sacks-Evertson dilatometer and two L4-C horizontal seismometers as sensors. Corresponding power spectra emphasize sensitivities of the dilatometer and seismometer to long- and short-period motions, respectively.

The experiments to record Earth strain have served to partly evaluate the usefulness of the GEOS design concepts for long-term-deployment applications involving low-sampling rates and continuous recording. These experiments suggested some modifications of the applications software that can be implemented at level 3 to improve performance. Disconnecting power to the mass-storage device while the data buffer is collecting data at low sampling rates in continuous-record mode will reduce total power consumption. Further reduction can be achieved by increasing the data-buffer size. Implementation of digital filtering, selectable sampling rates for each channel, and satellite telemetry will also improve the versatility of the GEOS for such experiments. Each of these changes, except for increasing the data-buffer size, is planned for implementation in present production models by addition of software at level 3.

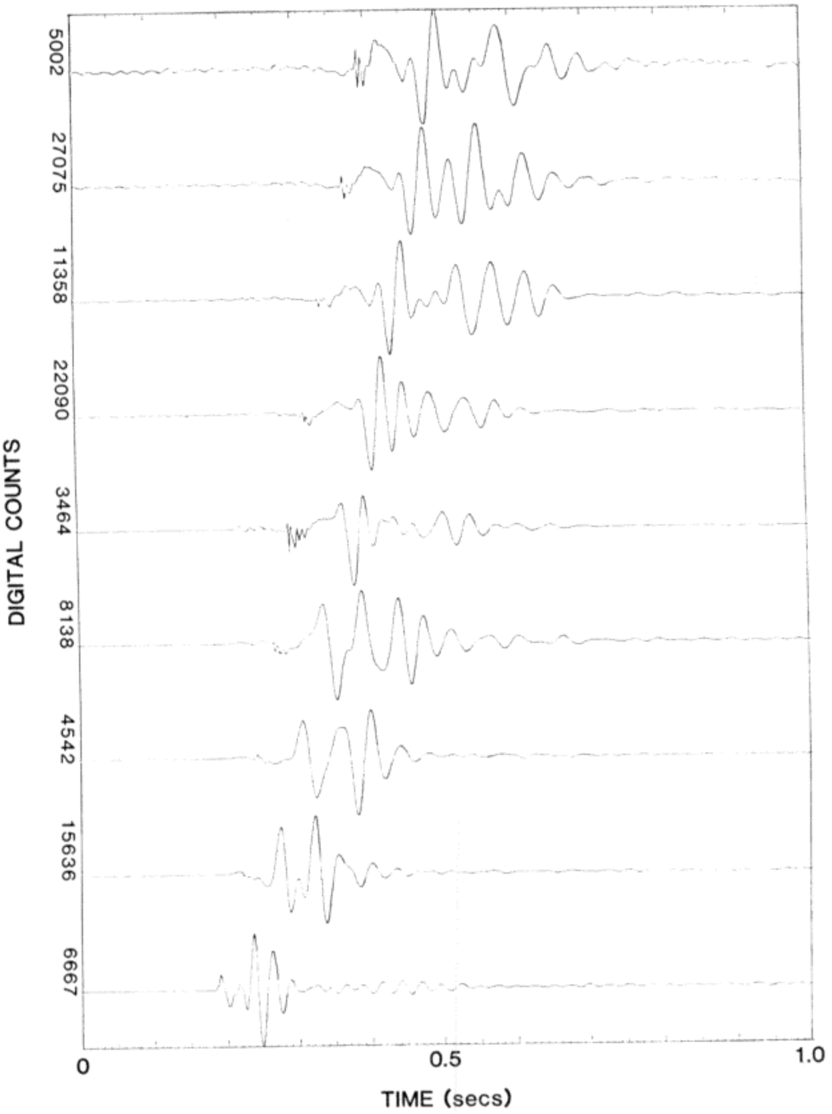

FIG. 22. Strong ground motions recorded at 600 sps on five GEOS units operated in preset-time mode, using linear array of radial velocity transducers. Ground motions were generated by a test explosion in a linear array of vertical line sources used for dynamic testing of engineered structures (Lindberg *et al.*, 1984).

The capability of the GEOS to record at selectable times or time intervals, as well as the option to simultaneously record in event-trigger mode, was used to record two seismic-refraction shots, and one contained explosion intended to simulate near-source earthquake-induced strong ground shaking. The data (Figure 22) were collected as part of an experiment to investigate the simultaneous detonation of explosives in a planar array of vertical line sources for the purpose of generating strong, earthquake-like ground motions useful for dynamic testing of soil structures and engineered structures. These data were recorded at 600 sps on five GEOS units operated in preset-time mode (see Figure 3), using a linear array of radial velocity transducers out to a distance of about 75 m from the source. The equiscaled data show signals varying in frequency content from about 20 to 100 Hz and some dispersion of the larger amplitude ground motions corresponding to wavelengths of only a few meters; these features suggest relatively high and varying radial-strain levels over the dimensions of the array (Lindberg *et al.*, 1984).

Field-Data Retrieval Via Minicomputer

A major consideration in the utilization of digital data-acquisition systems involves the capability to transfer data from initial recording media to desired computer system for data processing and analysis. The ease with which this transfer can be achieved is commonly significant for the success of certain experiments and, for microprocessor-based systems, somewhat crucial, because digital-data transfer also is needed for the design and implementation of operational software. Present computer technology permits the design of digital data-transfer capabilities for simultaneous implementation on small rugged computers appropriate for field deployment, as well as on compatible larger systems appropriate primarily for office use. Because the field-data retrieval and processing capabilities permitted by the mass-storage device chosen for the GEOS are essential to several design applications of the system, a brief description is included here for completeness.

Requirements for the hardware chosen to be incorporated into minicomputer data playback and analysis systems included: a common, standard CPU family suitable for real-time and multi-tasking applications, with a broad library of acceptable seismic data- and signal-processing algorithms; sufficient semi-conductor memory storage with error-correcting logic to allow several tasks to be simultaneously executed efficiently to provide rapid turnaround; substantial high-density random-access mass storage utilizing state-of-the-art Winchester sealed-media technology for the temporary storage of digital data recorded during experiments; hardware to provide additional applications, including editing and graphics cathode-ray tube terminals, low-cost graphics pen plotters, and floating-point arithmetic accelerators to improve speed of calculations; and ruggedized enclosures for ease of transportation to a remote base of field operations. A present version of the portable minicomputer playback system is implemented with an LSI-11 16-bit CPU with FPF-11 accelerator, 1 Mbyte of semiconductor RAM, 30 Mbytes of random-access mass storage utilizing Winchester technology, 60 Mbytes of removable cartridge-tape media, two cartridge-tape drives compatible with the GEOS mass-storage media, four serial communication ports with RS-232 compatibility, a low-cost pen plotter, and a cathode-ray tube terminal with both editing and graphics capabilities that also serves as the system console terminal.

Software requirements for the minicomputer playback systems were selected to provide maximum compatibility between field and laboratory systems. These requirements include: the use of a common user interface with the systems; the ability to execute identical data processing and analysis programs without requiring program conversion; the inclusion of program-development tools, such as editors, compilers, and linkers; a provision for system-management software for archiving data, diagnosing and analyzing hardware and software failures, and configuring system features; and the ability to transmit critical data to the laboratory in a timely manner.

Recent experiences with field deployments of the GEOS have illustrated the benefits of a field minicomputer playback system. Utilization of the system has provided field technicians and scientists with invaluable data concerning the verification of system operation and the appropriateness of array design during the course of various experiments. The minicomputer system has proved to be especially useful for editing and preprocessing data in the field, and can be a mandatory part of software development in either the field or the laboratory for microcomputer-controlled data-acquisition systems.

DISCUSSION

Although not all intended applications of the microcomputer-controlled data-acquisition system discussed herein have been tested, the applications to date have demonstrated the value of the design concepts in a wide variety of experiments. The different data sets collected have demonstrated the usefulness of the modular design concepts with central control by a single microcomputer and emphasized the significance of high resolution and broad bandwidth in achieving adaptability. Isolation of required hardware functions on separate modules has facilitated system upgrades to incorporate techological improvements. The general hardware and software architecture of the GEOS has provided a basis for continuing development and implementation of user-specified design features, and is expected to provide a useful environment for considerable expansion of system capabilities in the future.

The applications to date have provided an opportunity to examine several design features for a microcomputer-controlled system, including bandwidth, dynamic range, resolution, portability, power consumption, data-recovery capabilities and data capacity, and several field-selectable characteristics, such as type of sensor, number of channels, gain, digitization rates and resulting bandwidth, filter characteristics, record and playback modes, and system calibration. The resulting data sets have shown that these features, as presently implemented in the GEOS, are adequate for many land-based applications; however, adaptability can be increased with the implementation of additional features via software, such as satellite telemetry, digital filtering for low data-rate experiments, and steps to reduce power consumption in continuous-record mode. The design framework for a microcomputer-controlled system as implemented in the GEOS will facilitate development of additional design features as user needs dictate.

Preliminary specifications for large arrays of instrumentation have been proposed for studies of the continental lithosphere (Meyer, 1984; Phinney *et al.*, 1984). In general, these specifications call for a portable low-power microprocessor-based data-acquisition system having modular components configured to emphasize crustal-imaging or seismic-refraction experiments. Comparison of one set of proposed performance specifications (Meyer, 1984) with those for the GEOS (see Table 1) shows that the GEOS either meets, exceeds or can be easily modified, as intended at levels 1 to 3, to meet the proposed specifications. As the GEOS design was intended as a general framework from which a variety of special purpose data acquisition systems can be easily configured, it is of interest to examine a planned configuration of the GEOS that would allow it to be more easily deployed for such experiments.

Desirable system attributes for crustal imaging are small size and ease in operation. A planned configuration of the GEOS that would allow the system to exceed the proposed specifications for size, weight, and operating temperature is replacement of the cartridge tape and associated controller with a solid-state memory board. This change, which can be easily implemented at level 3, would permit reductions in both size and weight of the present system. Further reductions can be achieved by decreasing the number of channels, using external batteries, and utilizing an external CPU for operational-parameter selection. System size can thus be reduced to about 8 × 9 × 13 in, and by utilizing a fiberglass carrying case, the weight can probably be reduced to less than 15 lb. Slight software modifications would allow system operation to involve no more than power-up for routine applications. Utilization of a memory board for mass-data storage offers the advantage of the increasing the operating-temperature range over that imposed by the characteristics of magnetic tape and would allow use of the system in cold environments, such as Alaska. However, these proposed changes cannot be implemented without sacrificing beneficial attributes of the system for other applications. Utilization of the memory board reduces data capacity, data accessibility, and data transportability. Decrease in the number of channels can reduce the effective dynamic range and the usefulness of the system for studies requiring two types of three-component sensors, such as aftershock studies. Use of external batteries and external CPU for operational-parameter change eliminates the self-containment attribute of the systems and implies that full capability to reconfigure the systems in the field would no longer involve merely selection of menu mode via the field data-acquisition system. Nonetheless, repeated use of a large number of units for seismic-refraction experiments could justify production of a GEOS configuration for dedicated refraction use. Fortunately, the microcomputer, together with modular hardware components, provides a general framework (see Figure 1) from which special systems with emphasis on particular attributes can be easily configured. In addition, modern technology offers the possibility of reducing many of the module components of GEOS to chip level. Such efforts would generate a significant advance in seismic-data acquisition capabilities as a result of significant reductions in size, weight, and production costs, as well as improvements in reproducibility and reliability without loss of performance.

Experience gained during 5 yr of system development involving design specifications, prototype construction, and final production of an array of GEOS units indicates that the most crucial aspect of the system may be the development of robust and versatile software. Without appropriate software, the extensive capabilities of a microcomputer controlled system can only be partly realized. The software and its architecture, in addition to determining actual system capabilities, control the capabilities for system debugging, determine system reliability, provide the framework for development of future system capabilities, and unless designed carefully, can be the most costly aspect of system development.

Present cost (in 1984 United States dollars) of hardware components, including loading of boards, is approximately $6500 to $7000 for components ordered separately in lots sufficient for construction of 20 systems. Costs for contracting construction and some quality testing is expected to be about $3000 per system. Construction of systems by a standard instrument manufacturer could be expected to be about 2.5 times hardware costs. The hardware costs of the systems can be reduced by about $1700 by replacing the CMOS 16-bit A/D-conversion board, which costs about $2000, with a CMOS 12-bit A/D converter. Construction costs also can be reduced by increasing the size of production lots.

The data sets collected to date using the GEOS have emphasized repeatedly the significance of bandwidth and resolution in obtaining high-quality data. These instrumental characteristics were principal factors in obtaining the recordings of near-source seismic-radiation fields for events as large as *M* 5.1 with a resolution for some events higher than 84 dB at frequencies ranging from 0.1 to 300 Hz. These factors were major contributors to the essentially complete on-scale records of seismicity obtained with signal amplitudes ranging over 180 dB for further examination of source-scaling questions, and to the regional records that argue for extending bandwidth as high as 100 Hz for some teleseismic and nuclear detection studies. These design characteristics played a significant role in acquisition of the unique records of Earth strain, which permit the definition of noise characteristics down to 5×10^{-11} in the band 1.4×10^{-4} to 10 Hz, the observation of distant nuclear events for purposes of sensor-site calibration, and the possible observation of potential coseismic-strain release for a small earthquake in California. Broad bandwidth and high resolution, in addition to being basic requirements of any system intended for the acquisition of high-quality data, are also basic requirements of any microcomputer-controlled system intended for use in a wide variety of active and passive seismic experiments. Emphasis on reduction of appropriate modular system components to chip level could produce the next generation of seismic data-acquisition capabilities.

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