The Long-Term Measurement of Strong-Motion Earthquakes Offshore Southern California*

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ABSTRACT

This paper describes a new long-life Seafloor Earthquake Measurement System (SEMS) and presents earthquake data obtained from the seafloor near an offshore oil production field. The SEMS is a battery-powered (8 year life) digital data acquisition system which telemeters data via a sonar link. Seafloor earthquake data from SEMS indicate that the seafloor vertical acceleration is nearly an order of magnitude weaker than the corresponding on-shore vertical motions. The importance of the SEMS measurements in designing earthquake-resistant offshore structures is also described.

INTRODUCTION

A significant consideration in the design of offshore structures is their response to environmental stimuli. Information regarding climatic and oceanographic environmental stimuli for most offshore areas is extensive. As such, a solid data base is available for designing offshore structures that can withstand the threats of storm winds, waves, and ice floes. In regions such as offshore southern California and offshore Alaska, an equally important environmental stimulus is the seismic vibrations induced by local earthquakes. Data on the response of seafloor sediments to earthquake-induced seismicity has been scarce, thereby introducing significant uncertainty into the seismic-hazards aspect of offshore structural design. To reduce this uncertainty, a program was undertaken to develop and implement instrumentation to measure seafloor seismic motions. The result of this program has been two-fold: the deployment of a long-term, strong-motion digital seismograph offshore southern California; and the offshore recording of several significant earthquakes. Two of the earthquakes recorded by a seafloor instrument were simultaneously recorded by on-shore instruments, and by instruments located on a nearby offshore oil platform. Thus, some of the problems associated with the design of offshore earthquake-resistant structures can now be addressed with supporting data.

In this paper, the most recent Seafloor Earthquake Measurement System (SEMS) will be described. This system is currently operating in 210 ft of water, 10 miles offshore Long Beach, CA, in the Beta Field. Data obtained from this unit and previous prototype SEMS will be presented. The implications of this data on the design of offshore earthquake-resistant structures will also be described.

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INSTRUMENTATION DESCRIPTION

General System Overview

It has long been recognized [1] that offshore strong motion seismographs are needed to complement the on-shore strong motion networks. The main difficulties associated with implementing these offshore seismographs are the remoteness of the site and the severity of the site environment. As a result, previous attempts at sea-bottom seismographs tended to be experimental in nature. Previous offshore strong-motion seismographs can be grouped into two categories: those that are tethered by a long power and signal cable (e.g. [2]), and those that are electrically autonomous (e.g. [3]). Unfortunately, the tethered-type are inappropriate for remote sites and are relatively costly to deploy and maintain. Autonomous types, while suitable for remote locations, have the added complexity of an internal power source and a data-telemetry system. The use of a power source and telemetry system in prior attempts [4], have resulted in systems with relatively short lives and limited recording lengths.

The objective of the Seafloor Earthquake Measurement System Project was to develop and implement a long-term autonomous seafloor seismograph with virtually unlimited recording capabilities. The system concept for the SEMS is depicted in Figure 1. The SEMS consists of two subsystems, an autonomous seafloor package and a shipboard interrogation unit. The seafloor unit is referred to as DAGS (DAta Gathering Sub-system). The DAGS package captures and records seismic activity, and transfers the digital data, on-command, to the shipboard subsystem via underwater acoustic telemetry. The DAGS can be controlled from a surface computer, thus allowing data retrieval, diagnostic analysis, and variability in operating parameters. The surface instrumentation consists of acoustic transmitting and receiving circuitry, referred to as BRES (Buoy REpeater System), and a controlling IBM PC compatible computer. The link between BRES and the IBM PC is through a direct serial RS-232 line. The PC serves as a user-friendly interface and allows direct communication with the seafloor instrumentation package. Once retrieved from DAGS, the earthquake data are stored on floppy disks, and can be analyzed and graphically viewed onboard the ship during the interrogation.

Seafloor Unit Description

Situated on the seafloor is the seismic instrumentation package. The seafloor electronics package, referred to as DAGS (DAta Gathering Sub-system), is connected to a seismic probe which is embedded in the seafloor sediments. By embedding the probe in the sediments, greatly improved soil coupling is attained relative to a mud-line sensor [2]. The probe consists of three accelerometers (configured tri-axially) to record the seismic motions, and a two-axis magnetometer to determine the absolute orientation of the accelerometers. DAGS consists of a data acquisition interface, a microprocessor controller, a low-power digital signal processor, a volatile Random Access Memory (RAM), a permanent non-volatile bubble memory, an acoustic telemetry system, and a battery power pack. A block diagram of the DAGS electronic subassemblies is depicted in Figure 2 and system specifications are listed in Table 1.

The most recent DAGS is capable of an autonomous, battery-powered life of 8 years. This impressive long life is attained by the use of high energy-density lithium batteries and ultra-low power consumption electronics. The DAGS utilizes 606 DD-cell lithium batteries configured as 202 3-packs. Each 3-pack has a nominal voltage of 10.8 volts and a rating of 28 Amp-hours.

Low power consumption by the DAGS electronics is achieved by use of CMOS technology and other low power components wherever possible. Particularly low power consumption results from the use of special-design dc/dc converters which attain up to 90% efficiency. The non-volatile magnetic bubble memory is used for long-term data storage and is only activated (i.e. consuming power) when significant earthquake events are detected. This bubble memory device has the advantage that it can be de-energized indefinitely without loss or degradation of stored data.

The SEMS uses low power accelerometers which, after gain and filtering, are capable of measuring acceleration levels from 0.05 milli-g to 2 g over frequencies ranging from 0.05 Hz to 20 Hz. Each accelerometer signal is digitized at a 100 Hz rate by a high-precision (16 bit) data acquisition subsystem. The digital accelerometer data is placed into volatile RAM and analyzed by the microprocessor and the Digital Signal Processor (DSP).

The most recent DAGS uses a novel software detection algorithm to process the accelerometer samples in RAM and determine the onset of a quake. The algorithm, as depicted in Figure 3, simultaneously processes all three accelerometer channels. All incoming raw data is placed into a 15 sec. pre-event buffer for possible future storing. The data are then passed through a digital band-pass filter. This filter is implemented on the DSP. The filter is nominally set to a band-pass from 2-10 Hz since this corresponds to the dominant frequency range of nearby strong motion quakes. This band pass also greatly reduces the passing of non strong-motion earthquake signals. For example, this filter will reject teleseismic events (frequency content < 1 HZ) and local marine engine noise (frequency content > 10 Hz).

The digitally-filtered data are then squared to obtain an energy-equivalent signal. The energy signal is then windowed for a predetermined time, usually 0.6 seconds, and the average over that window computed. The resulting measurement is a calibrated mean-square acceleration response of the seafloor. The advantage of using a time window is that it reduces the possibility of false triggers from anomalous short-duration data spikes. All three energy measurements are then compared to pre-set thresholds to decide whether or not an earthquake is occurring.

If an earthquake is occurring, then the data flow to the pre-event buffer is halted, and incoming raw data flows to a 15 second event buffer. When the event buffer is filled, the processor searches for a free block of bubble memory. If a free block is found, the data is stored in bubble memory. In the unlikely event that all of the bubble memory is filled, then the processor compares the energy of the current event with the energy of the smallest event stored in bubble memory. If the current event has less energy than the smallest event in bubble memory, then the current event is rejected, and normal processing continues. However, if the energy of the current event exceeds the energy of the smallest event in memory, then the data from the smallest event is overwritten. In this manner, the algorithm guarantees that significant quakes continue to be recorded even after the bubble memory fills up. Consequently, the complete filling of bubble memory is rare since the memory can hold approximately 56 15-second earthquakes. It is unlikely that this many quakes would occur during the average 3 months between interrogations.

Four important points should be noted regarding the earthquake detection algorithm. First, only raw, i.e., unprocessed data, are stored in the bubble memory. Therefore, the data retrieved via telemetry contain the full 0.05 Hz - 20 Hz bandwidth data. Second, all processing and storing of data are performed in real-time so that contiguous 15-sec. data blocks are possible for long duration earthquakes. Third, various parameters of the algorithm can be modified by telemetry to custom-tailor the earthquake detection capabilities. The digital filter characteristics, the time-gate duration, and the detection thresholds can all be remotely varied. Fourth, the algorithm detects motions on all three accelerometer channels. As will be shown in the Results Section, seafloor seismic motions are primarily horizontal. Therefore, more conventional earthquake detection algorithms, which use vertical triggering only, would be extremely inadequate for this application.

Installation of Seafloor Instrumentation

The most recent SEMS was installed by placing the seismic probe at the end of a 12-ft long vibrocoring drill and vibrating the probe into the seafloor sediments. A photograph of the installation apparatus is shown in Figure 4. In the photograph, the DAGS is the white structure with the twin pressure vessel housings, located at the bottom of the apparatus. The overall dimensions of the DAGS structure is approximately 6 ft in diameter and 2.5 ft in height. Placed around the DAGS is a temporary cage for supporting the vibrocoring drill operations. At the top of the cage is the vibrocoring drill itself, which attaches to a 12 ft long drill stem. At the end of the drill stem, in the center of the DAGS, is the attached probe. The attached probe is held to the drill stem under tension by a kevlar line which exits at the very top of the vibrocoring drill. The cage is attached to the DAGS by four pinned chains at the bottom of the structure.

The entire installation structure was lowered to the seafloor. Upon seafloor impact, the mass of the vibrocorer and support beam, and the buoyancy of the floats, resulted in a 18 in. burial of the probe. The vibrocoring drill was then turned on for less than 5 minutes. The drilling operation resulted in a probe tip burial in excess of 8 ft below the mud-line. At that point, a one-man submersible used its hydraulic manipulator to pull the pin at the top of the structure to release the probe from the drill stem. The sub then pulled the four pins which attached the DAGS to the temporary drill cage. The drill cage, vibrocorer drill, and drill stem were then pulled up together to the surface leaving only the DAGS and its probe in place. The entire operation took less than four hours at the site. This installation approach was extremely cost effective, and resulted in deep, rigid burial of the probe.

SEMS HISTORY AND RESULTS

The SEMS project was established in 1977, upon which a two-year effort was begun to develop prototype hardware. During 1979 and 1980, four prototype units, named SEMS I, were placed in the Santa Barbara Channel offshore California [5]. These prototype units had an operational life of less than 1 year each. The Santa Barbara Island Earthquake of 4 September 1981 (Magnitude 5.5 on the Richter Scale) was simultaneously recorded by two SEMS units. One of the SEMS units was situated under 165 ft of water, 53 mi from the earthquake epicenter. The second recording unit was situated on-shore, 61 mi from the epicenter.

Between 1982 and 1984, the SEMS system was upgraded to serve as a long-term seismic station for offshore Alaska. A second generation prototype system was developed and was deployed as a demonstration system offshore Long Beach, California, in 1985 [6]. This SEMS II unit was situated in 240 ft of water, 10 miles offshore Long Beach, in the Beta Field. This system was designed to respond primarily to strong motion earthquakes, and had a 2.5 year life. This system recorded two significant earthquakes during the month of July, 1986 [7]. The earthquakes recorded were the 8 July North Palm Springs Earthquake (6.0-magnitude, 91 mi epicentral distance) and the 13 July Oceanside Earthquake (5.8-magnitude, 46 mi epicentral distance).

Both the SEMS I and SEMS II units utilized a vertical-only detection algorithm [8]. As a result, these units suffered from a high false-trigger rate (as many as 1000 per month). The excessive number of false triggers was considered unacceptable since it caused excessive drain on the batteries.

The most recent SEMS unit, referred to as SEMS III, was deployed in July of 1989 and has a design life of 8-years. The SEMS III is situated in 210 ft of water, 10 miles offshore Long Beach, in the Beta Field. As discussed in the previous section, this unit utilizes the new multi-axis earthquake detection algorithm. During the first six weeks underwater, the unit experienced about 20 false triggers. These triggers were identified as small shocks due to settling of the mud in the borehole around the probe, and have since ceased. During the following five months (Sep 1989 - Jan 1989), the system experienced two false triggers and one earthquake event. At least one of the two false triggers have been identified as vibrations from on-board the nearby oil platform. The earthquake recorded by SEMS III was the only occurrence [9] of significant ground motion in the Long Beach area between the July 1989 installation and the writing of this paper (February 1990). The recorded earthquake corresponds to the 3.5-magnitude quake of 17 January 1990, centered near Gardena, CA. The epicenter of the quake occurred about 15 mi north of SEMS III on the Palos Verde Fault. Data from this minor quake are shown in Figure 5.

INTERPRETATION OF DATA

As discussed above, the July 1986 earthquakes were simultaneously recorded by SEMS, land-based seismographs, and an instrumented offshore platform. Located about 2 km south of the Long Beach SEMS site, the instrumented Shell Platform Eureka [10] recorded the July 1986 earthquakes at mud-line and deck levels. Sandia has acquired, under a proprietary agreement, the platform acceleration records. The platform records have been compared with SEMS records and data obtained from on-shore seismographic networks [11,12]. A plot comparing land-based measurements and SEMS measurements is shown in Figure 6. The analysis of the July 1986 earthquake data for the SEMS, Shell, and on-shore data has led to the following observations:

- The vertical component of acceleration observed at both the SEMS' site (i.e. free-field seafloor motion) and on the platform legs at mud-line level is significantly different than the corresponding vertical components of acceleration observed on-shore. A statistical analysis has shown that the offshore peak vertical accelerations are nearly an order of magnitude weaker than the corresponding on-shore measurements.

- It appears that the peak horizontal components of acceleration observed at the SEMS site and by the platform legs at mud-line level are comparable to the corresponding on-shore measurements. Additional earthquake data obtained from future earthquakes will be required to either confirm this observation or point out the subtle differences between on-shore and offshore horizontal accelerations.

The above conclusions have important implications for the design of offshore structures. It is clear that the design process for offshore structures will greatly benefit from earthquake data obtained offshore.

The most recent SEMS unit, SEMS III, has been extremely successful during the first 6 months of operation. The unit accurately triggered on a small local earthquake and has maintained an extremely low false-trigger rate. Additionally, the first earthquake data from SEMS III confirms the lack of offshore vertical seismic motions. Based on these results, it is expected that the SEMS III will be providing invaluable offshore seismic data throughout the 1990's.

APPLICATION TO OFFSHORE STRUCTURE DESIGN AND FUTURE WORK

The present goals of the SEMS program are (1) to collect and analyze data from the offshore seismograph station and (2) to verify, or if necessary, modify, existing models for predicting the response of saturated sediments to earthquake-induced seismicity.

In Figure 7, the application of the SEMS data to the overall design of earthquake-resistant platforms is indicated. The primary focus of the SEMS program is to verify, and if necessary, modify, existing models for saturated soil response. Work on the soil/platform coupling problem is being performed in cooperation with research on-going at the Scripps Oceanographic Institute [13]. Future plans call for the assimilation of all three seismic data sets (on-shore, sea-bed, and platform) to verify, and if necessary, modify, existing models for the response of offshore platforms to strong earthquakes.

Future plans also call for the summer of 1990 installation of a SEMS III unit offshore near Point Arguello. The site will be within close distance of the Unocal Platform Irene. The Long Beach SEMS and proposed Point Arguello SEMS will form an offshore seismic array for significant southern California earthquakes.

It is estimated that between 10% and 20% of the U.S. arctic oil reserves are situated in the southern Bering Sea. In order to extract these reserves, offshore platforms must be designed to withstand the frequent, large earthquakes that are characteristic of that area. Due to significant geologic differences, seismic data obtained offshore California may not be relevant to offshore Alaska. Hence, it is necessary to acquire offshore seismic data for Alaska in order to aid in the eventual development of offshore-Alaska energy resources. The long term future goal is to deploy an array of long-term offshore seismic stations in the Southern Bering and Aleutian region. Such an array will answer many of the uncertainties regarding the earthquake-resistant design of offshore structures.

CONCLUSIONS

An important issue for the design of offshore structures in seismically active areas is the response of the seafloor to earthquakes. Several prototype Seafloor Earthquake Measurement Systems (SEMS) have been deployed off of California and have resulted in the recording of unique offshore seismic data. A long-term SEMS unit (8-year life expectancy) has recently been deployed off of southern California and has proven itself to accurately and reliably record earthquakes as they occur. Earthquake data obtained from these instruments have shown that the seafloor behaves differently than dry soils during an earthquake. In particular, dry land shakes roughly equally in both vertical and horizontal directions, whereas the seafloor shakes primarily in horizontal directions. Past and future seafloor earthquake recordings should prove invaluable to designers of offshore structures and to government agencies that regulate those structures.

ACKNOWLEDGEMENTS

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REFERENCES

1. Present and Recommended U.S. Government Research in Seafloor Engineering, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Ocean Engineering, July, 1978.

2. T.L. Henyey, et al, "A Sea-floor Seismic Monitoring Network Around an Offshore Oilfield Platform and Recording of the August 13, 1978 Santa Barbara Earthquake," Proceedings of the 11th Annual Offshore Technology Conference, Houston TX, May 1979, pp. 2219-2223.

3. R.L. Steinmetz, et al, "Seismic Instrumentation of the Kodiak Shelf," Marine Geotechnology, Vol. 4, No. 3, 1981, pp 193-221.

4. G. Latham, et al, "The Texas Ocean-bottom Seismograph," Proc. of the 10th Annual Offshore Technology Conference, Houston TX, May 1978, pp. 1467-1476.

5. D.E. Ryerson, "Seafloor Earthquake Measurement System, Volumes I, II, and III," Sandia National Laboratories Report No. SAND81-1810, Albuquerque, NM, December 1981.

6. J.P. Hickerson and A.A. Lopez, "Design of the Shell Project Seafloor Earthquake Measurement System (SEMS)," Sandia National Laboratories Report No. SAND85-2604, Albuquerque, NM, March 1987.

7. G.E. Sleefe and D. Engi, "Seafloor Response for Two Southern California Earthquakes," Proceedings of the SEM Spring Conference on Experimental Mechanics, June 14-19, 1987. pp. 747-753.

8. J.S. Eterno, et al., "Special Event Detection for an Unattended Seismic Observatory," C.S. Laboratory, Cambridge, MA, Report No. R-765, March 1974.

9. "Preliminary Determination of Epicenters," California Institute of Technology, August 1989 - January 1990.

10. R. Husid, J.H. Haws, and M.M. Patterson, "A System for Acquiring Earthquake Data on Offshore Oil Platforms," Offshore Technology Conference, May 1985.

11. Huang, M.J., et al, "CSIMP Strong-motion Records From the Palm Springs, California Earthquake of 8 July 1986," California Dept. Conserv., Div. Mines and Geol., Report OSMS 86-05, 1986.

12. Porcella, R.L., et al, "Strong Motion Data From the July 8, 1986 North Palm Springs Earthquake and Aftershocks," U.S.G.S. Open-File report 87-155, 1987.

13. T. Nogami, "Soil/Pile Interaction Due to Seismic Response of Offshore Seafloor," U.S.D.O.I. Minerals Management Service, Technology Assessment and Research Program for Offshore Minerals Operations, 1988 Report, OCS Study MMS 88-0057, pp. 126-128, 1988.

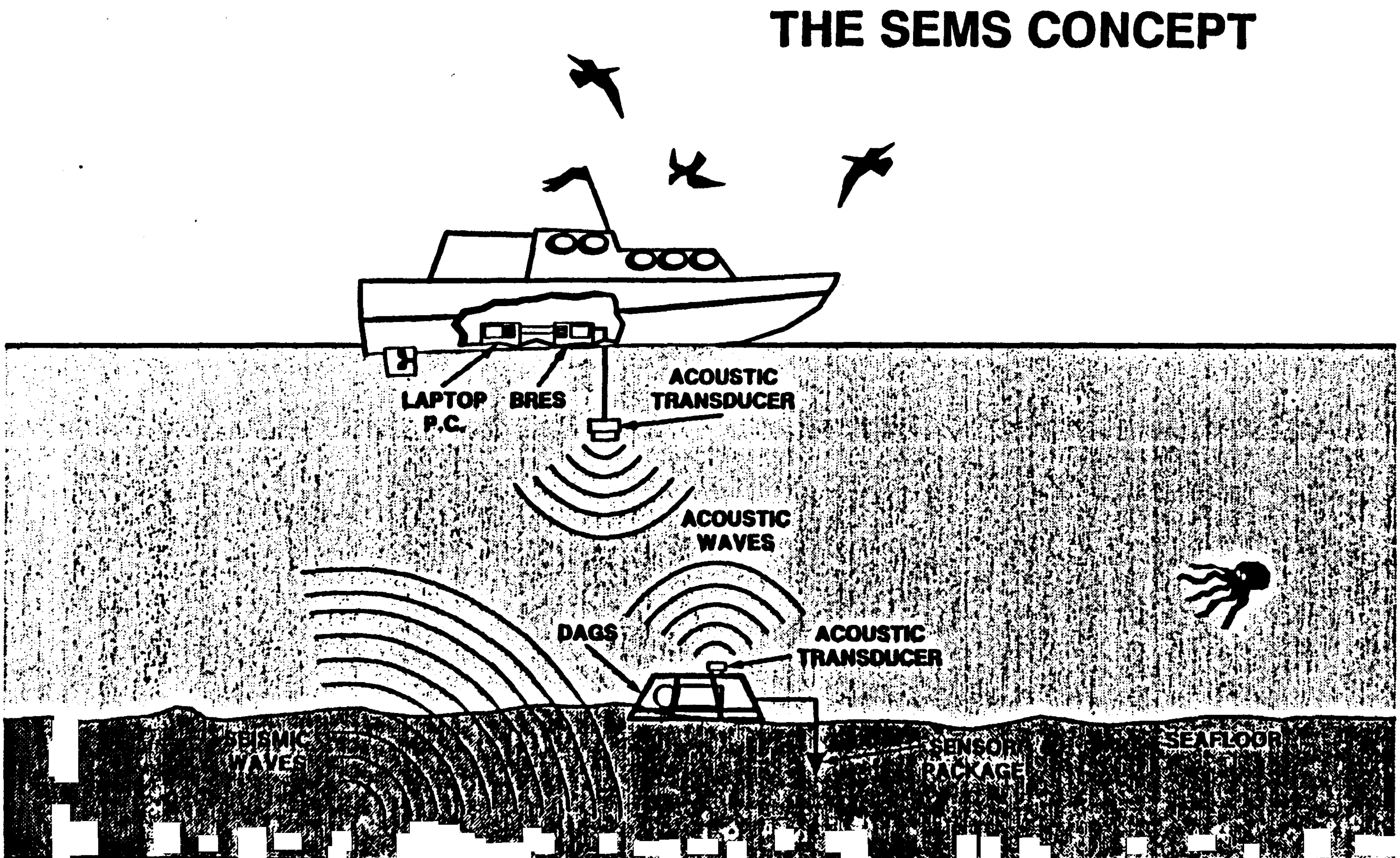


Figure 1 Illustration of Seafloor Earthquake Measurement System (SEMS) concept

SEMS III DAGS
ELECTRONICS OVERVIEW

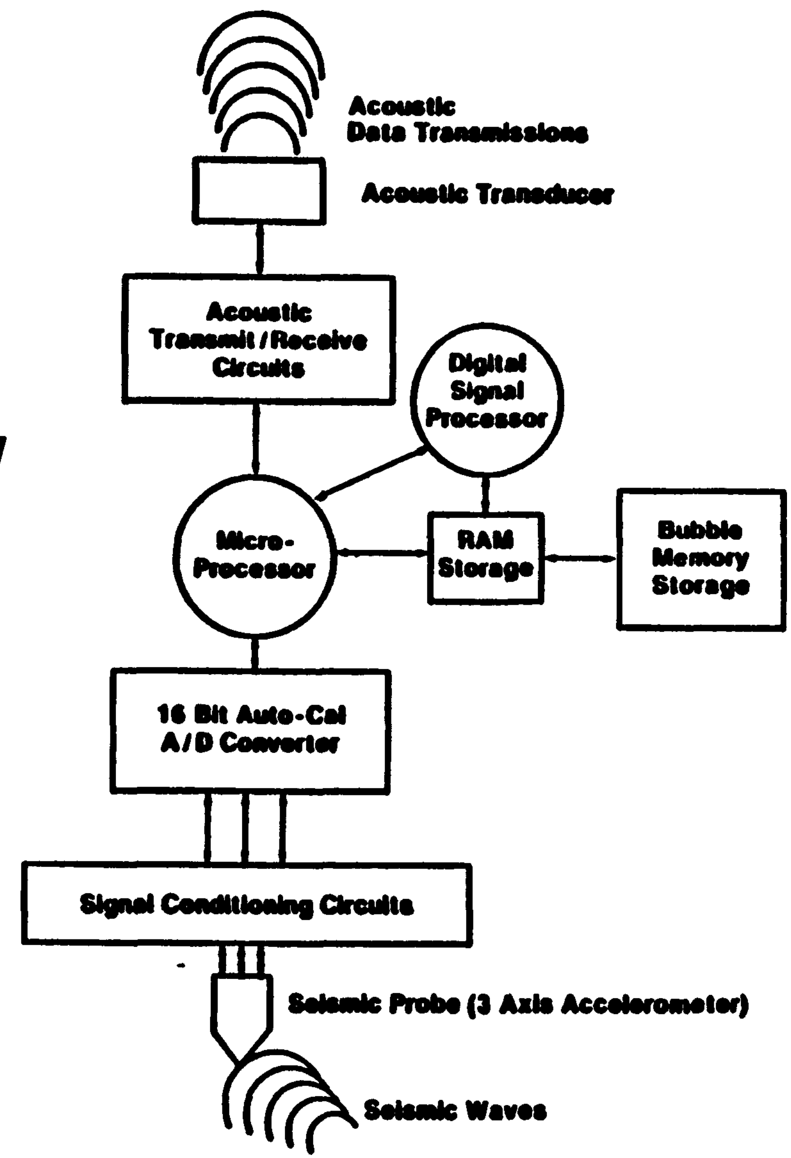
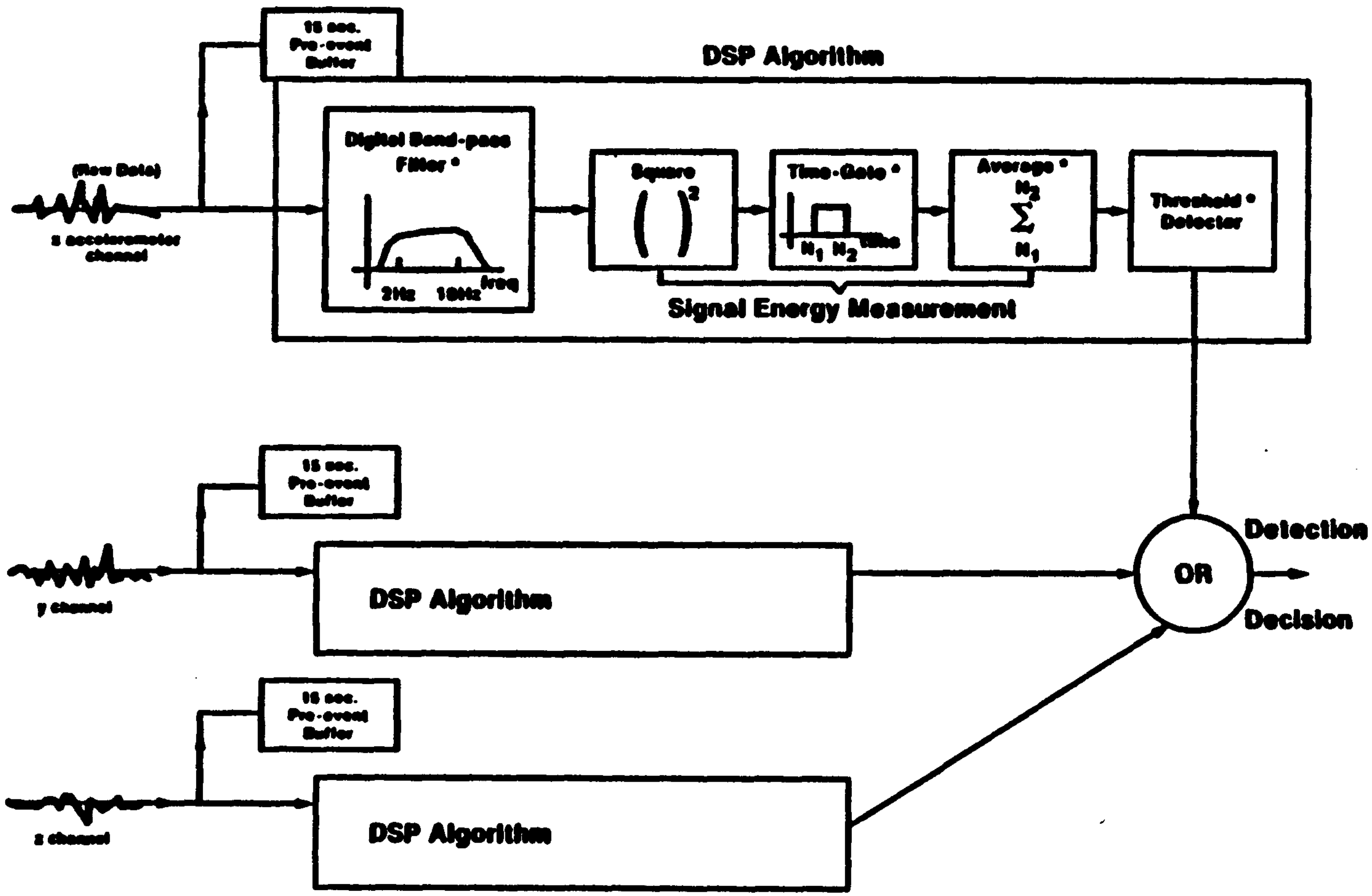


Figure 2 Block diagram of the Earthquake Data Gathering System (DAGS) electronics



Remotely Controlled Parameters: Filter characteristics, time-gate duration and detection thresholds.

*** = Variable Parameters**

Figure 3 Block diagram of the SEMS III real-time earthquake detection algorithm

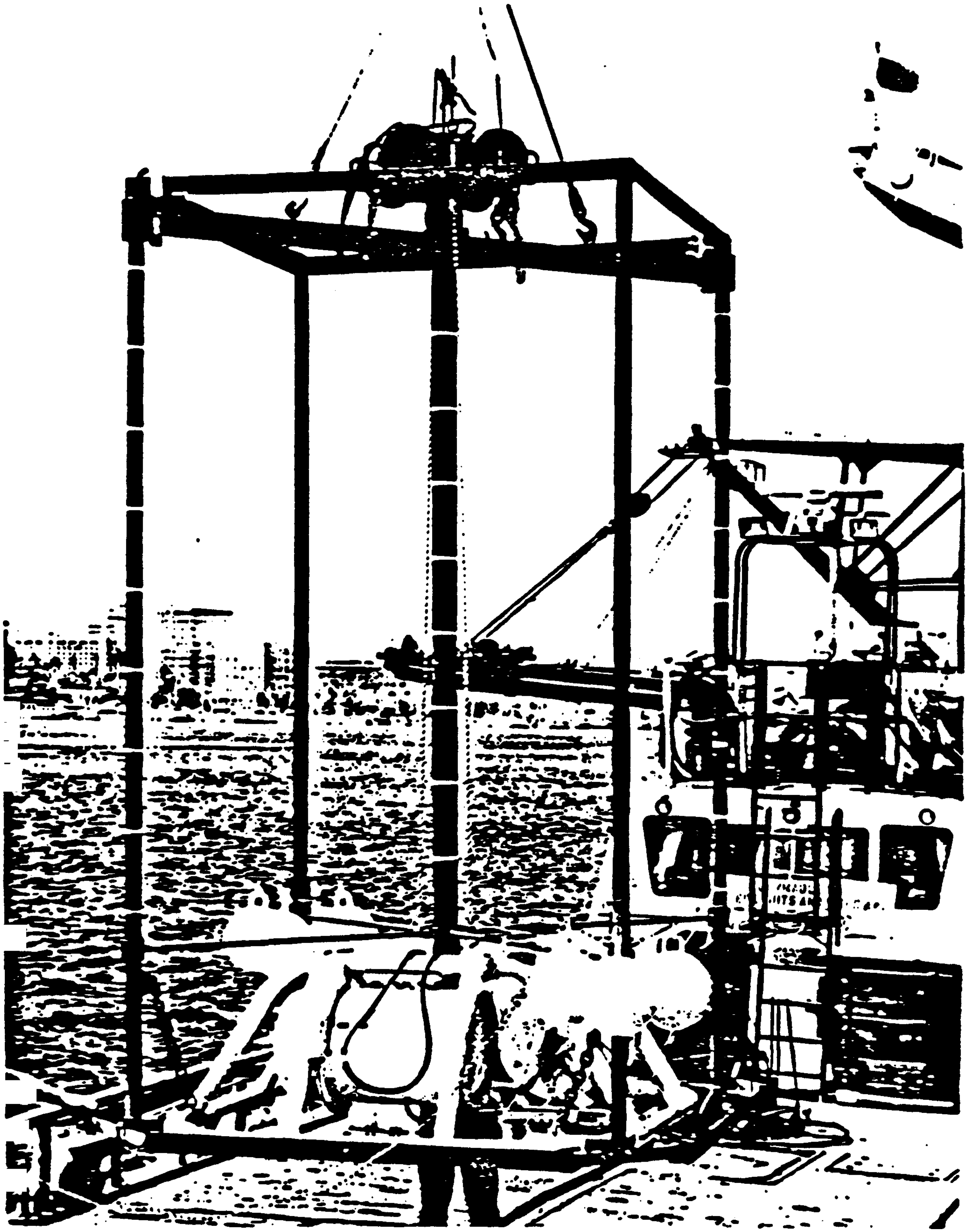


Figure 4 Photograph of DAGS and the installation apparatus used for July 1989 deployment

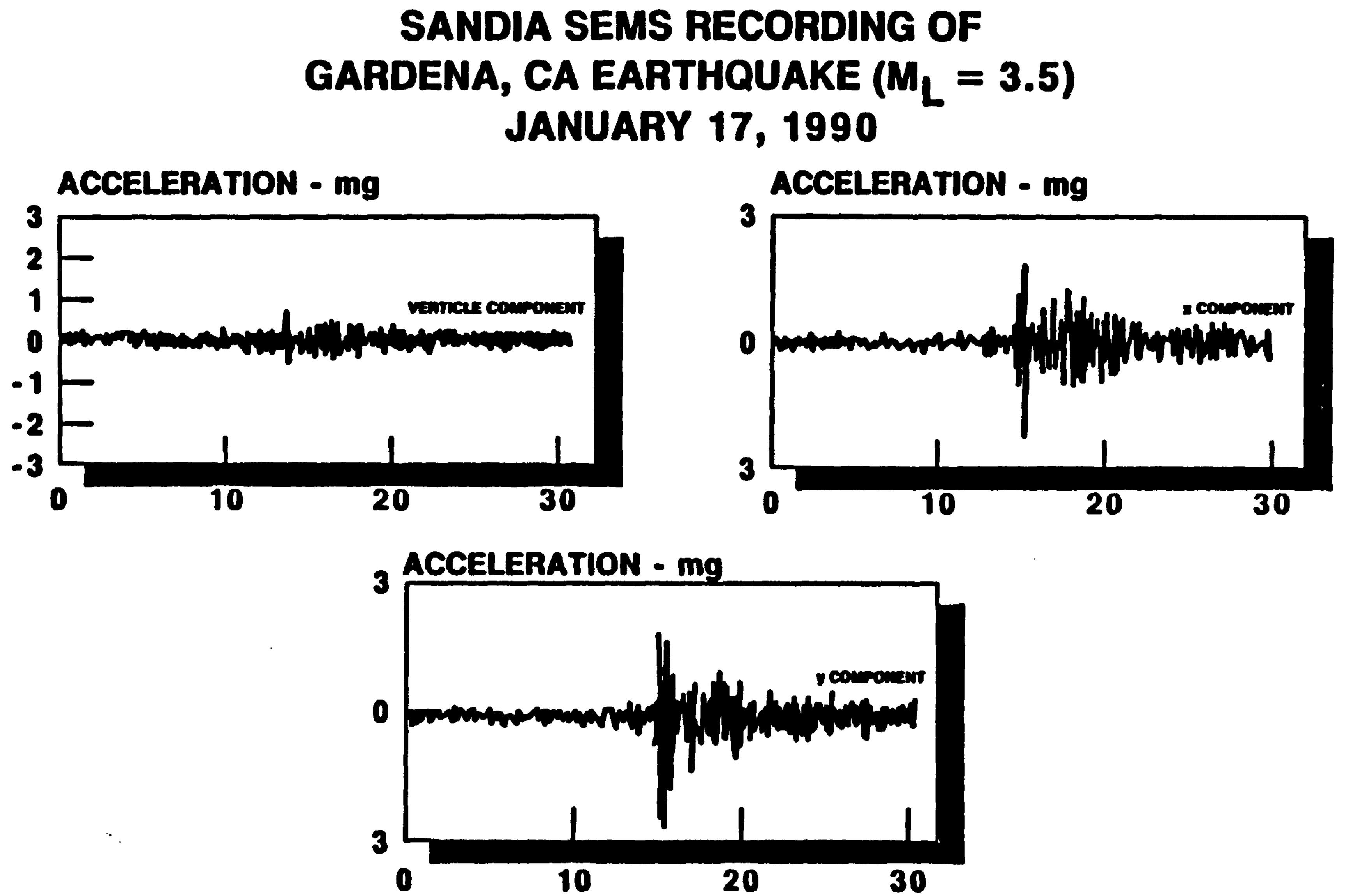


Figure 5 Plot of earthquake data from SEMS III (1-17-90 Gardena, CA, earthquake)

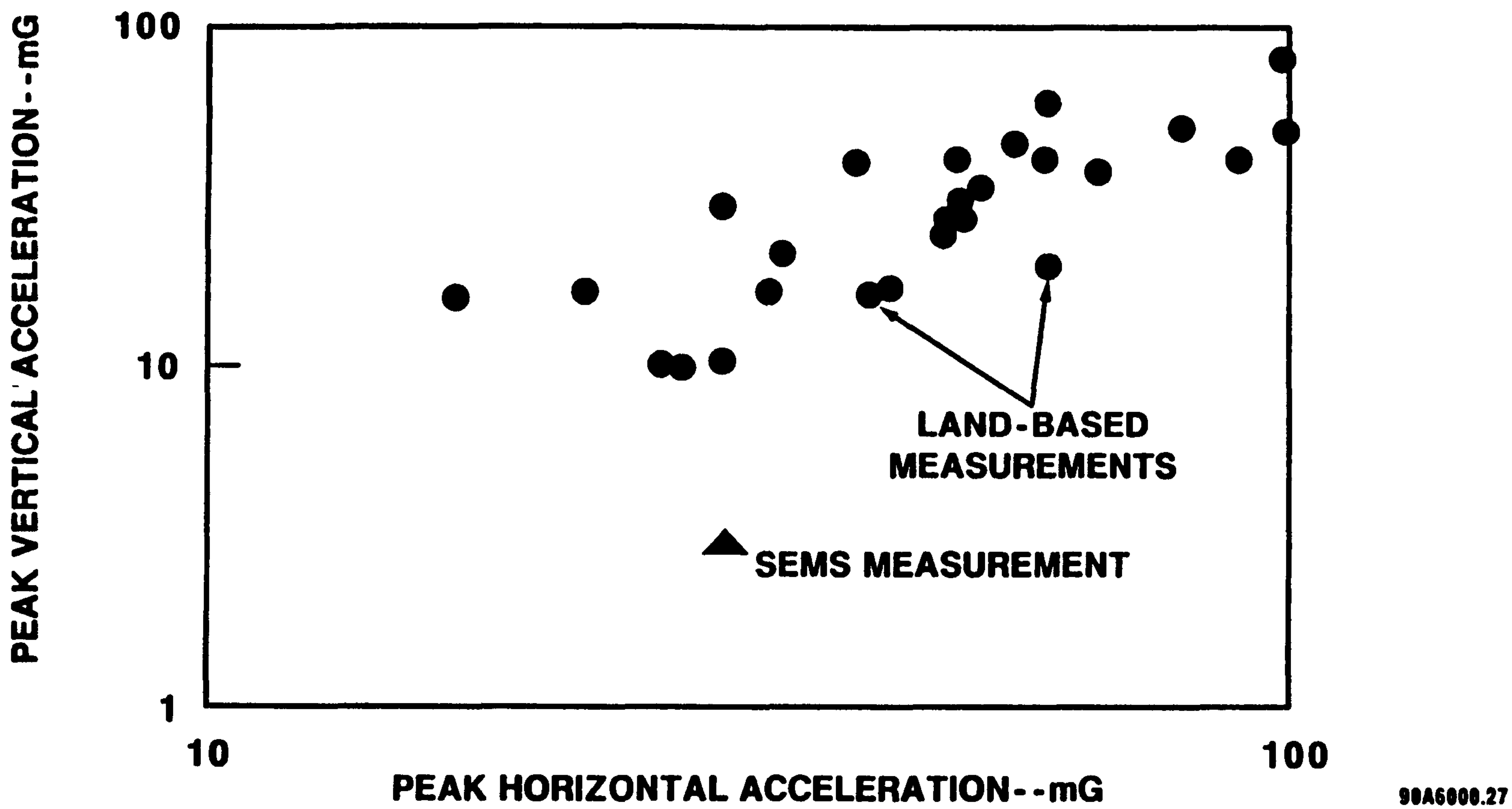


Figure 6 Comparison of Land-based and SEMS measured accelerations for North Palm Springs Earthquake of July 8, 1986

OFFSHORE PLATFORM RESPONSE TO EARTHQUAKES

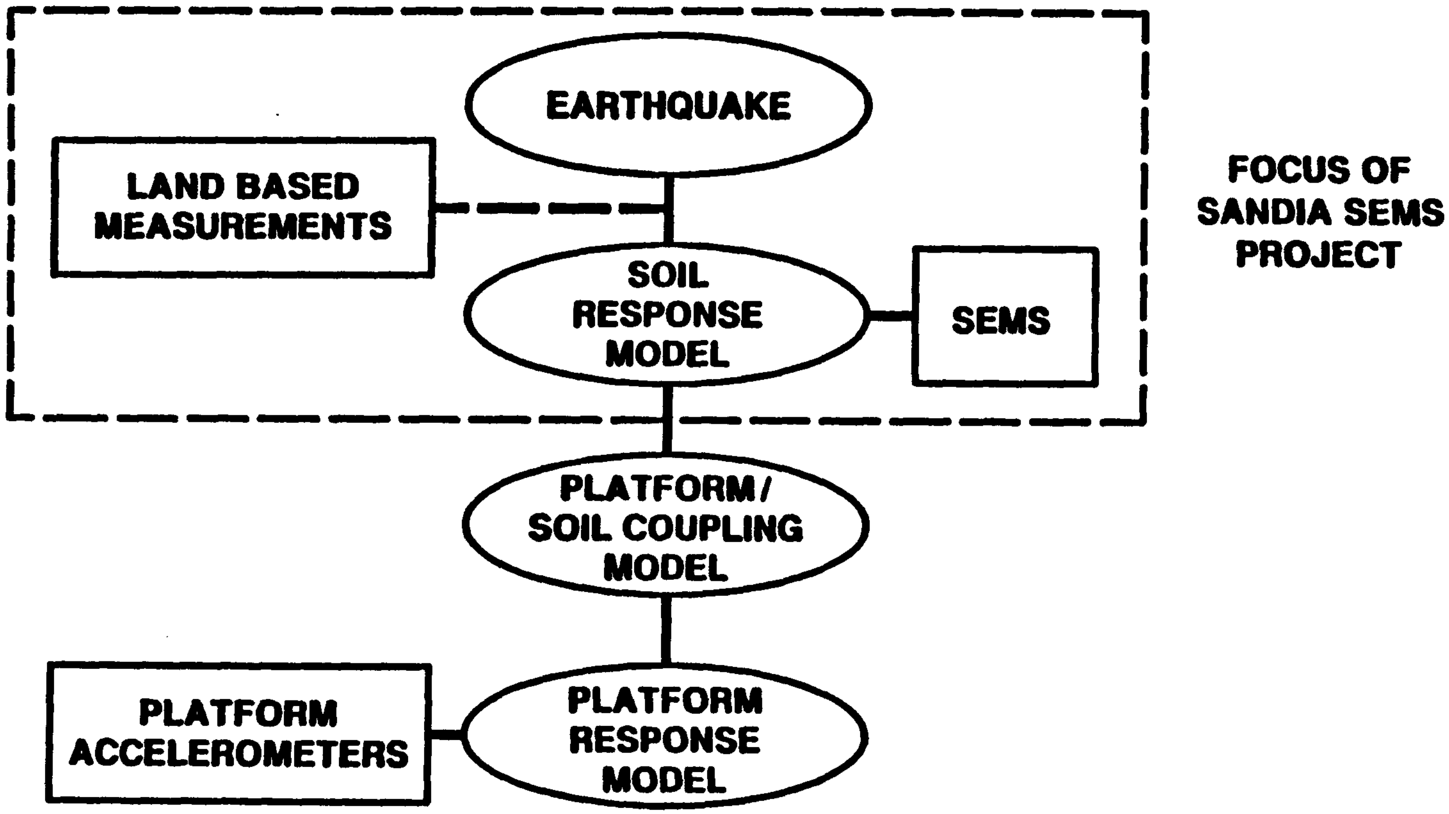


Figure 7 Diagram indicating the various elements involved in vibration modeling of earthquake-resistant offshore platforms

TABLE 1

Seafloor Seismograph Specifications

POWER REQUIREMENTS:	
Battery Supply -	8-12 VDC
Normal operating current -	70 mA from 10.8 VDC
SENSOR PACKAGE:	
General	
Size -	4" dia by 19" length
Weight -	13 lbs dry
Density -	Matched to seafloor mud
Accelerometers	
Type -	Endevco 7751-500
Sensitivity -	500 mV/g
Noise Floor -	< 50 micro-g rms
Number -	3 mounted triaxially
Magnetometer	
Type -	SAM-72C 2-axis mounted to read azimuth relative to north
Accuracy -	+/- 2 degrees
Power -	12 V @ 25 mA : only powered during interrogation
SIGNAL CONDITIONING BOARD:	
High Pass Filter -	0.05 Hz (3-dB point) 2-pole
Low Pass Filter -	20 Hz (3-dB point) 8-pole
Gain -	x4
A/D CONVERTER BOARD:	
Resolution -	16 bits, two's complement
Sample Rate -	100 SPS per channel
Noise -	approximately 1 lsb
Channel-channel Time skew -	<80 micro-sec
Calibration -	Auto-calibrating

Diagnostics -	Voltage test points Magnetometers Electronics Temp Electronics Humidity Battery Voltage Battery Current Drain

MICROPROCESSOR AND DSP BOARDS:

Type -	CDP 1805, CDP 1855
Clock -	1 ppm, can be set via telemetry
Arithmetic used -	16-24 bit fixed point
Trigger -	Software detection algorithm as per Figure 3
Pre-event Buffer -	15.36 seconds
Data Record length -	Increments of 15.36 sec
Data Reject Criteria -	Reject smallest strength event when bubble memory is full.

RAM/ROM BOARD:

RAM size -	48 kByte
ROM size -	16 kByte

BUBBLE MEMORY BOARD:

Size -	1 MByte (approximately 30 min. recording time)
Select/Deselect -	Via Telemetry in 16 kB blocks

ACOUSTIC TELEMETRY SYSTEM:

Transmit/Receive Beamwidth -	140 degrees (+/- 3dB points)
Max Depth -	1000 ft
Baud Rates -	150 Baud - 2400 Baud
Error Detection/Correction -	Extensive

Figure 6 Comparison of Land-based and SEMS measured accelerations for North Palm Springs Earthquake of July 8, 1986