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A Seafloor Electric Field Instrument

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A seafloor instrument has been constructed to measure a horizontal component of the electric field, using a long antenna (up to 1000 m) to increase sensitivity. The instrument has a depth capability of 5200 m and may be deployed for several months at a time, collecting over 14 Mbytes of data under the control of a microprocessor. Instrumental noise is mainly caused by the Ag–AgCl electrodes used to make contact with the sea water, and is about 10^{-24} V^2/m^2Hz at frequencies above 1 Hz, following an f^{-2} power law at frequencies (f) below 1 Hz. For controlled source signals averaging techniques such as synchronous stacking and block averaging have been used to detect narrow band (5.6×10^{-4} Hz) signals as small as 10^{-12} V/m. The instrument is designed to include the pressure transducer described by COX *et al.* (1984) and has already been used for the study of ocean bottom seismic signals, magnetotelluric experiments and controlled source electromagnetic soundings.

1. Introduction

Various experiments require measurement of the sea floor electric field. The study of seismic motions (WEBB and COX, 1982, 1984), magnetotelluric experiments (FILLOUX, 1982) and controlled source electromagnetic sounding (YOUNG and COX, 1981) are examples. The natural electric fields on the sea floor are much smaller than on land at frequencies above 1 mHz because the conductive sea water filters the external electromagnetic fields generated by variations in the magnetosphere. It requires a commensurately more sensitive instrument to measure these smaller electric fields.

The largest noise source for a seafloor electric field instrument is due to the electrodes used to make contact with the sea water (FILLOUX, 1980). Although the large Ag–AgCl electrodes, described later in this paper, have extremely low noise characteristics, they still dominate the measuring system noise. For low frequencies (below 0.01 Hz), water choppers have been effective at reducing the dominance of electrode noise (FILLOUX, 1974), but their use is inappropriate at higher frequencies, where the Johnson noise of the salt bridge would dominate. An alternative strategy is to measure the electric field across a very long antenna, effective if the scale of the electric fields being measured is considerably larger

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than the antenna length. The instrument described here has an antenna which may be up to 1000 m long, compared with antennae less than 10 m long for other seafloor instruments. Although primarily an electric field device, the instrument includes a pressure transducer of the type described by COX *et al.* (1984). Such a combination of electric field and pressure detectors is suitable for the detection of microseismic disturbances (WEBB and COX, 1984).

2. General Design

The electric field instrument is shown in Fig. 1, much as it would look when deployed on the sea floor. The instrument is a free vehicle, in the sense that there is no connection with the sea surface after deployment and it must return to the sea surface under its own buoyancy after data collection is completed. Mooring the instrument has been considered (see COX *et al.*, 1978), but is more expensive and requires more ship time. Vibration of the mooring cable might also degrade the quality of the measurements.

The pressure case containing the electronics is a 1.5 m long, 0.26 m inside diameter, 0.30 m outside dimmeter tube of aluminium alloy (7075 T6). An internal stiffening ring prevents failure due to mechanical instability (BROWN and COX, 1973). The end caps are flat plates of alloy, 9 cm thick, containing electrical bulkhead connectors for connections to electrodes, pressure transducer, radio antennae, a strobe light and acoustic transceiver. A few hemispherical end caps have been made, providing much more buoyancy but at greater expense. Double 'O' rings establish a watertight seal between the caps and tube. Such a pressure case is designed to withstand at most 62 MPa and has a working limit of 54 MPa, which allows the instrument to be deployed to a depth of 5200 m. The cylindrical pressure case is less expensive than the spherical ones often used, but requires a glass flotation sphere for additional buoyancy if hemispherical caps are not used. The pressure case and external wiring are protected by an outer 'hard hat' or casing of 1.6 mm polypropylene sheet, bent into a cylinder and strengthened with internal ribs made from 1.3 cm polypropylene sheet. Polypropylene has a lower density than water, so the casing does not detract from the buoyancy of the instrument, but provides an extremely strong and tough outer protection. The casing is split longitudinally for access to the wiring and pressure case, and is used to attach the 43 cm glass flotation sphere and a pressure transducer to the instrument package.

Negative buoyancy for deployment is provided by the steel anchor, which resembles a long sled. The anchor also serves to take the load of the long antenna during deployment and to protect the instrument when it hits the ocean bottom, or if it is accidentally dragged across the sea bed during deployment (see discussion on deployment).

The pressure case and hard hat are held in place on the anchor sled by a vacuum release system based on a design by Dr Jean Filloux of S.I.O. A 25 cm diameter plate (the vacuum plate) is attached to the instrument casing.

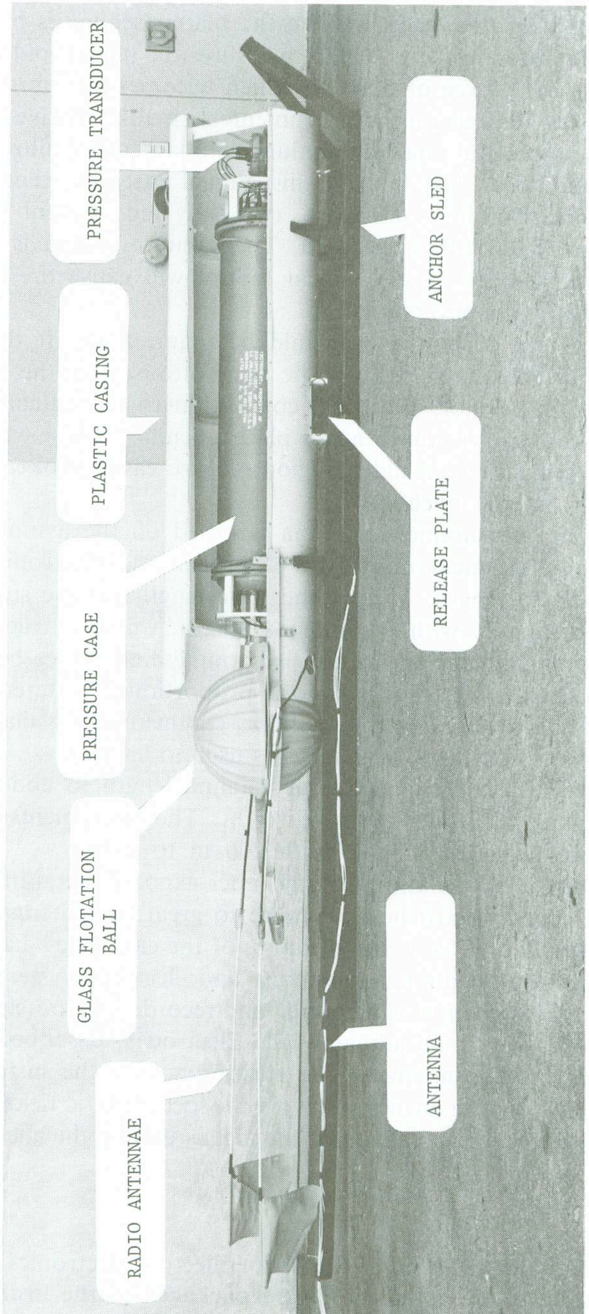

Fig. 1. The instrument package much as it would appear on the sea floor. The release mechanism at the centre of the instrument will allow the pressure case/casing/flotation/assembly to float free of the anchor sled and antenna, which are left on the sea bed.

The vacuum plate mates with a polished steel plate bolted to the anchor, and is held there by evacuating the space between the plates (sealing is provided by an 'O' ring on the circumference). At surface pressures the plates hold the instrument to the anchor with a force of 5000 N, which becomes an enormous force at sea bottom pressures. To release the instrument, a small explosive (a 'squib') is electrically fired to break a small aluminium capillary tube, allowing water to enter the evacuated area. The buoyant instrument assembly then floats to the surface. To ensure reliability of release, two fully independent systems of timers, explosives and break-tubes are used. The vacuum system is 'fail safe' in the sense that most modes of mechanical failure will cause the instrument to release early rather than never at all.

An enormous reserve of buoyancy would be required to lift the antenna to the surface, so the antenna is left on the sea bottom after the instrument releases, attached to the anchor. Electrical connection to the antenna is made by very fine wires within the vacuum/anchor plate assembly. These wires require minimal insulation within the evacuated region, so are easily broken when the instrument releases from the anchor.

The use of a long measurement antenna is based on the assumption that the major sources of instrument noise (the electrodes and electronics) are independent of the antenna length. Thus if the scale lengths of the signals being measured are large compared with the antenna length, which is true for ocean seismic waves below a few hertz and controlled source e.m. waves below a few hundred hertz, then the signal to noise ratio is proportional to antenna length. Because the antenna is left behind on the sea floor, commercially available unreinforced copper wire(#6 American Wire Gauge) is used to lessen cost. The limited strength of such wire restricts the maximum antenna length to about 1 km; a longer antenna might break under its own weight. The instruments have been deployed with antenna lengths ranging from 200 m to 1 km.

A break in the antenna insulation, or any other exposed metal in the antenna circuit, would result in electrochemical noise so great the antenna would be useless. This, and the still unreliable performance of the electrodes, have resulted in the practice of fastening a duplicate antenna and electrode system alongside the primary antenna. Each channel is amplified and recorded separately, so useful data will be collected should one antenna fail. Electrodes, described later, are attached to the ends of the antennae. The electrodes near the instrument are positioned at least 8 m from the anchor, to avoid the local electric fields associated with corrosion and electrochemical action of the metals used in the anchor system.

3. Electronics

Figure 2 shows a block diagram of the data collection electronics and Figure 3 shows a photograph of the actual hardware packaged in the instrument. As well as the two electric field channels, a third channel is used to measure sea floor pressure variations using a pressure transducer. The reader is referred to

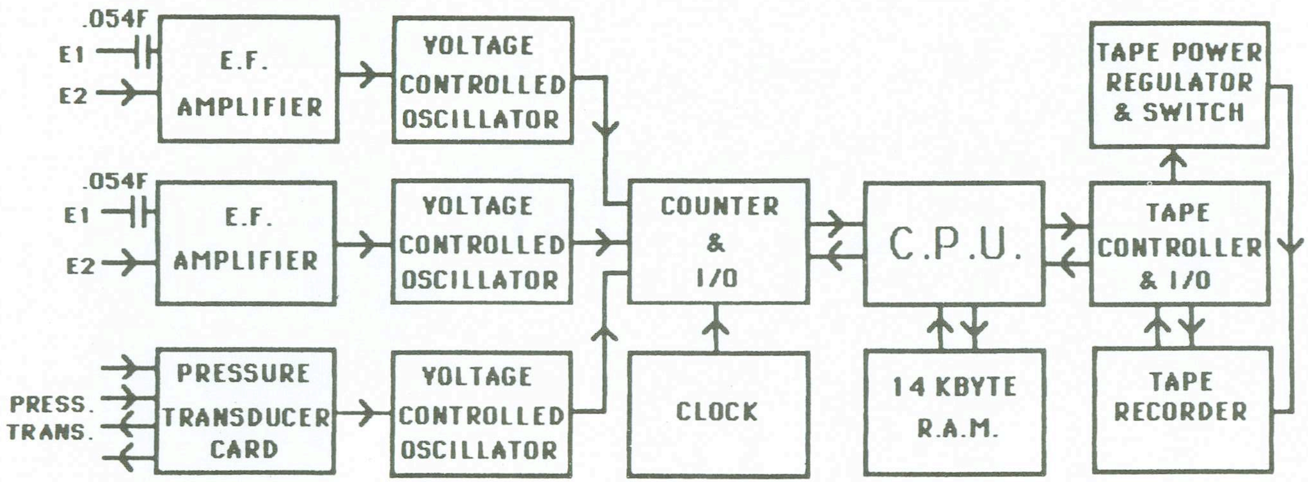

Fig. 2. Schematic of data collection electronics. The three amplifier channels are digitized using the VCOs and counter. The CPU accumulates the data in RAM and periodically transfers it in 14 kbyte records to the tape recorder. The tape controller allows the power to the recorder to be switched off between data transfers.

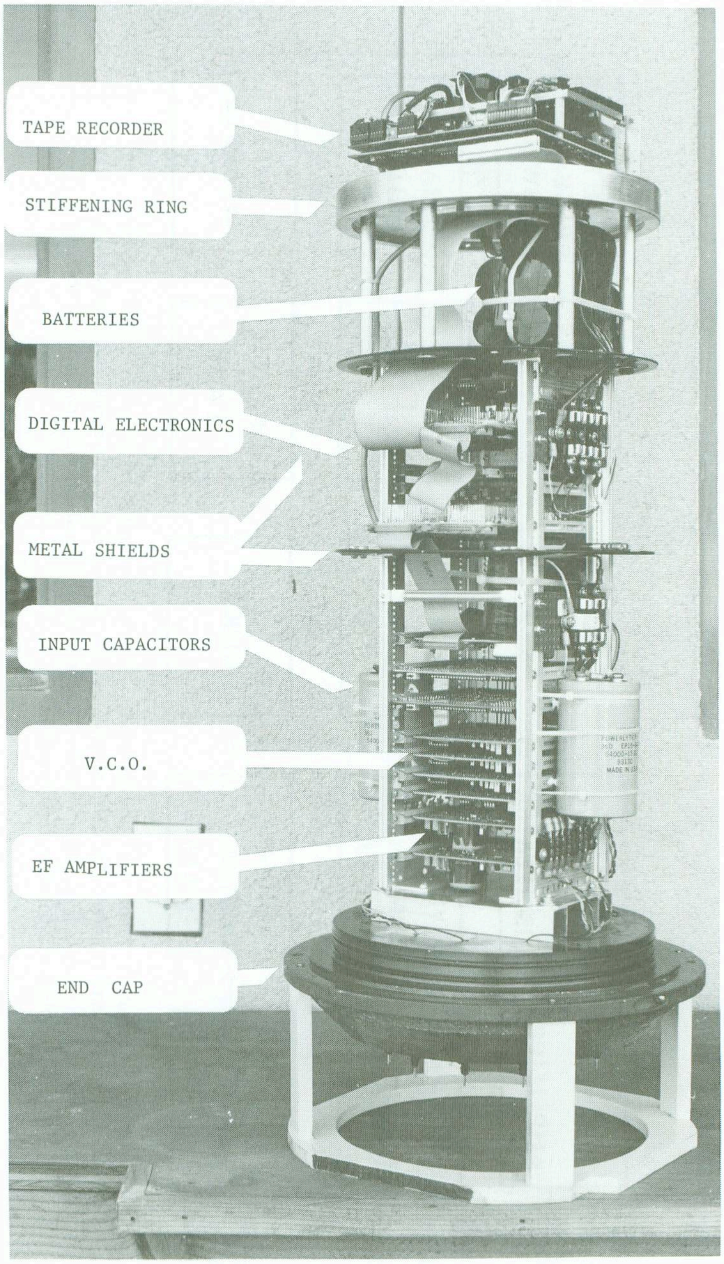

Fig. 3. Photograph of the data collection electronics. Note the stiffening ring, positioned so as to be at the centre of the 1.5 m long pressure tube to prevent collapse, and the 9 cm thick end cap. The tape recorder is positioned as far as possible from the electric field amplifiers to minimise noise, and two metal shields are provided. The lithium cells shown here power the instrument for about 1 month. The recovery and survey electronics (radios, strobe and acoustic transponder) occupy the other half of the pressure case.

Cox *et al.* (1984), for further details on the pressure instrument.

The amplifiers (Fig. 4) are characterized by very low noise (<0.13 nV/Hz$^{1/2}$) and have evolved from those described by Cox, Deaton and Pistek (in preparation). Each electric field amplifier has a large (54000 μF) electrolytic capacitor in series with the input to remove the very large, low frequency signals associated with ocean currents and drift in the electrodes.

Active amplifier components exhibit an $1/f$ noise at low frequencies. To avoid this problem it is common to modulate (chop) the inputs of d.c. amplifiers, which is accomplished here by the four field effect transistors (FETs) at a frequency of 2 kHz. However, because of the very low impedance of the source (the antenna, electrode, seawater system) it is necessary to have low resistance elements in series with the input, to avoid introducing additional noise. The commercially available FETs used here are for high power applications and fulfill these requirements. Chopping allows the use of a step-up transformer for the first amplification stage and for impedance matching with the later amplification stages. The input noise associated with this setup is less than the thermal agitation noise (Johnson noise) of a two ohm resistor. After transforming, the signal is amplified, demodulated, filtered and amplified again, giving a total gain of about 10^6. Presently, the upper limit of the bandwidth is set to 60 Hz. A double pole high pass filter pre-whitens the red background signal below 0.1 Hz.

The amplifier outputs are digitized by converting the voltage to a linearly related frequency and then counting that frequency over the data sampling inter-

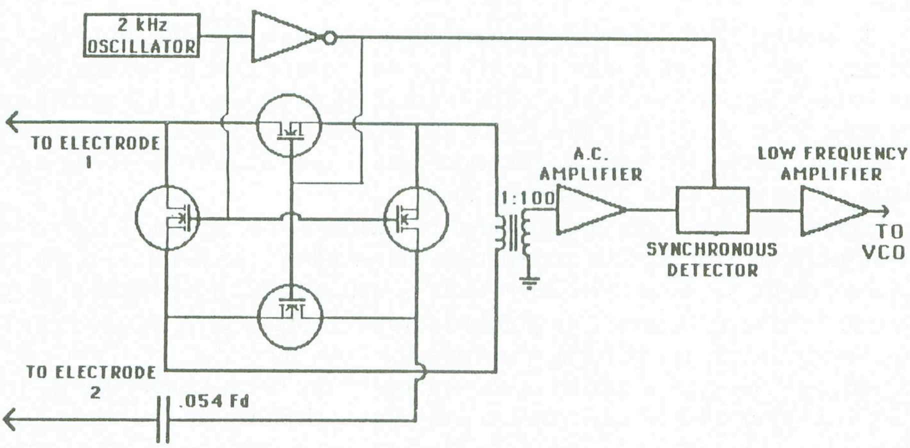

Fig. 4. The low noise amplifier circuit. The chopping frequency is 2 kHz, and the inputs are chopped by the four low noise FETs. The chopper is followed by a step-up transformer and the first stage of amplification. Synchronous detection occurs in the next stage, and is followed by filtering and further amplification. Total gain is 10^6.

val. The voltage controlled oscillators (VCOs) are designed for low power consumption and high centre frequency, and are linearized within a feedback loop. Counting is accomplished by a series of counters and latches which provide 16 bits of dynamic range for up to four channels (of which only three are used at present). The 16 bit data are read by the CPU and temporarily stored in RAM, which allows 14 kbyte blocks of data to be periodically written to the tape recorder. Data compression may be achieved by synchronous stacking and simultaneous block averaging of the data before transfer to tape. The tape recorder is a Digidata model 6430, which records four tracks of data on a 3M type DC300XL tape cartridge. The recorder draws over 1 A whilst running, but is switched off by the CPU between data transfers to conserve power. This on/off mode slightly reduces the amount of data that may be stored on a single tape because of inter-record gaps, but still allows over 1000 14 kbyte records to be collected. These commercially available tape recorders are electrically noisy because of the large current associated with the motor. The tape recorder is off most of the time and so this noise is absent, but the instrument has been designed to reduce the noise whilst the tape recorder is running. Metal shields have been placed between the amplifiers and the tape drive, which are separated as far as possible within the pressure case.

CMOS components have been used, apart from the in tape recorder, to minimize power consumption. The amplifiers, pressure card, VCOs and clock will all operate off two pairs of D-size lithium dry cells for about one month. The digital electronics run off a different supply to reduce noise, and two lithium D-cells will supply them for about three weeks. The tape recorder requires eight cells, which provide sufficient energy to write one tape, regardless of deployment time.

It is essential to isolate all the electronics, including grounds, from the instrument case. The electrodes must be the only connection to the sea water, otherwise noise associated with ground loops through the case would overwhelm the amplifiers. There must also be no DC connection between the electrodes, as current flowing through the electrodes could force dissolution of the AgCl plating (described later) and destroy them.

Additional electronics are provided to facilitate surveying and recovering the instruments. An acoustic transponder/pinger allows the position of the instrument on the sea floor to be determined, as well as being of use during deployment and recovery. Because transponders have occasionally been unreliable when positioned close to the sea bed, provision has been made for the transponder to ping regularly once a second at the request of the CPU. Usually the instrument is programmed to ping continuously during deployment and again after release from the sea floor. Two radio beacons and a strobe light aid recovery on the surface.

4. Deployment

The instrument package has been designed to facilitate quick and safe deployment. The 200–1000 m antenna which drags behind the instrument on deployment presents many difficulties, as the instrument must be deployed on the sea floor with the antenna stretched out along the bottom. If the instrument package gets tangled in the antenna it will never leave the sea bed. Figure 5 shows the instrument during deployment. At the start of deployment the instrument is mounted on the anchor sled, which is then positioned at the edge of the stern of the ship ready for launching. At this stage the instrument is not attached to the antenna, which is spooled on a small winch. An acoustic transponder package (with its own timed release, recovery radio and strobe) and a pair of electrodes are attached to the far end of the antenna. The transponder will be used to monitor the deployment and final position of the antenna, but also provides enough drag to keep the far end of the antenna under a little tension. The entire antenna, transponder end first, is paid out slowly while the ship moves forward at about 4 knots, which keeps the antenna stretched out. At this speed, the strain in the antenna is reduced because the lift generated by the motion supports much of the antenna's weight. After the antenna has been paid out, the near electrodes are taped on about 8 m from the end, and the antenna is fastened to the anchor sled, which takes the full load of the antenna henceforth. The impedance of the antenna and electrodes is checked and the electrical connection to the instrument made (through the break-wires in the vacuum plate assembly).

The armoured, single conductor cable, to be used to lower the instrument to the bottom, is now connected to the front of the anchor sled. This connection is made through a device, fastened to the end of the lowering cable, which combines a release and acoustic transceiver. (The release/transceiver is designed so that power and control signals to it and acoustical frequency signals from it may pass through a single conductor cable with a seawater return.) The load is taken by the lowering cable and a combination of drag on the antenna and use of the ship's 'A' frame causes the instrument to slide into the water. A ship speed of 3–4 knots is maintained while the instrument is being lowered on the cable, because the ship's motion in the waves periodically reduces the tension in the lowering cable. If a good speed is not maintained, the antenna may easily form knots by looping, twisting and being pushed through itself as the ship drops with the sea swell.

The acoustic transponders on the instrument and antenna allow progress to be monitored during deployment. The lowering rate is adjusted so that both ends of the antenna stay at equal heights above the sea floor. After 25% more cable than water depth has been paid out, both the cable and the ship are stopped. The lowering cable slowly drops to a vertical position, bringing the instrument to the bottom while maintaining continued forward motion of the antenna. When the instrument is within a few tens of metres of the sea bed, the instrument is released from the wire by a command from the ship and falls gently to the bottom. The concern at this point is to avoid having the antenna fall

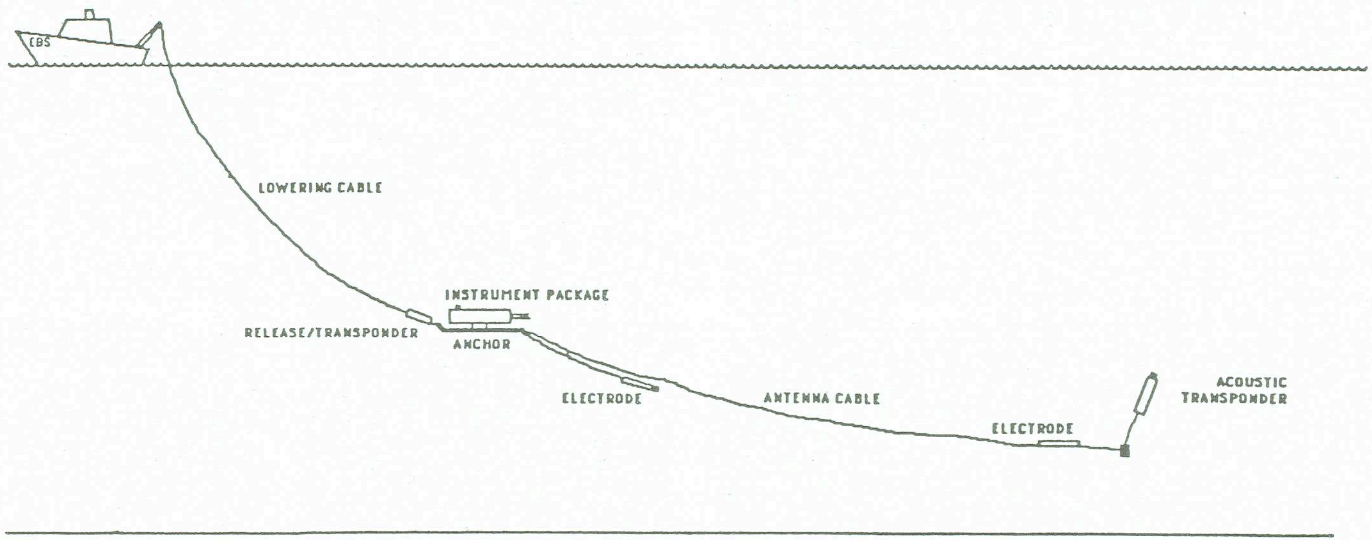

Fig. 5. Deploying the instrument. The antenna is paid out and then attached to the instrument, which itself is attached to a lowering cable via a release mechanism. The instrument is then lowered to the ocean bottom and released. A suitable ship's speed of 2–4 knots during the deployment keeps the antenna streamed out behind the instrument.

on top of the instrument, preventing its later release. The present design reduces the chance of this happening, and one instrument was (accidentally) released more than 200 m above the sea bed and still functioned correctly.

The initial launching of the antenna and instrument takes less than two hours, but since it may take more than five hours to lower the instrument package and recover the lowering cable it is difficult to deploy more than one instrument per day, although two per day is possible if all goes well. Once the instrument is down, the acoustic transponders allow the orientation and deployed length of the antenna to be determined but this procedure also takes several hours.

5. Electrodes and Noise

Measurement of the electric field requires that electrical contact with the seawater be achieved. In order to avoid the great noise associated with a direct contact of metal with sea water, non-polarizable electrolytic electrodes are used. Silver-silver chloride appears to be the best chemical system to use, although lead-lead chloride may be worthy of consideration (PETIAU and DUPIS, 1980).

The electrodes, shown in Fig. 6, are constructed as follows. A 5 cm by 65 cm piece of pure silver foil is wrapped around an inert, 1.25 cm diameter rod (plastic or plastic coated metal). The conductor of an underwater connector is soldered to one end of the silver, and the joint potted into a plastic cap using epoxy. The silver is then cleaned with a 30% HNO_3 solution and rinsed. A 4 cm outside diameter, 2.5 cm inside diameter tube of porous polyethylene is glued onto the cap and the space between the silver and the tube packed with a mixture of diatomaceous earth and silver chloride, mixed in a ratio of 6:1 by volume. After affixing an end cap, the electrode is immersed in a 35 g/l solution of

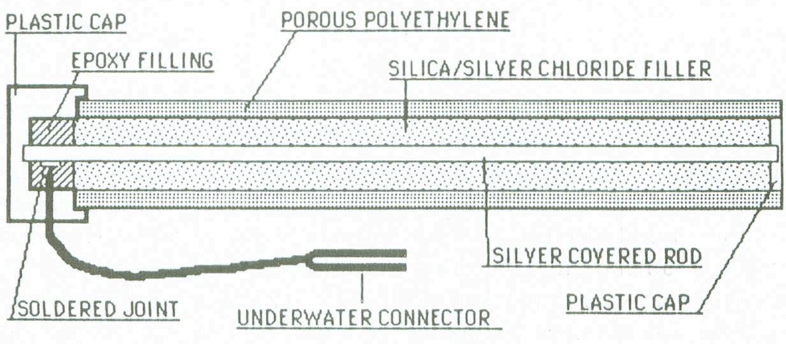

Fig. 6. A diagram of an electrode. Pure silver foil is wrapped around an inert rod. The electrical connection to the silver is potted into the upper end cap using epoxy. A porous polyethelene tube is attached and filled with a mix of diatomaceous earth mixed with silver chloride. A lower end cap is then glued in place. The underwater connector is used to connect the electrode to the antenna.

NaCl and vented under a vacuum to saturate the porous materials. It is necessary to coat the surface of the silver with silver chloride. A piece of silver foil is also immersed in the NaCl solution and electrical connection is made to it and the electrode. The electrode is made negative and a current of 1 A is passed for 20 s. This cleans the surface of the silver in the electrode. The electrode is then made positive and a similar current is passed for 120 s, plating (anodizing) the surface of the silver with silver chloride. The impedance of the unanodized electrodes is proportional to $(\text{frequency})^{-0.5}$, but becomes almost independent of frequency and much lower (1 Ω) after anodizing. The DC potential between a pair of electrodes is typically below 1 mV. The porous plastic and diatomaceous earth restricts water motion across the silver, which could create a streaming potential and cause noise. The powdered silver chloride reduces the dissolution of the AgCl from the silver.

It has been found that the quality of underwater electrodes is quite variable, with noise power differing over two decades for electrodes of similar construction. Progress in improving electrode design has been slow, because it is extremely difficult to make adequate laboratory measurements of the noise associated with the electrodes, since environmental noise is too great. The only method which has so far proved successful is to deploy the electrodes on an instrument and make the measurements on the sea floor, where the ambient noise is much lower (WEBB and COX, 1984). Curve A of Fig. 7 is a noise spectrum for the instrument when equipped with the electrodes described here, from WEBB and COX (1984). In their experiment, one channel was connected to a pair of electrodes separated by less than 1 m, for the express purpose of measuring electrode noise. The curve has been normalized to give the noise of an instrument equipped with a 1000 m antenna. To recover the voltages measured across the electrodes, multiply the scale by $10^6 m^2$. The low noise amplifiers and the antenna resistance (less than 2 Ω), do not contribute greatly to the noise of the instrument.

6. Examples of Use

Nine long antenna instruments have been constructed, of which three have been lost during twelve deployments. Two of the losses were of an early design which was prone to tangling in the antenna. The third loss is thought to be due to leakage of the pressure case. Curve B in Fig. 7 shows a spectrum of the sea-floor natural electric field 200 km southwest of San Diego, measured across a 600 m antenna in 3700 m of water (see WEBB and COX, 1985). Curve C shows a similar spectrum taken near 28°N, 122°W in a depth of 4300 m. This spectrum was obtained by taking the cross spectrum of the two channels, both recording the same signal across 680 m antennae. Both these spectra show the characteristic $1/f^4$ spectrum of the electric field, as well as peaks between 0.1 and 1 Hz due to microseisms (WEBB and COX, 1984). The leveling off of spectrum C above 3 Hz is probably due to noise from poorly functioning instrument electronics.

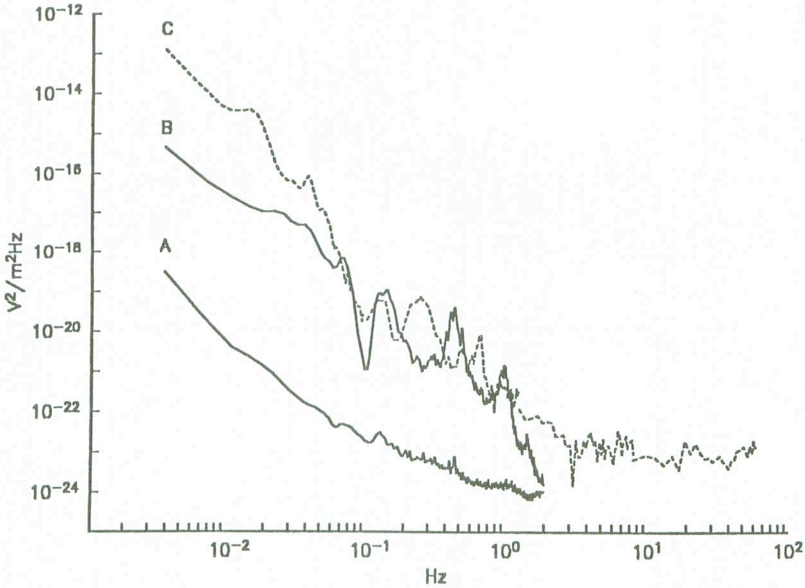

Fig. 7. Plot of spectra. Curve 'A' is from an experiment reported by WEBB and COX (1984), in which the electrodes were purposely set close together for an estimate of electrode noise. Curve 'B' is a spectrum of the sea-floor signal across a single 600 m antenna. Curve 'C' is from a later experiment in which a twinned, 680 m antenna was used to record the sea floor electric field on both channels, allowing a cross spectrum to be calculated. All curves are normalized to a 1000 m antenna.

The control of the instrument by a microprocessor allows great flexibility in the design of an experiment. During the same deployment which produced the second example mentioned above, the instrument was programmed to collect data for a controlled source E.M. experiment. In this experiment, a transmitting antenna is excited with a periodic current while the recording instrument 'stacks' measurements of the electric field synchronously with the transmitted signal (essentially the instrument has been programmed to act as a multipoint signal averager). Stacking allows a high sampling rate to be maintained without filling the tape very quickly, yet maintains the signal to noise ratio that uncompressed data would yield. Figure 8 shows an example of such data. The 8 Hz and 24 Hz signals due to the transmitter (which is 50 km distant) are easily seen in the time series data (A) and are obvious in the periodogram (B). The transmitter has dipole moment of 3.6×10^4 Am, so the signal detected is about 10^{-12} V/m. A half hour's stacking allows this signal to be measured to within 1×10^{-14} V/m. Lower noise levels could be achieved by additional stacking.

7. Conclusions

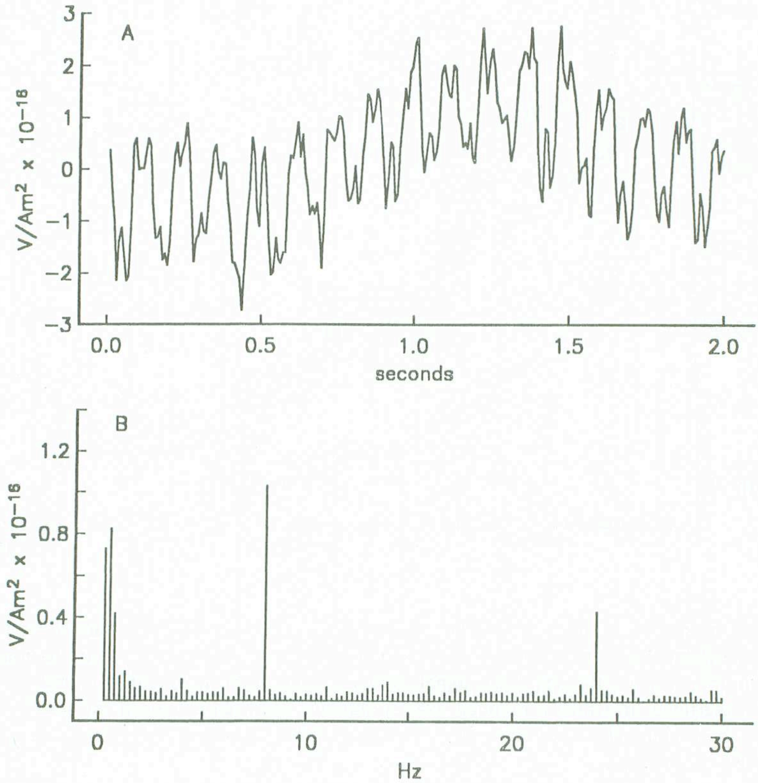

Fig. 8. Synchronous stacking used to recover the very small signal due to an artificial source located approximately 50 km away. 449 data sequences each 2048 points or 4 seconds long were stacked to give this record. The transmitted frequencies were 8 and 24 Hz. The dipole moment of the source antenna was 3.6×10^5 Am.

An instrument has been described which can measure small electric fields on the seafloor at frequencies above 0.01 Hz. The instrument may be deployed for months at a time, performing varied tasks under the control of a microprocessor. The present limitation in sensitivity is due to the Ag–AgCl electrodes. However, by using a long receiver antenna, natural electric fields of power as low as 10^{-24} V^2/m^2 Hz have been measured. Using signal averaging techniques, artificial signals of 10^{-12} V/m in a bandwidth of 5×10^{-4} Hz have been measured with a signal to noise ratio of ten.

The instrument is designed to be used in conjunction with the pressure transducer of Cox *et al.* (1984), and opens up new possibilities for the study of the ocean and oceanic crust. The instrument has already been used for the study of seismic signals, magnetotelluric experiments and controlled source sounding.

The funding for developing this instrument was provided by the Office of Naval Research. Messrs Paul Fortuin and John Lyons worked extensively on the software and hardware of the instrument, respectively.

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