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MEASUREMENT OF WAVE ENERGY TRANSMISSION THROUGH THE SAN PEDRO BREAKWATER

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ABSTRACT

A method for measuring the wave energy transmission characteristic of a breakwater by means of seafloor mounted wave sensors is described. The instrumentation is designed to measure the amplitude of surface waves having frequencies in the range of 10 to 100 mHz (wave periods of 10 to 100 seconds). Field studies were conducted on the San Pedro breakwater of the Long Beach-Los Angeles Harbor in southern California. An array of pressure transducer type wave sensors are mounted on the seafloor on the outside and inside of the rubble-mound breakwater. The subsurface pressure (and thus the sea-surface elevation) is measured at all sensor locations simultaneously and is recorded digitally in a computer-compatible format on a nine-track incremental tape recorder.

Power spectra are calculated for each sensor location and the wave energy transmission characteristic of the breakwater is determined. Wave attenuation decreases with frequency so that the breakwater is virtually transparent to tides, and only partially effective against low frequency swells. The results show that for swells having a wave frequency of 60 mHz (wave period of 16.6 seconds) 50% of the wave amplitude is reflected and 30% is transmitted with the remainder being dissipated inside the breakwater.

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CHAPTER 1-INTRODUCTION

1.1 Background

Harbors are used to provide a sheltered environment for the two-way transfer of cargo between ships and land based transportation systems. Man-made harbors may be constructed and natural harbors improved by dredging with the construction of breakwaters. The breakwaters serve to attenuate the wave energy coming from the open sea. In rubble-mound breakwaters, the attenuation is due to reflection of wave energy back out to the sea and dissipation of wave energy inside the breakwater. The remaining wave energy is transmitted through the breakwater into the harbor to be protected. Rubble-mound breakwaters provide large attenuation for short period waves and decreasing attenuation for waves of longer periods. The San Pedro breakwater protecting the Los Angeles-Long Beach Harbor complex is of rubble-mound construction.

Harbor surgings or seichi with periods of several minutes have been repeatedly observed inside the main harbor and its branch basin and have been reported by Knapp and Vanoni (1945) and Wilson (1968). Damage to ship mooring lines and dock structures as well as delays and interruptions in ship cargo transfer activities have occurred as a result of surging. Numerous investigators (Miles and Munk 1961, Wilson 1968, Lee and Raichlen 1970, Lee 1971, and Lee and Raichlen 1971) have analyzed the harbor surging problem by assuming that resonant oscillations within the harbor were excited by wave energy from the open sea. They assumed in their analysis that all wave energy enters through the harbor entrance and no wave energy passes throught the breakwater. In order to include the effects of wave energy transmission through the breakwater, the wave energy transmission characteristic of the breakwater (attenuation of wave energy versus wave frequency) must be known.

While many laboratory studies have been conducted on a variety of breakwater structures to determine their wave reflection, dissipation and transmission characteristics, there is a paucity of field studies on breakwaters. In fact, the work of Thorton and Calhoun (1972) appears to be the only field data available on a rubble-mound breakwater. With so little field data available to validate results, the accuracy of predictions of the wave energy transmission characteristic based on extentions of laboratory data is questionable. Measurement of the wave energy transmission characteristic of the San Pedro breakwater was deemed necessary both for the analysis of the harbor surging problem and to obtain additional field data to confirm the results previously reported for a rubble-mound breakwater.

1.2 Objective of Study

The objective of this study is to determine the wave energy transmission characteristic of the San Pedro breakwater. This will involve simultaneous measurement of ocean waves inside and outside of the breakwater. While sea-surface waves are most easily considered as being sinusoidal (single frequency sinusoidal waves are often used in laboratory model studies) they are in reality much more random and confused. The operations required in the acquisition and processing of wave data may be divided into five primary categories (after Bendat and Piersol, 1971):

1. Data collection
2. Data recording (including transmission)
3. Data preparation
4. Data qualification
5. Data analysis

"Data collection" refers to the use of a transducer to convert the sub-surface pressure fluctuations at some location into an electrical signal which is related to the sea-surface elevation by some known transfer function. The sea-surface elevation changes as waves pass by, so a record of the time history of the electrical signal may be considered as the raw wave data. "Data recording" covers the recording process as well as the transmission of the raw wave data from the breakwater instrumentation to the recording location. "Data preparation" refers to the digitizing, editing and preprocessing procedures. Digitizing is performed prior to the recording process in the system to be described so that editing and preprocessing as well as "data qualification" and "data analysis" can be performed after the data has been recorded.

The results of the computer data analysis will be in the form of wave energy spectra for locations inside and outside of the breakwater. After correcting the spectra amplitudes for the effects of standing waves and the nonlinear pressure attenuation factor, the ratio of the spectra may be calculated. The ratio of the inside power spectrum to the outside power spectrum yields information on the wave energy transmission characteristic.

1.3 Scope of Report

This report will cover the design, construction and installation of the instrumentation system as well as the acquisition and recording of the raw wave data. The data preparation, qualification and analysis will be briefly mentioned and the resulting wave energy transmission characteristic of the San Pedro breakwater will be reported.

1.4 Method of Approach

Numerous instrumentation techniques for the measurement of sea-surface waves are available to the researcher. A narrowing of the field is necessary and is usually accomplished by considering the various limitations imposed by the field location, the accuracy desired from the measurements, the quantity of data to be collected, the duration of the measurements and monetary constraints. Instrumentation techniques for the measurement of waves may be broken down into four broad categories (after Grace, 1970) for discussion.

First, is the category in which the measurement apparatus is located above the sea-surface (remote sensing). Instruments based on the use of radar, ultra-sound, light, laser beams and photographic techniques fall into this category. These instruments may be mounted on satellites, airplanes and ships, or on towers and other fixed structures.

The second category encompasses instruments which operate on the sea-surface. These are surface following floats or buoys which are instrumented in various ways. Wave-produced, vertical displacement of a buoy may be measured by observing pressure fluctuations sensed by a pressure transducer hung far below the buoy in still water. Wave action may be deduced from forces on the buoy monitored directly by strain gauges on the mooring or indirectly by accelerometers mounted on the buoy itself.

The third category of instruments are elongated so as to pass through the air-sea interface. Instruments in this category are designed to operate from stable platforms such as piers, docks, towers and specially designed stable buoys. They include wave staffs utilizing resistance dividers (either continuous wires or tapped resistor chains) which change resistance by seawater shorting. Wave staffs which rely on changing capacitance effects are also available.

The fourth category includes all instruments which rest on the seafloor or are mounted well below the surface on sub-surface buoys anchored to the seafloor. Pressure transducers which detect subsurface pressure fluctuations produced by surface waves and inverted acoustic echo-sounders which look up at the sea-surface are examples of instruments in this category. Draper (1966) discusses some of the problems and trade-offs to be considered in the selection of a technique for measurement of ocean waves near to shore. For the present work, the non-availability of stable mounting platforms and the shallowness of the water (16 m) at the field location dictated the use of instruments in category four. Pressure transducer type wave sensors mounted on the seafloor were considered to be the better choice.

Esteva and Harris (1970) have shown that wave data comparable to that produced by wave staffs can be obtained by using pressure type wave gauges. This conclusion was based on comparison of the power spectra calculated from wave data gathered by four different wave gauges operating simultaneously at the same location. Panicker and Borgman (1970) have developed an analytical procedure to obtain the directional spectra from wave data gathered by an array of wave sensors. The directional resolving power of wave sensor arrays of various configurations is also tabulated in their paper.

The use of two wave sensor arrays, one outside and one inside the breakwater, would appear to provide adequate wave data for the calculation of both wave power spectra and directional spectra. A requirement which must be met to enable analysis by either of these techniques is that the raw wave data must be obtained from all wave sensors simultaneously and at equally spaced time intervals. Since both calculations require the use of the Fast Fourier Transform (FFT) algorithm, a powerful computer is required. The raw wave data then must at some point be converted into a format which will enable it to be entered into the computer. The quantity of data points involved makes the use of punched cards for this purpose impractical. The best solution appears to be to record the raw wave data directly on magnetic tape in a computer compatible format.

Non-compatible recording systems can be obtained which are much less costly and complicated than those using the 800 BPI nine track format required by the USC computer center equipment. Tape thickness and width, number of tracks, gap size, recording density, and coding technique may all be optimized to produce a suitable record at minimum cost. Not to be overlooked, however, is the fact that a second system is necessary to convert this record into a computer-compatible format. The total cost of the two systems is usually greater than buying a computer-compatible system at the outset. If commercial power and a protected location are available, a computer-compatible recorder is the logical choice. If the recording must be performed at a remote site, where the equipment must be sealed against the marine atmosphere and only portable power sources are available, then a non-compatible recorder is usually chosen.

The exact location of the anchor blocks on which the wave sensors are mounted must be determined so that wave spectra calculated from the wave records can be corrected for the effects of standing waves. (Knowledge of the precise sensor location is also necessary for the calculation of directional spectra from an array of wave sensors.) The wave sensors send their data to a shore station along a seafloor cable and are powered by the same cable. Underwater cables deteriorate with time and allow electrical leakage through the insulation which can degrade voltage or current data signals in a manner that is not easily detected. The use of FM data signals circumvents this problem as well as enabling the use of a two conductor cable to both power the sensors and provide a data signal transmission path back to the shore station. Since each wave sensor output operates in a different frequency band, it is possible to send many signals simultaneously over the same two-wire cable.

The wave data collection system then consists of FM output wave sensors arranged inside and outside of the breakwater and connected to the shore station through a seafloor cable. This cable provides power to the wave sensors and acts as a data link to carry the FM signals back to the shore station. The shore station samples and digitizes the raw wave data from all the sensors simultaneously at fixed time intervals. An asynchronous digital data recorder is used to store the raw wave data in a computer-compatible format on one-half-inch-wide magnetic tape. This raw wave data is then entered directly into the computer for analysis.

A three-element linear wave sensor array was chosen for the initial installation because of its simplicity. The site selected for the installation of the array was on the middle breakwater, midway between the east light of the Angels Gate and the point where the breakwater changes direction (see Figure 1). This segment of the breakwater was chosen because it is perpendicular to the wave propagation direction of the most commonly observed Pacific swells. Since the linear wave sensor array is unidirectional, it is most effective when the crests of the waves of interest arrive parallel to the breakwater.

The seafloor cable lies along the harbor side of the breakwater. From the corner point of the breakwater it is routed directly across the main ship channel to the shore station. The shore station is physically located in the electronics laboratory at the Long Beach ocean-engineering facility of the Battelle Memorial Institute. In this way, power and a laboratory environment can be provided for the electronic equipment.

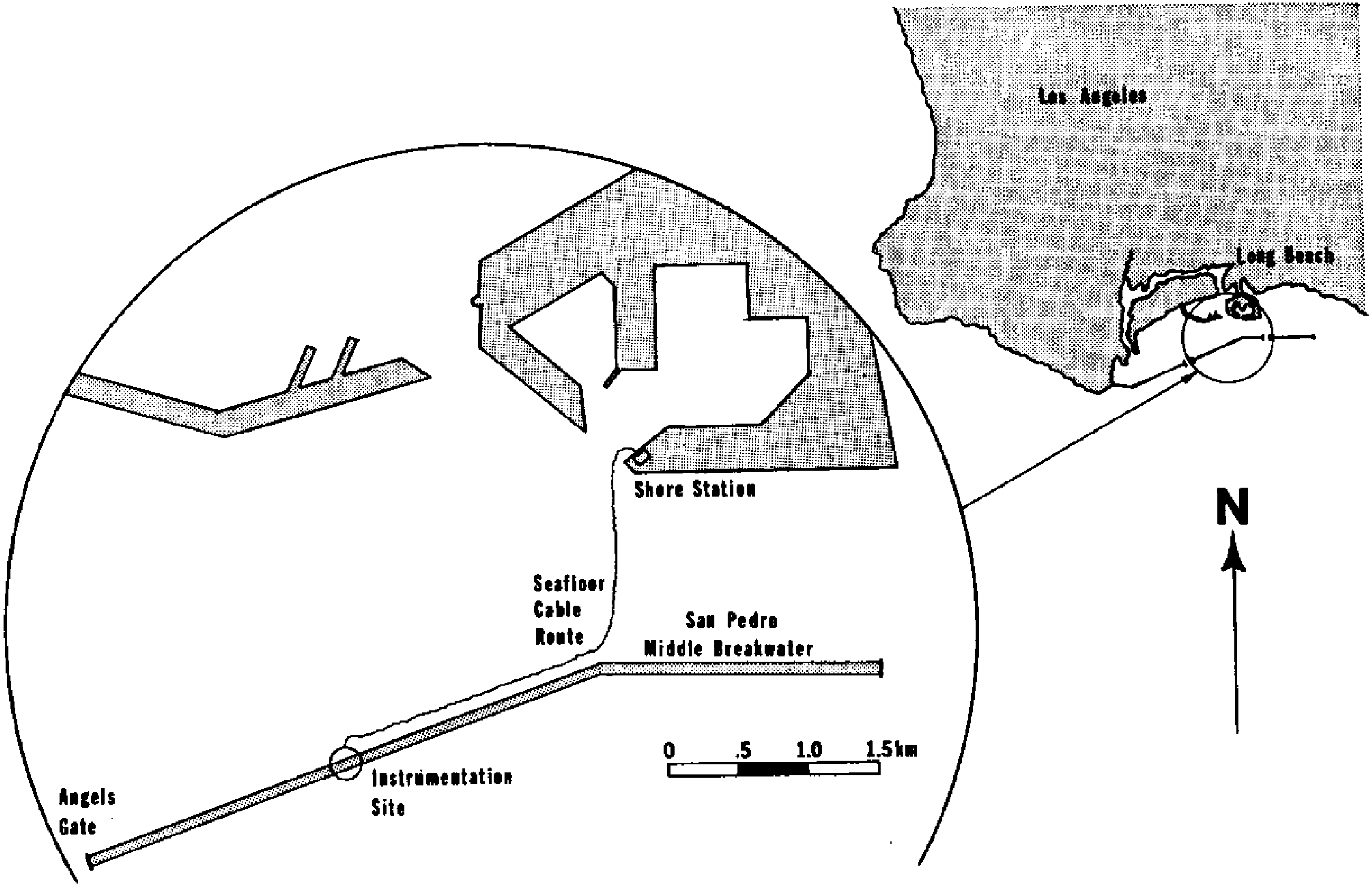

Figure 1. Location of Wave Sensor Array and Shore Station

CHAPTER 2-INSTRUMENTATION SYSTEM

2.1 General Description

The instrumentation system is composed of three sub-systems: the wave sensor array, the seafloor cable and the shore station. The wave sensor array is comprised of six individual wave sensors and a signal multiplexer unit. The wave sensors are mounted on concrete anchor blocks resting on the seafloor. Two sensors are mounted inside with four sensors mounted outside of the breakwater. The surface pressure fluctuations at each wave sensor location are translated into a frequency modulated (FM) signal which is sent through an underwater cable to the signal multiplexer unit. All connecting cables are two conductor cables and supply direct current voltage to power the wave sensor electronics while simultaneously transmitting the frequency modulated output signal. The signal multiplexer unit combines the FM signals from the six wave sensors in the array into a composite amplitude modulated FM signal which is transmitted to the shore station on a single,two-wire seafloor cable. This method of transmitting several sensor signals over a common data link is called frequency division multiplexing (FDM). Just as radio stations transmit on different frequencies, each wave sensor operates in a specific frequency band.

At the shore station,six receivers, each one tuned to a frequency band assigned to one of the six wave sensors, are used to

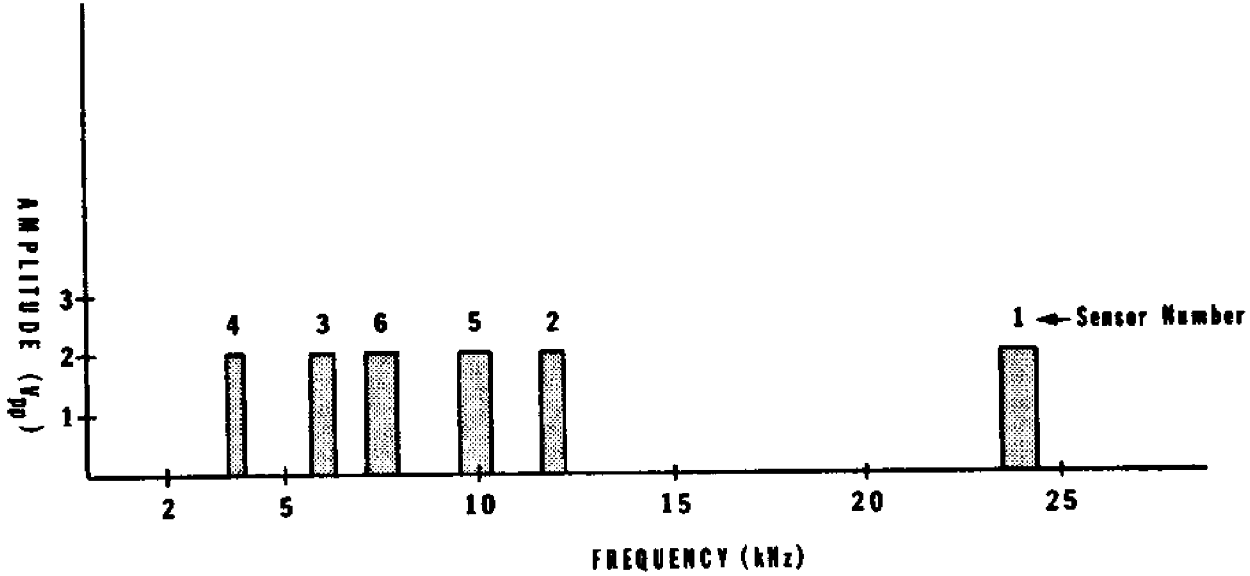

Figure 2. FDM Transmission Frequency Band Assignments

recover the data. (Frequency band assignments are shown in Figure 2.) The seafloor cable is 4 km long and connects the wave sensor array to the shore station. It carries DC voltage from the shore station to power the array and serves as the data telemetry link between the wave sensor array and the shore station. At the shore station, the FM-AM composite signal from the wave sensor array is amplified and sent to the data digitizers. Each data digitizer is tuned to receive a single wave sensor FM signal. It converts the FM signal into a digital number which is related to the sea-surface elevation at the wave sensor location. Raw wave data from the six wave sensors are received simultaneously and are recorded once every two seconds on a nine-track computer-compatible magnetic digital data tape. This recorded raw wave data is supplied to a computer from which the wave spectra inside and outside of the breakwater are calculated.

2.2 Wave Sensor Array

The linear wave sensor array consists of six wave sensors and a signal multiplexer unit interconnected by waterproof cables. The wave sensors are mounted in pairs on concrete anchor blocks which sit on the seafloor. Two anchor blocks are mounted outside the breakwater and one inside the breakwater. A diagram of the locations of the wave sensors in the linear array is shown in Figure 3. Distances to the sensor locations are measured from the center of

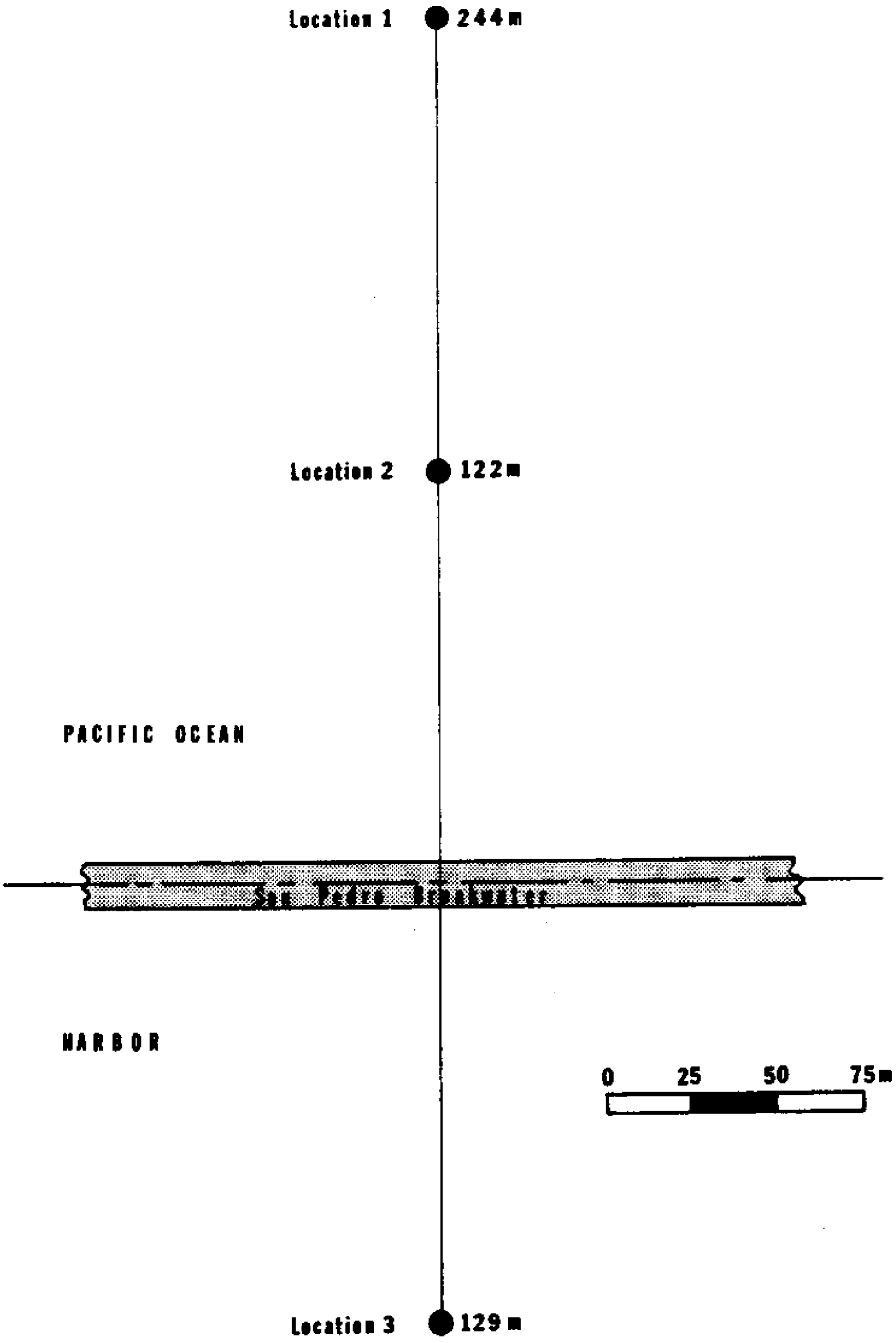

Figure 3. Layout of Linear Wave Sensor Array

the top of the breakwater. The signal multiplexer unit is placed on the top of the breakwater and is readily accessible for servicing. Only one wave sensor at each location is actually required for data collection. The second sensor is used to gather redundant data and allows for comparison of the performance of wave sensor pairs. A favorable comparison of wave data records obtained by two wave sensors from the identical seafloor location will build confidence in the operation of the entire system.

The wave sensors at locations 1 and 2 on the ocean side of the breakwater are 15.8 meters below MLLW. The wave sensors on the harbor side at location 3 are 14.6 meters below MLLW. The bottom topography on both the seaward and shoreward sides of the breakwater is very gently sloped, thus wave transformation due to wave refraction is very minor. The linear wave sensor array forms a straight line which is perpendicular to the breakwater.

2.2.1 Wave Sensors

Each wave sensor consists of a Vibrotron pressure transducer and a Vibrotron oscillator contained in a pressure-proof, waterproof case. The Vibrotron pressure transducer translates pressure into a frequency which decreases with increasing pressure. As shown in Figure 4, it contains a pressure sensitive diaphragm which is exposed to seawater pressure on one side. A small diameter tungsten wire is held in tension between the center of the opposite side of the

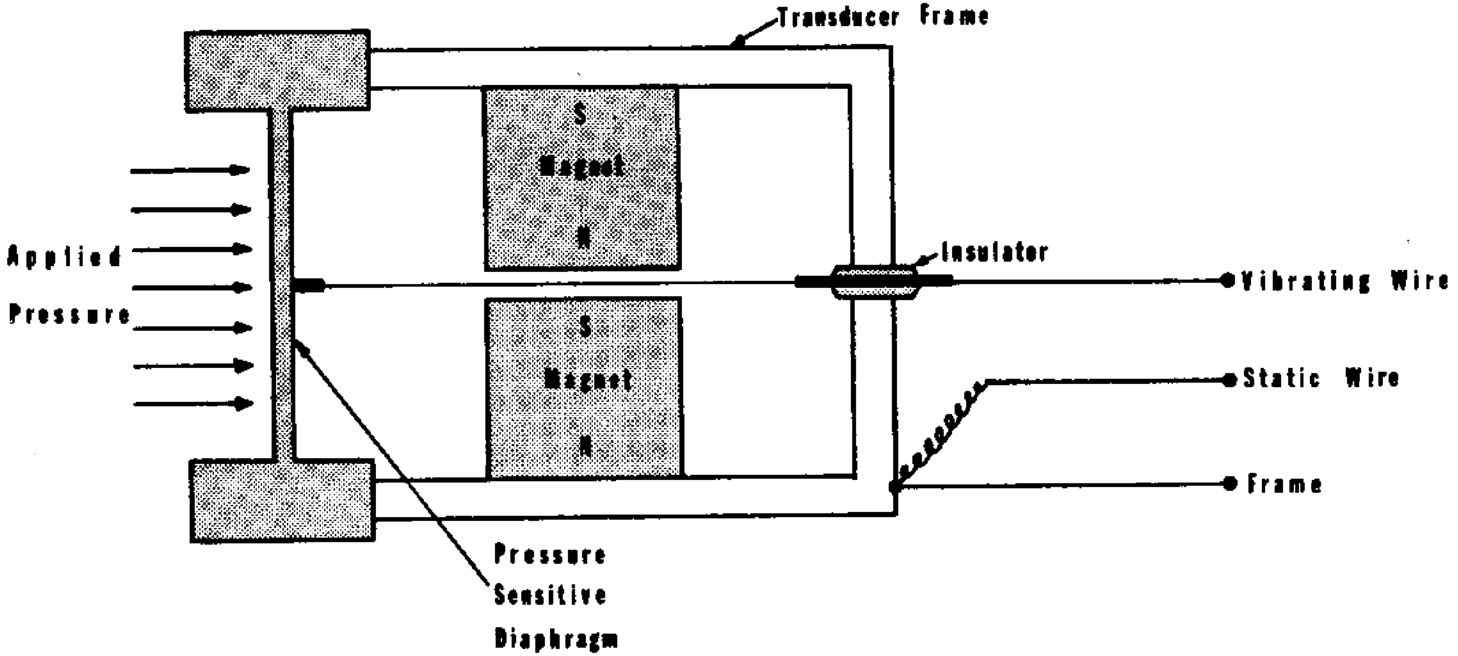

Figure 4. Diagram of Vibrotron Pressure Transducer

diaphragm and a support point on the transducer frame. A change in the pressure applied to the diaphragm changes the deflection of the diaphragm and decreases the tension in the wire. Decreasing the wire tension lowers the natural resonant frequency of the wire. The wire is continuously driven at its natural resonant frequency by the Vibrotron oscillator, so the frequency of the oscillator output signal is inversely proportional to the seawater pressure. The fluctuations in sub-surface pressure produced by surface waves are translated into variations in the Vibrotron output frequency. This frequency modulated signal output when digitized and recorded comprises the raw wave data record.

A detailed discussion of the design and construction of Vibrotron pressure transducers may be found in the paper by Lefcort (1968). The theory of operation is as follows: When an electrically conducting wire moves in a magnetic field, it cuts across lines of magnetic flux and an electric current is induced in the wire. Conversely, when an electric current flows through a wire located in a magnetic field, a force is generated which acts upon the wire. If a small diameter wire held under tension is deflected from its equilibrium position and released, it vibrates at its natural resonant frequency. If a magnetic field is now applied, an alternating electric current of the same frequency is generated in the wire. The reverse is also true. If an alternating current is applied to the wire, the wire is forced to vibrate at the same frequency as the alternating current which is driving it. Now amplify the alternating current generated by a taut wire vibrating at its natural resonant frequency in a magnetic field, and use the amplified signal to drive the wire in phase at the same frequency. The result of this "bootstrapping" is that the wire is self-excited and oscillates continuously at its natural resonant frequency. Further, the frequency of the electrical signal output of the amplifier corresponds to the mechanical oscillation frequency of the wire.

In the Vibrotron pressure transducer, one end of the taut wire is attached to the center of a pressure diaphragm and the other end is attached to a fixed point. The magnetic field is provided by a pair of permanent magnets mounted on the transducer frame. The natural resonant frequency of a taut wire depends upon the density and cross-sectional area of the wire, the tension in the wire and the wire length. Since in the Vibrotron, the physical characteristics (density, cross-sectional area and wire length) remain constant, the natural resonant frequency is only a function of tension. As pressure is applied to the seawater side of the diaphragm, it deflects away from the pressure source. This reduces the tension in the wire and lowers its frequency of resonance. Thus, the natural resonant frequency of the wire and also the analog electrical output from the amplifier are both a direct function of the pressure applied to the diaphragm.

Various Vibrotron oscillator circuits have been described by Snodgrass and Cawley (1957), Morris (1967) and Rolfe (1968). In modern circuits (see Figure 5), the vibrating and static wires are used as the two lower legs of a wheatstone bridge and the output of the bridge is amplified by a differential input amplifier. The static wire is made of the same material as the vibrating wire and it has the same length. Thus, the DC resistances are identical and remain so with changes in temperature.

The AC impedances of the wires are also identical for frequencies far away from the natural resonant frequency of the vibrating wire. At the resonant frequency, however, the impedance of the vibrating wire rises sharply and this produces an unbalance in the wheatstone bridge which is amplified by the differential amplifier. The output of the amplifier is a sinuoidal voltage having a frequency identical to that of the vibrating wire. If this output is fed back in phase by using it to drive the bridge, the system oscillates with ever increasing amplitude until clipping occurs in the amplifier. Unfortunately, as the amplitude of vibration of the wire is increased, the effective tension in the wire increases and thus its natural resonant frequency also increases. Therefore, for maximum stability, the amplitude of the wire oscillations should be maintained at a constant level. To fulfill this requirement, an auto-

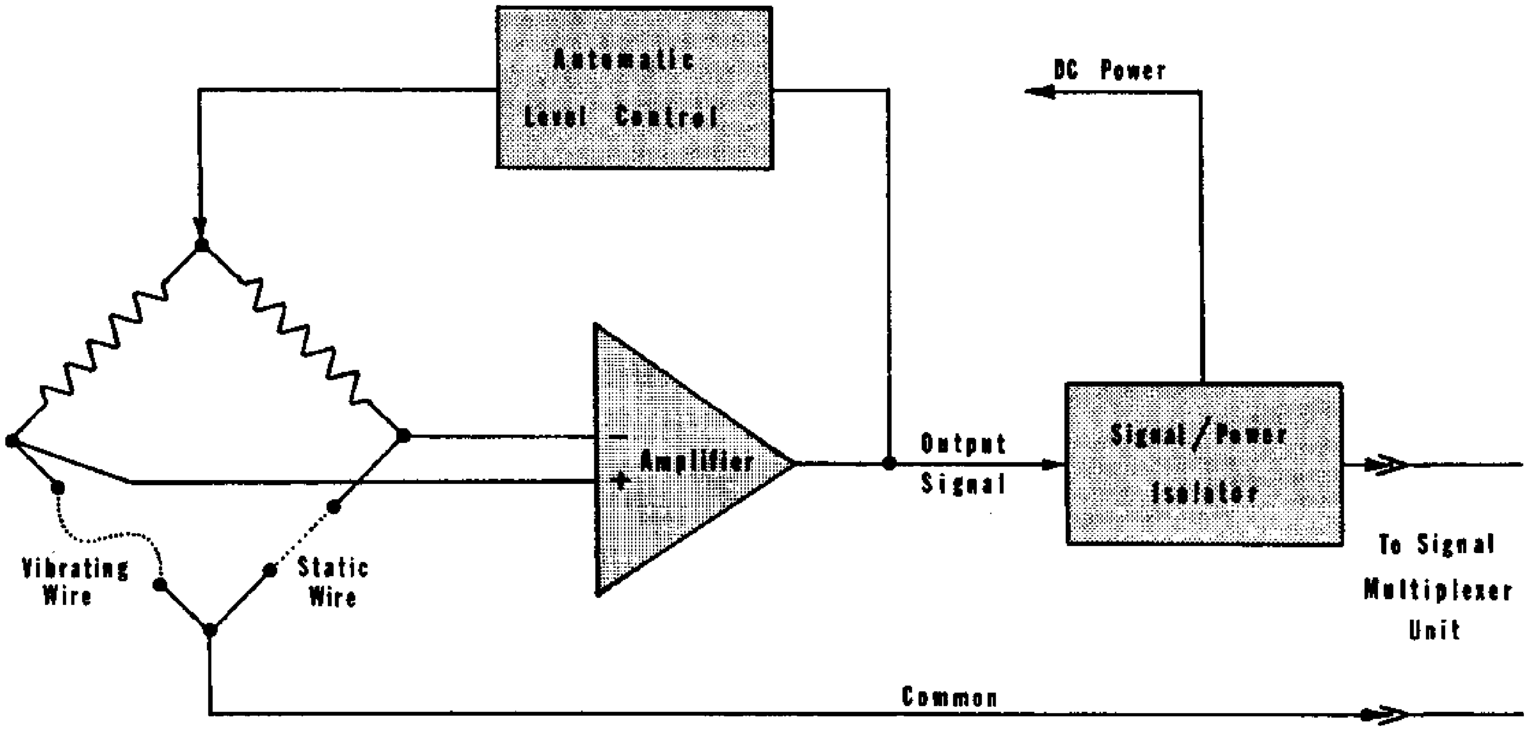

Figure 5. Vibrotron Oscillator Block Diagram

matic level control is incorporated into the oscillator which varies the amplitude of the sine wave signal driving the bridge circuit in such a manner as to keep the wire vibrating at a constant amplitude.

Commercially available Vibrotron oscillators (Ramsay Engineering Company, Model A-32) were used in the construction of the wave sensors. These oscillators require an input voltage of 25 to 35 Vdc at a current of 5 milliamperes and operate on a two-wire system. A single pair of wires carry DC power to the sensor and also carry the frequency signal output. By using frequency division multiplexing, one or more wave sensor signals may be carried simultaneously on the same pair of wires which carry DC power to the sensors.

2.2.2 Signal Multiplexer Unit

The signal multiplexer unit has two important functions. First, it distributes the DC voltage received from the shore station to its internal electronic circuits and to each of the six wave sensors. Second, it receives the FM output signals from each of the wave sensors, combines them into a composite FM signal and sends the composite signal through the seafloor cable back to the shore station.

Referring to Figure 6, DC voltage generated at the shore station travels along the two-conductor seafloor cable, passes through the signal/power isolator, and is applied to the DC voltage

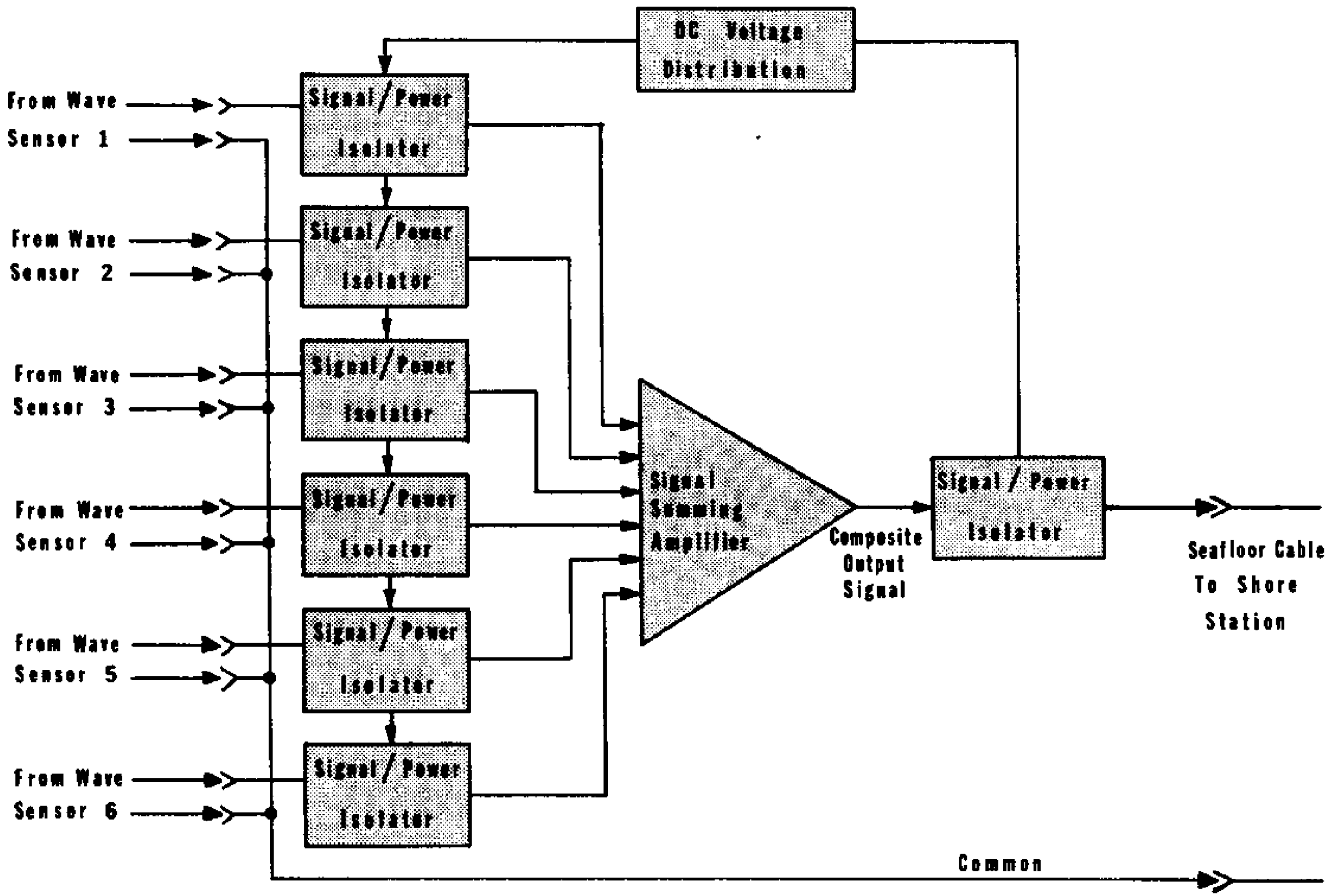

Figure 6. Signal Multiplexer Unit Block Diagram

distribution circuit. Some of the voltage is used to power the electronic circuits inside the signal multiplexer unit and the rest is applied to the six, signal/power isolators which provide DC voltage to the cables connected to each of the six wave sensors.

FM signals generated by the six wave sensors travel back along the underwater cables and are routed through the signal/power isolators. The individual FM signals emerge from the isolators and are applied to the summing amplifier. The summing amplifier linearly combines the six FM signals into one composite amplitude modulated signal. This composite FM-AM signal is then applied to the seafloor cable through another signal/power isolator and is transmitted to the shore station. For proper operation, the signal multiplexer unit requires 32 Vdc at the seafloor cable connector and it draws 40 mA. The DC voltage distribution circuit contains two, 15 V Zener diode regulators which hold the bus voltage level at a constant 30 Vdc. The electronic circuits inside the unit and the wave sensors are powered by the 30 Vdc bus.

2.2.3 Pressure Cases and Underwater Connectors

Since the sensors are to be used in water depths of less than 20 meters, low pressure, corrosion-resistant pressure cases were fabricated from polyvinylchloride (PVC) plastic. Each waterproof pressure case consists of a connector endplate, a pressure transducer endplate and a pressure barrel. The connector endplate is drilled and tapped to receive an Electro-oceanics 53F2M-1 bulkhead mounted two-wire connector. These connectors can withstand very high pressures and can be unmated and remated underwater. When used with the 51F2F-1 cable mounted matching connector, the pair can be mated underwater and still maintain a leakage resistance between conductors and/or seawater in excess of 100 megohms. This feature allows divers to remove or install the wave sensors without having to disturb the cables laying on the seafloor.

The transducer endplate is drilled, tapped and ported to receive an AN-4 type pressure fitting from either side. The Vibrotron pressure transducer is mounted on the inside of the endplate and the outer AN-4 pressure port is used to apply pressure to the wave sensor during laboratory calibration. Each endplate is additionally grooved for an "O" ring face seal and is threaded to mate with the pressure barrel. The pressure barrel is internally threaded on each end to accept the endplates. It provides a protective housing for the Vibrotron pressure transducer and the A-32 Vibrotron oscillator and isolates them from seawater. A cross section view of a wave sensor appears in Figure 7.

The signal multiplexer unit mounted on the breakwater is subject to wave overtopping during severe storms as well as being exposed to the corrosive marine atmosphere in the splash zone. It, like the wave sensors, is housed in a sealed PVC plastic case.

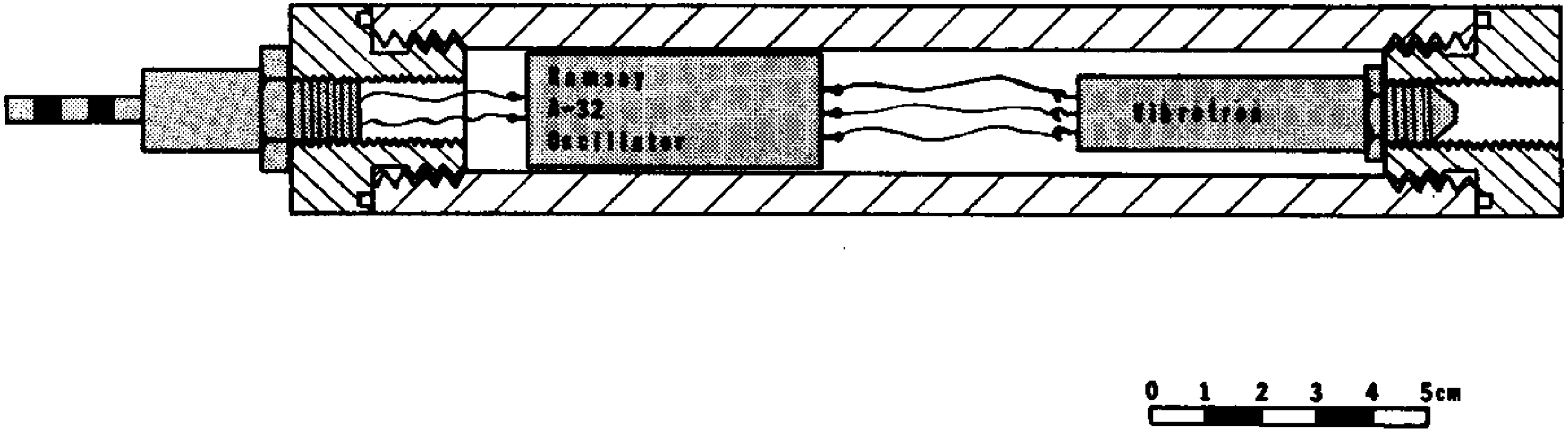

Figure 7. Cross Section View of Wave Sensor

Interconnections to the waterproof cables are achieved by using connectors of the same type as used on the wave sensors. The protective case has three wave sensor connectors on one end, and three wave sensor connectors and one seafloor cable connector on the other. This arrangement provides the capability of running any combination of wave sensors from one to six depending upon the data collection requirements.

2.3 Breakwater to Shore Station Seafloor Cable

The seafloor cable is 4 kilometers long and contains two #16 gauge insulated wires and a metalized mylar shield. An outer insulating jacket of black polyurethane provides an abrasion resistant covering. The same type of cable is used to interconnect the sensors in the wave sensor array. Waterproof connectors are molded directly to the ends of the cable and provide trouble-free connections. The total resistance of the cable (one #16 conductor 8 km long) is 50 ohms. With all six sensors operating in the array, the current in the seafloor cable is 70 mA, and the total voltage drop in the cable is less than 4 volts. Therefore at the shore station, the wave sensor array power supply must deliver 36 Vdc at 70 mA. This supply has an adjustable output voltage so that the current level can be set to 70 mA.

2.4 Shore Station

The seafloor cable coming from the signal multiplexer unit located on the breakwater terminates in the signal/power isolator at the shore station (Figure 8). DC voltage to power the wave sensor array originates in the wave sensor array power supply and is applied to the seafloor cable through the signal/power isolator. The composite FM-AM signal arriving from the signal multiplexer unit is isolated from the DC supply voltage and supplied to the data digitizers. Each of the data digitizers contains a signal demultiplexer which separates the wave sensor signal from the composite signal. Each individual wave sensor signal is then totalized and converted into a parallel digital number which represents the sea-surface elevation in meters at that particular wave sensor location. The constants used to convert frequency to sea-surface elevation are different for each wave sensor. Consequently, each data digitizer must be matched to a particular wave sensor and can be used only in conjunction with that sensor. Each individual wave sensor is calibrated in the laboratory and the output frequency versus applied pressure relationship is determined. The required constants are then calculated from this relationship (see Appendix 1) and are hard-wired into the data digitizer circuitry. The parallel digital outputs of the six data digitizers are applied to a common output bus in serial format. By looking at the signals on the common bus during a specific time interval, the parallel digital number output representing the sea-surface elevation at a particular wave sensor location

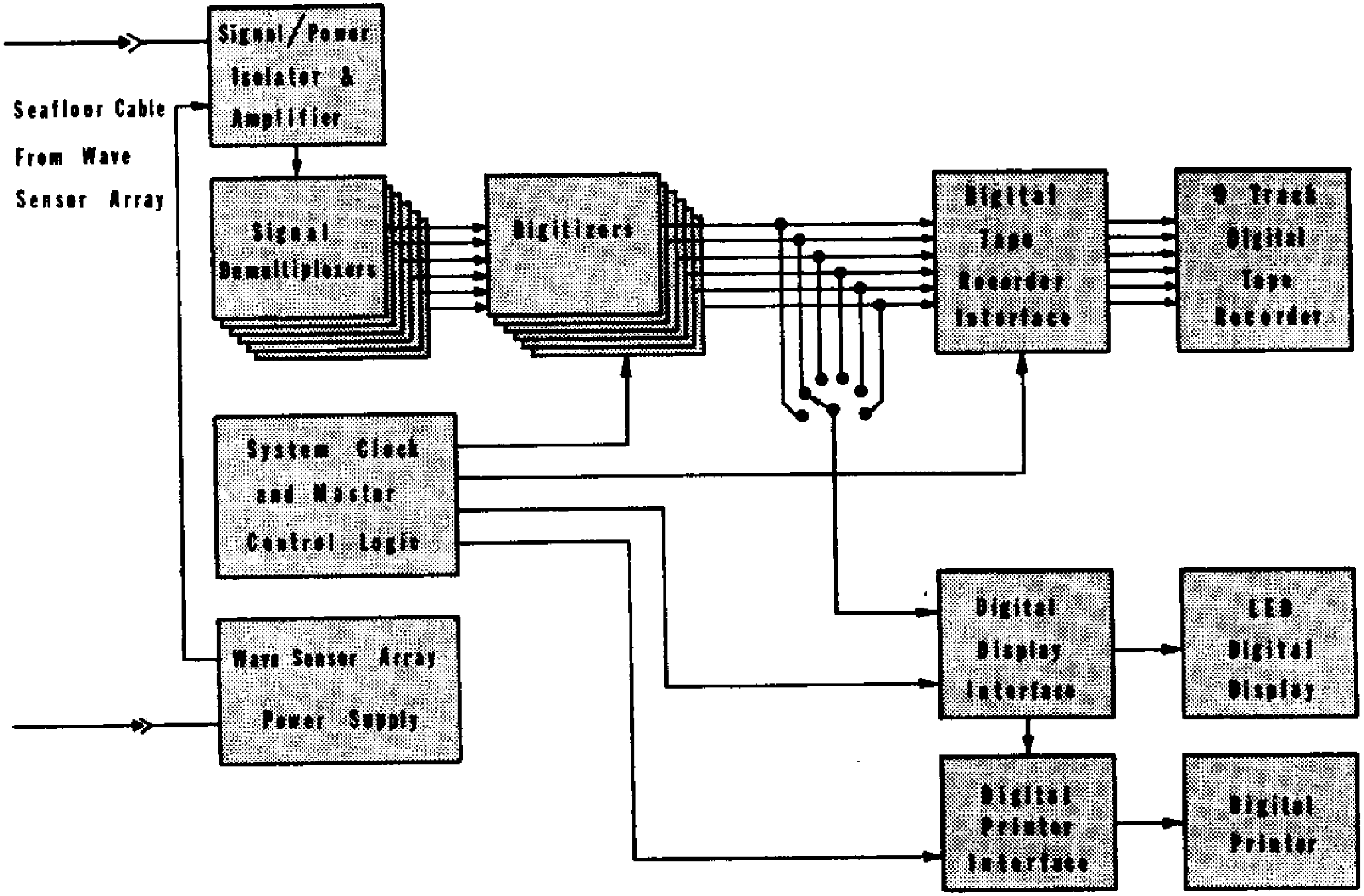

Figure 8. Shore Station Electronics Block Diagram

can be observed. This value represents the sea-surface elevation averaged over a period of approximately one second.

Sea-surface elevations are updated every two seconds and can be applied to various output devices. Four output devices are included in the system:

1. Digital display
2. Digital printer
3. Oscilloscope
4. Digital tape recorder

The digital display enables the operator to ascertain that the data digitizers are functioning properly. When any anomalous behavior is observed on the digital display it can be recorded on the digital printer to aid in system troubleshooting. The four-channel oscilloscope allows observation of various signal levels while the system is in operation. The permanent data record which is used for later analysis is recorded on a nine-track digital tape recorder. The tape format used is compatible with that of the IBM 360 computer so the data can be read directly into the computer memory. Unlike the other output devices which can look at only one wave sensor output at one time, the digital tape recorder records simultaneously the data from each of six wave sensors every two seconds.

2.4.1 Signal/Power Isolator and Amplifier

The signal/power isolator separates the direct current supply voltage from the FM-AM composite signal coming from the wave sensor array. A line transformer is used to isolate the AC signal from the DC voltage. The AC signal appearing at the output of the transformer is first filtered by a high-pass filter to remove 60 Hz hum which is generated by the power mains and inductively coupled into the seafloor cable. The signal is then amplified by an operational amplifier operating in the inverting mode. The gain of this amplifier is adjustable so that adequate signal amplitude is available to drive the data digitizers. The output level is set to 2 Vpp for each of the six signals or 12 Vpp for the composite signal.

2.4.2 Data Digitizers

The data digitizers convert the FM signals produced by the wave sensors into parallel digital numbers. In the static case, when the sea-surface is at rest, the sub-surface pressure and the sea-surface elevation are linearly related and the digital numbers represent actual sea-surface elevation. In the dynamic case, the sea-surface is covered with waves and the fluctuating sub-surface pressures are related to actual sea-surface elevations in a complicated fashion. To convert the raw wave data into actual sea-surface elevations for the dynamic case, it is necessary to correct for the nonlinear attenuation of dynamic pressure with depth. This correction cannot be performed by the data digitizers, but must be applied later on to the stored data after it is entered into the computer. The data digitizers perform only the linear conversion corresponding to the static case.

The circuit values needed to convert frequency into raw sea-surface elevation are different for each wave sensor, so a given wave sensor will operate properly only in conjunction with the data digitizer which has been tailored to match it. Each data digitizer (whose block diagram is shown in Figure 9) performs three functions. First, it separates a single wave sensor signal from the composite signal. Second, it performs the linear wave sensor frequency to raw sea-surface elevation conversion. Third, it transfers the data in BCD form onto the 8-line digital data bus.

The separation of a single wave sensor signal from the composite signal is accomplished by the signal demultiplexer. Each demultiplexer contains a bandpass filter and a phase locked loop, both tuned to the same frequency band. A pair of operational amplifiers are connected in a multiple feedback bandpass configuration to produce an active bandpass filter. Two control adjustments are available in this circuit. One varies the "Q" of the filter (the steepness of the cutoffs outside the pass band) and the other varies the center frequency of the pass band. Since this circuit has only two poles, the rolloff or steepness of cutoff is not sufficient to eliminate all interference between wave sensors having adjacent output frequencies. Therefore, the bandpass filter is followed by a phase

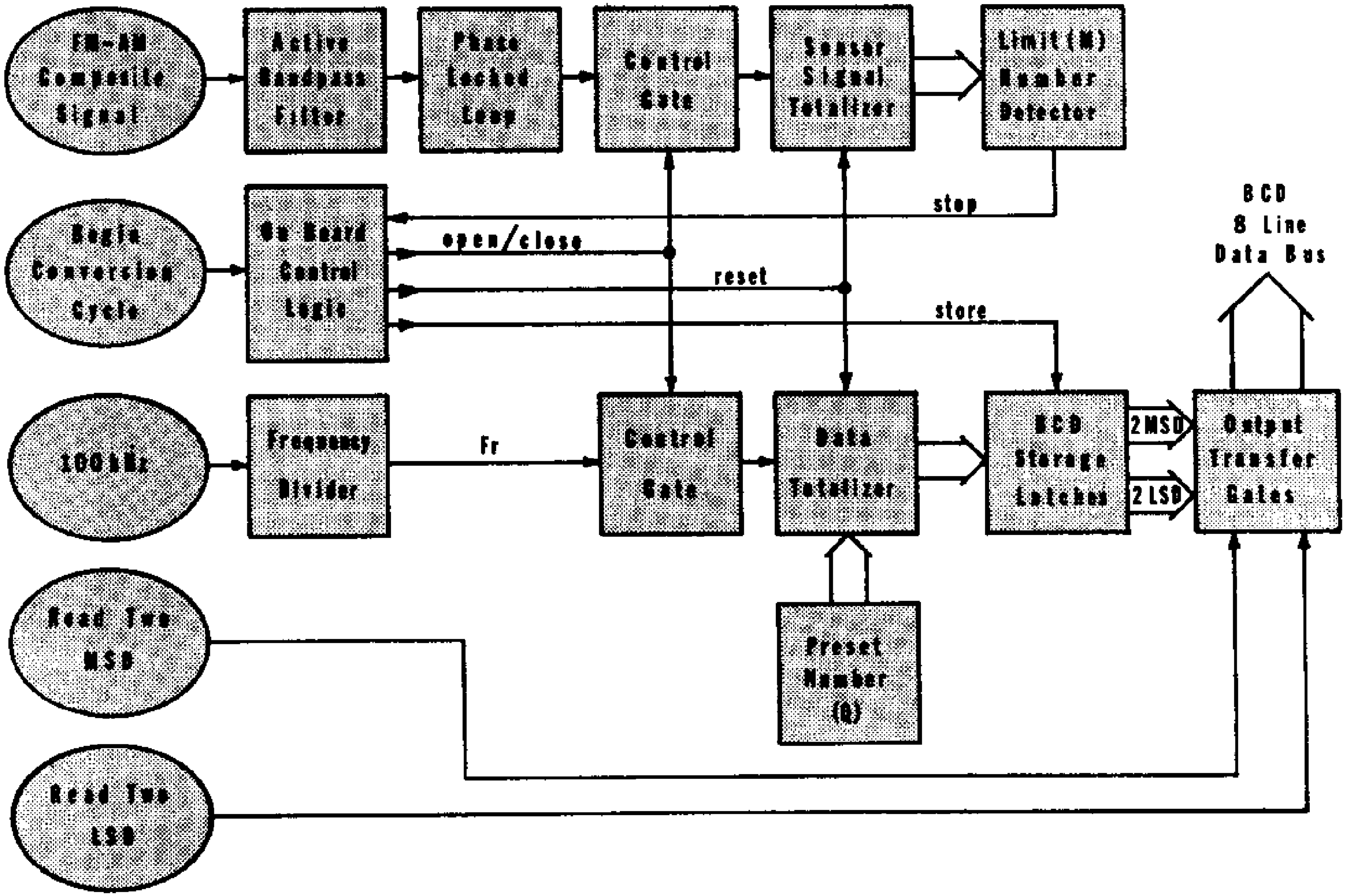

Figure 9. Data Digitizer Block Diagram

locked loop (PLL) circuit. The PLL removes the interference produced by adjacent frequencies and provides a square wave output whose voltage levels are compatible with the digital circuitry which follows.

When a begin conversion cycle command (BCC) is received, individual cycles of the wave sensor frequency are totalized in the sensor signal totalizer until a limit number (M) is reached. The time interval required for the totalizer to reach the limit number varies with the value of the number and the frequency of the wave sensor output signal. This conversion time interval is in the range of 0.9 seconds to 1.3 seconds. The sensor signal totalizer starts its count at zero at the beginning of each conversion cycle and totalizes until it reaches the limit number which is detected by the limit number detector and a stop signal is generated.

During this time interval individual cycles of a fixed reference frequency (Fr) derived from the master clock are totalized in the data totalizer. Unlike the input signal totalizer, the data totalizer starts counting at a pre-set number (Q) rather than zero at the beginning of each conversion cycle. The final value which appears in the data totalizer at the end of the conversion cycle is the sum of the pre-set number and the number of cycles arriving from the fixed reference frequency input during the conversion time interval. Numerical values for the limit number and the pre-set number as well as which fixed reference frequency to use are determined from the calibration data as explained in Appendix 1.

At the conclusion of the conversion time interval, the data totalizer contains a 4-digit number which represents the raw sea-surface elevation in centimeters at the wave sensor location. Each decimal digit is available as a binary coded decimal (BCD) number. Four wires or lines are required to handle each decimal digit using BCD format. Thus, 16 lines are required to handle all four digits.

After the stop signal is generated by the limit number detector, the onboard control logic generates a store command which causes the digital data appearing on the 16 lines to be jammed into the BCD storage latches. (Jamming automatically erases any data which was stored previously.) Once this data is stored, the onboard control logic generates a reset command which resets the sensor signal totalizer to zero and jams the pre-set number into the data totalizer. The data digitizer is then ready for the next conversion cycle.

The 16 bits of BCD data stored in the latches is transferred to the 8-line output data bus in two bytes. Since the incremental tape recorder records in 8-bit bytes, the system is organized around an 8-line data bus. Each of these bytes represents two decimal digits. One byte contains the centimeters portion of the raw sea-surface elevation data and will be referred to as the least significant digit (LSD) byte. The other byte contains the meters portion of the raw sea-surface elevation data and will be referred to as the most significant digit (MSD) byte. Strobe commands from the master control logic can transfer the LSD byte or the MSD byte onto the 8-line BCD data bus.

The master control logic may generate a strobe command on any one of twelve separate lines. Each line corresponds to a LSD byte or MSD byte from one of the six data digitizers. By generating twelve strobe commands in sequential fashion, the data outputs of each of the six data digitizers may be recorded on magnetic tape.

2.4.3 Digital Tape Recorder Interface

The digital tape recorder interface transfers data from the 8-line BCD data bus to the Kennedy Model 1600/360 incremental magnetic tape recorder. The recorder records the 8 data bits in a single byte on the magnetic tape each time a write/step command is received. The tape then steps one increment (.00125 inch for 800 bytes per inch recording) and stops and awaits the next write/step command. The spacing between bytes on the magnetic tape is thus constant and independent of the time interval between write commands. This means that tapes recorded asynchronously on an incremental tape recorder can be mounted on a standard computer tape drive and read as though they had been written by the computer itself. The tape format used in this system is compatible with IBM 800 BPI recording.

Transfer of data from the 8-line BCD data bus to the recorder takes place under the direction of the master control logic. In response to a strobe command from the master control logic an 8-bit data byte appears on the 8-line BCD data bus. Twelve separate strobe lines are available so that a MSD or LSD byte from one of the six data digitizers may be selected. When, for example, a strobe command (S1M) is applied to the data digitizer #1 MSD byte strobe line, the meters portion of the sea-surface elevation at wave sensor #1 appears on the 8-line BCD data bus. After the voltage levels on the lines have had time to stabilize, a write/step command (WRS) is generated by the master control logic. The incremental recorder records the data as one byte and increments one step. The strobe command is then terminated. The next strobe command (S1L) is now applied to the data digitizer #1 LSD byte strobe line and the centimeters portion of the sea-surface elevation at wave sensor #1 appears on the 8-line BCD data bus. After the voltage levels on the lines have again stabilized, a write/step (WRS) command causes the recorder to record the data and increment one step. The strobe command is then terminated. This sequence of operations continues until all twelve bytes representing the digital data output of all six digitizers have been recorded. Every two seconds, new digital data is generated by the data digitizers and a new record sequence is initiated.

To organize the data into record blocks on the magnetic tape, the master control logic generates an inter-record gap (IRG) command once each hour on the hour. The incremental tape recorder responds by recording an end of record (EOR) code and leaving a 0.6 inch long record gap on the magnetic tape. Each record block represents one hour of real time data and contains 1800 raw sea-surface elevation data points for each wave sensor (one point every two seconds.) To accommodate all six wave sensors, 10,800 data points must be recorded in each one hour record block. Since each data point is contained in two bytes (one MSD byte and one LSD byte), the total record block size is 21,600 bytes. The data is recorded on the tape at 800 bytes per inch (800 BPI) so the total length of tape required for recording one hour's data (including the IRG) is less than 28 inches. Therefore, a single 1200 foot reel of digital data tape can be used to record continuously for a three week period.

2.4.4 Digital Display Interface

The digital display interface transfers data from the 8-line BCD bus to the digital display storage registers. The data stored in the registers is continuously displayed by 4, seven-segment, light-emitting diode (LED) digital readouts. A six-position selector switch allows the raw sea-surface elevation at any one of the six wave sensor locations to be observed in real time. The elevation data is up-dated every two seconds.

The 8-bit data bytes appear on the 8-line BCD data bus in sequence under the direction of the master control logic. After the voltages on the lines have had time to stabilize, a display digital data (DDD) command is generated by the master control logic and the data is jammed into four, 4-bit storage registers. The digital display interface monitors the twelve strobe lines so that the data received is identified as to source and is stored in the correct storage registers. The selector switch position determines which pair of master control logic strobe lines are monitored and which data digitizer output is stored in the storage registers. The BCD coded digital number stored in each storage register is decoded by a 4-line BCD to 7-line seven-segment display driver circuit which drives a LED readout.

Each of the four LED digital readouts continuously displays the BCD coded character stored in the corresponding storage register. Two storage registers contain the MSD byte which is displayed as the meters portion (two digits) of the raw sea-surface elevation. The other two registers contain the LSD byte which is displayed as the centimeters portion (also two digits) of the raw sea-surface elevation. A decimal point is continuously displayed between the meters and centimeters portion of the digital display.

2.4.5 Digital Printer Interface

The digital printer interface transfers data from the storage registers in the digital display to a Hewlett Packard Model 562A Digital Printer. The printer prints simultaneously the identical four digits which are displayed by the digital display. In addition to the sea-surface elevation, the printer output also indicates which wave sensor is being printed out. This is accomplished by a coded switch section on the digital display interface selector switch. It produces a four-line BCD coded number between one and six which identifies the selected wave sensor. This identification number is automatically printed with each sea-surface elevation printout. The printer is used primarily for system troubleshooting and for a quick look at the digital data being recorded on the digital recorder. It is also useful for later comparison to see that the number displayed is indeed the number recorded on magnetic tape and later read into the computer memory.

2.4.6 System Clock and Master Control Logic

The system clock consists of a 1 MHz, quartz-crystal-controlled oscillator which is divided by a decade divider (divide by power of ten) to provide a 100 kHz symmetrical square wave clock signal. All reference frequencies and command pulses are derived from this single frequency source. Only three different fixed reference frequencies (Fr) are used in the data digitizers: 100 kHz, 50 kHz and 25 kHz. These frequencies are derived directly from the 100 kHz system clock by binary dividers located on the data digitizer cards.

A frequency of 100 kHz corresponds to a pulse rate of one pulse every 10 microseconds (10 μs). To obtain slower pulse rates, the system clock signal is divided down to lower frequencies. The 100 kHz signal is first divided by 100,000 (five decade dividers in series) so that a frequency of 1 Hz (a pulse rate of one pulse per second) is obtained. The 1 Hz signal is divided by sixty to provide a pulse rate of one pulse per minute. This signal is again divided by sixty to produce a pulse rate of one pulse per hour.

The begin conversion cycle command (BCC) is obtained at the output of a divide-by-two circuit connected to the one-pulse-per-second signal line so that it generates one BCC command every two seconds. The inter-record gap command (IRG) is derived from the one-pulse-per-hour signal line. A digital one-shot circuit is used to generate an IRG pulse with a duration of exactly 50 microseconds which is needed to drive the magnetic tape recorder circuitry.

The command pulses on the twelve strobe lines, the DDD line and the WRS line must be synchronized together. A sequence of 12 command pulses is used to transfer data from the storage latches in the data digitizers to the digital display and incremental tape recorder. Transfer of data is made via the 8-line BCD data bus under the control of the master control logic. A data transfer occurs every two seconds at the beginning of the data conversion cycle. The data from the previous conversion cycle are read from the storage latches while the new data are being accumulated in the data totalizers. Twelve data bytes appear in sequential order on the BCD data bus in response to the sequential strobe command pulses.

The first byte in the sequence is the sensor number 1 MSD byte which appears on the data bus in response to a strobe command pulse applied to the S1M strobe line. The twelfth and final byte in the sequence is the sensor number 6 LSD byte which appears on the data bus in response to a strobe command pulse applied to the S6L strobe line.

Pulse widths and timing relationships for the sequence of command pulses generated during a data transfer are shown in Figure 10. Strobe command pulses are applied to the strobe lines in sequential order beginning with line S1M and ending with line S6L. Each strobe pulse is 10 ms long. The voltage levels on the data bus lines are allowed to stabilize for 3 ms and then a 1 ms long command pulse occurs on the DDD line. This pulse jams the data present on the data bus into the data display storage registers. These registers are used to drive both the digital display and the digital printer. Twelve command pulses occur on the DDD line during a data transfer sequence. Each pulse appears 3 ms after the leading edge of a strobe command pulse and has a duration of 1 ms.

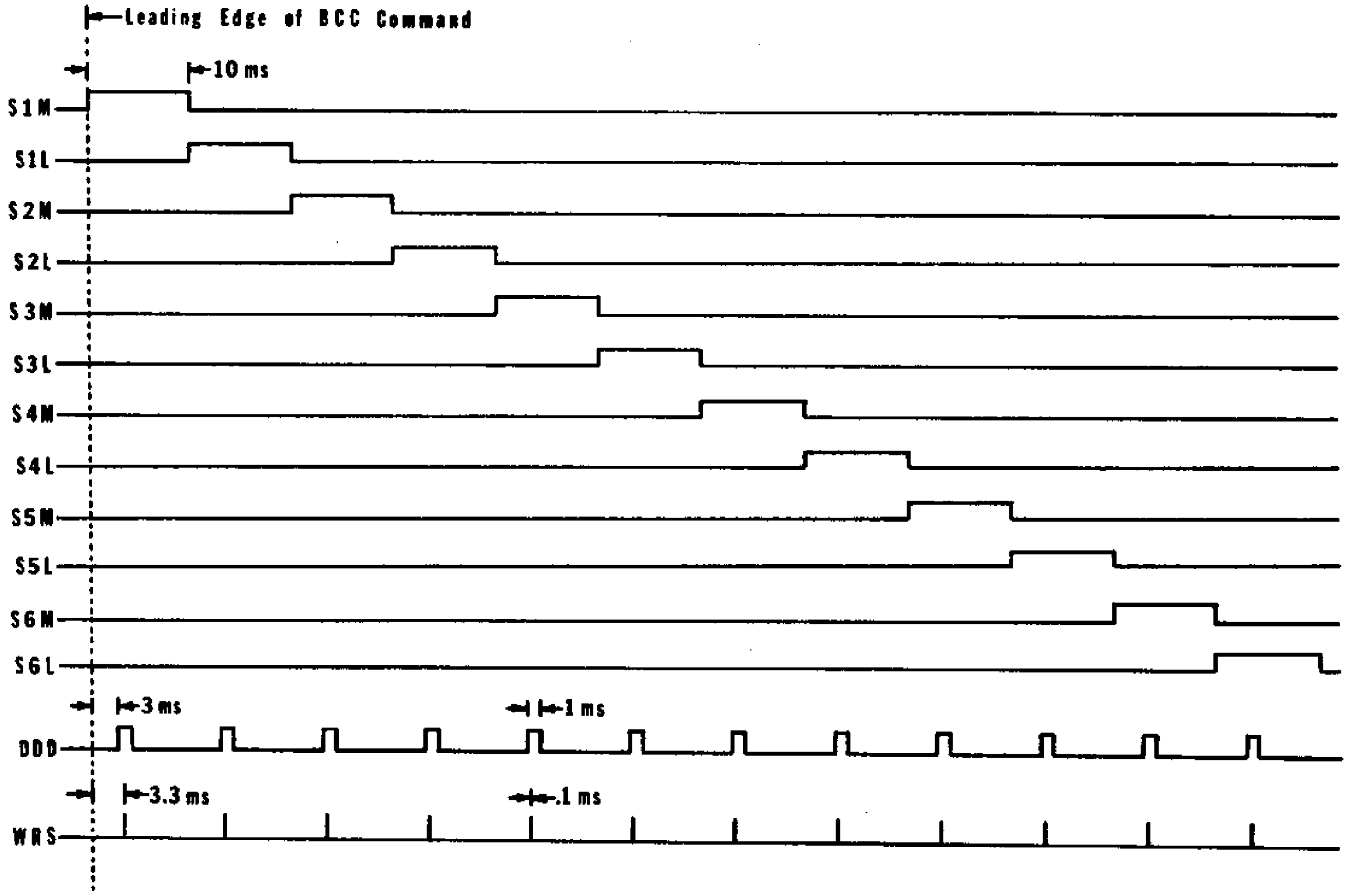

Figure 10. Data Transfer Command Pulse Sequence

Command pulses are also generated to operate the incremental recorder. Command pulses on the WRS line appear 3.3 ms after the leading edge of a strobe command and have a duration of only 0.1 ms. As each pulse occurs on the WRS line, it causes the tape recorder to copy the 8 bits of data from the data bus and store them as a byte on the tape. The recorder then automatically increments the tape forward by one step. After the recorder has stored all twelve bytes, it stops and waits until the next data transfer sequence is initiated two seconds later.

2.4.7 System Power Supplies

Three separate power supplies are required to operate the system. First is a +5 volt supply which is used to provide power to the TTL integrated circuits. It is a Trygon Electronics Model MS6-30-OVS354 and is capable of delivering +5 Vdc at 30 amperes.

Second is a ±15 Vdc supply which is used to provide power to the operational amplifiers and phase locked loops. It is an analog devices Model 902 and is capable of delivering ±15 V at 100 mA.

Third is the wave sensor array power supply. This power supply has an adjustable output voltage which is used to compensate for the voltage drop that occurs in the seafloor cable. For proper operation, the wave sensor array requires 32 Vdc at the breakwater electronics unit. The voltage range of this supply is 10 V to 60 V and it is capable of delivering 200 mA. The output voltage level is set so that the current drain is 70 mA. This assures that adequate voltage is available at the wave sensor array.

CHAPTER 3-INSTALLATION OF WAVE SENSOR ARRAY

3.1 Wave Sensors and Connecting Cables

To install the wave sensor array, the anchor blocks were first offloaded from the deck of the surface vessel and hand-lowered by means of block and tackle to the seafloor. The initial location was in the general vicinity of the final surveyed position. The anchor chain of the surface marker buoy was then attached to the anchor block lifting ring by divers.

The line used to lower the anchor block was allowed to remain attached and was used as a towing line. A taut mooring was used so that the marker buoy remained positioned as closely as possible directly over the anchor block. Two transit operators, located on the breakwater, observed the marker buoy and used triangulation to determine its exact location. In response to hand signals from the transit operators, the anchor block was towed into the desired position in the array. The wave sensor seafloor cables were then installed from the breakwater to the buoy location. Divers took the wave sensors down to the anchor block, attached them onto the mounting bracket with hose clamps, and connected them electrically to the seafloor cables.

The installation was then tested to see that everything was functioning properly. Finally, the marker buoy mooring chain was was adjusted for adequate scope, the towing line was removed, and the installation job was complete. The same method was used to install each anchor block and wave sensor in the array.

The initial installation of wave sensors was in the form of a three-element linear array having its axis normal to the breakwater (see Figure 3). This is adequate for power spectrum analysis of waves whose direction of propagation is normal to the breakwater. An omnidirectional array will be installed at a later time so that data can be obtained to enable calculation of wave directional spectra as well as power spectra.

3.2 Wave Sensor Anchor Blocks

The wave sensor anchor block must perform two functions. First, it must be massive enough to provide a stable mounting platform on the seafloor so that wave sensor mounted on it does not change location or depth with time. Second, it must act as the anchor for a surface location marker buoy. Each anchor block is fabricated from concrete and weighs about 95 kg in water. It is in the shape of a disk 75 cm in diameter and 13 cm thick. A wave sensor mounting bracket fabricated from half-inch steel reinforcing bar is embedded in the center of the disk. A cage consisting of lengths of reinforcing bar with their lower ends cast in the concrete and their upper ends welded to a lifting ring is installed over the mounting bracket. The wave sensor is clamped to the mounting bracket by a stainless-steel hose clamp and is protected from ex-

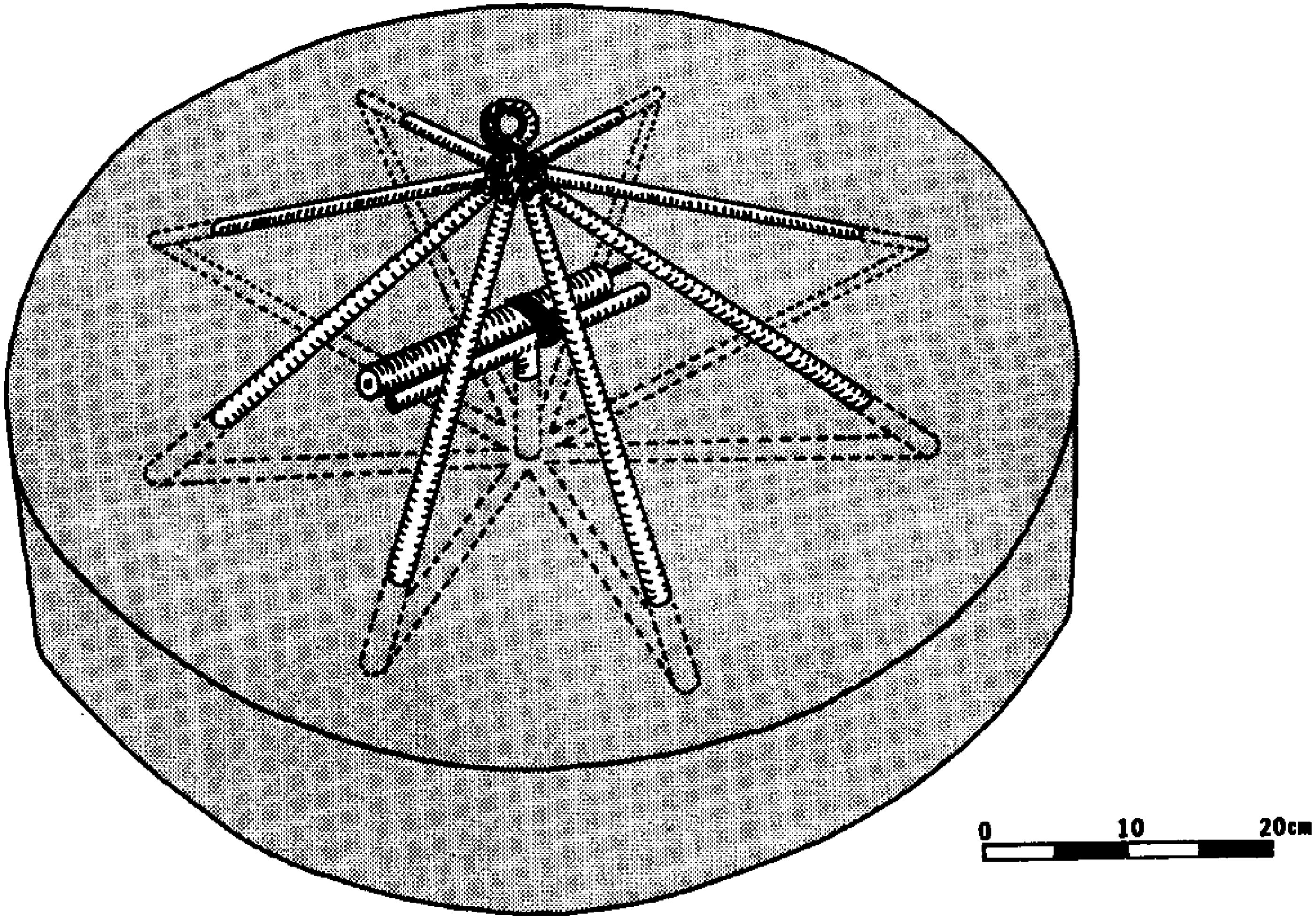

Figure 11. Wave Sensor Anchor Block

ternal damage by the cage (a diagram of the anchor block design appears in Figure 11).

The lifting ring is used to attach cables during handling of the block and the lowering of the block onto the seafloor. Once on the seafloor, the anchor chain from the marker buoy is attached to the lifting ring. Positioning of an anchor block in the array is done by using two transits on the breakwater to survey the location of the marker buoy. The circles of uncertainty of the mooring are less than four meters in diameter and repeated observations of the marker buoy from the breakwater can pinpoint the location of the anchor block to within a one meter radius.

3.3 Surface Marker Buoys

The surface marker buoys are used to enable divers to locate the wave sensors mounted on the anchor blocks and also provide a means of surveying the exact location of each wave sensor in the array. The surface marker buoys are of the spar buoy type (Figure 12). Each buoy is constructed from a single 6 m(20 foot) length of 7.5 cm (3 inch) diameter schedule 80 PVC pipe. Both the upper and lower ends are sealed with pipe caps and an attachment ring for the mooring line is bolted to the lower cap. A flotation collar fabricated from a rectangular block of polystyrene 30 cm square and 60 cm long is glued to the pipe with its upper surface located 2 m below the top of the buoy. Bands of fluorescent orange

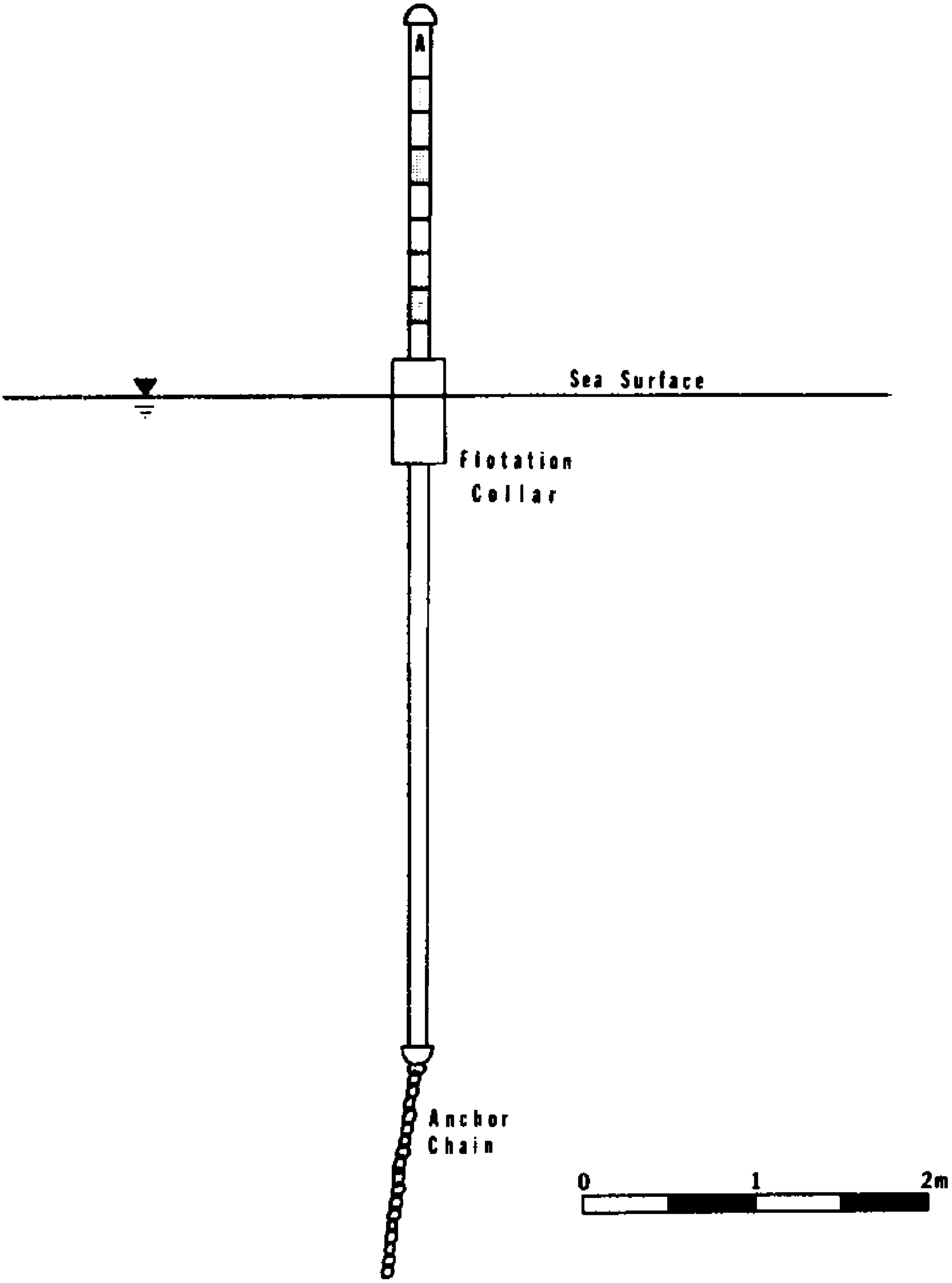

Figure 12. Surface Marker Buoy

paint alternated with unpainted bands of equal width from the flotation collar to the top of the buoy. Black vinyl identification letters are attached just below the upper endcap.

The buoy mooring line consists of 19 meters of $\frac{1}{4}$ inch hot-dip galvanized steel chain. The lower end of the chain is attached to the lifting ring on the anchor block with a shackle. Sufficient scope is allowed so that the buoy mooring line is taut at high tide. The buoyancy of the marker buoy is such that in case of very high tides or waves, the collar can sink below the surface without producing excessive lifting forces which would move the anchor block.

3.4 Breakwater Cable Protection

At both the breakwater and the shore station, various cables lying on the seafloor must pass through the surf zone to make electrical connection with other system components. A cross section of the breakwater is shown in Figure 13. Seafloor cables coming from the wave sensors arrive at the inside and outside bases of the breakwater. They are then routed through protective sheathing which carries them up the side of the breakwater to the signal multiplexer unit located on the top of the breakwater. The original protective sheathing consisted of about 20 meters of 7.5 cm (3 inch) diameter schedule 80 PVC pipe anchored to the rocks and extending from the top of the breakwater to about 10 meters below the MLLW level. The large diameter enabled the easy removal and replacement

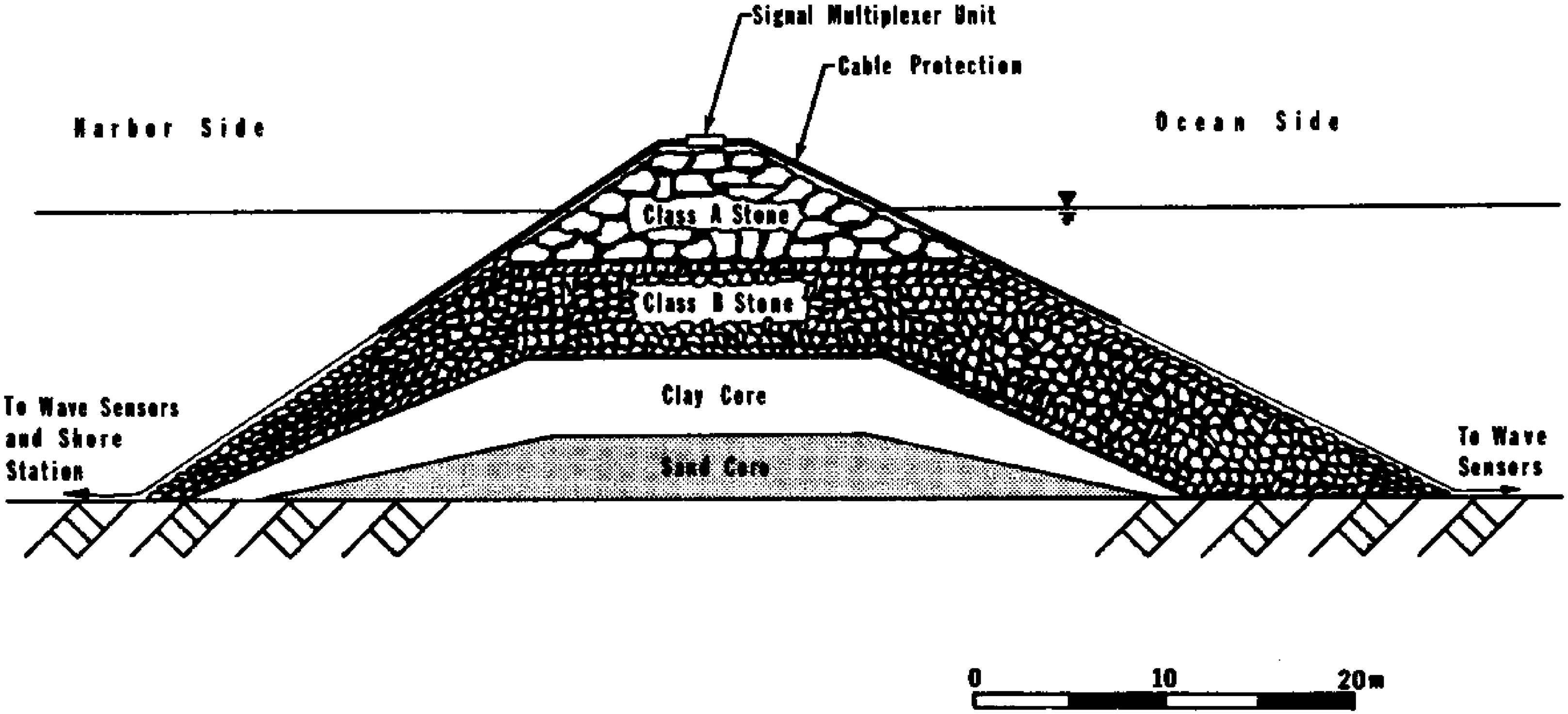

Figure 13. Cross Section of San Pedro Breakwater

of damaged cables. A severe storm in the winter of 1973-74 carried away the sheathing and cables on the ocean side of the breakwater. The protective sheathing on the harbor side remained intact.

After the storm, the ocean side sheathing was replaced by a 30 m length of one-half inch plastic covered flexible metal conduit (Anaconda "Sealtite" type UA). The four cables were pulled through the conduit prior to installation. The conduit was then anchored to the rocks every few meters by means of anchor bolts and metal clamps. Holes were drilled, both above and below water, in the granite rocks of the breakwater using a compressed air powered rock drill (Pneumatic Tool Sales Company, Model PTS-86). One-quarter inch "red head" anchor bolts were then hammered into place and finally the clamps were installed and the conduit clamped firmly to the rock surface. At the shore station, the seafloor cable is routed through a length of plastic pipe attached to a piling on the pier. No problem has been encountered at the shore station end since the wave action is small inside the harbor.

3.5 Breakwater to Shore Station Seafloor Cable

The seafloor cable connecting the signal multiplexer unit on top of the breakwater to the shore station located at Battelle Memorial Institute is the most vulnerable portion of the entire system. Lying, as it does, across the main ship channel it has received considerable damage. After laying the cable in the fall of 1973, no problems were encountered for the first three months. Following this period, the cable has been broken repeatedly on a average of once per month. The breaks appear to be due to ships dragging their anchors as they leave the harbor.

The cable was originally installed by mounting the single cable reel on the stern of a boat and reeling cable off into the water as the boat travelled from the breakwater back to Battelle. Except for the large size and weight of the cable and reel, it was a relatively easy and straightforward task. Repair of breaks in the cable is a much more arduous task. Beginning at the Battelle end, the researcher in a small boat pulls up the cable from the seafloor by hand and follows it until a break is reached. As cable is pulled up from the seafloor at the bow, an equal amount is allowed to fall back into the water at the stern. Once located, the bitter end is tied to a float and the process is repeated beginning at the breakwater end. When the two bitter ends are finally brought together at the surface, electrical checks are made and the ends are reconnected with a waterproof splice. Once the splice is completed, the cable is allowed to drop back to the seafloor and system operation is resumed.

CHAPTER 4-STORAGE OF RAW WAVE DATA

4.1 Data Recording

Real time analysis of the output of a wave sensor array is very costly and is, in this case, not at all necessary. By transmitting the raw wave data to a remote location and storing it digitally on magnetic tape, the cost of analysis may be substantially reduced. The raw wave data may be stored until needed and as computer time is made available it can be read into the computer memory for processing.

4.2 Digital Recorder Tape Format

Data processing of the raw wave data is performed at the USC Computer Center. In order to enter the data into the computer memory, the raw data tapes must be compatible with the IBM/360 system magnetic tape readers. Toward this end, the incremental tape recorder uses standard 8-1/2 inch diameter computer tape reels. Each reel contains 1200 feet of 1/2 inch wide 1.5 mil thick computer tape. The tape is marked near each end with beginning-of-tape (BOT) and end-of-tape (EOT) reflective marker strips. The interface electronics contained in the recorder generate all necessary gaps and marks to produce an IBM/360-compatible tape record.

Nine independent recording tracks run parallel down the length of the tape with 800 data bytes written on each inch of tape. This is referred to as a recording density of 800 bytes per inch or 800 BPI.

Each time the incremental tape recorder receives a write/step command (WRS) it writes a data byte and then increments the tape forward one step. An 800 BPI recording density corresponds to steps of .00125 inch. A data byte consists of nine bits(each bit has two possible states and is recorded as a one or a zero) which are recorded simultaneously on each of the nine tracks, one bit per track. Each nine-bit byte contains two,4-bit binary coded decimal (BCD) digits and a parity bit. This is referred to as "packed decimal" format. The parity bit is used as part of an error checking code which enables the computer to detect recording errors.

The computer normally interprets the 8 data bits in each byte according to the extended binary-coded decimal interchange system (EBCDIC) which allows the storage of only one digit or character per byte. It was necessary to utilize a special subroutine to unpack the two decimal digits from the pack decimal bytes. The reason for using the packed decimal byte format was to extend the recording time of a reel of recording tape. A doubling of the data storage capacity of a reel of tape (as compared to the EBCDIC format) was achieved by using this technique.

4.3 Raw Wave Data Recording Sequence

The incremental tape recorder writes twelve bytes of raw wave data every two seconds. The two data bytes from each wave sensor are recorded in sequence beginning with wave sensor #1 and ending with sensor #6. For each sensor the MSD data byte is recorded first, followed by the LSD data byte. Each hour on the hour an inter-record gap (IRG) is generated and written on the tape. This divides the raw wave data record into a series of one hour records and provides a means of indexing the data. Each record block has a blocksize of 21,600 bytes. With two bytes per wave sensor and six wave sensors, this corresponds to 1800 raw sea-surface elevation points for each wave sensor recorded in each one hour period. A computer program enables the raw wave data for a selected wave sensor to be extracted from the data tape and copied directly into the computer memory. Once the raw wave data is in the computer memory, the data processing may begin.

CHAPTER 5-ANALYSIS OF DATA AND PRESENTATION OF RESULTS

5.1 Data Preparation

A number of operations are necessary to prepare the raw wave data record for analysis. Initial preparation was accomplished prior to recording the data on magnetic tape. Two steps were performed; digitizing of the data (the conversion of frequencies into digital numbers) and the conversion of the digitized data into physical units (raw sea-surface elevation in centimeters). Note that this conversion is for the static pressure case and the actual raw digital data represents the sub-surface pressure in kilopascals. A sub-surface pressure of 150 kPa is approximately equal (within one percent) to the pressure exerted by a column of seawater 1500 cm high and thus corresponds to a static sea-surface elevation of 15.00 meters. The relationship between the sub-surface pressure and the sea-surface elevation for the dynamic conditions produced by waves is more complex and is examined in Appendix 2.

Once the raw wave data has been entered into the computer it must be edited and preprocessed. Data editing is designed to detect degraded data which contains obvious errors and spurious data points. Such data may result from recording digitized signals which suffer from excessive noise, or are erroneous due to wave sensor malfunctions or cable breaks. This is accomplished by plotting the data points in analog form and examining the analog record for spurious data points. Data preprocessing refers to the detection and removal of isolated outliers, level shifts and trends. Isolated outliers are detected and removed during the examination of the analog record. If more than one or two such points are present in a set of 1024 data points (the array size used in the FFT program), the set is considered to be excessively degraded and is not used. Level shifts and trends may be detected by computing the running sample mean. If level shifts are present, they indicate a malfunction in the wave sensor or digitizer and the data is not useable. If a trend is in the data (defined as any frequency component whose period is longer than the record length), which is invariably the case due to the effects of tidal fluctuations on the data, it may be removed by using regression analysis (method of least squares).

5.2 Data Qualification and Analysis

After the data preparation operations are completed, the wave data from each wave sensor comprises a time series sample record of finite length which represents a random physical phenomenon. It is usually assumed, in order to calculate the power spectrum, that this time series (and the continuous random process it represents) is an ergodic, stationary, Gaussian time series. This means we assume that our wave data record is sufficiently typical of all other records we could take in the same way, that statistics calculated on it will provide useful guidelines to the laws governing the situation.

Determination of the spectral energy density as a function of wave frequency (power spectrum) for sea-surface waves assumes that the sea-surface elevation record can be decomposed into elementary periodic waves of various frequencies. If indeed, data points read at equal time intervals from sub-surface pressure records do come from a random process which is stationary, normal and ergodic, then the power spectrum of the process may be estimated from the data. If the process is non-Gaussian, valuable information about the process can still be determined from power spectral estimates even though the spectra do not describe the data completely.

Several basic characteristics determine whether or not the power spectral estimate will be able to closely describe the process under investigation. Whether or not the data exhibits these basic characteristics determines how the data is to be processed and what interpretation is to be given to the analyzed results. The three most important characteristics for which the data should be tested are stationarity, normality and the presence of periodicities. Verification of stationarity for a single sample record justifies an assumption of stationarity and ergodicity for the random process from which the sample record is obtained. The validity of the assumption that the data (excluding periodicities) have a normally-distributed probability density function should also be verified. The presence of almost periodic components (the frequencies of the components are not related by rational numbers) in otherwise random data will appear as sharp peaks in the power spectrum. If the measured spectral peak represents a sine wave (periodicity), the indicated bandwidth will always be equal to the bandwidth of the analyzer filter and the indicated spectral density will always increase in direct proportion to the reduction in filter bandwidth.

In the analysis of ocean waves the data is thought to consist almost exclusively of periodicities. Wave data analysis involves calculation of the auto-correlation function which correlates the data obtained from a wave sensor at one point in time, to data obtained from the same sensor at later points in time. The Fourier transformation of the auto-correlation function produces the power spectrum. Power spectra measurements inside and outside of the breakwater may be compared and interpreted to obtain the breakwater wave energy transmission coefficient.

5.3 Results

Preliminary results (Lee and Walther, 1974) based on data collected by the three sensor linear array indicate that the predominant energy at the site is centered around a frequency of 60 millihertz (wave period of 16.6 seconds). For 60 mHz swells approaching the breakwater with their wave crests parallel to the breakwater (perpendicular to the wave sensor array), 50% of the incident wave amplitude appears to be reflected back out to sea and about 30% of the wave amplitude is transmitted through the breakwater into the harbor. This implies, that for swells of this frequency, only 20% of the wave amplitude is dissipated within the breakwater itself.

Figure 14 shows the energy spectra for each of the three sensor locations analyzed from records obtained during the low tide period on 15 November 1973. Fifteen hundred data points for each sensor were used in the computations. The data points were regularly spaced at a real time interval of two seconds. From the figure, it is apparent that the energy spectra from each sensor location indicates the presence of a periodic component centered about a wave frequency of 60 mHz. Note that the wave energy at sensor location 2 is greater than at location 1. (These two locations are on the ocean side of the breakwater - see Figure 3.)

This apparently anomalous result is due to the existance of a partial standing wave pattern caused by the reflection of wave energy from the ocean side of the breakwater structure. If no reflected wave energy were present, the spectral densities for 60 mHz waves at both locations would be identical. If a 100% reflection were to occur, the wave energy of 60 mHz waves measured at sensor location 2 would be over three and one-half times as great as at location 1. Thus, a reflection coefficient of about 50% for waves of 16.6 second period is inferred from the data.

The diagram of Figure 15 shows the standing wave envelope

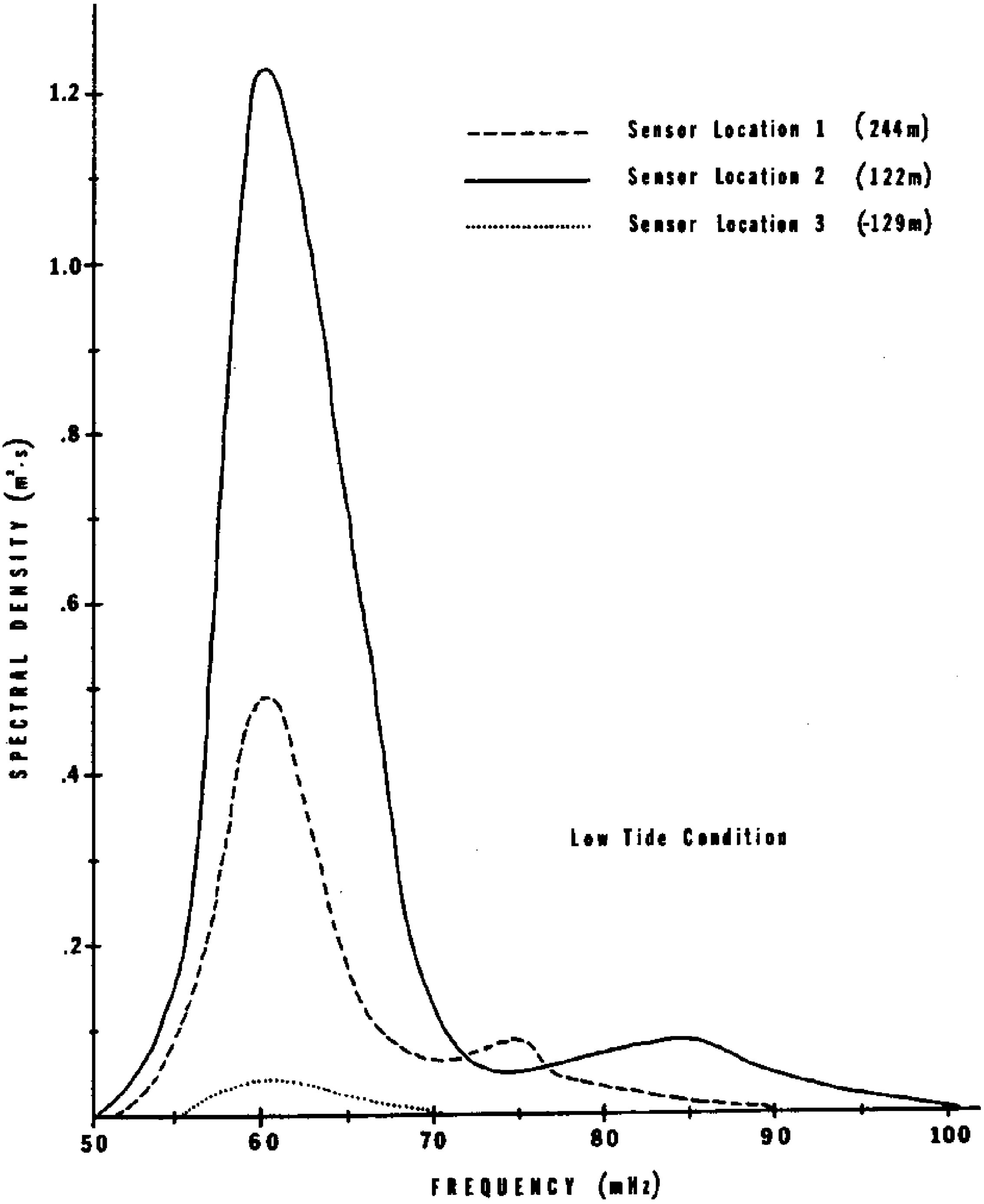

Figure 14. Spectral Curves at Three Sensor Locations

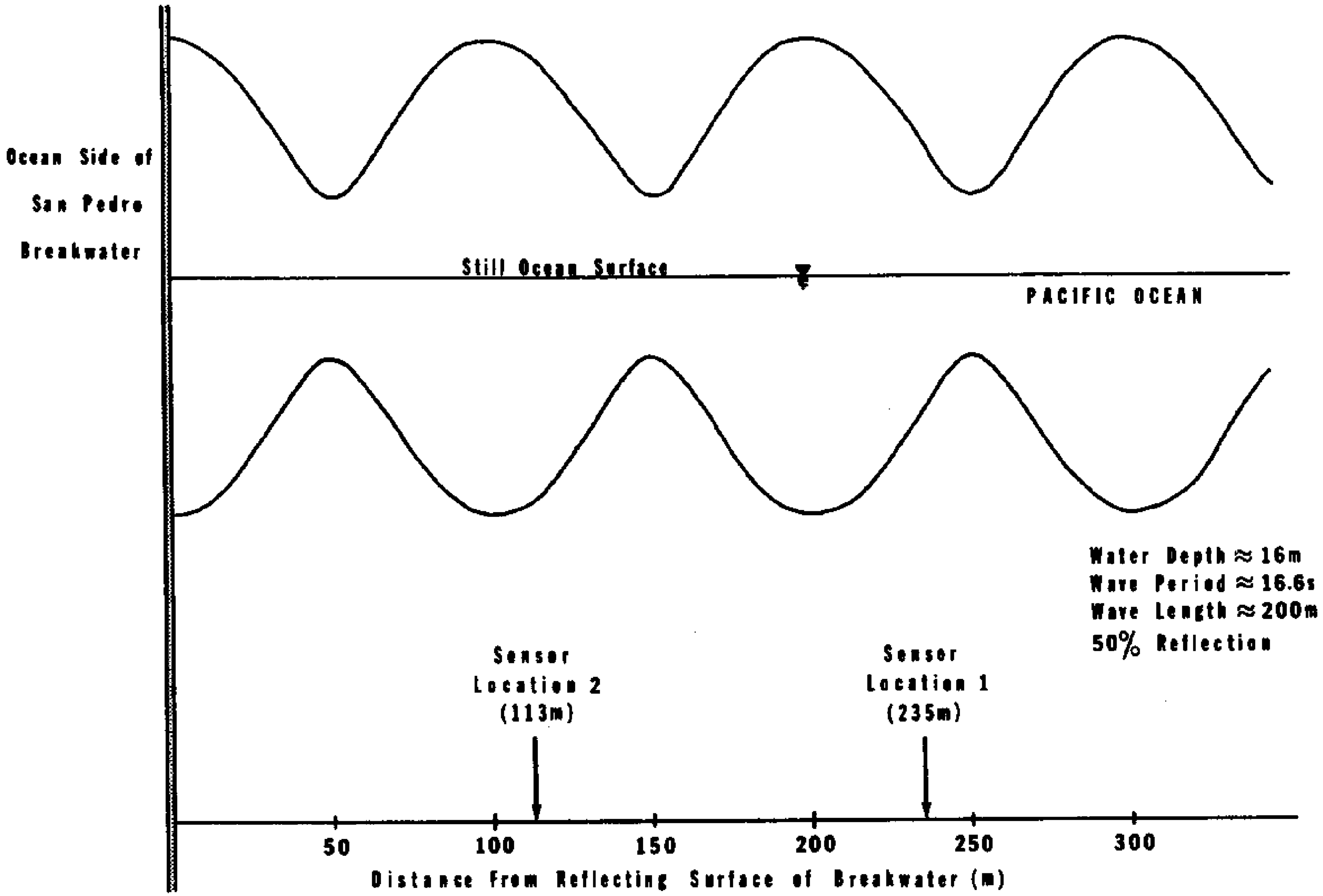

Figure 15. Standing Wave Envelope

which would be produced by a reflection coefficient of 50%. Incident waves with a frequency of 60 mHz will have a wavelength of 199 meters in the 16 meter water depth at the instrumentation site. The difference in the standing wave amplitudes for 60 mHz waves at the two sensor locations is apparent from the figure.

Assumming that only progressive waves having a period of 16.6 seconds are responsible for the wave energy which appears at sensor location 3 inside the breakwater, the wave transmission coefficient is calculated to be 30%. The wave transmission coefficient is defined as the transmitted wave amplitude divided by the incident wave amplitude. Thus, it appears that only about 20% of the wave amplitude of 16.6 second period waves is dissipated by the breakwater as the wave passes through the spaces between the rocks.

Figure 16 shows the energy spectra for each of the three sensor locations analyzed from records obtained during the high tide period on 15 November 1973. Analysis of these spectra indicates that there is very little tidal effect on the calculated reflection and transmission coefficients for waves having a 16.6 second period. Energy spectra calculated from a separate wave record obtained in the southeast basin of the harbor show that the energy content for 60 mHz waves is the same as that measured at sensor location 3. This would indicated that at least for waves having a 16.6 second period, the wave system inside the harbor is progressive.

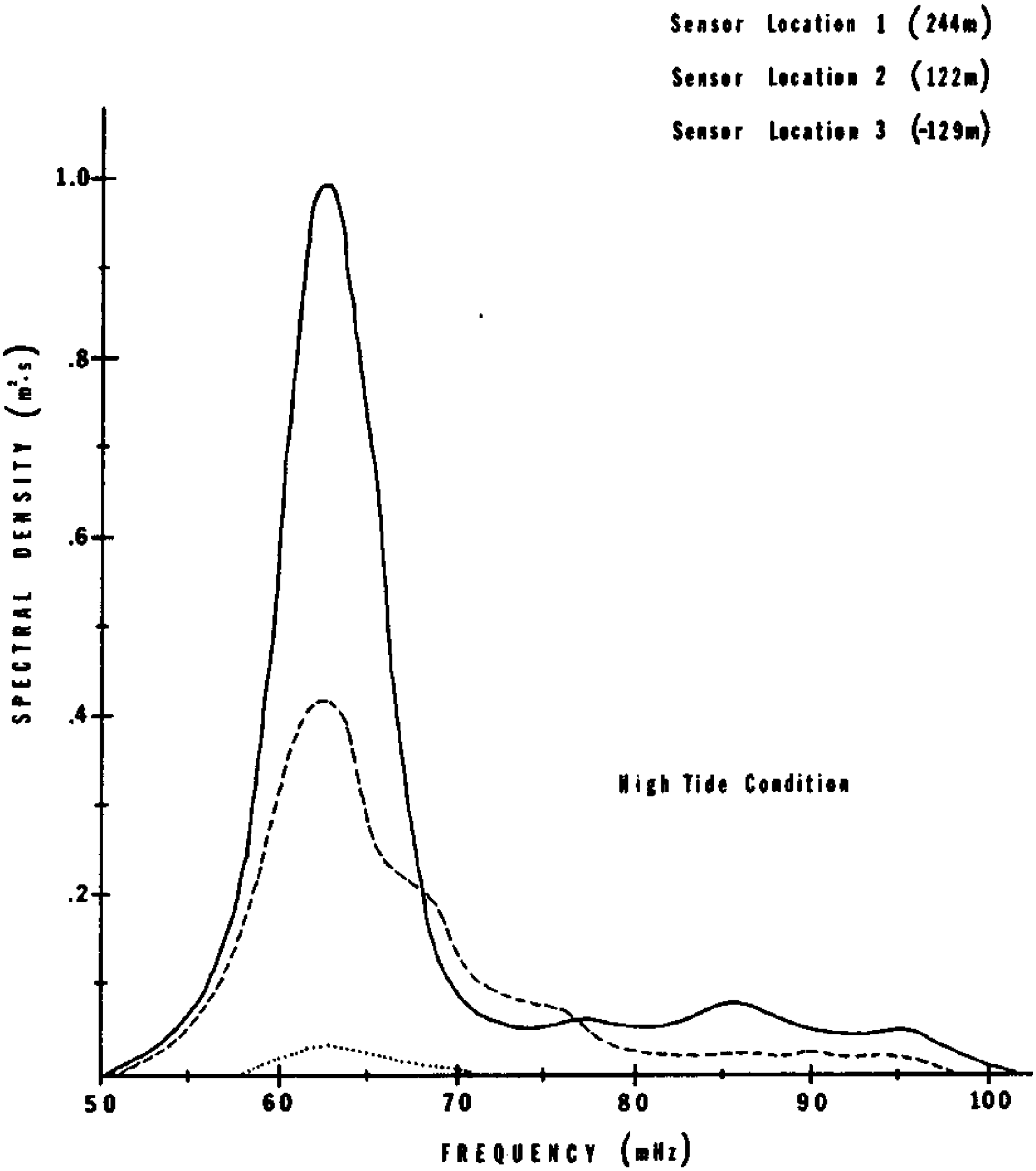

Figure 16. Spectral Curves at Three Sensor Locations

CHAPTER 6-CONCLUSIONS AND RECOMMENDATIONS

Several conclusions based upon system operation and the preliminary results are in order. First, the instrumentation system is capable of gathering and storing on magnetic tape ocean wave data of good quality. The intercomparison of wave data gathered simultaneously by two adjacent transducers shows quite comparable results. Second, (after initial problems were solved) the entry of the raw wave data recordings into the computer by means of the tape reader may be accomplished without incident. Subroutines in the computer program have been modified to allow the use of packed decimal recording which results in a more efficient use of recording tape. Third, the results of wave data analysis indicate that significant amounts of wave energy do indeed penetrate directly through the San Pedro breakwater into the harbor complex.

The recommendations proposed fall into two categories; additional data collection necessary for further analysis of the harbor resonance problem, and a discussion of existing instrumentation system problems with proposed solutions.

Additional data collection is necessary in view of the fact that data gathered by the linear wave sensor array used in the initial installation could not be used for calculation of the direction spectrum. In order to determine the relationship between energy transmission through the breakwater as a function of wave incidence angle, the wave sensors must be positioned to form an omnidirectional array. The waves arrive normal to the breakwater only a limited portion of the time, so knowledge of the incidence angle vs. energy transmission relationship is essential for calculation of the real-life situation. A possible array configuration using six wave sensors is presented in Figure 17. Data from the five wave sensors on the ocean side of the breakwater can be used to calculate the directional spectra while the sensor located on the harbor side can provide data on energy transmission through the breakwater.

Another area where data collection could be profitable would be to instrument several selected locations inside the harbor complex. Then, whenever surging occurs in the harbor, the power spectrum and directional spectrum of the incoming wave energy would be known and the relationship between the two could be analyzed in a quantitative manner.

Instrumentation problems arose in several areas. The initial design philosophy for the instrumentation system was based on the premise that gradual failure of seafloor cable insulation would occur with time. This would degrade the data in an undetectable fashion if voltage or current levels were used to transmit the data. In order to provide reliable transmission of data through poorly insulated cables, the frequency modulation technique was used. The inherent reliability of this method was demonstrated when one of the con-

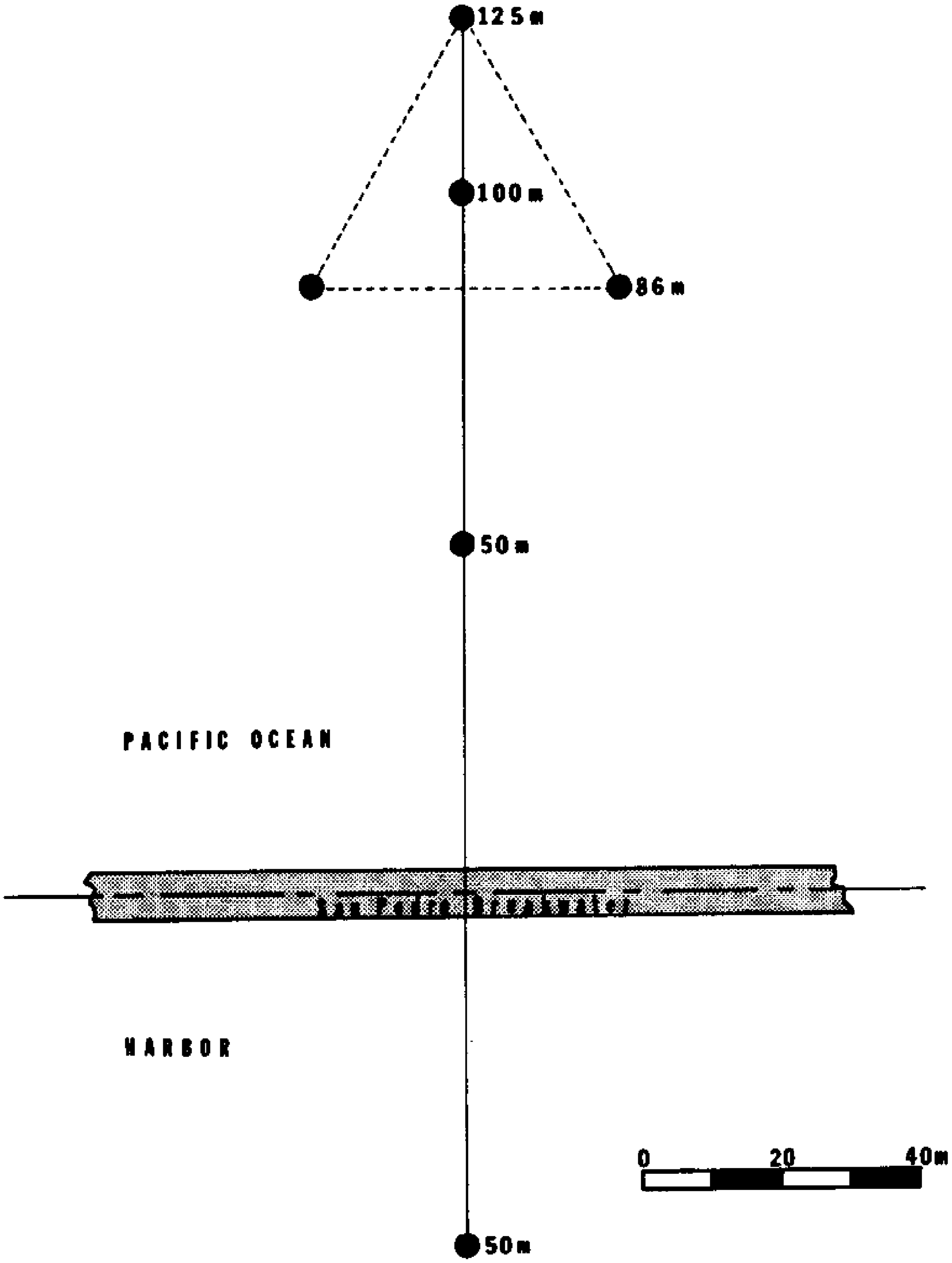

Figure 17. Layout of Omnidirectional Wave Sensor Array

ductors on the main seafloor cable became shorted to seawater. Since the entire signal and power system connected to the wave gauge array was isolated from ground, the system remained operable for several weeks. The only difference noted was an increase in the 60 Hertz AC signal appearing on the seafloor cable wires.

All cable problems to date, except for a single case, have been due to catastrophic failure rather than gradual degredation of cable insulation. Both the array to shore station and the breakwater to wave sensor cables have been broken with monotonous regularity. Breaks have averaged one per month and the long term gradual failure of the cable insulation has not been observed to occur. Perhaps this points up the adequacy of the cable protection installed in the surf zone as this is the region where cable problems normally occur. Our breaks on the other hand take place in deep water and appear to be due to ship anchors snagging the cable and pulling it until it breaks. On one occasion, a section of cable over 400 meters long disappeared from the middle of the breakwater to shore station seafloor cable. The bitter ends showed signs of great stress before final parting of the wires.

The short cables connecting the wave sensors to the signal multiplexer unit on the breakwater usually unplug themselves from the sensors when they are pulled. This does not always occur and on one occasion an anchor block and marker buoy were displaced about 100 meters from their surveyed location. The cables going to the breakwater were broken and the anchor block was buried in the mud upside down. The two wave sensors mounted on the anchor block were damaged beyond repair. These two wave sensors have not been replaced because the Vibrotron pressure transducers are no longer manufactured and replacement FM output transducers are not readily available. It seems reasonable then to consider redesign of the system in the light of the fact that problems related to broken cables have kept the system inoperable, except for a two month period, for the last 14 months. The proposed modified system could use any of the following suggestions either singly or in combination.

The wave sensors could be designed around voltage output pressure transducers in a four-wire system (two signal wires and two power wires in a single cable). A cable insulation leakage check circuit inside the wave sensor pressure housings could be activated by reversing the polarity of the voltage applied to the power wires and would produce a calibrated output on the signal wires. Thus, the integrity of the cable insulation could be checked monthly from atop the breakwater.

An alternate method might be to use a two-wire system with the voltage output of the wave sensor converted to a current output. The output signal could be recovered by monitoring the voltage drop across a fixed resistor in series with the wave sensor power wire.

By installing a diode inside the wave sensor in series with the power wire, a cable insulation leakage test could be made from atop the breakwater. This would involve reversing the votage applied to the power and ground return wires and measuring the resultant leakage current. An electrical leakage path inside the cable or waterproof connector would manifest itself as an increase in the normally small leakage current which would occur through a reverse-biased diode.

The main seafloor cable has two functions: It must carry power to the wave gauge array and it must serve as the data link to carry FDM signals back to the shore station. These two functions could be separated and the cable done away with. The power-carrying functions could be replaced by storage batteries located on the breakwater. This approach was rejected as unwieldy in the initial design but the broken cable problems encourage its reconsideration. Note that the problem of broken and pulled cables between the breakwater and the wave sensors would still be present.

The data transmission function could be replaced by a radio or optical data link between the breakwater and the shore station at Battelle. An alternate method would be to install a tape recorder directly on the breakwater. This gets us back to the original problem of requiring the raw wave data stored on magnetic tape to be in a computer-compatible format for entry into the computer for analysis. This problem could probably be solved by reformatting the tape generated by the breakwater recorder by means of the incremental tape recorder we are now using. A preliminary check of digital cassette recorders indicates that the storage capacity of a cassette will enable the recording of raw wave data from six wave sensors every two seconds for a period of 12 hours. This would only be adequate if storms and high waves could be conjured up upon command.

For future wave data acquisition efforts it is desireable to eliminate or reduce the number of seafloor cables and also reduce the cost and complexity of the wave sensors. Wave sensors which convert pressure variations into changes in the electrical current they draw from the power source (current transmitter technique) require only two wires for both power and data transmission. These could replace the FM output wave sensors now in use. A self-contained electronics unit powered by storage batteries could be mounted on top of the breakwater. Inside, an analog-to-digital converter would rapidly sample the outputs of the wave sensors and temporarily retain the values in a storage register. A serial formatter and radio transmitter would then send the data to a shore station where it would be received, formatted, and recorded on a nine-track, computer-compatible magnetic tape.

REFERENCES

1. J.S. Bendat and A.G. Piersol, Random Data: Analysis and Measurement Procedures, Wiley-Interscience, New York, 1971, p. 214.

2. L. Draper, "The Problems of Sea-Wave Recording", Proceedings of the I.E.R.E. Conference on Electronic Engineering in Oceanography, I.E.R.E. conference proceedings no. 8, Paper No. 3, 1966.

3. D. Esteva and D.L. Harris, "Comparison of Pressure and Staff Wave Gauge Records", Proceedings of the 12th Coastal Engineering Conference, ASCE, Washington, D.C., 1970, pp. 101-116.

4. R.A. Grace, "How to Measure Waves", Ocean Industry, Vol. 5, No. 2, February 1970, pp. 65-69.

5. R. T. Knapp and V.A. Vanoni, "Wave and Surge Study for the Naval Operating Base, Terminal Island, California", Hydraulic Structure Laboratory, California Institute of Technology, 1945.

6. J. J. Lee and F. Raichlen, "Resonance in Harbors of Arbitrary Shape", Proceedings of the 12th Coastal Engineering Conference, ASCE, Washington, D.C., 1970, pp. 2163-2180.

7. J. J. Lee, "Wave Induced Oscillations in Harbors of Arbitrary Geometry", Journal of Fluid Mechanics, Vol. 45, 1971, pp. 375-

394.

8. J. J. Lee and F. Raichlen, "Wave Induced Oscillations in Harbors with Connected Basins", Report KH-R-26, W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, 1971.

9. J. J. Lee and J. A. Walther, "Wave Energy Permeation of San Pedro Breakwater", Sixth Annual Offshore Technology Conference, Paper No. OTC-2124, 1974.

10. M. D. Lefcort, "Vibrating Wire Pressure Transducer Technology", Journal of Ocean Technology, Marine Technology Society, Vol. 2, No. 2, April 1968, pp. 37-44.

11. J. Miles and W. Munk, "Harbor Paradox", Journal of the Waterways and Harbors Division, ASCE, Vol. 87, No. WW3, 1961, pp. 111-130.

12. F. E. Morris, "Vibrotron Analog Microbarograph System", The Review of Scientific Instruments, Vol. 38, No. 4, April 1967, pp. 514-516.

13. N. N. Panicker and L. E. Borgman, "Directional Spectra From Wave Gauge Arrays", Proceedings of the 12th Coastal Engineering Conference, ASCE, Washington, D.C., 1970, pp. 117-136.

14. R. C. Rolfe, "Vibrating Wire Pressure Transducer Electronics", Journal of Ocean Technology, Marine Technology Society, Vol. 2, No. 2, April 1968, pp. 45-48.

15. J. M. Snodgrass and J. H. Cawley, "Temperature and Depth Circuitry in a Telerecording Bathythermometer", Proceedings of the National Electronics Conference, Chicago, 1956, Vol. 12, pp. 1-9.

16. E. B. Thornton and R. J. Calhoun, "Spectral Resolution of Breakwater Reflected Waves", Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE, Vol. 98, No. WW4, November 1972, pp. 443-460.

17. B. W. Wilson, "Surge and Wave Action Study for Los Angeles-Long Beach Harbor", Vol. 1, Science Engineering Associates, 1968.

APPENDIX 1

Determination of Wave Sensor Calibration Constants

The conversion of actual sea-surface elevation at the breakwater location into a digital representation of sea-surface elevation at the shore station is a four-step process. First, the actual sea-surface elevation is determined indirectly by measurement of subsurface pressure. Second, the pressure is converted to an inverse frequency analog which is transmitted to the shore station. Third, the data digitizer at the shore station converts the frequency into a digital number related to pressure. Finally, the digital number is converted to raw sea-surface elevation and is recorded for later analysis.

The relationship between the resonant frequency of the wire and the pressure applied to the diaphragm of a Vibrotron is called the transfer function. For large variations in pressure, the transfer function is nonlinear. The pressure range of interest is 150 to 200 kilopascals (corresponding to a sea-surface elevation of 15 to 20 meters). For this narrow pressure range, the transfer function may be approximated by a linear relationship.

A linear transfer function which relates a digital number to inverse frequency may be expressed as:

$$N = C + D\frac{1}{F} \qquad 150\text{kPa} < P < 200\text{kPa} \qquad (1)$$

Where:

F = Frequency at any pressure within the range (Hz)

N = A digital number related to the pressure

C = Constant determined for each gauge during calibration

D = Constant determined for each gauge during calibration

N is obtained at the shore station by totalizing the frequency for a predetermined number of cycles and simultaneously measuring the elapsed time period by means of counts of a reference frequency accumulated in a data totalizer which begins at a preset number. If only the four least significant digits (LSD) of N are retained in the data totalizer (i.e. all digits greater than 9999 are allowed to overflow), then the four digit number remaining represents the applied pressure in hundreds of pascals. In equation form:

$$P = \left[\left(C + D \frac{1}{F} \right) \qquad 4\ \text{LSD only} \right] 100 \qquad (2)$$

To find the sea-surface elevation (or the depth of the wave sensor below the sea-surface) use the hydrostatic equation:

$$P = \rho g h = \gamma h \qquad (3)$$

$$h = \frac{P}{\gamma} \qquad (4)$$

where:

P = sub-surface pressure (Pa)

ρ = seawater density (kg/m^3)

g = acceleration of gravity (m/s^2)

h = sea-surface elevation (m)

γ = specific weight of seawater (1×10^4 Pa/m)

Combining (4) and (2), the sea-surface elevation in meters is given by:

$$h = \left[\left(C + D \frac{1}{F} \right) \qquad \text{4 LSD only} \right] \frac{1}{100} \qquad (5)$$

Thus, the four digits retained in the data totalizer represent the sea-surface elevation in centimeters. The method by which the data digitizer converts wave sensor frequency into raw sea-surface elevation is described in detail in section 2.4.2. The constants C and D are related to the three parameters hardwired into the data digitizer circuitry by:

$$C = Q \qquad (6)$$

$$D = M \cdot Fr \qquad (7)$$

where:

Q = pre-set number in data totalizer

M = signal totalizer limit number

Fr = fixed reference frequency

The values of these three parameters are determined from the wave sensor calibration data and are different for each sensor. Since the relationship between frequency and pressure is assumed to be linear, only two calibration points are necessary.

The calibration is performed at a temperature of 10° C which is the mean of the expected annual temperature variation the wave sensors will encounter on the seafloor (10°C ± 3°C). Pressures of 150 kilopascals and 200 kilopascals are generated by a dead-weight pressure tester and applied to the pressure port on the wave sensor pressure case. The corresponding output frequencies are then recorded:

Pressure	Frequency
150 kPa	Fa
200 kPa	Fb

The design goal is to have the data totalizer output represent the raw sea-surface elevation in centimeters. Since a pressure of 100 Pa is equal to a seawater depth of 1 centimeter, a pressure change of 50 kPa represents a seawater depth difference of 500 centimeters (5 meters).

The value of Fr is selected by trial and error to provide a 150 kPa conversion time interval (Ta) on the order of one second. The conversion time interval for 150 kPa pressure, Ta, is given by:

$$Ta = \frac{M}{Fa} \tag{8}$$

With a frequency selected for Fr, the next step is to determine the value of the signal totalizer limit number, M. The value of M may be calculated from:

$$M = \frac{\Delta P \cdot R}{\frac{Fr}{Fb} - \frac{Fr}{Fa}} = \frac{\Delta P \cdot R\,(Fa \cdot Fb)}{Fr\,(Fa - Fb)} \tag{9}$$

where:

ΔP = the pressure range (50 kPa) = (5m depth)

R = resolution (1 count/100 Pa) = (1 count/cm depth)

Fr = fixed reference frequency

Fa = output frequency at lower end of pressure range

Fb = output frequency at upper end of pressure range

Finally, the pre-set number, Q, may be found from the relationship:

$$Q = 1001500 - M \cdot Fr \frac{1}{F} \qquad (10)$$

It is necessary to hardwire only the four least significant digits of Q into the circuitry since only the four least significant digits of the output count are retained in the data totalizer.

APPENDIX 2

Instrumentation Error Analysis

The conversion of a time record of sub-surface pressure fluctuations into a time record of sea-surface elevations is a complex task. Error sources exist at every level in the conversion process. The further conversion of a sea-surface elevation record into a wave energy spectrum allows more error sources to interfere. Finally, in order to convert a simultaneous set of sea-surface elevations taken at different locations into a wave direction spectrum one must consider a few additional error contributions. All of the possible error sources should be examined to determine the magnitude of the error contribution in the frequency band of interest due to each source. If this contribution is small, we may neglect it, but one cannot ignore a possible error source until the magnitude of its error contribution is known.

We desire to study the wave energy spectrum in the frequency range of 10 to 100 mHz (wave periods of from 10 to 100 seconds). Individual error sources contribute errors only into certain frequency bands, so only those sources which have significant error contributions in the 10 to 100 mHz band are of importance. As we shall see, this fact allows us to immediately eliminate from more detailed analysis many potential error sources. Let us first consider sources which contribute errors to the sub-surface pressure to sea-surface elevation conversion process. We may divide these error sources into four broad classes for discussion.

The first class of errors are pressure transducer errors. The electronic circuitry which converts the pressure transducer output frequency into an equivalent pressure assumes that each pressure transducer has a linear frequency to pressure transfer function. The actual relationship is somewhat nonlinear and contributes a nonlinearity error which is proportional to the amplitude of the pressure fluctuations. The magnitude of the nonlinearity error is about 2% of wave height. Hysteresis is always present in pressure transducers, but it tends to be small in the low pressure range transducers. The error contribution due to hysteresis is also a function of the magnitude of the pressure fluctuations and is, for our transducers, less than .1% of wave height.

A more severe error source is that due to the secondary sensitivities of pressure transducers. Not only are they sensitive to applied pressure, but also to ambient temperature and power supply voltage. The design of the Ramsay A-32 Vibrotron Oscillator has been optimized to minimize the effect that varying the supply voltage has on output frequency. Tests on the system indicate that the worst wave sensor exhibits an equivalent sea-surface elevation change of 5 cm when the power supply voltage is varied from 25 to 35 VDC. The Zener diodes and filter capacitors within the signal multiplexer unit mounted on the breakwater regulate the voltage applied to the wave sensors to between 29 and 31 Vdc. The magnitude of this error contribution then is equivalent to a 1 cm sea-surface elevation change.

The secondary sensitivity due to ambient temperature would be quite significant were it not for the fact that temperature variations on the seafloor where the transducers are located, change slowly and are of small magnitude. The seafloor temperature varies from a maximum of about 13°C in late summer to a minimum of 8°C in early spring. These seasonal temperature variations produce errors of significant magnitudes but since their frequency is so low they do not contribute errors in the frequency band of interest. Diurnal temperature variations also occur but they are also outside the 10 to 100 mHz band so they are removed as trends in the data processing along with pressure fluctuations due to tides.

The only possible temperature effect which could contribute errors in the frequency band would be due to wave action or surging which could possibly move a temperature gradient back and forth across the wave sensors. If this did occur, it could produce a temperature effect which would lie in the frequency band of interst. This remote possibility is prevented by the fact that the pressure transducer mounted in its pressure case has a temperature time constant in excess of 15 minutes. This means that the effects of any thermal changes on the order of 100 mHz or faster would be attenuated by almost 99%. Since the size of the temperature gradient involved in such a phenomenon would be small, the error contribution would be negligible.

The second class of errors are water flow errors. Tidal currents and normal circulation currents do not have cyclic fluctuations in the frequency band of interest. The wave sensors are mounted about 25 cm above the seafloor, so cyclic, sub-surface, water particle velocities produced by surface wave action in intermediate depth water (d/L is greater than .05 but less than .5) can cause hydraulic errors. The orientation of the sensor pressure port with respect to the direction of the water flow and the speed of the flow determine the magnitude of the error produced. The largest effect would occur at the 10 mHz end of our frequency band.

A wave having an amplitude of 2 meters (4 meter wave height) and a frequency of 40 mHz (T = 25 seconds) would cause the water particles near the seafloor to move back and forth a distance of less than 2 meters as it passed overhead. In a water depth of 15 m the wave celerity would be around 6.5 m/s. For a worst case step function, water particles would travel a distance of 2 meters (1 meter forward, 1 meter back) in 12.5 seconds as the wave approached and the same amount as the wave left the area. This works out to a velocity of 1 meter per 6.25 seconds or 16 cm/s (0.5 ft/sec).

This current flowing across the wave sensor pressure port will produce an error which will be on the order of .1% of the wave height under worst case conditions.

The third class of errors have to do with the conversion electronics. The electronic circuitry assumes there is a linear relationship between pressure and sea-surface elevation. This relationship is nonlinear in two ways. For the static pressure case, the assumption must be made that the density of the seawater column and the acceleration of gravity remain constant. While the latter may be a valid assumption, the former is not. The density of seawater is a complex function of temperature, salinity and pressure. For the range of these variables encountered at the wave array location, the density variation range is small and may be expected to change slowly and in a like manner over the entire array.

Since the parameter of interest for measurement of energy transmission through the breakwater is the ratio of the amplitude of the wave spectra inside and outside of the breakwater, the errors due to density variations will cancel out if the error contributions are equal on each side of the breakwater.

The bandwidth of the FM subcarriers places an upper limit on the highest wave frequencies which can be transmitted. The nominal frequency response of the narrowest bandwidth transducer is 12 Hz which is more than adequate for our use. The slow rate of the PLL tracking filters also poses a potential upper frequency limit but they are adjusted to respond at a rate greater than 10 Hz. An error source inherent in the electronics is the least count error which appears in every digital counter. This introduces a random error equivalent to ± 1 cm of sea-surface elevation change.

The fourth class of errors contains those errors due to time sampling alaising, time averaging of sea-surface elevations and filtering effects of the water column. Time sampling alaising is an error peculiar to systems which sample the data at equal time intervals and its prevention is extremely important. The time between sampling intervals is called the sampling rate. If the sampling rate is not often enough, high frequency data can be mistaken for low frequency data. If alaising is not prevented by proper system design, the data will be useless as there is no method by which alaising errors may be removed at a later time. The elimination of high frequency components must be accomplished prior to recording the data.

It is quite simple for a pressure transducer mounted on the seafloor to detect the static pressure head produced by the water column. If surface waves appear, sub-surface pressure fluctuations are produced. These bottom pressure fluctuations are related to those produced at the surface by a nonlinear relationship. Small amplitude (Airy) wave theory may be used to calculate the pressure response factor (Kp) for various wave frequencies and water depths.

$$Kp = \left[\frac{1}{\operatorname{Cosh} \left(\frac{2 \pi d}{L} \right)} \right]$$

For waves having a wavelength (L), the portion of the surface pressure fluctuation (Δ P) which appears at a depth (d) below the surface is given by Kp(Δ P). The attenuation of pressure with depth is then:

$$\text{Attenuation} = 1 - \left[\frac{1}{\operatorname{Cosh} \left(\frac{2 \pi d}{L} \right)} \right]$$

A plot of this theoretical relationship for a water depth of 15 meters appears in Figure 18. Grace (1970) references the work of several authors which have found that this theory seems to be valid only in the region where d/L is greater than .3 and less than 1.0. Since for our location and frequency band, d/L is greater than .01 and less than .14, it may appear that we are not on firm ground when using this theory. But if the Kp curve in Figure 1 is not really correct for d/L less than .3, then the wave power spectrums taken outside and inside the breakwater are merely distorted. Since we are interested only in their ratio and not their absolute values, the errors due to this source should cancel out.

In water having a depth of 15 meters, small amplitude wave theory predicts that for waves having frequencies of 330 mHz (T = 3.03 seconds) and higher, the pressure response factor (Kp) is less

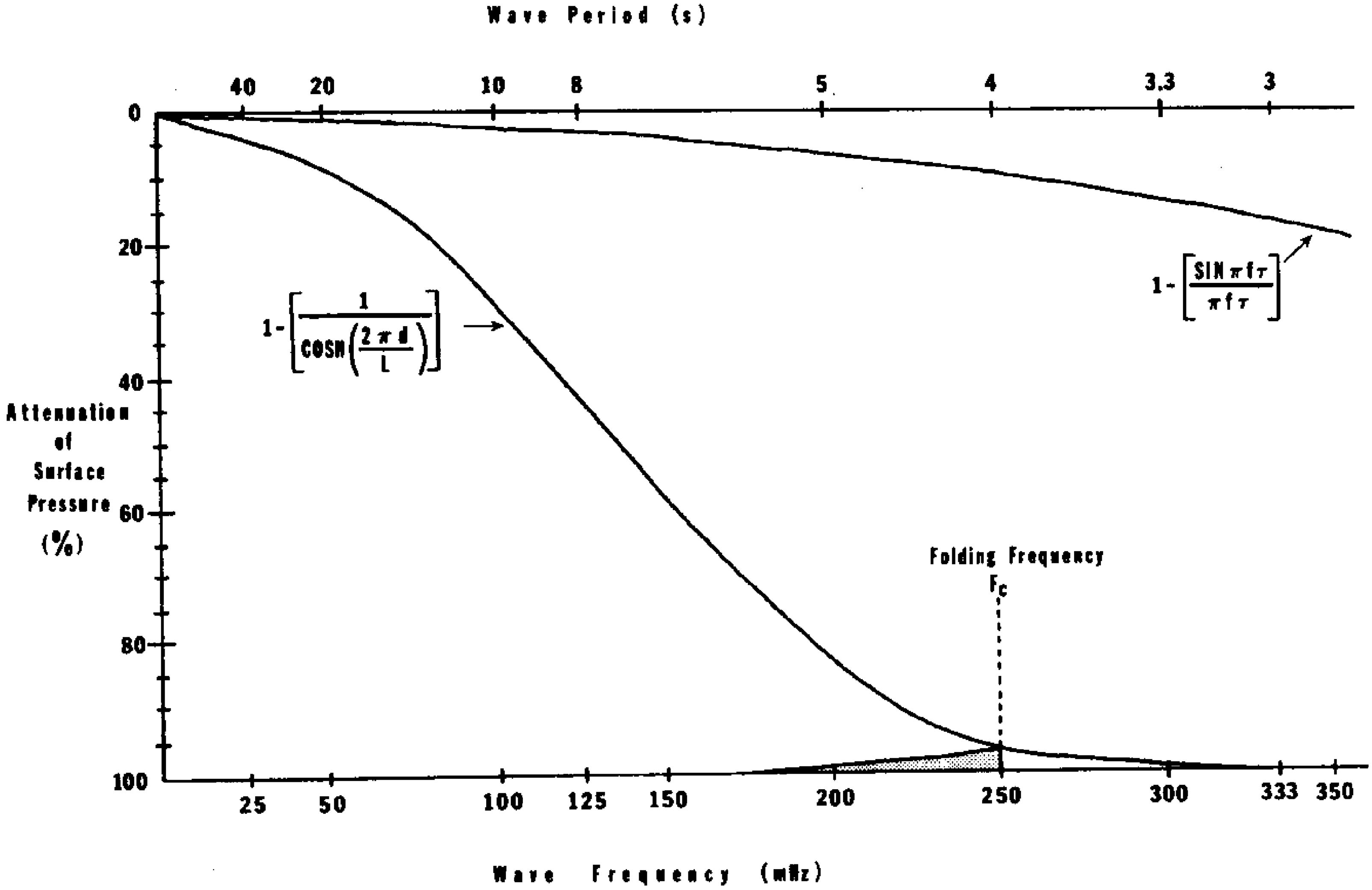

Figure 18. Attenuation Versus Frequency at 15 Meter Depth

than .05%. This means that the amplitude of surface wave produced seafloor pressure fluctuations is only .05% of that at the surface. So no significant energy is detected by our wave sensors from waves having frequencies above 330 mHz.

Our sampling rate (Δt) is one sample every two seconds. The folding or Nyquist frequency (Fc) is defined by:

$$\frac{1}{\Delta t} = 2Fc$$

For our case Fc is 250 mHz. This means that the wave spectrum up to 165 mHz ($T \approx 6$ seconds) is free of errors due to folding. With a 250 mHz folding frequency, energy in the 250 mHz to 330 mHz range (above which the energy is negligible) is folded back into the 165 mHz to 250 mHz range. Therefore data in this range suffers from alaising errors, while no alaising errors are present below 165 mHz.

Time averaging of sea-surface elevations also produces a filtering effect on the apparent wave power spectrum. The electronic circuitry averages the sea-surface elevation for around one second and records this value once every two seconds. The net result may be considered as a series of one second averages with every other reading decimated. This sampling method is equivalent to a low pass filter having a response:

$$\frac{E_o}{E_i} = \frac{\sin(\pi f \tau)}{\pi f \tau}$$

Where τ is the averaging time (1 second with every other sample decimated) and f is the wave frequency in hertz. This filtering action is also plotted in Figure 18. To obtain the true shape of the power spectrum, the amplitudes must be corrected by using both curves. This is not necessary if only the ratio of the amplitudes of two power spectra is required.

Once a sea-surface elevation record is obtained, a digital computer can be used to calculate the power spectrum of the wave energy. The use of the Fast Fourier Transform assumes that the data points are equally spaced in time and that the sampling interval is known. The magnitude of the error contribution due to this error source is quite small since a stable 100 kHz crystal oscillator is used as the master time reference. The short-term stability of this signal is better than 1 part in 10^5 so each 2 second period is identical to within ±.002% (±20 microseconds). If a simple ratio of inside and outside power spectra is taken to obtain the breakwater wave energy transmission coefficient, the number obtained must be corrected for wave sensor location. This is due to the fact that standing waves are generated by the interaction of incoming waves and reflected waves having the same frequency. To make this correction, the exact distance from the wave sensor to the reflecting surface of the breakwater must be known. Since any such distance measurement must have an error associated with it, an error is introduced into the calculation of the correction factor which is then introduced into the final results. The magnitude of the error contribution generated by this error source has as yet not been evaluated. It is a function of the distance measurement or wave sensor location measurement error.

In order to calculate the wave direction spectrum from an omidirection array, all of the previously described error contributions are present as well as additional error effects based on errors related to the measurements required to determine the individual wave sensor locations in the array as well as the location of the array with respect to the breakwater. The magnitudes of the errors in wave direction determination produced by the wave sensor location errors have also not as yet been evaluated.