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A Three-component Borehole Seismometer System: Development and Operation

R F Burch

Recommended for issue by

A Douglas, Superintendent

Approved by

A C Machin, Head of Division

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SUMMARY

AWE in co-operation with the University of Reading have developed a three-component borehole seismometer system with a broad-band response (the Blacknest Guralp). The system is simple, reliable, and inexpensive and is easily manufactured by any competent machine shop. It is currently operating in a 40 m borehole with a six-inch internal diameter lining, drilled into the Chalk in the seismic vault at Wolverton (some 6 km from AWE).

Both the vertical- and horizontal-component seismometers use an inertial mass in the form of a pivoted boom with two transducers: a capacitance displacement device to provide the signal, and a magnet-coil assembly to accept a feedback signal to give a force-balance mode of operation. A novel period-lengthening device is used with the vertical suspension.

Although digital recording systems are now available to accommodate the large dynamic range of the basic feedback seismometer the output signals have been conditioned to facilitate recording on an existing 15 bit digital recording system. Each signal is filtered into two bands - velocity broad band (0.05 Hz to 4 Hz) and long period narrow band (0.025 Hz to 0.06 Hz). This enables simultaneous recordings to be made from the three-component set in the borehole and a similar set of instruments at the surface in the vault, with all the signals being carried by private wire telephone lines between Wolverton and the recording laboratory.

The report traces the history of the development of the system and describes each of the major components of the complete system with the theory and transfer functions of the feedback and signal conditioning circuits. The mechanical suspensions of both instruments are shown with the elements of the period-lengthening method. The noise level of the seismometers is shown to be close to the predicted value of $10^{-19}(m/s^2)^2/Hz$ and it is suggested that a major redesign of both the suspensions and the electronic circuits would be necessary to significantly reduce this figure. Examples of background seismic noise and seismograms from underground explosions are used to demonstrate the advantages of operating horizontal-component seismometers in a borehole. A problem was experienced with the existence of impulsive noise superimposed on the long period output. Random pulses are thought to be due to mechanical stress release in the seismometer, package and borehole. However an additional display of continuous pulses was only solved after redesigning the seismometer base assembly that locates with the bottom of the borehole. Although reliable in operation the electronic circuits have been put out of action by lightning on two occasions. A method of orienting the borebole package using coherence measurement of the six second microseisms recorded downhole and at the surface is described which enables the relative alignment to be determined within ±1°.

Similar transducers with identical performance are now available commercially in UK. With the advantage of more recent improvements this makes it unnecessary to develop further the Blacknest Guralp design.

1. INTRODUCTION

As part of the UK research programme of forensic seismology (that is seismology applied to the detection and identification of underground explosions) AWE, Blacknest* has developed various seismometers. Since 1970 the work on seismometers has concentrated on the development of broad-band systems that record over the frequency range 0.01-10 Hz. As well as producing a broad-band recording, such systems allow the conventional short period (~1 Hz) and long period (~0.05 Hz) seismograms to be produced by filtering of the output from one instrument. Other advantages of recording with broad-band systems are discussed by Marshall, Burch & Douglas [1].

The first broad-band systems made by AWE used conventional long period (LP) seismometers (with natural frequencies around 0.05 Hz) and electronic amplification. Such instruments are bulky and heavy (inertial mass about 10 kg; total mass about 80 kg) and sensitive to changes in temperature and pressure, although these effects are minimised by the use of a pressure jacket and good thermal insulation.

To make a broad-band system using a conventional seismometer significantly smaller than a LP instrument is difficult. Reducing the suspended mass and the linear dimensions of the suspension increases the natural frequency, and the sensitivity of a seismometer (relative displacement of mass and frame for a given ground motion) below its natural frequency decreases as the natural frequency increases. Further, the Brownian noise increases as the suspended mass decreases so that the relative displacement of mass and frame due to this noise tends to swamp that from the seismic background. Brownian motion can be reduced by reducing the damping on the mass-spring system but this leads to a seismometer which has a response with a sharp resonance peak at the natural frequency, which is undesirable. In 1966 however, P B Fellgett (then at the University of Edinburgh) suggested [2] that by using electronic feedback it should be possible to build a miniature broad-band seismometer with a suspended mass of 1 gram.

In 1970 a revolutionary miniature broad-band seismometer was described by Block & Moore [3]. This instrument was made mainly from quartz, used an inertial mass of only 10 g and had electronic feedback to stabilise its performance. Although it was never produced commercially the design stimulated research into the possibilities of making miniature instruments using conventional materials.

In 1971 Fellgett (then Professor of Cybernetics at the University of Reading) obtained a grant to develop a miniature feedback seismometer. Financing of the project was taken over by AWE in June 1974. The aim of the project was to design and make a small instrument with a suspended mass of a few tens of grams, using metals rather than quartz so that the seismometers could be manufactured and repaired by any well equipped workshop, something that is not possible with instruments made of quartz. The instrument was to be small enough to be installed in a borehole. Installing the seismometer in a borehole would itself reduce the effects of surface variations in temperature and pressure and also enable signals to be recorded with higher signal-to-noise ratios than at the free surface because seismic noise amplitude decreases with depth. Even when operated at the surface such miniature seismometers have advantages over conventional instruments being more convenient to handle and easier to isolate from environmental changes.

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*From 1954 to 1973 AWE (then AWRE) was part of the United Kingdom Atomic Energy Authority. In 1973 AWE was transferred to the Ministry of Defence. AWE has been responsible for research in forensic seismology since the programme started in 1959. For most of the time the work has been carried out at Blacknest an outstation of AWE. AWRE was renamed AWE in 1988.

Development of a miniature seismometer to record the horizontal component of ground motion was relatively straightforward. However, to develop an instrument for measuring the vertical component proved to be more difficult. As an interim solution a vertical-component sensor (the Mk IIIC) was developed based on a Willmore Mk III, a commercially available short-period (SP) instrument (natural frequency 1 Hz). The Mk IIIC system is capable of recording over the required frequency range 0.01-10 Hz. Burch [4] gives a detailed description of the Mk IIIC together with a brief history (to 1983) of the AWE programme of seismometer development.

The Mk IIIC is too large (diameter 0.20 m) and too heavy (suspended mass 1.3 kg) to make a satisfactory borehole instrument. Work has therefore continued with the development of a three-component (1 vertical- and 2 horizontal-component) borehole system. Such a system has now been successfully built and tested and is described here.

The report gives a brief history of the project and a detailed description of the complete system, including its response and calibration both closed loop (that is with the feedback loop in operation) and open loop (that is without feedback). Sources of system noise are discussed and estimates made of Brownian, transducer, and filter noise and of the dynamic range. The noise estimates are compared with the values expected from theoretical considerations. The results of surface and borehole tests, including an investigation of methods of orienting the horizontal components N-S and E-W in the borehole, are described and assessed.

The borehole tests were carried out in a hole, the top of which lies within the AWE seismological vault at Wolverton (Hampshire) about 6 km from Blacknest. Signals from the vault can be telemetred to Blacknest over British Telecom private wires (PW's).

2. HISTORY OF THE BOREHOLE SEISMOMETER PROJECT

Fellgett published his patent in 1966 demonstrating the feasibility of building a wide band seismometer employing electronic feedback using an inertial mass of 1 gram. The Natural Environment Research Council (NERC) gave a grant in 1971 for the development of a practical instrument. The project was assigned to I W Buckner under the guidance of Dr M J Usher of the Department of Cybernetics, University of Reading. Although there was co-operation between Blacknest staff and Buckner and Usher from this time, AWE only became directly involved when an Extramural Research (EMR) Contract was placed with the University in 1974. By that time Buckner and Usher had designed and tested several different miniature seismometers resulting in a promising horizontal instrument based on the inverted pendulum and using an inertial mass of 40 g [5,6].

2.1 Contract with Reading University for Seismometer Development: 1974-80

During 1975 Buckner's horizontal-component seismometer was tested by comparing its output with that from a conventional Geotech S-12 LP Narrow Band system at the Wolverton vault [6,7]. Although the new instrument produced good results all attempts to develop a small vertical-component seismometer were unsuccessful due to the mechanical problems associated with supporting a small mass on a spring with a natural period of one second. In 1977 C M Guralp (the successor to I W Buckner) designed and produced a new vertical-component seismometer of similar dimensions to the successful Buckner horizontal-component instrument. A novel method of reducing the natural frequency of the suspension was used allowing a patent application to be filed in March 1978. (The full patent was granted in the UK as Patent 79095/79 and in the USA as Application No. 20502 (Guralp)). Buckner's seismometer was redesigned by Usher and Guralp so that the overall dimensions of both the vertical- and horizontal-component instruments and many parts were the same.

To commercially exploit these designs an approach was made by the National Research Development Corporation (NRDC) on behalf of AWE to Sensonics Ltd - then the only commercial manufacturer of seismometers in the UK. It was believed at the time that an agreement was reached with Sensonics Ltd to commercially produce the instruments. All the existing designs for the seismometer and electronics were handed over to Sensonics Ltd and an order for four vertical-component instruments was placed with them by AWE, Blacknest. The four instruments (referred to by Sensonics Ltd as the F-300) were delivered but in the event no commercial agreement was reached between the NRDC and Sensonics Ltd and the subsequent technical development at AWE, Blacknest has been completely independent of the company.

(In 1985 C M Guralp set up an organisation (Guralp Systems) to design, manufacture and market seismometers. One product in his range, known as the CMG 3 has some similarities to the vertical-component seismometer developed under the EMR and described in this report. However the CMG 3 does not include the spring configuration which is the subject of the patent. To avoid confusion the instruments developed for AWE under the EMR are referred to here as Blacknest-Guralp seismometers because the AWE patent describes Guralp as the inventor of the suspension system of the vertical component).

A borehole package incorporating a three-component set of miniature seismometers was designed and the proposed system was shown at the meeting of the UK Geophysical Assembly III in April 1979 [8].

Preparatory estimates had been obtained in 1975 for a borehole to be drilled at Blacknest but the cost proved to be prohibitive due to problems associated with drilling in the layer of loose gravel beneath the topsoil. The hole was therefore drilled through the existing seismic vault at Wolverton (which is sited on chalk) to a depth of 40 m and lined with a 6 inch ID steel casing. The work was completed in 1979.

A complete prototype borehole seismometer system was assembled by Reading University and tested in the Wolverton borehole during 1980. The performance of the complete system was found to be unsatisfactory although individual units performed well in isolation. The EMR contract expired at the end of 1980 but had achieved its target: the development of a three-component broad-band seismometer system suitable for emplacement in an 8 inch borehole. To complete the EMR contract a set of drawings were supplied by the University and passed to a small engineering company (Rivers Engineering, Winchester) to manufacture three seismometers: one vertical and two identical horizontal components. The reason for their manufacture was twofold - to prove the drawings; and to demonstrate that manufacture could be undertaken by any small but competent machine shop. However, the instruments that were produced would not operate because of faults arising from drawing errors and as a result of other priorities further development of these instruments and the prototype borehole package was halted.

2.2 Development and Testing of the Borehole System since 1980

Although no development work was undertaken on the borehole system during 1981 and 1982 the small size of the seismometer made it ideally suited for portable operation. Whereas no form of clamping of the inertial mass of the seismometers is incorporated in the design for borehole operation (ie, the seismometers are lowered downhole unclamped and unpowered) it was considered that some form of clamping of the mass was necessary to enable the seismometer to be transported on field trials. To this end a means of manually clamping the inertial mass of the seismometer was incorporated into one of the vertical components. This enabled a battery-operated portable system to be assembled whose reliability was proved when it was transported between four widely-spaced sites in East Anglia during the course of one afternoon to obtain samples of seismic noise at each of the sites [9].

During the summer of 1982 AWE, Blacknest obtained the services of a Student Engineer (R Armstrong) for several months. With his assistance the two horizontal-component seismometers built by Rivers Engineering were made operational and further modifications were made to the Reading prototype borehole package. It was concluded that the borehole package needed to be re-designed to incorporate:

(i) seismometers in individual pressure jackets;

(ii) two separate packages, one containing the three seismometers the other the downhole electronics;

(iii) facilities to enable the seismometers to be operated on command, either open or closed loop.

In May 1983 the author took part in performance tests of both vertical- and horizontal-component seismometers at the Sandia National Laboratories in the USA. The output signals from combinations of the UK and the US National Seismic Station (NSS) systems were recorded and compared. These short tests were confined to surface operation and took place in a newly constructed underground vault with the instruments placed in pressure-tight clamshells. Subsequent evaluation of the recordings proved that the performance of the UK seismometers reached their design specification.

In 1984 a mechanical engineer (C Vincent) was contracted from Hunting Engineering Ltd to work on the project. The main objective was to engineer the system. The downhole electronics package and the surface equipment for control, monitoring and signal conditioning were redesigned. Two complete sets were manufactured. Initial configuration of the seismometer package in 1986 used the three separate seismometers mechanically interconnected by means of duralumin cages. (The cages were identical to those used in the NSS system.) Preliminary operation showed that this mechanical arrangement gave the package an unwanted resonant frequency at only 18 Hz. To overcome this problem the pressure jackets and base plates were redesigned to have a wall thickness of half inch. This increases the rigidity of the assembly by enabling them to be directly "bolted together" without the need for a support cage. An electrically driven hoist was designed and installed at Wolverton to facilitate deployment of the complete package down the borehole. Designs were completed for the mechanical system to allow the seismometer and electronics packages to operate in a borehole as small as 4.5 inch ID. This was done by positioning the holelock "leaf" below the seismometer package instead of concentrically external to it. These designs were not tested at that time.

To evaluate the performance of the complete system a second set of three-component seismometers was assembled for operation in the Wolverton vault on the piers at the surface alongside the top of the borehole. To this end four more horizontal-component seismometers were purchased - two from a local engineering firm (Panmure Instruments Ltd, Newbury) built to drawings supplied by Blacknest, and two from Guralp Systems, Reading of the type known as CMG 3.

Various tests on the surface piers were made with nine of the miniature seismometers (six horizontal and three vertical components) and the conventional three-component set of two Geotech S-12 horizontal- and S-11 vertical-component seismometers with all instruments operating simultaneously. These tests took place between August and November 1986. Whilst proving that the outputs from all corresponding seismometers were identical the tests showed that the different surface piers responded differently to wind effects (see section 8.3).

Between November 1986 and February 1987 the borehole package was operated downhole with three horizontal-component seismometers. A method which had been proposed by the author for determining the true azimuth of the downhole horizontal-component seismometers was proved (see section 7). Within the package the upper and lower instruments were aligned parallel with the middle seismometer aligned at right angles to them. This particular alignment allowed a further check to be made: that the position of the seismometer in the stack was unimportant, ie that the outputs from the upper and lower seismometers were identical. This proved to be so. The new package was reassembled with a three-component set. Long-term operation began on 19 March 1987 with the correct alignment of the horizontal components as N-S and E-W.

A vertical-component CMG 3 seismometer was obtained on loan from Guralp Systems for evaluation. A special pressure jacket 2 cm taller than standard was manufactured for the CMG 3 in order for it to be able to operate downhole. The borehole package was raised on 3 February 1988, dismantled and examined (see section 8.1). It was then reassembled with three vertical- component seismometers: the CMG 3 with its fixed natural frequency (f_0) of 3 Hz and two Blacknest-Guralp seismometers (one with f_o = 2.5 Hz and the other with f_o = 1.4 Hz). After initial testing on a surface pier the package was lowered on 25 February and operated downhole until 26 July 1988. The package was again raised and finally reconfigured to contain the three-component set (one Blacknest-Guralp vertical, a N-S and an E-W). After lowering downhole it continuously operated from 4 August 1988 until the end of 1989.

In January 1990 all the mild steel components in the borehole package were replaced with stainless steel versions to eliminate corrosion. The azimuth of the long axis of Wolverton vault was determined to be 58 degrees averaging three methods: surveying using a theodolite and large scale maps, magnetic compass and finally using the shadow of a suspended plumb line at mid day taking into account the equation of time. A calibrated turntable was bolted to one of the piers at the surface and a second seismometer package mounted on it to enable a second identical system to be operated at the surface to that down the borehole.

During April 1990 the borehole package was retrieved in order to measure the tilt of the borehole from the vertical as a possible reason for the continuing presence of spurious impulsive signals (weight lift glitches - section 8.4). A new holelock manufactured to the design described earlier was installed during August 1990 after which the problem of the glitches has been significantly reduced.

Since 1990 there has been little continuous development of the borehole system with both the borehole and surface systems operating in a reliable manner. The only work necessary has been for repairs after lightning strikes that have damaged the surface and downhole equipment once in each of the following years.

3. DESCRIPTION OF THE COMPLETE BOREHOLE SYSTEM

In addition to a steel lined borehole, electronic and lifting cables, hoist and mains power there are five essential elements of the system:

(i) A Holelock Mechanism to provide a stable platform for the seismometers, that clamps onto and can be released from the inside of the hole casing at any chosen depth.

(ii) A Holelock Tool used to position or recover the Holelock mechanism.

(iii) A Seismometer Package containing a stack of three instruments - usually one vertical- and two horizontal-component seismometers.

(iv) A Downhole Electronics Unit containing three identical circuit boards providing the necessary feedback and initial signal processing to provide the broad-band data signals (VEL) and the loop output signal (ACC).

(v) A Surface Electronics Unit containing three sets of power supplies and the filters to convert the VEL signals to the required output, ie, velocity broad band (VBB) and long period narrow band (LPNB) responses. Also included are the electronics necessary to convert these signals to frequency modulated (FM) audio carrier waves, which are multiplexed together for transmission along PW's, as well as facilities for monitoring and calibrating the system. A diagram of the installation is shown in figure 1 and dimensions and other information on the five components are given in appendix A.

3.1 Holelock Mechanism

The purpose of this element is to provide a stable platform for the seismometers whilst down the hole. It consists of a steel cylinder to which are pivoted three spring-loaded arms that extend radially to enable pivoted feet to grip the inner surface of the borehole with a wedging action. By using the tool described in 3.2 to apply a compressive force to the spring, the three feet may be retracted hence allowing the mechanism to be recovered or repositioned at any depth in the hole, although no attempt is made to fix its orientation.

As mentioned above, for the last three years the system has been operating using a holelock of a completely revised design. Both designs are shown for comparison in figures 2 & 3. With the old design, attached around the upper part of the base cylinder is a large diameter "curled leaf" cylinder with three equally-spaced radial holes in its wall and a U-shaped slot at the lower end of the leaf. The purpose of the holes is to receive the lifting pins from the positioning tool whilst the leaf shape and slot enable either the tool or the seismometer package to locate and enter the holelock and achieve the same consistent orientation relative to the lock. With the new design the "curled leaf" and slot are reduced in size and are positioned in the centre of the holelock. The holes to receive the lifting pins are replaced by a continuous groove in the internal circumference of the base cylinder.

Attached to the upper face of the base cylinder are cones which act as inverted feet for the seismometer package. During the installation of the lock and whilst lowering the seismometer package debris from the tube is often dislodged and falls onto the lock mechanism. With these cones a small accumulation of this debris can be tolerated.

3.2 Holelock Tool

The tool for the new holelock is shown in figures 4 & 5. It is only used for insertion, recovery or repositioning of the holelock mechanism and is then removed from the borehole. The tool contains a linear actuator driven by mains power whose displacement is limited by internal microswitches. Power and directional control of the actuator are provided from a control box at the surface which is connected to the tool by a power cable of sufficient length to reach the maximum operational depth.

Consider the operation of changing the depth of the lock in the hole. With the seismometer and electronic packages removed from the hole the tool is lowered down the hole to locate in the lock. When power is supplied from the surface the tool is activated and three pins extend radially from it to enter through the circumferential internal groove in the lock. When this action is completed further extension of the actuator compresses the main coil spring of the lock allowing the three arms and feet to retract and the full weight of the lock to be taken by the three pins of the tool. The limit switches now cut off the power to the motor. The combined tool and lock can now be raised or lowered in the hole to the new position. The power is now supplied to reverse the actuator. The spring is allowed to extend, forcing the arms and feet to grip the tube, the pins then withdraw from the groove in the lock into the tool and the limit switches cut off the power to the actuator. The tool can now be raised and removed from the hole.

3.3 Seismometer Package

This unit contains three seismometers - in normal operation two identical horizontal-motion detectors (mounted orthogonally) and one vertical-motion detector (see figures 6 & 7). The ground motion is sensed only through the contact of the base of the package on the three cones of the holelock and in normal operation all the signal cables and the hoist wire are designed to be slack in an attempt to decouple ground motion from the top of the package. Although the seismometers have individual pressure jackets no attempt is made to evacuate the package casing whose primary function is to rigidly interconnect the three seismometers. Fixed below the seismometers is a guide cone and locating rod. This is attached to a rotatable collar graduated around its circumference in degrees. The locating rod ensures a fixed orientation of the package and hence the seismometers relative to the holelock during installation. After the initial installation of the lock into the hole and after any subsequent change of depth of the lock an orientation procedure must be followed (see section 7) whereby the seismometer package is removed from the hole, the cone and rod rotated by a known angle and then lowered to give the correct alignment of the horizontal-component seismometers, ie, facing true N-S and E-W.

3.3.1 Vertical-component Seismometer

The seismometer (figure 8) consists of an inertial mass mounted at the end of a pivoted boom with a capacitance displacement transducer to give an electrical output proportional to the vertical position of the mass relative to the instrument frame (figure 9). The inertial mass is electrically insulated from the frame of the instrument and acts as the central (moving) capacitor plate of the transducer - the two equally-spaced insulated capacitor plates being rigidly fixed to the frame. Attached to the inertial mass is a small coil which locates with a conventional cylindrical magnet attached to the upper capacitance plate to form a second transducer. This generates a restoring force on the inertial mass, proportional to the current flowing through the coil provided by a feedback signal. (For details of the transducer and feedback theory see appendix C).

The gravitational force on the inertial mass is neutralised by means of a flat triangular pre-stressed spring so that with the beam horizontal it forms a flat vertical cantilever. The tip of the main spring is connected to the tip of a second flat triangular pre-stressed spring. The subsidiary spring serves two functions:

(a) it allows the main spring to flex along its whole length by allowing the fixing block at the junction of the springs to rotate;

(b) it provides a constant compressional force along the axis of the main spring. This causes a reduction in the effective stiffness of the main spring (and so reduces the natural frequency of the suspension) whilst maintaining its static pre-stress necessary to balance the beam. The theory for this spring arrangement is given in appendix B.

Mechanical centering of the inertial mass between the capacitance plates is achieved by rotating the junction of the two springs by means of a weak spiral spring attached at its inner end via a gearbox to a motor. This recentering mechanism is only needed after initial installation to compensate for the inclination of the borehole from vertical and for temperature effects - it plays no part in the operation of the feedback circuits.

Mounted at the top of the seismometer frame (and inside the pressure jacket) is a miniature transformer and the data signal preamplifier. A block diagram showing the electronic and electrical components is shown as figure 10.

3.3.2 Horizontal-component Seismometer

These instruments (see figures 11 & 12) use many parts (such as transducer, boom and suspension pivots) which are identical to those of the vertical-component seismometer but are in the form of an inverted pendulum. The purpose of the main spring is to enable the initial centering of the inertial mass to be achieved with an inclined borehole and in addition allow the seismometer to be operated open loop for testing. (With a perfectly vertical inverted pendulum the feedback signal would overcome the instability of this geometry and make the main spring redundant for closed loop operations). The electronic preamplifiers for these instruments are mounted at the top in a similar arrangement to that of the vertical-component seismometer. The electronic and electrical components are also identical to those of the vertical component (figure 10).

3.4 Downhole Electronics Unit

This unit contains three identical printed circuit boards (see figure 13) each assigned to a particular seismometer in the package which lies about one meter below the unit in the hole. Fixed to the outer casing of this unit is a spring-loaded arm to which is attached a rope that is connected to the top of the seismometer package. This is so designed that whilst lowering the electronics unit the weight of the seismometer package pulls the arm against the spring so that the arm is vertical. When the seismometer package has seated in the holelock down the borehole the stress is relieved in the interconnecting rope allowing the arm to extend towards the borehole casing. Further lowering of the electronic unit causes the arm to "jam" the unit in the hole about one meter above the seismometer package and leaves the rope and interconnecting cables slack (see figure 1).

A block diagram of a circuit board is shown as figure 14. The drive signal for the capacitance transducer in the seismometer is generated by a 10 kHz constant amplitude oscillator circuit. The data signal from the seismometer preamplifier is further amplified by the channel amplifier before undergoing phase sensitive detection through analogue switches. This smoothed analogue output (ACC) is used as the input signal for three circuits:

(1) It is fed back to the seismometer to close the loop by means of the feedback circuit components R_F, C_F and the feedback transducer coil attached to the inertial mass of the transducer.

(2) It is buffered and connected to the monitoring equipment at the surface for monitoring the position of the mass with reference to the seismometer frame. (For a mass on a spring the relative displacement of the inertial mass is proportional to the acceleration of the frame for frequencies below the natural frequency of the suspension.)

(3) It is the input data signal for a bandpass filter centered at 0.05 Hz to give a signal with a response that is flat to ground velocity that is then converted from a

single-sided to a push-pull output for transmission to the surface as the primary data signal VEL.

Three relays are included that are operated by the surface control unit. Two relays are simultaneously controlled to enable the seismometer to operate in both open and closed loop modes. In the open loop mode, one relay breaks the feedback current path whilst the second relay reduces the gain of the channel amplifier. The third relay connects the seismometer feedback coil via a resistor to the surface control unit to allow input signals generated at the surface to be used as forcing signals to the seismometer for calibration purposes.

3.5 Surface Electronics Unit

This unit (figure 15) contains electronic circuits to fulfil three main functions:

(1) to provide DC power for the downhole electronics;

(2) to accept the three raw data signals VEL from the downhole electronics unit, filter each into two different frequency bands VBB and LPNB and convert them to three multiplexed FM tone audio signals for direct connection to three PWs for transmission to Blacknest;

(3) to provide individual monitoring, control and calibration facilities for the downhole seismometers.

A block diagram for a single channel is shown as figure 16.

3.5.1 Power supplies and earthing

Four regulated power supplies are used for this system. A ±12 volt supply powers all the functions of the surface electronics unit and is common to all three channels. Its "0 volt" rail is directly connected to mains power earth.

Each downhole channel has its own power supply system. Originating from a ± 15 volt regulated power supply at the surface the voltage level is reduced to ± 12 volts by means of further regulators located on each of the three feedback cards in the downhole electronics unit. This supply then powers the card and its corresponding transducer. The three "0 volt" rails are only earthed at the frames of the transducers and are connected to real earth via the holelock and borehole casing. The casing of the downhole electronics unit is connected to this earth by means of its jamming arm mechanism. Thus there are two system earths - one at the bottom of the borehole, the other, the mains earth, at the surface. The data signal VEL is transmitted in push-pull mode between them.

Two BNC sockets on the front panel of the surface electronics unit are insulated from the chassis. They are labelled ACC (output of the loop or mass position) and CAL (calibration signal input). Both use the seismometer earth at the bottom of the hole and should only be connected to equipment with a floating earth when the system is normally operating downhole.

This restriction does not apply when the seismometers are operating at the surface either within the seismometer package or as separate instruments on the concrete piers. In this case it is essential to earth the seismometer casing(s) to the surface (mains) earth along with the casing of the downhole electronics unit.

3.5.2 Signals

The data signal (VEL) is converted back from a push-pull to a single-sided signal before becoming the input signal for two filter systems:-

(a) LPNB Filter. This consists of three second-order low-pass filters (with corner frequencies of 0.05, 0.05 and 0.033 Hz), a single-pole high-pass filter (0.005 Hz) followed by a gain stage of x400.

(b) VBB Filter. Three stages are used to give a four-pole Butterworth low-pass filter with a corner at 4 Hz and a gain of 2.5.

The outputs from each filter are then converted to become a frequency modulated (FM) carrier (270 Hz and 2160 Hz for the LPNB and VBB respectively) which are then summed to form a multiplexed output signal. Protection for the circuits from lightning is incorporated into the unit using gas diodes, chokes and surge suppression diodes so that the output signals can be connected directly to BT private wire circuits.

3.5.3 Re-centering

After initial installation the drift of each seismometer mass relative to its frame is large due to the effect on the suspension of the temperature difference between the top and bottom of the borehole (typically 10°C). Each channel contains a circuit that enables automatic recentering of the seismometer inertial mass. A detector circuit continuously monitors the ACC output which gives an output proportional to mass displacement, ie gives an offset due to the drift of the mass as well as sinusoidal higher frequency signals due to cultural noise such as vehicular traffic. In order to isolate this offset voltage the circuit includes a second-order low-pass filter with a corner at 0.05 Hz. It is arranged that when the output of the filter exceeds a predetermined threshold, electrical pulses of the correct polarity are applied to the recentering motor in the seismometer package.

A complete description of the operation of this circuit is given in reference 4.

3.5.4 Calibration and Control Units

Separate calibration and control units are used for each of the three channels. A centre zero meter is used in conjunction with a rotary switch to monitor the following parameters:

(i) the ± 15 volt power rails sent down to the borehole electronics package where it is regulated to give ± 12 volts for the seismometer and feedback circuits;

(ii) the ±12 volt power rails used for the surface electronics circuit only;

(iii) the mass position signal (ACC), the raw data signal from the borehole electronics unit (VEL) and the analogue signals immediately before conversion to FM (VBB and LPNB).

The rotary switch is also used to allow external signal waveforms to be suitably attenuated for injection into the seismometer feedback coils for calibration purposes. Such waveforms should be floating, (ie, not tied to mains earth) except when the seismometers are operating at the surface (see section 3.5.1).

The current passed through the feedback coil is: 10μA/volt for ACC input; 0.5 μA/volt for VEL and VBB input; 9.9 nA/volt for LPNB input. A push button allows a current step to be generated through the switched attenuator using the internal +15 volt supply rail.

3.5.5 Audio Confirmation of FM Tone Outputs

A circuit is included that enables the operator to listen to the multiplexed FM tone outputs from each channel at their input to the lightning protection for the private wires (PWs). This facility is necessary when fault finding to check for any failure of the PWs.

4. FREQUENCY RESPONSES

A block diagram of the signal circuits is shown as figure 17. The frequency response of the two final outputs VBB and LPNB are obtained by filtering and amplifying the signal from the closed loop seismometer (ACC). However it is necessary to have the open loop response of the seismometer alone, ie, ACC Open, so that checks can be carried out with the feedback disconnected to confirm correct operation of individual stages of the seismometer. The Nyquist response which determines the stability of the seismometer when the loop is closed, allows the stability to be predicted for any subsequent design changes of the closed loop response. The expressions for the various responses and their derivation are given in appendix C. In deriving the response of feedback seismometers it is usual to consider them as force-balance systems. Here however they are effectively torque-balances with the inertial mass (M) located at the end of a boom with its centre of gravity a distance x_{cg} from the pivot. Responses are given for seismometers with a natural frequency of 1 Hz (the Blacknest-Guralp) and 3 Hz (the Guralp CMG 3).

4.1 Open Loop Response (ACC Open)

The transfer functions of the open loop response (appendix C) relates output voltage (V_{OUT}) to ground acceleration ($\ddot{x}$) and is given by:

$$V_{OUT}/\ddot{x} = M\ T_P x_{CG}$$

where T_F is the transfer function of the forward path of the feedback loop. The response is shown in figure 18.

4.2 Nyquist Response

If a feedback seismometer is to be stable when the loop is closed the feedback signal must be of opposite phase to the input signal and have a phase margin greater than 40% and a gain margin of greater than 50%. (Ref [4] explains these parameters). The phase and gain margins are derived from the Nyquist response which has a transfer function given by $T_F T_R$ where T_R is the transfer function of the reverse path. The transfer function for the Nyquist response is shown in figure 19 from which it can be seen (figure 19b) that the phase margin is 54° and the gain margin is >90% for both a natural frequency of 1 Hz and of 3 Hz.

4.3 Closed Loop Response (ACC)

The torque T applied to the seismometer boom due to ground acceleration $\ddot{x}$ is given by

$$T = M\ddot{x}\ x_{CG}$$

With the loop closed this torque is balanced by the feedback circuit. The transfer function of the signal output V_{OUT} of the loop circuit is given by

$$V_{OUT}/T = T_F/(1 + T_T)$$

where T_T is the transfer function of the total path (= $T_F\ T_R$)

So $$V_{OUT}/\ddot{x} = MT_F x_{CO}/(1+T_F T_R)$$

This response is shown in figure 18. The signal output (ACC - which is flat to ground acceleration up to 10 Hz) is proportional to the relative movement between the inertial mass of the seismometer and its frame. The signal output at this point is therefore used as a monitor for the mass position.

The effect of the change of suspension natural frequency from 1 Hz to 3 Hz only results in a decrease of sensitivity of ~ 7% at low frequencies. (An open loop system would result in a decrease of 900%!.)

4.4 Signal Outputs (VBB and LPNB)

The ACC signal is taken from the loop circuit and filtered using a bandpass filter to give an output (VEL) which is essentially flat to ground velocity for frequencies above 0.05 Hz. Separate filters then give the required outputs VBB and LPNB. It should be noted that the Mk IIIC seismometer system uses loop components that enabled the output of the loop to be essentially flat to ground velocity over the seismic band of interest [Burch 4] - thus avoiding the need for the low pass section of an external bandpass filter to obtain the conversion. The earlier design is more cumbersome but is necessary because of the high levels of cultural noise at high frequencies at the UK sites. With this borehole design it is expected that the borehole site will be selected to be well away from the main source of cultural noise.

The VBB filter consists of a four-pole anti-aliasing filter to cut off signals at frequencies above 4 Hz whilst the LPNB filter consists essentially of a six-pole low-pass filter to cut off frequencies above 0.06 Hz (15 seconds period) in order to suppress the six second microseisms.

Table 1 lists the poles and zeros for the VBB referred to ground velocity and the LPNB referred to ground displacement. For each set of poles and zeros the associated constant has one of four values depending on the location of the output signal. These are:

(a) analogue at the sockets on the surface electronic unit;

(b) FM signal as transmitted along the PWs;

(c) analogue after demodulation of the FM signal using standard Blacknest demodulators

(d) digital data replayed after decoding all sixteen bits of the Blacknest digital recording system.

Although only (a) and (b) are directly applicable to the equipment described in this report, (c) and (d) are required for the recording systems in operation and are included for completeness.

The amplitude response of the VBB channel is shown as figure 20 as volts/ground velocity and that of the LPNB channel as figure 21 as volts/ ground displacement. These sensitivities refer to the analogue signals at the socket outputs of the surface electronics unit. (The further constant to enable complete conversion is that ±10 volts at this point gives ±33⅓% deviation of the FM carrier signal applied to the PWs.)

The poles, zeros and constants for all the separate stages for the electronic signal paths are given in appendix D.1 and those for ACC (open and closed loop) and the Nyquist responses are given in appendix D.2.

5. CALIBRATION OF THE SEISMOMETER SYSTEM

5.1 Closed Loop

The sensitivities of individual channels can be checked during normal operation by injecting known electrical signals into the feedback coil. (The proof of the equivalence of an electrical current and ground acceleration is shown in appendix C). With the system operating in its normal closed-loop manner three types of signal can be injected - current step, sinusoidal current at a known frequency, and random noise. For all inputs the selection of the analogue output (ACC, VBB or LPNB) by the switch on the front panel of the surface electronics unit determines the correct resistor-attenuator network necessary to obtain practical output signals. (When calibrating the ACC output the resulting signals will be large enough to operate the automatic recentering system. For this reason the automatic recentering circuit should be disabled by setting the control switch to MANUAL). For all calibration procedures the switch on the front panel marked CAL needs to be switched. This connects the injected signal to the feedback coil by means of a relay situated in the feedback card at the bottom of the borehole. Its purpose is to isolate the downhole cable from the coil in normal operation to prevent the injection of unwanted signal due to the cable acting as an aerial.

5.1.1 Current Step

This calibration is simply operated by pressing the STEP CAL button on the front panel of the unit and keeping it pressed. This connects 15 volts to the coil via the attenuator. The ACC output is in the form of a voltage step whilst those from the other responses give classic "weight lift" waveforms. When the button is released the output waveform is repeated but with reverse polarity.

5.1.2 External Sinewave Calibration

An external signal generator is connected to the BNC socket on the front panel of the surface electronics unit to enable the response to be calculated at any selected signal frequency. A series of measurements need to be taken for a range of frequency points and calculations made to produce the amplitude response over the band of interest. This is the classical method of calibrating seismographs and although tedious, is the only practical method for observatories with simple electronic test equipment.

5.1.3 External Random Noise Calibration

This method of calibration uses pseudo-random noise as the input signal to the calibration coil. A Hewlett-Packard spectrum analyser (HP 3582A) is used to carry out the calibration. The analyser takes any two channels of input and compares the spectra of the two signals. The analyser also includes a pseudo-random noise generator. The output from this generator is used both as input to the seismometer calibration coil and input to one of the channels of the analyser. The input to the second channel of the analyser is the seismometer output. The ratio of the Fourier spectrum of the seismometer output to that of the pseudo-random noise is the seismometer response and is displayed on the screen of the analyser. The outputs are also passed as digitised signals through the Hewlett-Packard interface bus to a Hewlett-Packard computer so that the data can be further manipulated and system responses plotted automatically.

For all the above calibration signals the equivalent ground acceleration $\ddot{x}$ is related to i, the input calibration current by the expression:

$$\ddot{x} = \frac{G_e i}{M}$$

where M is the mass of the inertial mass and boom and G_e is the equivalent motor constant of the feedback magnet-coil transducer (see appendix C).

The sensitivity of the seismometer in terms of output voltage V_{OUT} and ground acceleration is MR/G_e at the ACC output, ie, the VBB and LPNB sensitivities are proportional to $1/G_e$. Combining these equations shows that it is not valid to use the feedback coil to calibrate any closed-loop system because it is dependent on the invariance of the motor constant of the feedback coil. The method is perfectly valid for obtaining a relative response curve but is useless for the determination of the value of the sensitivity.

Unfortunately it is impossible to calibrate the feedback coil with the system in operation without recourse to a tilt table but some degree of confidence in the correct operation of the loop can be obtained by measuring F_0 (the new corner frequency for the ACC output at ~10 Hz). This can be most easily accomplished as in 5.1.2 above and displaying both the input (from a sinewave generator) and output signals to give a Lissajous figure. At the natural frequency the input and output are 90° out of phase so the Lissajous figure shows circular motion.

5.2 Open Loop

The feedback loop can be disconnected by means of a switch on the front panel of the surface electronics unit. This energises two relays in the downhole electronics unit - one to disconnect the loop and the second to reduce the gain of the second channel amplifier from 11 to unity. In this mode of operation the seismometer has little electrical damping and the signal output is dominated by the resonance of the mechanical suspension at ~1 Hz. It is for this reason that the gain is reduced by the second relay. The outputs from ACC can now be used to determine the mechanical natural frequency and the open loop response and to check that the suspended mass is moving freely.

When operating open loop the suspension has a high response at its natural frequency so that the seismic noise at this frequency is amplified and consequently the signal-to-noise ratio of the calibrations signals is low. The mechanical natural frequency is therefore best measured using a sinewave input signal and comparing input and output as described in 5.1.2. The open loop response can be most reliably determined using pseudo-random noise as input as described in 5.1.3. Measurement of the open loop response using sinewaves is very difficult because of the seismic noise but the DC sensitivity can be estimated using a signal period of say 20 s and averaging over several cycles.

If the inertial mass or part of the boom of the seismometer touches any part of the frame, static friction (stiction) will prevent correct operation. Stiction is most likely to occur in the feedback magnet-coil transducer. Examination of the VBB output gives no indication of such a fault because the feedback tends to linearise the system. In this situation the main advantage of a feedback system becomes a drawback. However, the fault can usually be detected as long period noise on the LPNB output and the presence of the fault can then be confirmed using the ACC open loop output to a current step. If the boom is moving freely the ACC output should show a smooth sinusoidal decay into the background noise.

6. LIMIT TO DETECTION AND DYNAMIC RANGE

6.1 Instrument Noise

The detection of ground motion is limited by instrument noise generated by three separate sources - Brownian motion of the inertial mass, electronic noise of the primary transducer, and the electronic noise of the bandpass filter following the loop. To allow seismic and instrument noise to be compared it is usual to express the latter in terms of noise equivalent acceleration (NEA) power.

Brownian noise is the fundamental limit to the detection of ground motion. It can be shown (see for example Ref [4]) that for a mass-spring suspension, the NEA power for a mass M with a natural frequency f_o, damping factor n, over a bandwidth Δf is

$$\frac{4\,k\,T\,(2\,\pi\,f_o 2\,n)\,\Delta f}{M}$$

where k is Boltzman's constant (1.38 x 10^{-23}J/°K) and T is the absolute temperature.

For the present system the NEA power density is calculated to be 8 x 10^{-20} say 10^{-19}(m/s/s)^2/Hz assuming n is 0.0625 at 1 Hz.

The transducer noise is equal to the Johnson noise of a 4000 ohm resistor [7]. This gives a flat voltage spectrum of ~8 nV/√Hz. The displacement sensitivity r, of the transducer is 14000 volts/meter. To obtain the NEA power the response of the inertial mass, suspension must be taken into account. Because the effect of the feedback does not affect the level of the system signal-to-noise ratio the open-loop spring-mass response can be used for this calculation. Below the natural frequency ω_o of the suspension the NEA power is given by the expression

$$4k\,T\,Rn\left(\frac{\omega_o^2}{r}\right)^2\ (m/s/s)^2/Hz$$

where R_n = 4000 ohms. Above the natural frequency the NEA power increases as ω_o^4. A sketch showing the variation of the NEA power with signal frequency and suspension natural frequency is shown as figure 22.

At the output of the loop the signal (ACC) has a response that is flat to ground acceleration from DC to 10 Hz. This output alone could be recorded using an analogue to digital converter with a large dynamic range - say 20 bits. However, it is still necessary to filter these broadband signals into the more conventional responses for visual analysis of signals. The first stage of this filtering is a two-pole bandpass filter centred at 20 seconds period (0.05 Hz). Its purpose is twofold: to convert the response to be flat to ground velocity for 0.05 Hz to 10 Hz and to reject the DC offset at the ACC output that is proportional to the mass position in order to enable the output signals to be further amplified.

Measurements of the noise of this filter [10] give a value of just less than 1 μV/√Hz referred to the input over both the VBB and LPNB frequency ranges. With a sensitivity of ACC of 10^4 volts/m/s/s the NEA power becomes $10^{-20}(m/s/s)^2/Hz$.

The contribution from the three sources of instrument noise are shown on figure 23. Also included are the NEA spectra for conventional open loop SP and LP systems and the ground motion spectra for a noisy site (UK in winter) and for a very quiet site (Queen Creek, USA). From this plot it can be seen that the borehole seismometer system is better than the conventional open loop seismometer system but is only just capable of resolving the seismic noise at Queen Creek at signal periods of ~50 seconds. The largest noise contribution is that due to the Brownian noise. If we rearrange the equation for this noise the NEA power is

$$\frac{8\,k\,T\,\pi\,f_o}{MQ}\ (m/s/s)^2/Hz$$

where Q = 1/2n.

Without redesigning the instrument to have a larger mass or to operate at a very low temperature the only way to lower this noise is to increase the Q of the suspension or reduce its natural frequency. Unfortunately these two parameters are directly linked, ie halving the natural frequency halves the resulting value of Q so that no benefit is achieved. The classic method of increasing the Q is to evacuate the air from the instrument. However the difficulties of this solution are apparent when, for example, other researchers [12] have attempted to maintain a vacuum of 1 millitorr in order to obtain a Q of ~1000.

The transducer noise only becomes dominant at signal frequencies above 3 Hz. As shown in figure 22 the natural frequency of the suspension can be increased to say 3 Hz without significantly increasing the total sum of the instrument noise. This has been experimentally verified by downhole measurements of the instrument noise with combinations of vertical-component seismometers set to different natural frequencies. Figure 24 gives the output from a typical noise check between two different seismometers located one above the other in the package at the bottom of the borehole. The two seismometers were both vertical components, V3 being the Blacknest-Guralp with f_o = 2.5 Hz and V4 a CMG 3 with f_o = 3 Hz. The two LPNB signals were used for this test and were analysed using a HP 3582A Analyser at Blacknest after demodulation of the FM signals from the PWs. Figure 24(a) shows the two spectra in terms of voltage power density as measured by the Analyser and figure 24(b) is a plot of the calculated coherence. Converting the signals to ground acceleration gives the NEA power density in figure 24(c). The noise spectrum was calculated using the spectra for the two instruments and the coherence and is shown in figure 24d. This spectrum is the sum of the noise of both instruments and so should be 2 x $10^{-19}(m/s/s)^2/Hz$ but it is not possible to separate the contributions made by each instrument.

Recently, interest has been shown [13] in recording signals outside the conventional SP range with signal frequencies up to 50 Hz. The seismic noise for two very quiet sites (Queen Creek and Lajitas) taken from [13] is shown plotted on figure 22. It can be seen that the Blacknest-Guralp can easily cover its design range up to 4 Hz. The whole frequency range can be covered by reducing the transducer noise. Guralp (private communication) has achieved this by reducing the noise of the preamplifier (R_n) by a factor of three and by increasing the sensitivity of the transducer by a factor of six. This should result in the input noise spectrum shown in figure 22 as CMG 3. With these improvements the low frequency noise level is equivalent to that of the Blacknest-Guralp seismometer even though the natural frequency of the CMG 3 is 3 Hz.

The noise of the bandpass filter is acceptable as it is less than the Brownian noise at all signal frequencies of the conventional SP and LP bands. This is of course because the sensitivity of the ACC signal was set to ensure that this was so.

6.2 Dynamic Range

This is defined as the maximum input signal to the minimum input signal under specified conditions. The maximum input signal is usually determined by the onset of overloading at the output stage, and the minimum input signal is usually the NEA.

Consider only the ACC signal (output from the loop) which has a flat response of 10^4 V/m/s/s over the range DC to 10 Hz. The maximum signal is ± 10 v limited by the power rails of the electronic circuits which is equivalent to ± 6 volts RMS. The NEA power is $10^{-19}(m/s/s)^2/Hz$. Over the bandwidth DC to 10 Hz the RMS is therefore 10^{-9} m/s/s which gives 10^{-5} V at the output so the dynamic range is $6/10^{-5}$ or 116 dB. This range could be extended if required by eliminating the analogue filters and recording the ACC signal using an A-D converter of 24 bit resolution; such converters being now readily available. If the sensitivity of the ACC output is reduced to 10^3 V/m/s/s the dynamic range increases to $6/10^{-6}$ or 136 dBs. With a 24 bit converter this would give 23 bits of signal with the least significant bit as noise jitter.

7. ALIGNMENT OF THE SEISMOMETERS DOWNHOLE

The design of the seismometer package and holelock mechanism is such that not only can the instrument package be made to operate at any depth in the borehole, but it can be aligned in any compass direction.

Alignment of the seismometer package relative to the holelock can be guaranteed using the external pin fixed below the package to locate into the slot of the holelock via the curled-leaf cylinder (see 3.1, 3.3, figures 3 and 6). This relative alignment can be altered by unclamping the collar from the package and rotating it by the required angle (as indicated by a scale and pointer) before reclamping the collar.

The operational depth can be changed by withdrawing the instrument and electronics packages from the hole and repositioning the holelock mechanism to the new depth using the Holelock tool. Unfortunately changing the depth loses all absolute directional information and so the system must be realigned.

The method used for realignment is to correlate the signals from a horizontal-component seismometer located downhole with the signal from a similar instrument at the surface. The source of the signals are the everpresent oceanic microseisms which dominate the VBB output and have a period of around six seconds. The equipment is shown in figure 25. A surface horizontal-component seismometer is positioned on a calibrated turntable with its known reference to true North. The VBB output of the borehole seismometer and that on the surface are displayed on a dual-beam oscilloscope. The turntable is rotated to give the best visible coherence between the two traces and the error read directly from the turntable. The seismometer is then withdrawn from the borehole and the external location pin is repositioned by being rotated by the error angle. The package is then returned to the borehole when the alignment should be correct once the location pin re-enters the slot in the holelock. Using this method, correlation by eye of the raw VBB traces allows the seismometers to be aligned to within say 10°.

A much more accurate and consistent set of results is obtained when the coherence is measured using a dual channel precision spectrum analyser interconnected to a computer. Such equipment is the Hewlett Packard HP 3582A analyser and HP 85 computer. (Although the analyser gives a visual output of the coherence at any frequency, it is displayed only as two decimal places which, as will be seen later, is insufficient). The computer is programmed to reset and restart the analyser at five minute intervals and to accept the raw data from the analyser at the end of each run. The coherence is calculated from the raw spectral data for the signal frequencies of 0.12 to 0.4 Hz with increments of 0.04 Hz. The average of these eight values is also printed as output. A degree of automation is included in the program as it is found more convenient to let the analyser and computer run continuously in the recording room at Blacknest, leaving the operators to be stationed at the borehole site. To ensure sufficient readings the operators rotate the turntable by one degree every fifteen minutes (noting, of course, the angle on the table and the time). The computer results for this test gives remarkably high values of coherence (see figure 26 which shows two portions of a HP85 printout). The results for the whole series of measurements is shown as figure 27 which covers nine different azimuths with an average of three runs at each.

It can be seen that as the coherence reaches its maximum so does its consistency; scatter in the measurements being a minimum. From this plot it can be seen that the orientation should be resolvable to within one fifth of one degree! However, it is estimated that there could be a tolerance of $\pm 2°$ in the finger/slot mechanism and an error of a similar order in the alignment of the true North direction in the vault and surface turntable. The total error should be less than $\pm 4°$.

8. RESULTS

8.1 Condition of Borehole Units after the First Year's Continuous Operation Downhole

After 45 weeks of continuous and satisfactory operation downhole the seismometer and electronic packages were raised in February 1988 for reconfiguration of the seismometers to allow a further series of tests to be undertaken (section 2.2). It was found that:

(a) all cables, connections and lifting equipment showed no signs of deterioration;

(b) the electronics package (figure 13) showed no sign of corrosion although the cadmium plating had discoloured considerably and showed signs of scratching and scuff marks;

(c) the seismometer package (figure 6) showed considerable pitting and minor corrosion on its outer surface and at the interfaces between the seismometer pressure jackets apparently due to faulty plating;

(d) rusting had occurred on the seismometer baseplates around the glass to metal seal probably due to the local removal of the plating in order to solder the seal to the baseplate;

(e) the seismometers were found to be dry with no sign of corrosion;

(f) the holelock contained a considerable amount of debris (rust and scale from the borehole casing) on its top face surrounding the feet, that had accumulated from a number (at least six) package installations and removals from previous tests showing that the holelock should be modified to allow the debris to escape;

(g) the leaf shape of the holelock (figure 2) showed signs of rusting on the leaf edge.

The three units normally downhole (holelock, seismometer and electronics packages) were made from mild steel with cadmium or nickel plating. The holelock is made of stainless steel but had a mild steel leaf coated with red lead paint. Components have now been manufactured from stainless steel to replace all the mild steel items in the seismometer package.

8.2 Drift of the Mass Position

In order to determine the long term drift of the inertial mass of the vertical-component transducer the ACC output was passed through a 20-second low-pass filter, amplified and displayed on a pen recorder. The recorder consists of a clockwork thermograph modified to operate with a helicorder amplifier and pen combination. During the period March-July 1988 the downhole package contained three vertical-component seismometers (two Blacknest-Guralp instruments with $f_0 = 1.4$ Hz and $f_0 = 2.5$ Hz and one CMG 3 with $f_0 = 3.0$ Hz). Recordings were made sampling the ACC output for the three seismometers in turn.

A graph of the rate of drift for each instrument (figure 28) shows the following points:

(1) the mass drift is always in the same direction (downwards);

(2) the rate of drift of the 1.4 Hz mass is ~2.8 times the rate of the 2.5 Hz mass which is very close to its predicted rate of $(2.5/1.4)^2 = 3.2$ worse;

(3) the CMG 3 drift rate is an order of magnitude worse than the equivalent Blacknest-Guralp which may be because the CMG 3 was new and the suspension had not yet aged or it may be due to the different design but in practise this makes no difference to the quality of the seismic signals that are recorded (see later section 8.5).

Figure 29 shows a recording for the week 11-18 April 1988, eight weeks after installation of the package. The drift rate is seen to be 80 mV/week. The automatic recentering unit operates after the mass has drifted two volts from its last recenter position. At this rate recentering should only occur after 25 weeks, ie, twice per year. Also prominent on figure 29 are the signals from two other sources - the surface waves from three teleseismic earthquakes and earth tide signals with a period of ~12 hours and an amplitude of ~ 150 μgal peak-to-peak.

8.3 The Effect of the Wind on the Seismic Vault at Wolverton

Wolverton vault is near the top of a hill with a farm track passing its entrance. It was constructed in 1962 by excavating a cutting into the hill, building the vault and covering it with rubble or topsoil. The borehole was drilled through the vault in 1979. A plan view and a cross section through the vault are shown in figures 30 and 31. The vault has no deep-seated piers and can be regarded as a concrete box sitting on the Chalk. The hillside and access doors face southwest - the direction of the prevailing wind. All the instrument piers (labelled P1, 2, 3 and 4) are parts of a single mass of concrete with P1 and P2 separated from P3 and P4 by a suspended walkway. Since 1973 a three-component set of conventional LP seismometers has been continuously operating in the vault. These instruments are a Geotech S-11 vertical component in a pressure tight clamshell on P4 and two Geotech S-12 horizontal-component instruments on P1.

Before installation of the seismometer package downhole, the individual seismometers were operated on the piers so their output signals could be compared with those from similar instruments already in the vault. When the LPNB signals were compared it was found that although the outputs from the vertical components were very similar, the coherence was poor between the outputs of horizontal components when they were not on the same pier. A series of tests (at a constant magnification of 13 K at 20 s period) were then conducted to determine the cause of this anomaly. It was soon found that it was due to the effects of wind on the vault.

Figure 32 shows the recordings from three vertical-component borehole seismometers during a period of high seismic noise and high winds. The three borehole seismometers were on separate piers (P1, P2 and P3) and the S-11 on P4. The coherence between the outputs is excellent showing that the anomalous behaviour of the piers does not affect vertical-component seismometers. Figure 33 shows recordings from seven horizontal-component seismometers (six borehole instruments and the S12) oriented N-S on pier 1 during a period of high winds. The outputs are again highly coherent. (Note that only the small size and ease of installation of the borehole instrument makes it now possible to conduct such an experiment.) The corresponding recordings for calm conditions are shown in figure 34 when the seismic noise is also seen to be low. Although the coherence generally is very good, most traces shown signs of weight lift glitches. These are discussed below (section 8.4) but are most commonly observed, as in this experiment, after repositioning of the seismometers.

The low coherence between the outputs from the horizontal components operating in windy conditions on different piers is shown in figure 35. The seismometers were operated orientated N-S and E-W on all four pier surfaces. The four traces show simultaneous recordings for the highest and lowest amplitudes for the N-S and for the E-W instruments. Analysis of all the combinations of alignments and piers indicates that for the N-S component P4 is significantly quieter than any other pier whilst for the E-W, P1 and P2 are similar and both significantly quieter than P3 or P4. (For the N-S it might have been expected that P3 would have been comparable with P4 but this was not found to be so.)

Although it was known from experience with conventional instruments that the noise on horizontal components is high when the wind is strong, until this time when several LP instruments could be operated simultaneously in the same vault it had not been possible to check the variation of the effect with position inside the vault. It had never been suspected that the wind caused the piers to tilt independently as has been found from the results given above.

Surface and down-hole recordings were also compared in windy conditions with the borehole package containing three horizontal-component seismometers - two aligned N-S (the upper and lower instruments in the package) with one aligned E-W. With the package operating at 34 metres depth it was found that the surface noise due to the wind was absent downhole. Figure 36 shows a recording from four instruments aligned N-S - two downhole (H5 and H2) and two at the surface on the best and worst piers (P4 and P1). A surface wave train is clearly visible on the downhole traces but is completely masked at the surface by the wind noise.

8.4 Weight Lift Glitches

A feature that frequently occurs on LPNB seismograms is a waveform that closely resembles a "weight lift". Such a waveform could result from a step of acceleration input and can be simulated exactly by passing a step of electrical current through the feedback coil (or calibration coil of a conventional seismometer). It is suggested that the defect is due to the gradual release of stress in the mechanical suspension of the seismometers. It is certainly true that the number of glitches decreases with time after installation which supports the suggestion. Examples of glitches are described in section 8.3 but another good example can be seen in figure 37 showing their occurrence with an old Geotech S-12 seismometer. This instrument had just previously been realigned to N-S after thirteen years continuous operation aligned as E-W.

A similar but different mechanism originally gave rise to swarms of weight lifts when the horizontal component instruments were operated downhole. Whereas the stress release discussed above is limited to single instruments, downhole the effect was common to the whole package. (Curiously though, the effect on the vertical-component seismometer was negligible as is the effect of the wind noise; see 8.3.) An example (which occurred soon after installation) is shown as figure 38. At that time the downhole package contained three horizontals (two N-S and one E-W) and the traces shown enable comparison to be made with the surface N-S and E-W. From this it can be seen that the defect is caused by the borehole itself or by the contact surfaces between the package, holelock and borehole. As with the single instrument effect described above these "weight lifts" did decrease in both amplitude and rate over a long time-scale although even after twelve months operation they did still occur. The problem of the weightlift swarms appears to have been solved by the introduction of a new holelock with its matching base for the seismometer package. The results of measurements of the verticality of the borehole showed that its tilt linearly increases from 0.5 degrees at the surface to 4.5 degrees at approximately 25 meters before reducing to 3.25 degrees at 40 meters depth. Calculation of the stability of the old seismometer package showed that it would be unstable, ie, fall over, at a tilt of greater than 3.7 degrees. Analysis of the geometry of the old holelock showed that with the seismometer package in place there was a possibility of the package resting on only two of its feet and leaning against the "curled leaf" of the holelock (see figure 3). The distance between the package feet was limited by the necessity of requiring a conical section for guiding the package into the holelock. Although the new design was originally intended to reduce the diameter of the borehole necessary for any borehole seismometer package, it increased the stability angle to 5.2 degrees by allowing the feet to operate on a diameter of 120 mm instead of 85 mm.

8.5 Examples of Recordings from Underground Nuclear Explosions

Figures 39 and 40 show seismograms from borehole and surface instruments for the E Kazakh explosion of 3 April 1988. At the time of the recording the borehole package contained three vertical-component seismometers: two Blacknest-Guralp seismometers, one with an f_0 of 1 Hz the other 2.5 Hz and one Guralp CMG 3 with an f_0 of 3 Hz. Figure 39 is a comparison of the SP seismogram derived from the VBB output of the borehole and surface instrument (a Mk IIIC) and figure 40 a comparison of the LPNB seismograms. From the figures it can be seen that:

(1) the SP signals show almost perfect coherence not only between themselves but also with the surface recording;

(2) there is no sign of any spurious signals on the recordings from the downhole instruments;

(3) the signals of the surface waves are coherent between all four instruments although there is a distinct difference in the character of the pre-signal noise between the downhole instruments and that at the surface.

Figure 41 shows pen recordings of the LPNB signals from the Kazakh explosion of 14 September 1988 derived by demodulating the FM tone and <u>not</u> from the VBB channel. For this explosion two sets of conventional three-component instruments were recording - one set downhole and the other at the surface. The figure shows the advantage of the borehole in reducing the background noise due to wind on the horizontal instruments (see section 8.3) although the record is still marred by borehole glitches (see section 8.4).

8.6 Damage due to Lightning Strikes

A remaining weakness with the borehole system is its susceptibility to damage from lightning. During three consecutive years, 1990 to 1992 one or other of the two systems at Wolverton vault has been put out of operation during a summer storm. In 1990 a strike on the 16 August put the surface system out of action. The power units supplying the DC volts located in the control unit were destroyed along with many integrated circuits in the electronics unit. The following year a strike on the 23 July caused even more damage although only the downhole system was affected. The same units as before were damaged but in addition one horizontal component seismometer had its feedback transducer sensitivity reduced by a factor of FOUR. This resulted in a fourfold increase in sensitivity of the closed loop seismometer with a bandwidth reduced by a factor of two. This was only discovered after the electronic circuits had been repaired and the whole system tested by comparison of the seismic signal outputs from the three seismometers. As Burch [4] predicted such a loss of sensitivity is not revealed if conventional techniques are used to try and determine the absolute calibration of a feedback seismometer.

On 9 August 1992 the downhole system was again damaged by lightning but the damage was minor - only the power supplies and a few integrated circuits were destroyed. Perhaps surprisingly none of the lightning strikes damaged the Mk IIIC seismometer and associated electronics operating as a single component system at the surface.

The possible reasons for the strikes are difficult to prove as they fortunately occur only rarely. The borehole system has been in almost continuous operation since 1986 although only in the last two years has it suffered strikes. A possible explanation for this is that it is due to the lack of rainfall during the past few years. Only one mile from the vault on the other side of the valley is the television transmitter mast at Hannington. During storms this mast would safely dissipate the atmospheric charge into the surrounding ground. It may be that due to the dry surface soil our steel cased borehole is acting as a probe. This would explain how the lightning only affects electronics in the vault with no sign of damage to external lines (PW or mains power). The only simple change that can be made is to "earth" the top of the hole casing to the mains power "earth".

9. CONCLUSIONS

A three-component wide-band seismometer system has been developed and put into operation at a depth of 34 metres in a nominal 6 inch ID cased borehole. With the exception of the pivots for the transducers all the mechanical components can be shaped by any competent machine shop and all the electronic components are commercial standard and are easily available.

The broad band output (which was tailored specifically to the conventional teleseismic frequency band of 0.01 to 4 Hz) gives a system noise level that is close to its predicted design level with an equivalent ground acceleration power density of 1×10^{-19} $(m/s^2)^2/Hz$. Teleseismic recordings from underground explosions have been recorded and analysis confirms correct operation of the complete system.

The mechanical and electronic components of the system have proved very reliable in operation with the only outages caused by lightning strikes.

A method of determining the alignment of the downhole seismometer package with respect to a surface package has proved to give consistent results with an error similar to that of the absolute alignment of the surface instruments.

The replacement of the original design of holelock has almost completely solved the problem of "weight lift glitches".

Analysis of the performance of the seismometers in the vault at the surface and down the borehole have shown that large concrete piers can be a source of noise due to tilt which mainly affects LP horizontal component seismometers. This suggests that when these instruments are used at the surface they should be installed in shallow holes in bedrock without any concrete floor, with any disturbance to the surrounding material being kept to a minimum.

Comparison tests of Guralp Systems CMG3 and Blacknest Guralp seismometers show that the performance of the two types appears to be identical. Several hundred CMG3 seismometers, modified as necessary to meet each customer's requirements, are now in use around the world. With their recent advanced developments and commercial availability there is no requirement to further develop the Blacknest Guralp design of seismometer.

APPENDIX A

Dimensions and Weights of Main Components

Component	Length (mm)	Diameter (mm)	Depth (mm)	Height (mm)	Mass (kg)
Holelock	390	130			12
Holelock Tool	850	100			14
Seismometer Package including instruments	600	110			23
Downhole Electronics Unit	680	100			10
Surface Electronics Unit	530		420	220	20
Holelock Tool Cable	50000				3
Three Borehole Cables	50000				3 (each)
Single Seismometer without Pressure Jacket	120	80			1.1

APPENDIX B

Theory of the Suspension of the Vertical Component Seismometer and the effect of the Subsidiary Spring

The inertial mass is fixed to the end of a pivoted boom (see figure B1). Along the axis of the pivots the boom is connected to the end of the triangular main spring. This spring is prestressed so that when its tip is vertically above the pivot axis the boom is in a horizontal position and the main spring is substantially flat. The tip of the subsidiary spring is rigidly fixed to the tip of the main spring whilst its other end is firmly anchored to the instrument frame. Figure A also shows the springs in their released positions before connection using the spring clamping block.

The behaviour of the main spring can be determined by regarding it as a horizontal beam subjected to an end moment and an axial load as shown in figure B2.

The moment equation of any point x along a beam of rectangular cross section is

$$EI\ \frac{d^2y}{dx^2} + Py = \frac{Mx}{L}$$

where
M is the end moment
P is the axial load
x is the distance along the line joining the two ends of the beam
y is the deflection at right angles to the x direction
E is the modulus of elasticity
I is the moment of inertia of the cross section of the beam
L is the length of the beam

Rearranging the equation and using the parameters for a triangular spring gives the expression

$$\frac{d^2y}{dx^2} + \frac{12L}{Et^3b} \cdot \frac{Py}{x} = \frac{12M}{Et^3b}$$

where t is the spring thickness and b is the spring width at its broad end.

$$Put\ R = \frac{12LP}{Et^3b}\ and\ S = \frac{12M}{Et^3b}$$

$$then\ \frac{d^2y}{dx^2} + \frac{Ry}{x} = S$$

For a selected value of R this equation can be solved to give a set of values of dy/dx(=θ) for corresponding values of S. A family of curves - for different values of R is shown as figure B3. The stiffness of the spring K = S/θ and is the slope of the straight lines of figure B3.

The natural period of oscillation of a body of moment of inertia I attached to a spring of stiffness K is given by

$$T = 2\pi\sqrt{\frac{I}{K}}$$

$$I = 2.26 \ x \ 10^{-4} \ kg^2$$

The four values of R (0,20,34,36) correspond to axial loadings of 0, 0.06, 0.10 and 0.11 kg. Substitution in the expression above gives natural periods of 0.40, 0.51, 1.16 and 2.17 seconds. These results are shown plotted in figure B4 as curve A. These results assume that the pivots have no stiffness. In practice their combined stiffness is 2.64 x 10^{-3} Nm/radian which would give a natural period of 1.84 seconds even if the main spring had zero stiffness. Reworking the expression for the natural period for the sum of the spring and pivot stiffness gives the practical result shown as curve B (figure B4) and shows that:

(i) The maximum period attainable is 1.84 seconds.

(ii) The minimum period (with no compression) is 0.39 seconds.

(iii) The threshold of buckling of the main spring occurs for an axial loading at 130 g.

From this it can be seen that a natural period of one second can be obtained with an axial load of 100 g. This axial load is achieved by the prestress of the subsidiary spring so that when the seismometer is fully operational the boom and the subsidiary spring are horizontal and flat with the main spring vertical and flat. In practice due to imperfection and misalignments of the components of the seismometer a natural period of 1 Hz although attainable is subject to patience and careful assembly.

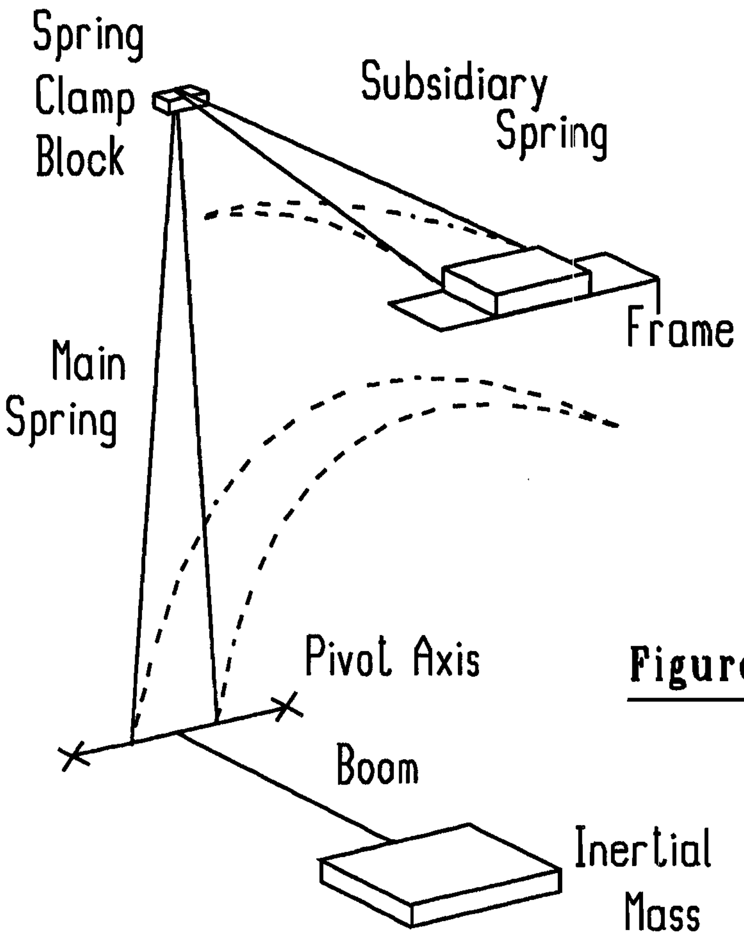


Figure B1

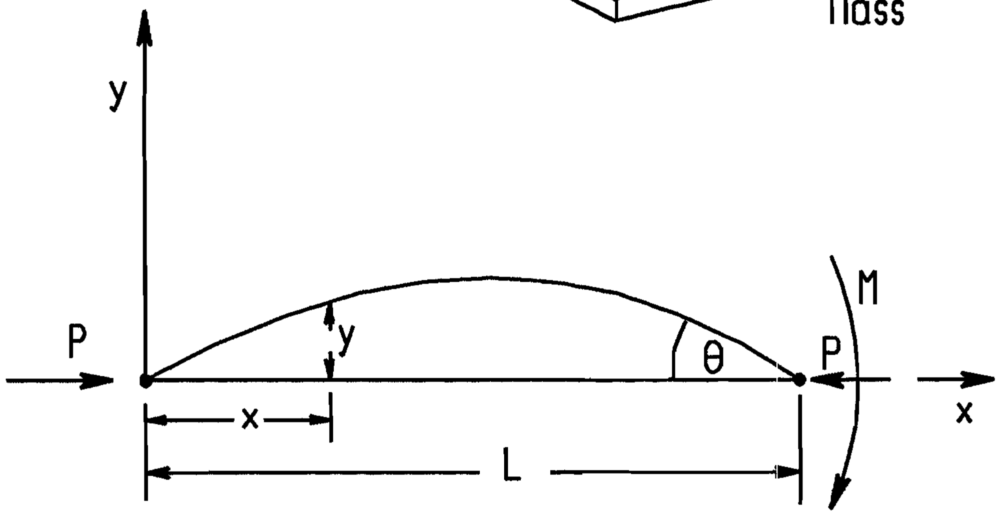


Figure B2

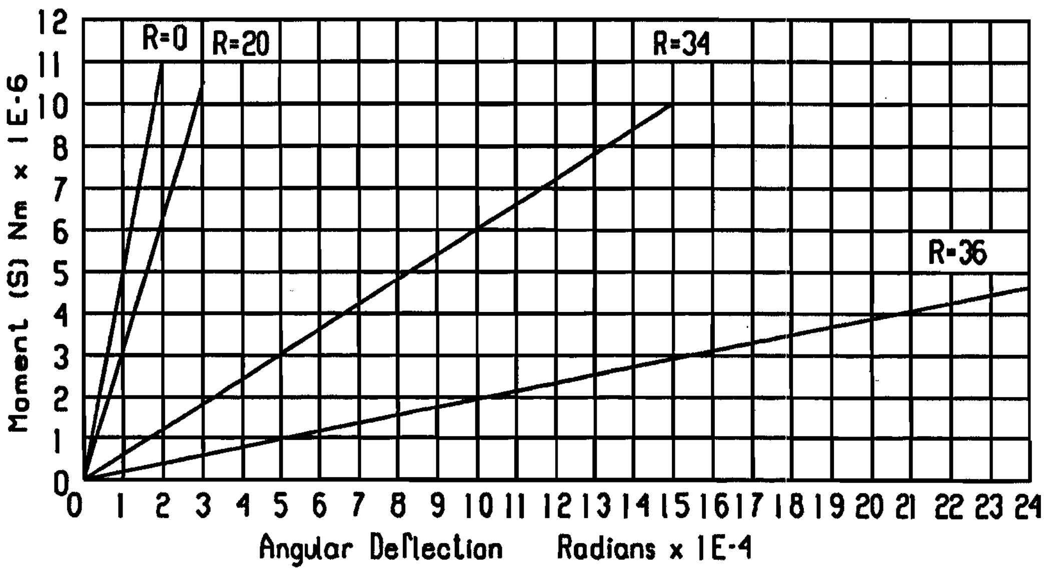


FIGURE B3

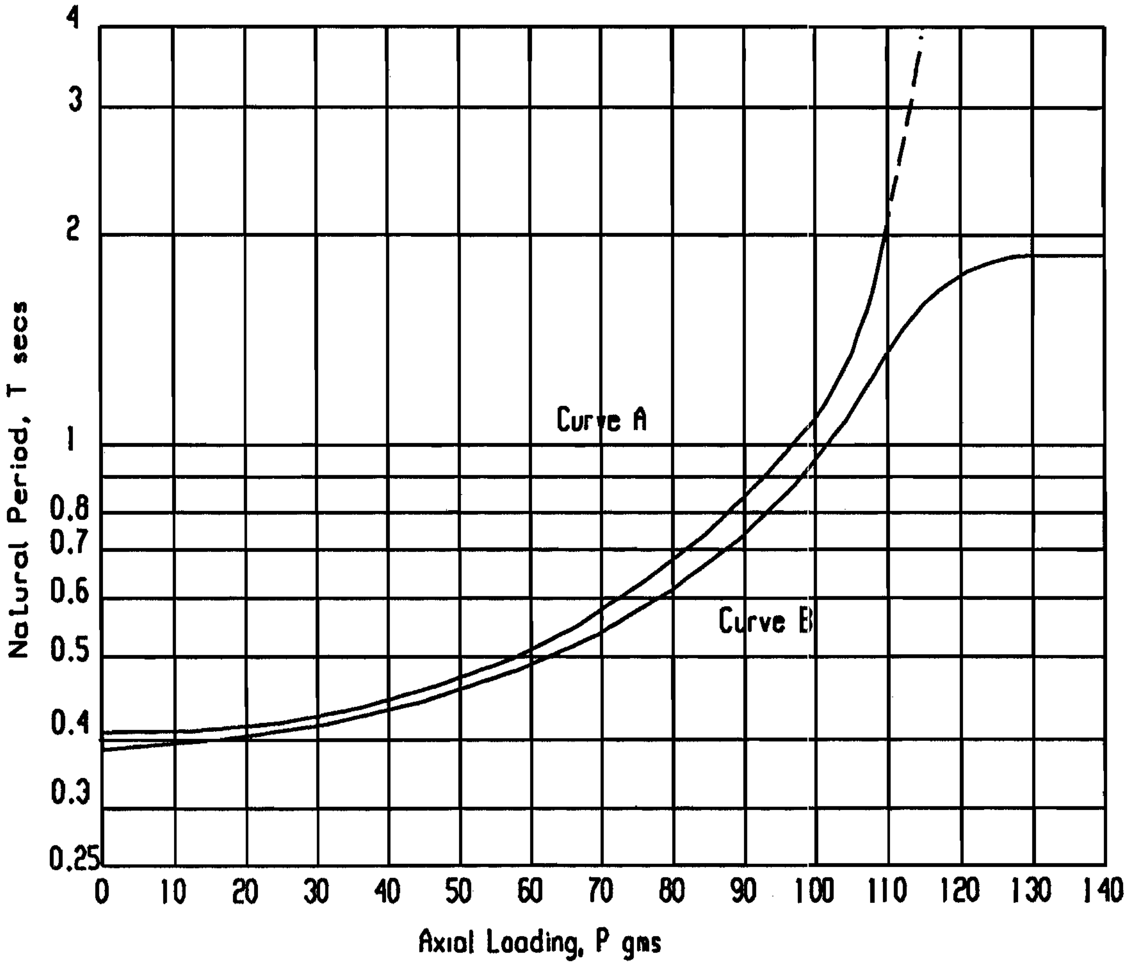
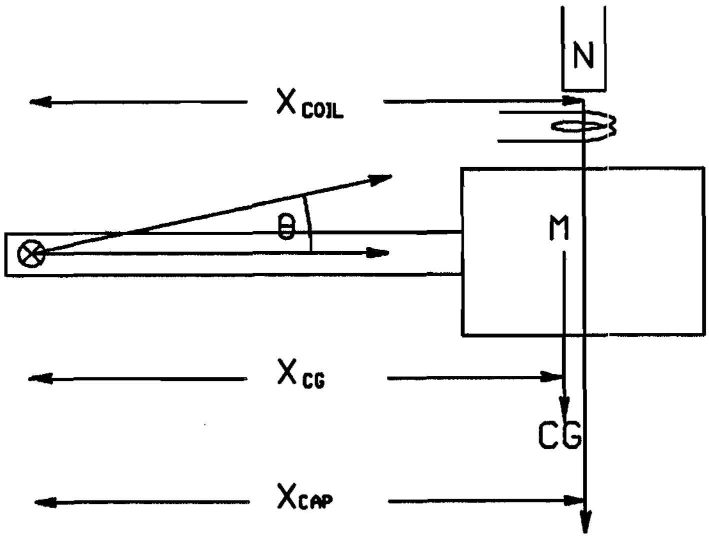


FIGURE B4

APPENDIX C

Theory of the Borehole Seismometer

C1. OPEN LOOP



The indicator torque equation for the seismometer is:

$I\ddot{\theta} + B\dot{\theta} + C\theta = 0$ where θ is the angular deflection of the boom,

$\ddot{\theta} + \frac{B}{I}\dot{\theta} + \frac{C}{I}\theta = 0$

I is moment of inertia of the boom about the pivot,
B is the damping term,
C is the restoring torque/rotational angle

It can be shown that the natural frequency of the suspension (ω_o) and the damping factor (n_o) are related to B, C and I by the expressions

$\omega_o^2 = C/I$ and $2n_o\omega_o = B/I$.

If a steady current i is passed through the coil then $I\ddot{\theta} + B\ddot{\theta} + C\theta = Gi\ x_{COIL}$ where G is the motor constant (Newtons/ampere) of the magnet/coil.

The deflection $\theta = Gi\ x_{COIL}/C = Gi\ x_{COIL}/I\omega_o^2$

The vertical linear displacement of the centre of the central capacitor plate is $x_{CAP}\theta$ which is

$Gi\ x_{COIL}\ x_{CAP}/I\omega_o^2$.

If the displacement transducer and following amplifier have a total sensitivity of D volts/metre then the signal voltage output for a steady input current i is
$Gi\ x_{COIL}\ x_{CAP}D/I\omega_o^2$ volts or V_{OUT}/ampere $= G\ x_{COIL}\ x_{CAP}D/I\omega_o^2$

For ground acceleration $\ddot{x}$: $I\ddot{\theta} + B\dot{\theta} + C\theta = M\ddot{x}\ x_{CG}$

$I(s^2 + 2n_o\omega_o s + \omega_o^2)\theta = M\ddot{x}\ x_{CG}$

$\theta = M\ddot{x}\ x_{CG}/I(s^2 + 2n_o\omega_o s + \omega_o^2)$

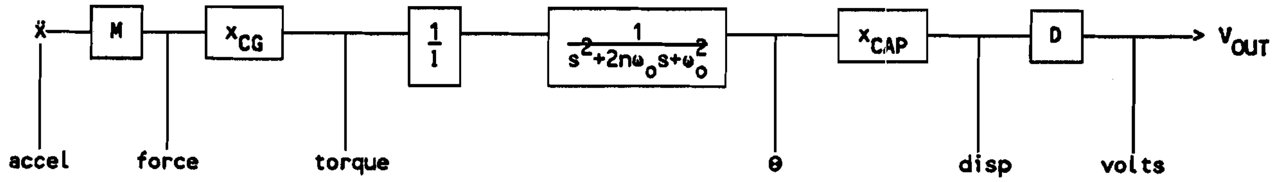
But voltage out for deflection θ is $\theta x_{CAP}D$ and so

$$V_{OUT}/\ddot{x} = Mx_{CG}x_{CAP}D/I(s^2 + 2n_o\omega_o s + \omega_o^2) \text{ V/m/s}^2$$

As $Mx_{CG}x_{CAP} \approx I$ then at zero frequency (DC)

$$V_{OUT}/\ddot{x} \approx D/\omega_o^2$$

The various elements of the seismometer system linking ground acceleration to output voltage can be represented schematically as follows:



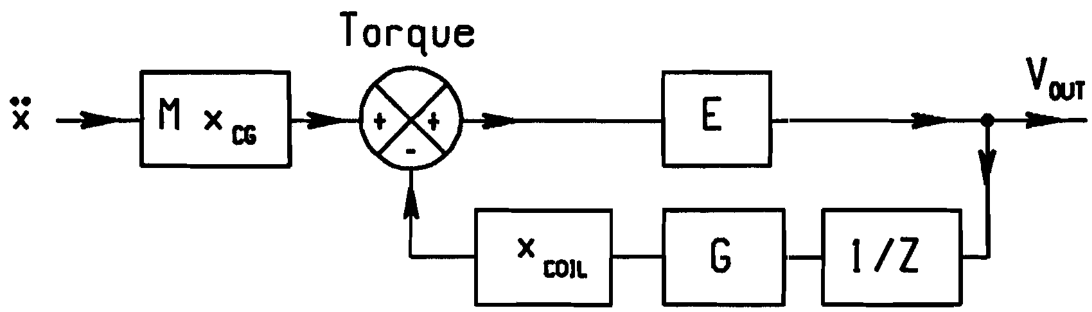
From the equations derived above for V_{OUT}/ampere and $V_{OUT}/\ddot{x}$ the equivalence of a constant ground acceleration to a steady electrical current can be shown to be

$$\text{m/s}^2\text{/ampere} = G\, x_{COIL}/Mx_{CG}.$$

C2. CLOSED LOOP

Linking the output voltage V_{OUT} through an impedance Z to the magnet/coil transducer creates a torque balance. If we simplify the block diagram by putting

$$\left(\frac{1}{I}\right)\left(\frac{1}{s^2+2n_o\omega_o s+\omega_o^2}\right) x_{CAP}\, D = E \textit{ then}$$



$$V_{OUT}/\text{Torque} = \text{Forward Path}/(1 + \text{Total Path}) = E/(1 + \frac{EG}{Z} x_{COIL})$$

If the impedance Z consists of a resistor R in parallel with a capacitor C

$$Z = R/(sCR+1)$$

$$V_{OUT}/Torque = 1 \Big/ \left(\frac{1}{E} + \frac{G\, x_{COIL}}{Z} \right) = 1 \Big/ \left(\frac{1}{E} + \frac{G\, x_{COIL}}{R}\,(sCR+1) \right)$$

But Torque = $\ddot{x} M x_{CG}$

$$\therefore \frac{V_{OUT}}{\ddot{x}} = \frac{M x_{CG}}{\dfrac{I(s^2+2n_o\omega_o s+\omega_o^2)}{x_{CAP} D} + \dfrac{G x_{COIL}(sCR+1)}{R}}$$

$$= \frac{M x_{CG} x_{CAP} D}{I(s^2+2NW_o s+W_o^2)}$$

$$\text{where } W_o^2 = \omega_o^2 + \frac{G x_{COIL} x_{CAP} D}{IR}$$

$$\text{and } 2NW_o = 2n_o\omega_o + \frac{G x_{COIL} x_{CAP} DC}{I}$$

(a) The Closed Loop Sensitivity at Very Low Signal Frequencies (s=0)

(i) Putting $M x_{CG} x_{CAP} \approx I$, the closed loop sensitivity at zero frequency is given by $V_{OUT}/\ddot{x} \approx D/W_o^2$

(ii) Or assuming $W_o >> \omega_o$

$$V_{OUT}/\ddot{x} = \frac{M x_{CG} x_{CAP} D}{(G x_{COIL} x_{CAP} D)/R} = \frac{MR}{G} \; \frac{x_{CG}}{x_{COIL}}$$

Putting $G_e = G\, x_{COIL}/x_{CG}$ then $V_{OUT}/\ddot{x} = MR/G_e$

which is identical to the linear case (such as the Willmore Mk IIIC [4]) except that here the magnet/coil motor constant is G_e rather than G.

(b) The Closed Loop High Frequency Sensitivity

The closed loop sensitivity at high frequencies is given by

$$\frac{V_{OUT}}{\ddot{x}} = \frac{M x_{CG} x_{CAP} D}{I\, s^2}$$

which is the same as the open loop case.

C3. THE RELATIONSHIP BETWEEN THE CORNER FREQUENCIES (ωo AND Wo) AND THE FEEDBACK RESISTOR (R)

For a steady current i_{OPEN} passed through the coil with the loop open the expression for the output voltage is:

$$V_{OPEN} = G\ i_{OPEN}\ x_{CAP}\ D/I\omega_o^2,$$

$$so\ \frac{DG\ x_{COIL}\ x_{CAP}}{I} = \frac{V_{OPEN}\ \omega_o^2}{i_{OPEN}}.$$

But when the loop is closed

$$W_o^2 = \omega_o^2 + \frac{G\ x_{COIL}\ x_{CAP} D}{IR}$$

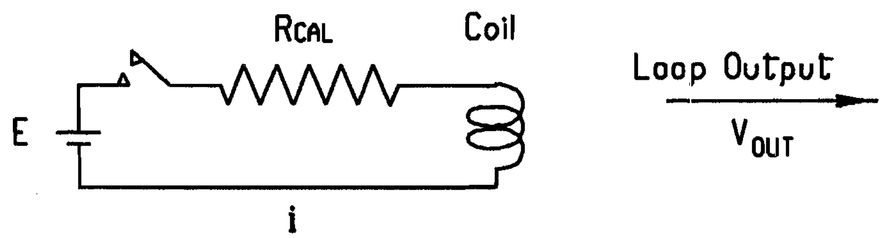
$$and\ so\ W_o^2 = \omega_o^2 + \frac{V_{OPEN}}{i_{OPEN}}\ \frac{\omega_o^2}{R}.$$

$$and\ \frac{V_{OPEN}}{i_{OPEN}} = R\left(\frac{W_o^2 - \omega_o^2}{\omega_o^2}\right) = R\left(\frac{W_o^2}{\omega_o^2} - 1\right)$$

or putting $W_o = 2\pi F_o$ and $\omega_o = 2\pi f_o$

$$= R\left(\frac{F_o^2}{f_o^2} - 1\right)$$

C4. <u>THE SIGNIFICANCE OF THE VALUE OF THE FEEDBACK RESISTOR (R) WHEN USED IN CONJUNCTION WITH AN EXTERNAL STEADY CALIBRATION CURRENT</u>



(a) <u>OPEN LOOP</u>

$$Current\ i = i_{OPEN} = E/R_{CAL}$$

From section 3 above:

$$\frac{V_{OUT}\,R_{CAL}}{E} = R\left(\frac{F_o^2}{f_o^2}-1\right)$$

so if R_{CAL} = feedback resistor $x[(F_o/f_o)^2-1]$

$$then\ V_{OUT} = V_{IN} = E$$

(b) <u>CLOSED LOOP</u>

For a steady current i_{CLOSED} passed through the feedback coil with the system CLOSED loop, the resulting torque on the boom is $i_{CLOSED}\ x_{COIL}$ G and the equivalent ground acceleration is torque/M x_{CG} = $i_{CLOSED}\ x_{COIL}G/M\ x_{CG}$

$$\therefore V_{OUT}(DC) = \frac{MR\ x_{CG}}{G\ x_{COIL}}\ x\ \frac{i_{CLOSED}\ x_{COIL}\ G}{M\ x_{CG}}$$

$$\frac{V_{OUT}(DC)}{i_{CLOSED}} = R$$

$$V_{OUT} = V_{IN} = E\ if\ R_{CAL} = Feedback\ resistor.$$

The significance of the equations for R_{CAL} derived in 4(a) and 4(b) above is that a further check can be made on the operation of the loop. In sections 5.1 and 5.2 a Lissajous method was described to determine the closed loop natural frequency F_o and the suspension natural frequency f_o respectively.

With the system in its normal operating closed loop condition a constant amplitude voltage E is connected directly to the calibration (feedback) coil through a variable resistance R_{CAL}. This resistor is adjusted until the output of the loop (ACC) is of the same value as the input amplitude E. The value of this resistance should be the same as the feedback resistor R.

By means of the switch on the front of the control unit the seismometer can be made to operate in an open loop condition with its sensitivity reduced by a factor of 11 (see section 5.2).

Using the same steady voltage source E the value of R_{CAL} should be increased to $\frac{R}{11}\left[\left(\frac{F_o}{f_o}\right)^2-1\right]$

the output should again be the same amplitude as the source voltage E.

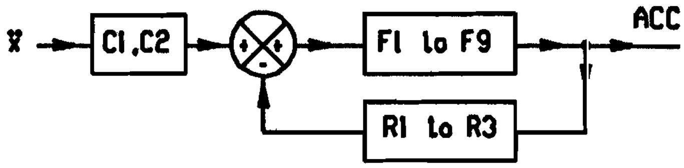
Thus, having once measured the two frequencies F_o and f_o the value of R and the correct operation of the loop can be confirmed using a steady voltage source and two known resistors.

APPENDIX D

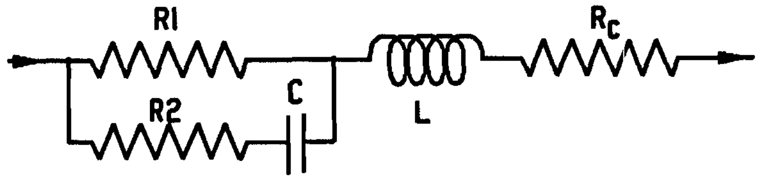
Poles, Zeros and Constants

1 INDIVIDUAL STAGES

(a) Feedback Seismometer



			CONSTANT
C1	Inertial Mass M = 158 g	No Poles, no zeros	0.158
C2	Dist from c of g to pivot x_{CG} = 32.2 mm	No Poles, no Zeros	3.22E-2
F1	Mass/spring suspension f_o = 1 Hz Q=8 so the transfer function is $(s^2+0.7854s + 39.478)^{-1}$	Two Poles, no Zeros -0.3927, ± 6.2709 (-0.3927, ± 18.845 for f_o = 3 Hz)	1
F2	$(\text{Inertia})^{-1}$ (Inertia = 2.26E-4 kg^2)	No Poles, no Zeros	4.42E3
F3	Transducer (V/2d√2)	No Poles, no Zeros	1.4E4
F4	Preamplifier Gain (11 x C/5pF) = 132 (C = 60pF)	No Poles, no Zeros	1.32E2
F5	Channel Amp 1 Gain = 5	No Poles, no Zeros	5
F6	Channel Amp 2 Gain = 11	No Poles, No Zeros	11
F7/8	Switch and smooth circuit	One Pole, no Zeros	
	$((2\sqrt{2})(R_{IN}C_F)(s+(C_FR_F)^{-1}))^{-1}$	-1.418E3,0	7.524E2
F9	Distance from centre of capacitor plates to pivot x_{CAP} = 40 mm	No Poles, no Zeros	4.0E-2



$R1 = 12K\Omega$ $C = 2.2\mu F$
$R2 = 1K\Omega$ $L = 90\mu H$
$R_c = 6.1\Omega$

$$TF = \frac{\left(s + \frac{1}{(R1+R2)C}\right)}{(L)\left(s^2 + \left(\frac{R1R2C+R_cC(R1+R2)+L}{(R1+R2)CL}\right)s + \left(\frac{R1+R2}{(R1+R2)CL}\right)\right)}$$

		Two Poles -4.525E2,0 -1.0324E7,0	CONSTANT
		One Zero -34.965,0	1.111E4
R2	Distance from centre of feedback coil to pivot x_{COIL} = 40 mm	No Poles, no Zeros	4.0E-2
R3	Motor constant of feedback coil and magnet G = 0.138 N/Ampere	No Poles, no Zeros	0.138

(b) Filters Outside the Loop

(b1) Band Pass Filter (0.05 Hz, 20 sec) (n = 0.76)

Filter Stage	Two Poles -0.2371, ± 0.2034 One Zero 0,0	CONSTANT 4.546
Gain Stage	No Poles, no Zeros	2.4

(b2) <u>VBB (Velocity Broad Band) Filter</u>

	Equivalent Damping	Equivalent Natural Frequency $\omega_o(T_o secs)$	Pole Locations	Zero Locations	CONSTANT
4 Hz low pass filter	1.0	24.42 (0.26s)	(-24.42,0) (-24.42,0)	-	596.3
4 Hz low pass filter	0.377	24.33 (0.26s)	(-9.17,22.5) (-9.17,-22.5)	-	592.1
Amplifier	-	-	-	-	2.471
		Total =	4 Poles	No Zeros	8.724×10^5

(b3) <u>LPNB (Long Period Narrow Band) Filter</u>

Stage	Equivalent Damping n	Equivalent Frequency $\omega_o(T_o secs)$	Pole Locations	Zero Locations	CONSTANT
1	0.7071	0.2074(30.30)	(-0.14663, + 0.14663) (-0.14663, - 0.14663)	-	0.042999
2	0.5767	0.2953(21.28)	(-0.1703, + 0.2413) (-0.1703, - 0.2413)	-	0.08721
*3	0.5767	0.2953(21.28)	(-0.1703, + 0.2413) (-0.1703, - 0.2413)	-	0.08721
4	-	0.03157(199)	(-0.03157, 0.0)	(0.0, 0.0)	1.0
5	-	-	(-25.64, 0.0)	(-1.003×10^4,0.0)	1.0
		Total =	8 Poles	2 Zeros	3.2703×10^{-4}

* Stage 3 is identical to Stage 2.

(b4) <u>Analogue to FM Converter Stage</u>

Percentage deviation of tone carrier/volt input ± 33% for ± 10 volts	CONSTANT 3.333

D2 GROUPS OF STAGES

(a) ACC Open Loop

3 Poles	-0.3927, ± 6.2709,	-1.418E3,0

No Zeros
Constant 6.8787E10

(b) ACC Closed Loop

The solution of the equations gives five poles and two zeros but the value of one real pole is identical to that of one real zero, so the numbers reduce to

4 Poles	-172.4, ± 68.25,	-1.4704E3,0	-56.056,0
1 Zero	-452.5,0		
Constant	6.8787E10		

(c) Nyquist Response

5 Poles	-0.3927, ± 6.2709,	-1.418E3,0	-452.5,0	-1.0324E7,0
1 Zero	-34.965,0			
Constant	8.2928E14			

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TABLE 1.

Poles, Zeros and Constants for the Output Signals

VBB to Ground Velocity	LPNB to Ground Displacement
10 Poles	14 Poles
-1.7240E2, ± 6.8253E1	-1.7240E2, ± 6.8253E1
-5.6056E1, 0	-5.6056E1, 0
-1.4704E3, 0	-1.4704E3, 0
-2.3710E-1, ± 2.0340E-1	-2.3710E-1, ± 2.0340E-1
-2.4420E1, 0	-1.4663E-1, ± 1.4663E-1
-2.4420E1, 0	-1.7030E-1, ± 2.4130E-1
-9.1710E0, ± 2.2500E1	-1.7030E-1, ± 2.4130E-1
	-3.1570E-2, 0
3 Zeros	-2.5640E1, 0
-4.5250E2, 0	
0, 0	6 Zeros
0, 0	-4.525E2, 0
	-1.0030E4, 0
Constant	0, 0
6.5476E17 V/m/s (Surface Electronics Unit)	0, 0
2.1825E18 % deviation/m/s (FM Tone)	0, 0
3.2738E17 V/m/s (Demodulated)	0, 0
1.2069E21 digits/m/s (Digital Tape)	
	Constant
	2.4544E8 V/m (Surface Electronics Unit)
	8.1813E8 % deviation/m (FM Tone)
	1.2272E8 V/m (Demodulated)
	4.524E11 digits/m (Digital Tape)

FIGURE CAPTIONS

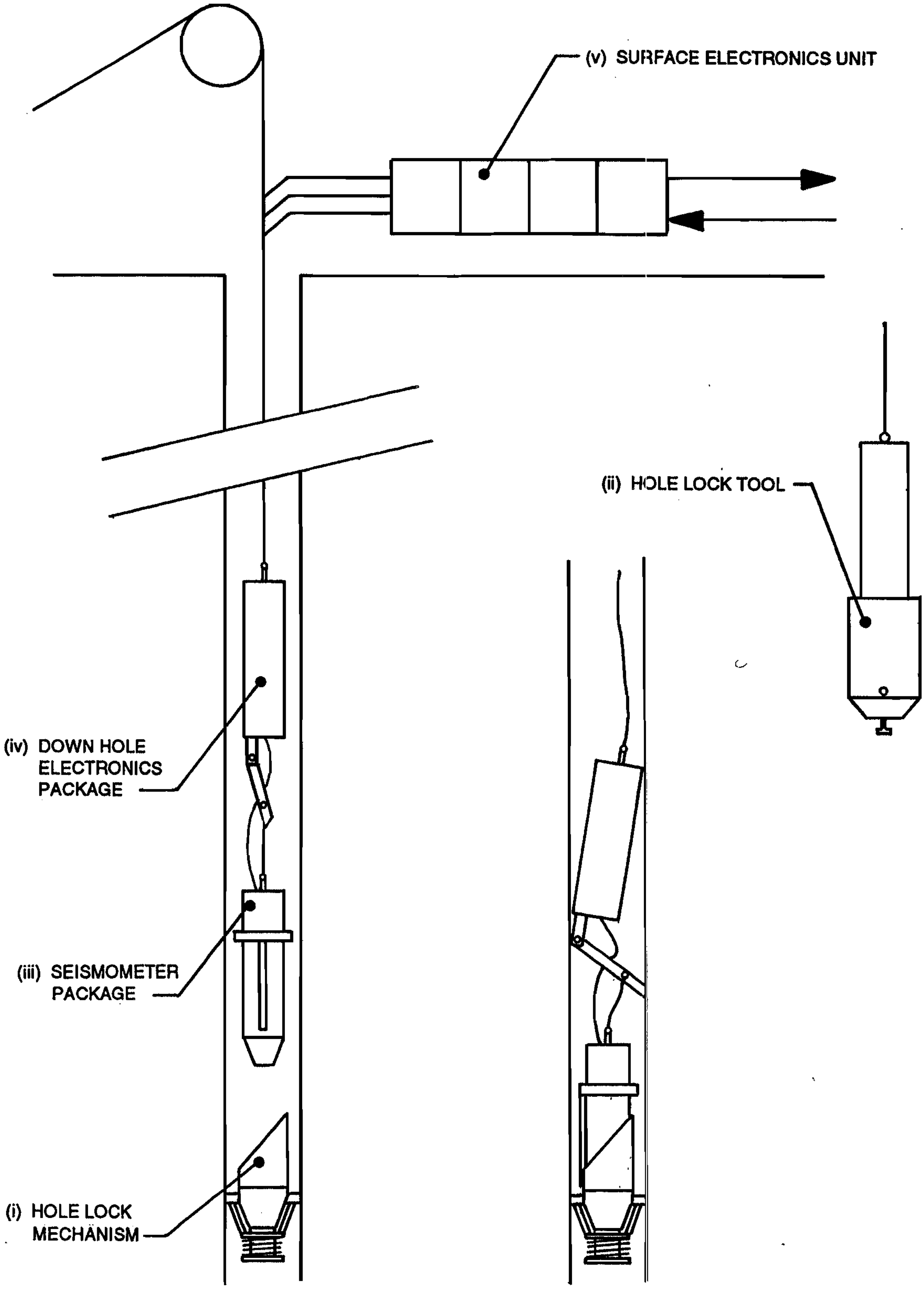
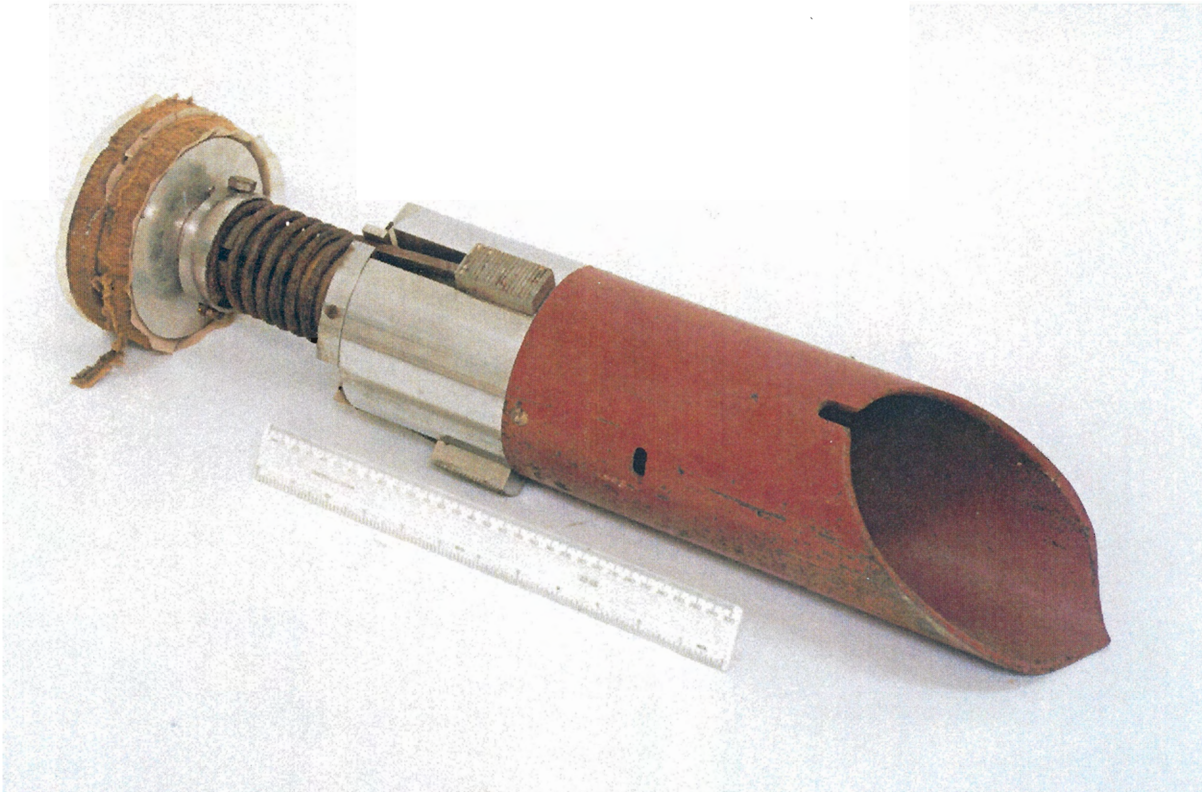


FIGURE 1 Complete System Installed in Borehole



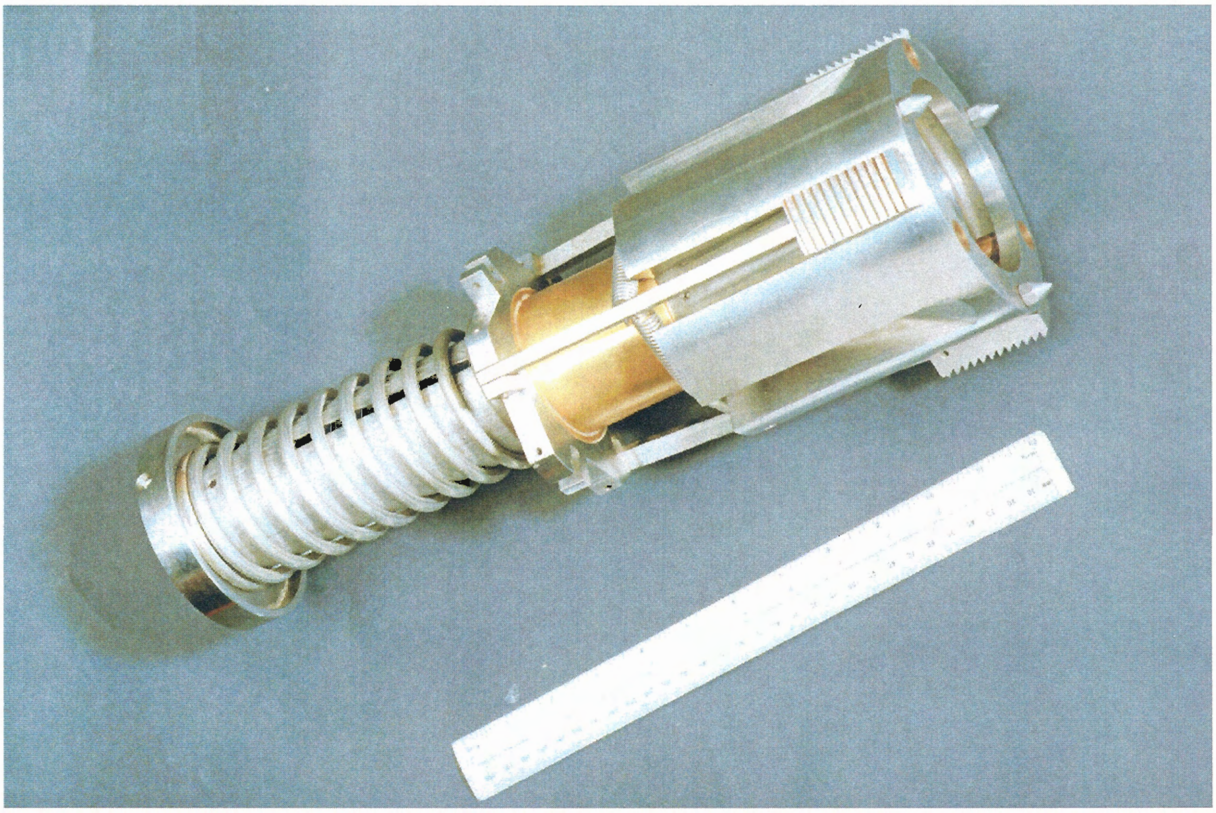


FIGURE 2 Original and Replacement Holelock mechanisms

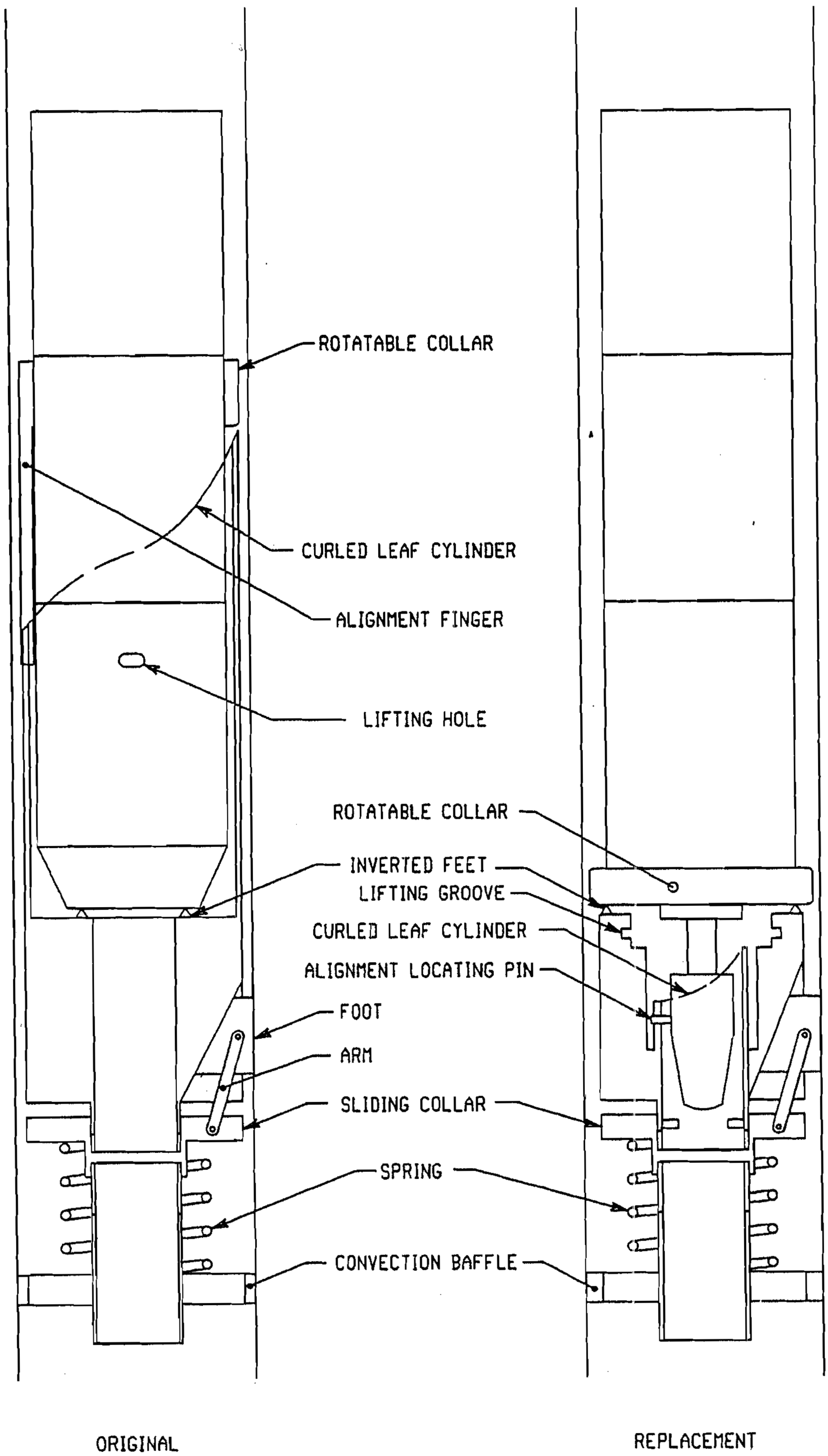


FIGURE 3 Sections of Holelock Mechanisms with Seismometer Package Installed

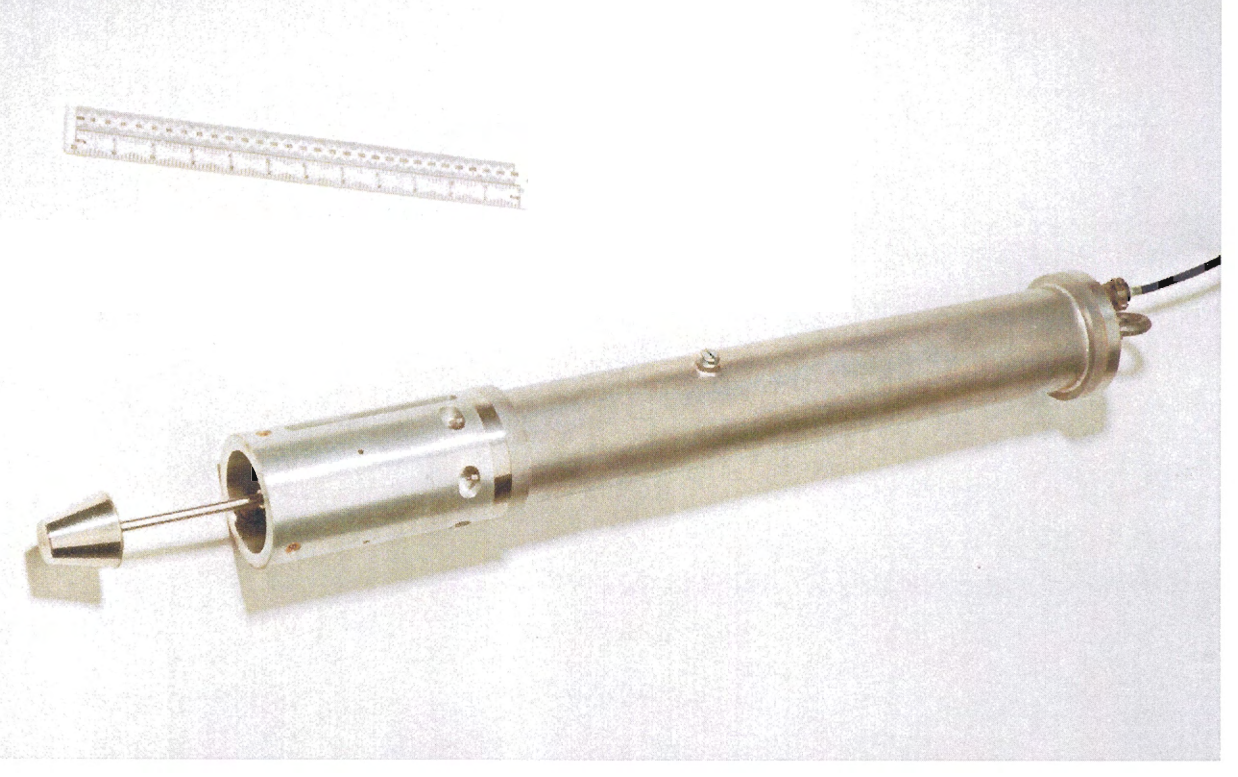


FIGURE 4 Holelock Tool

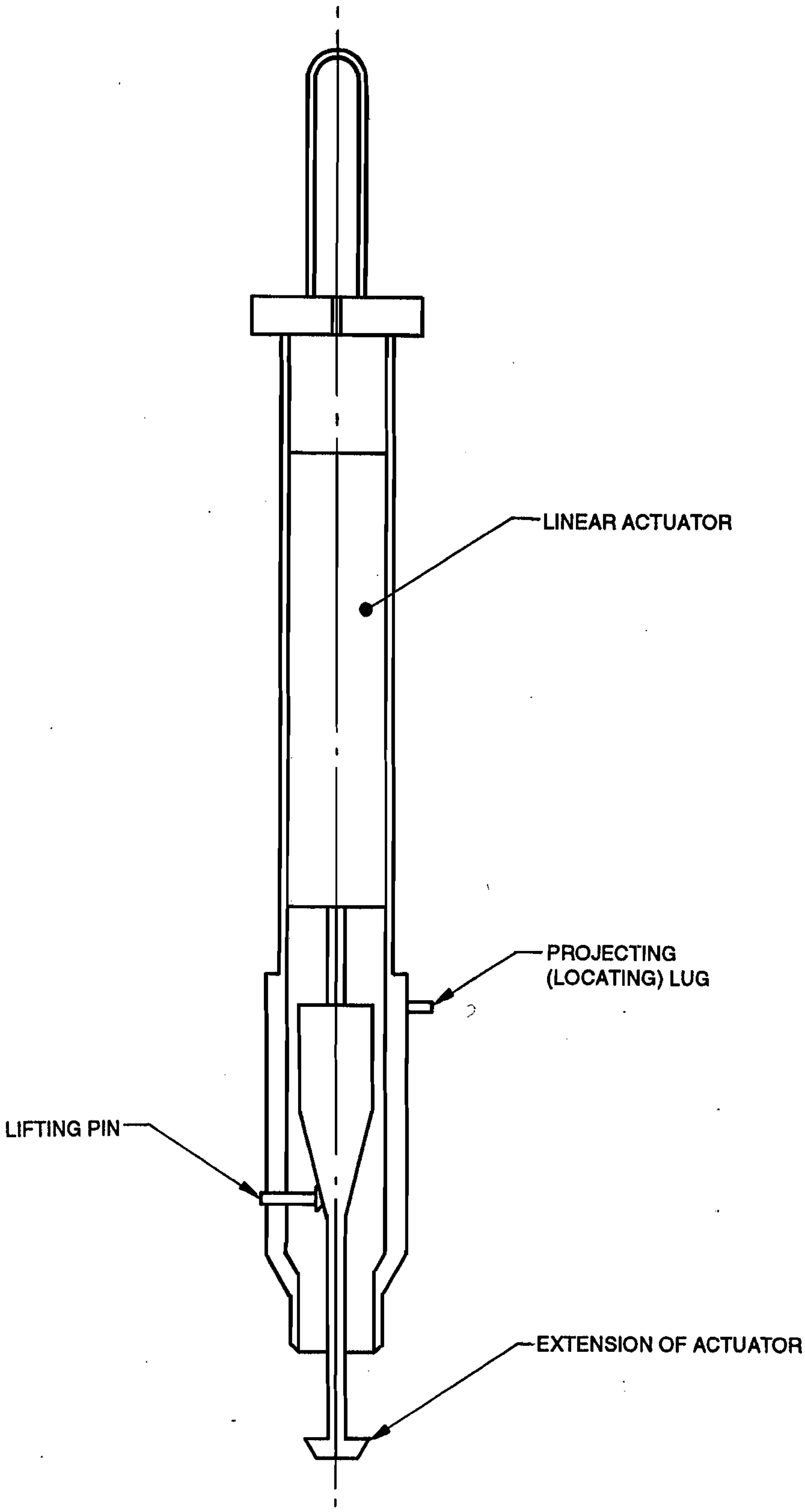
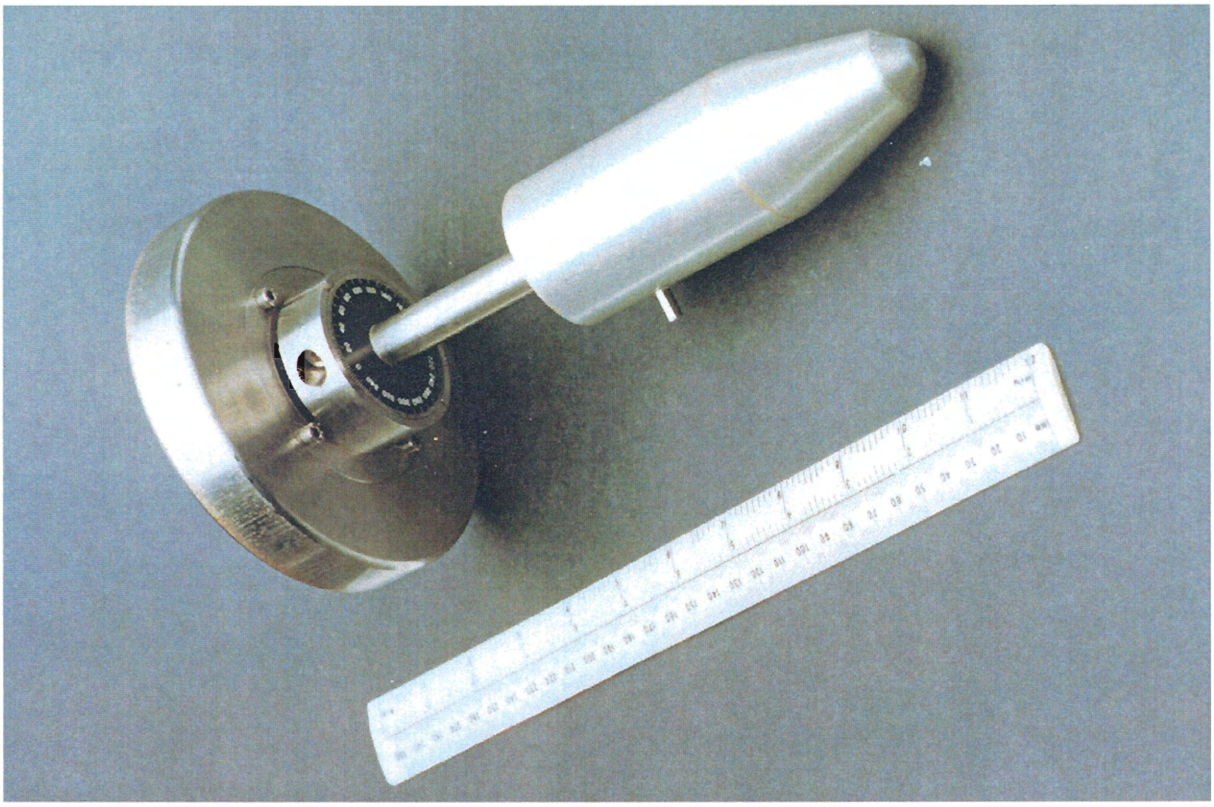


FIGURE 5 Section of Hole Lock Tool



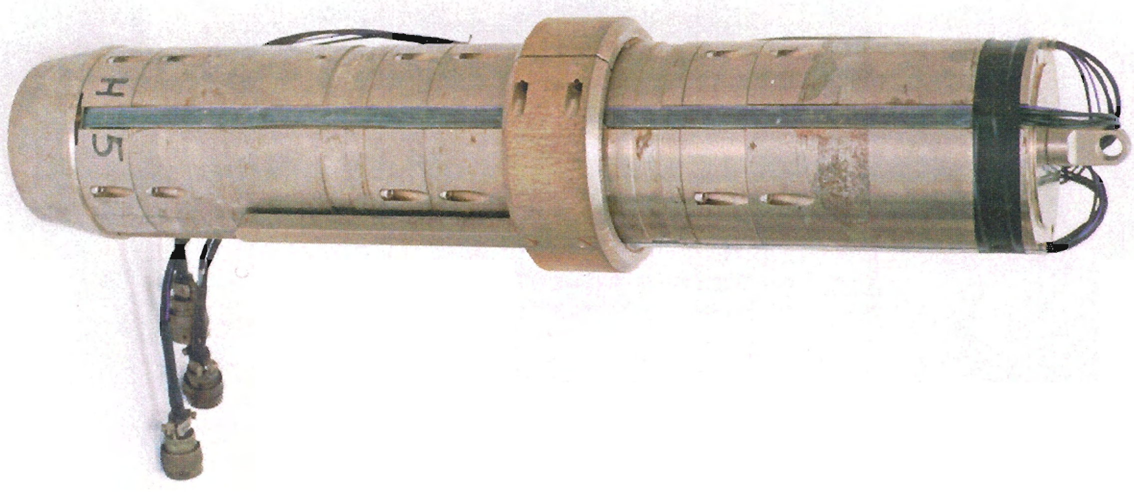


FIGURE 6 Seismometer Package

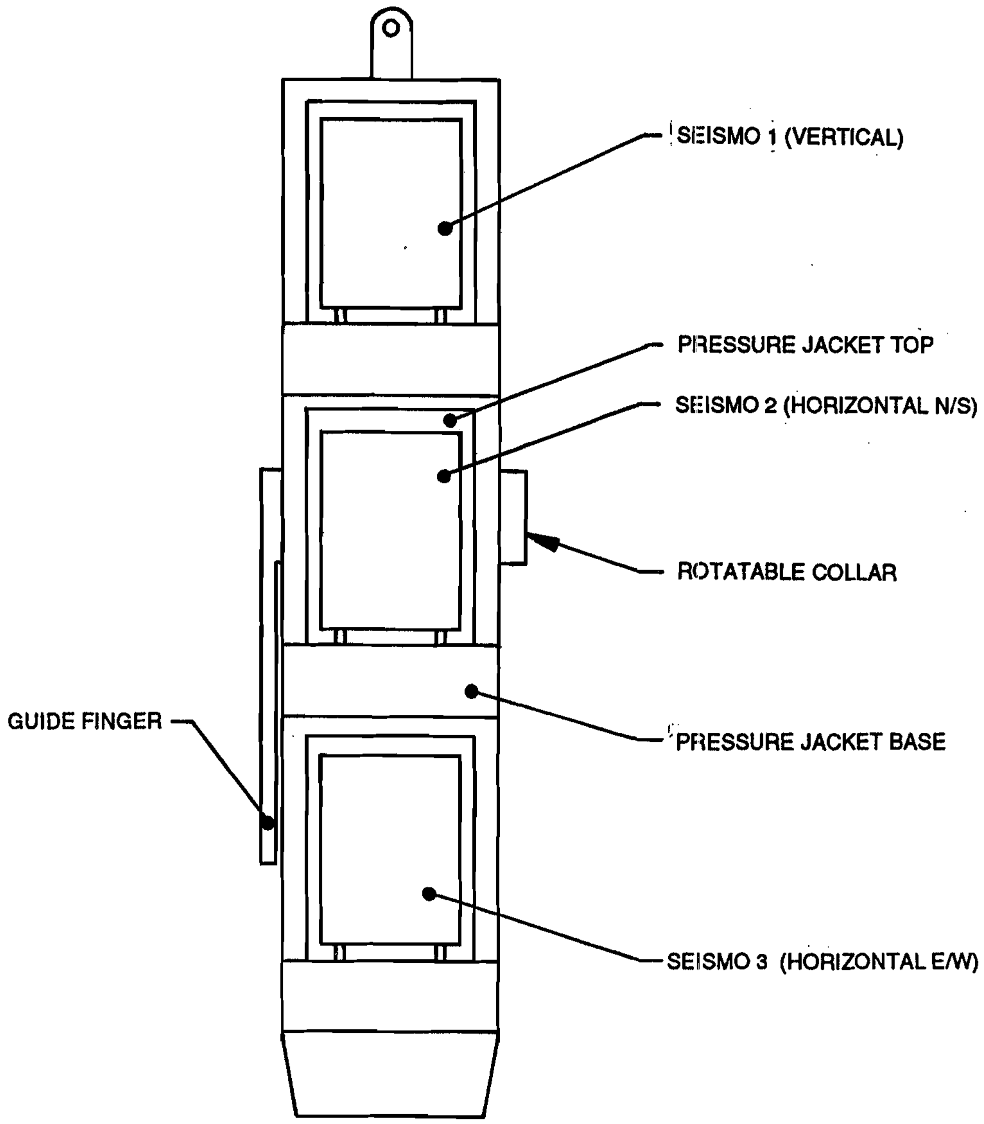


FIGURE 7 Section of Seismometer Package

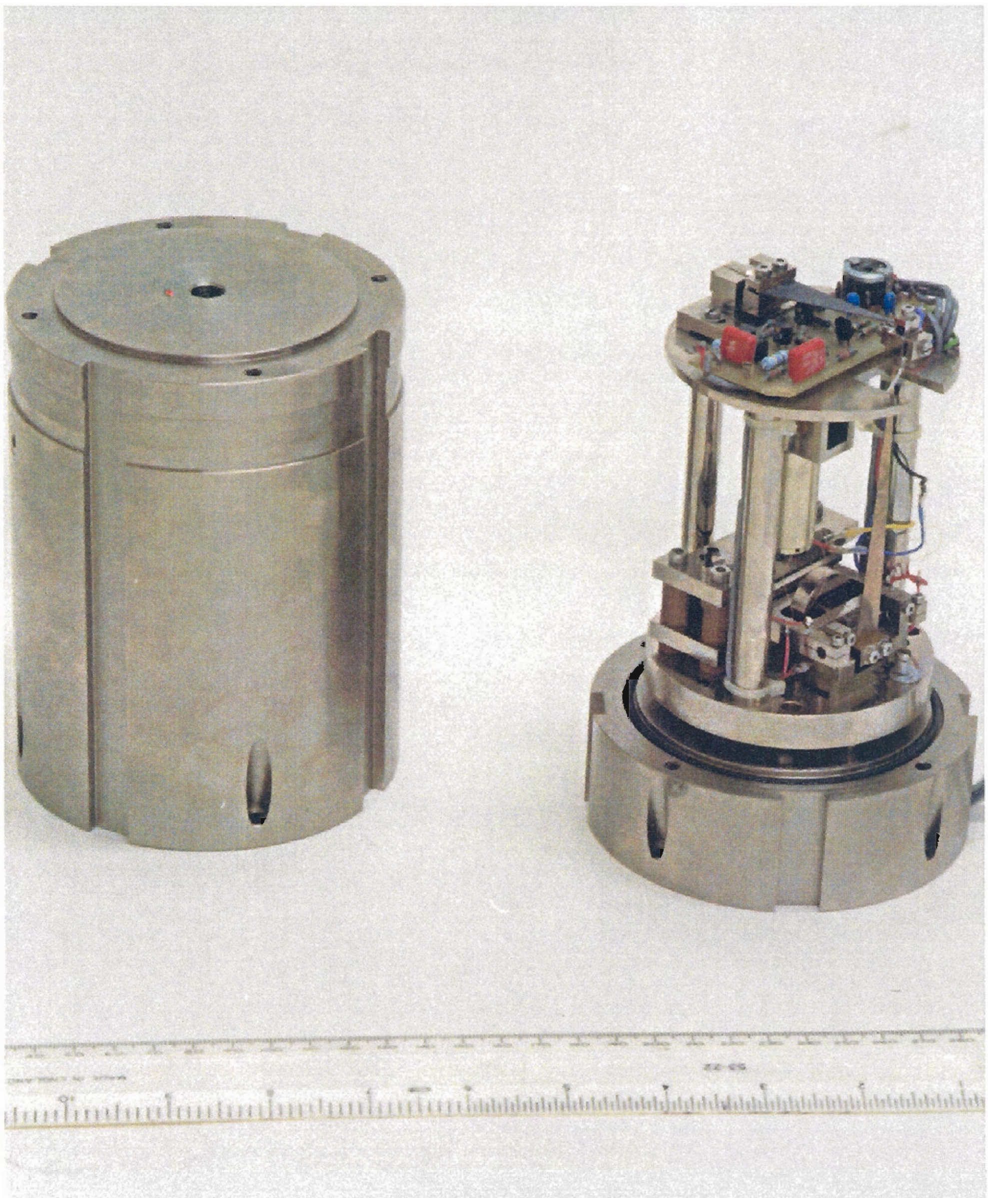


FIGURE 8 Vertical Component Seismometer with Pressure Jacket

6060/BURCH/08

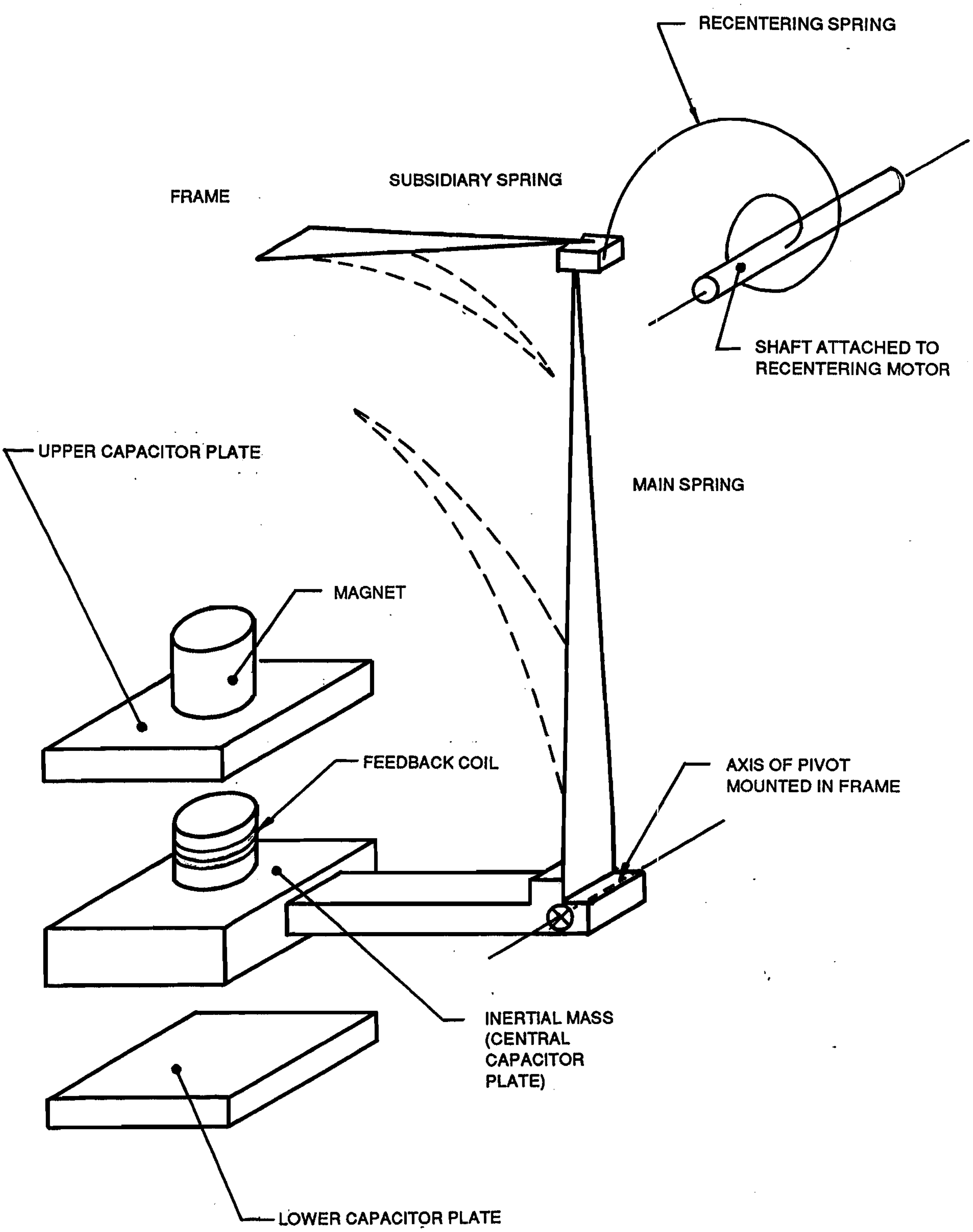


FIGURE 9 Basic Elements of Vertical Component Seismometer

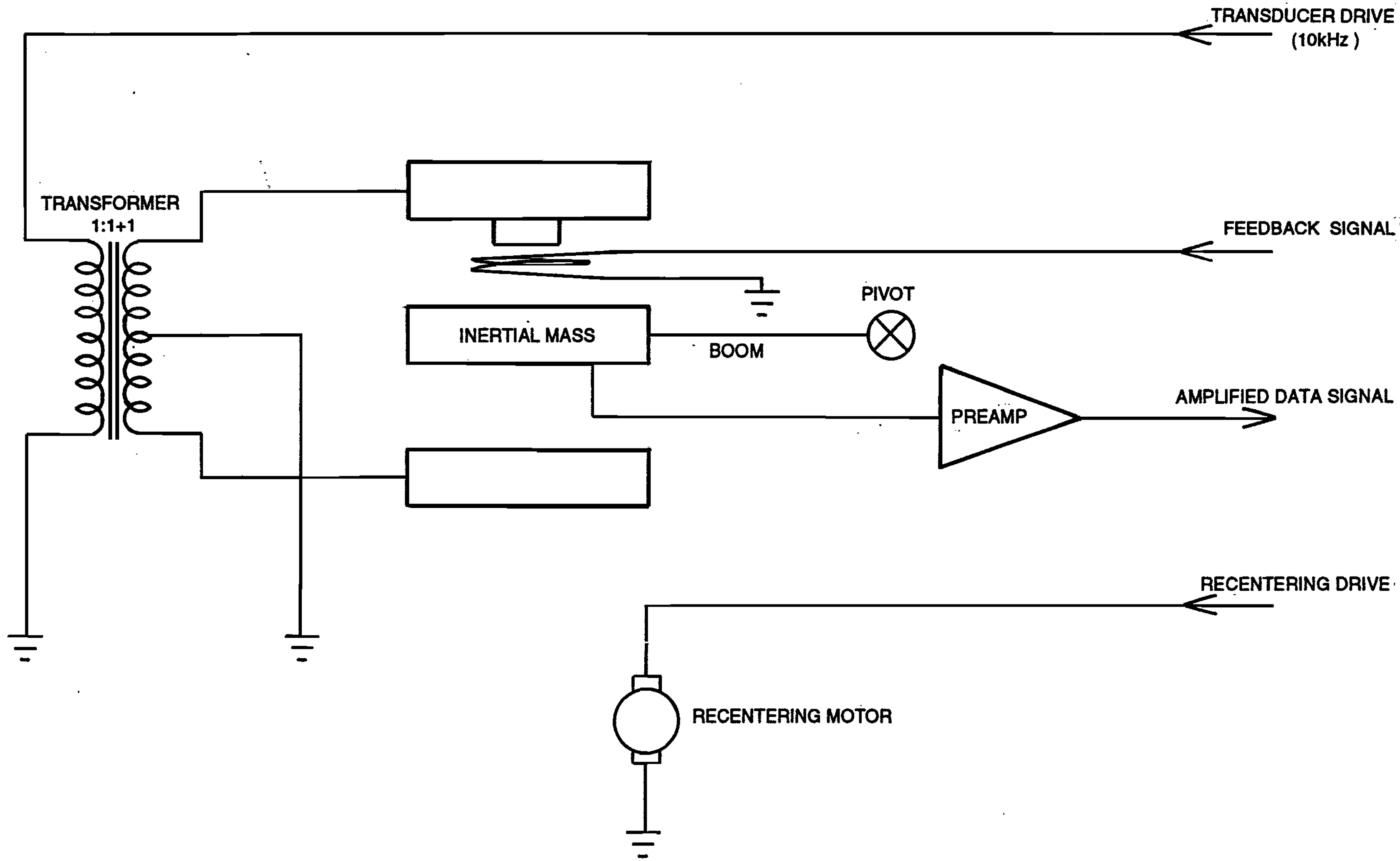


FIGURE 10 Basic Electronic / Electrical Components of Seismometer

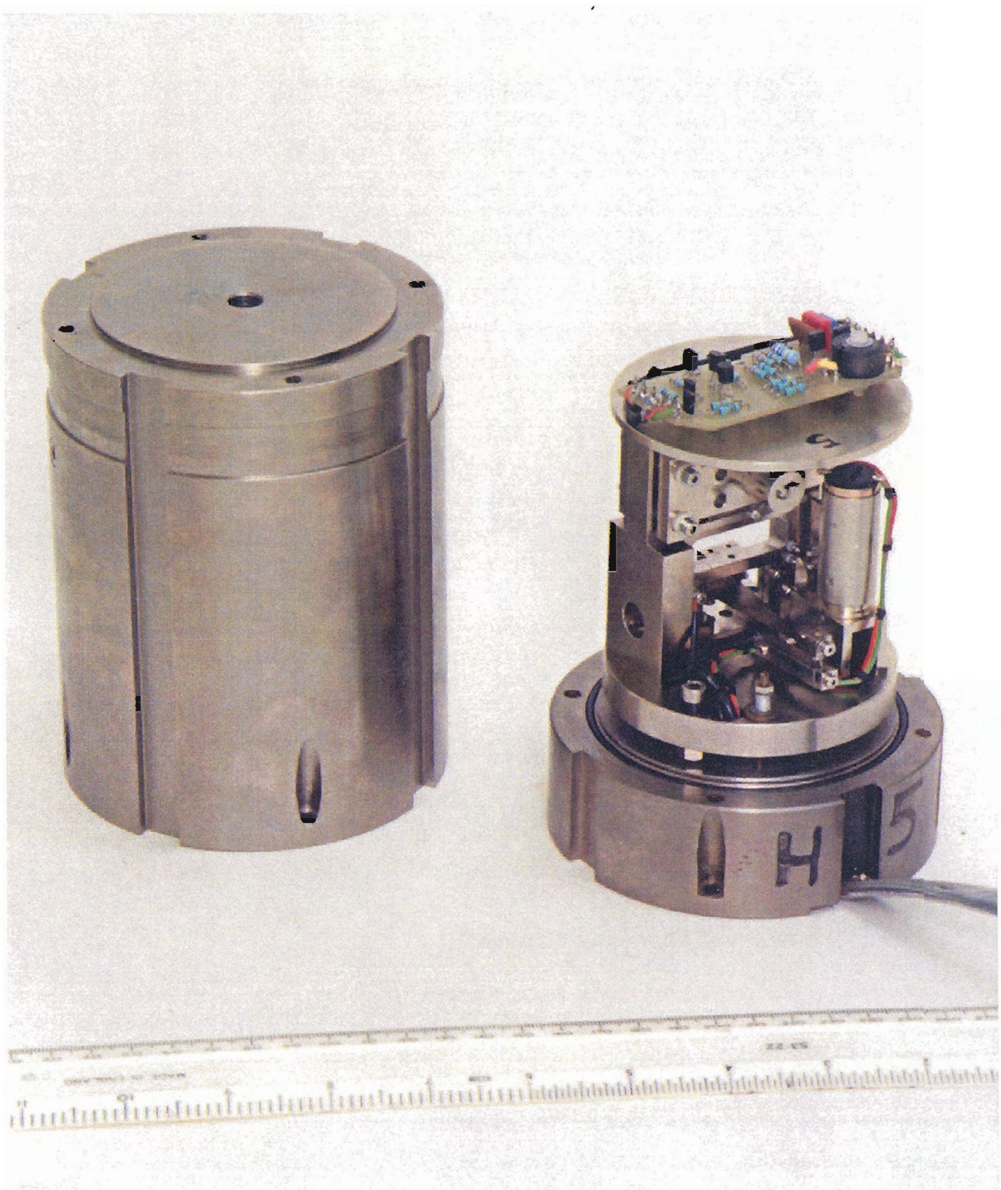


FIGURE 11 Horizontal Component Seismometer with Pressure Jacket

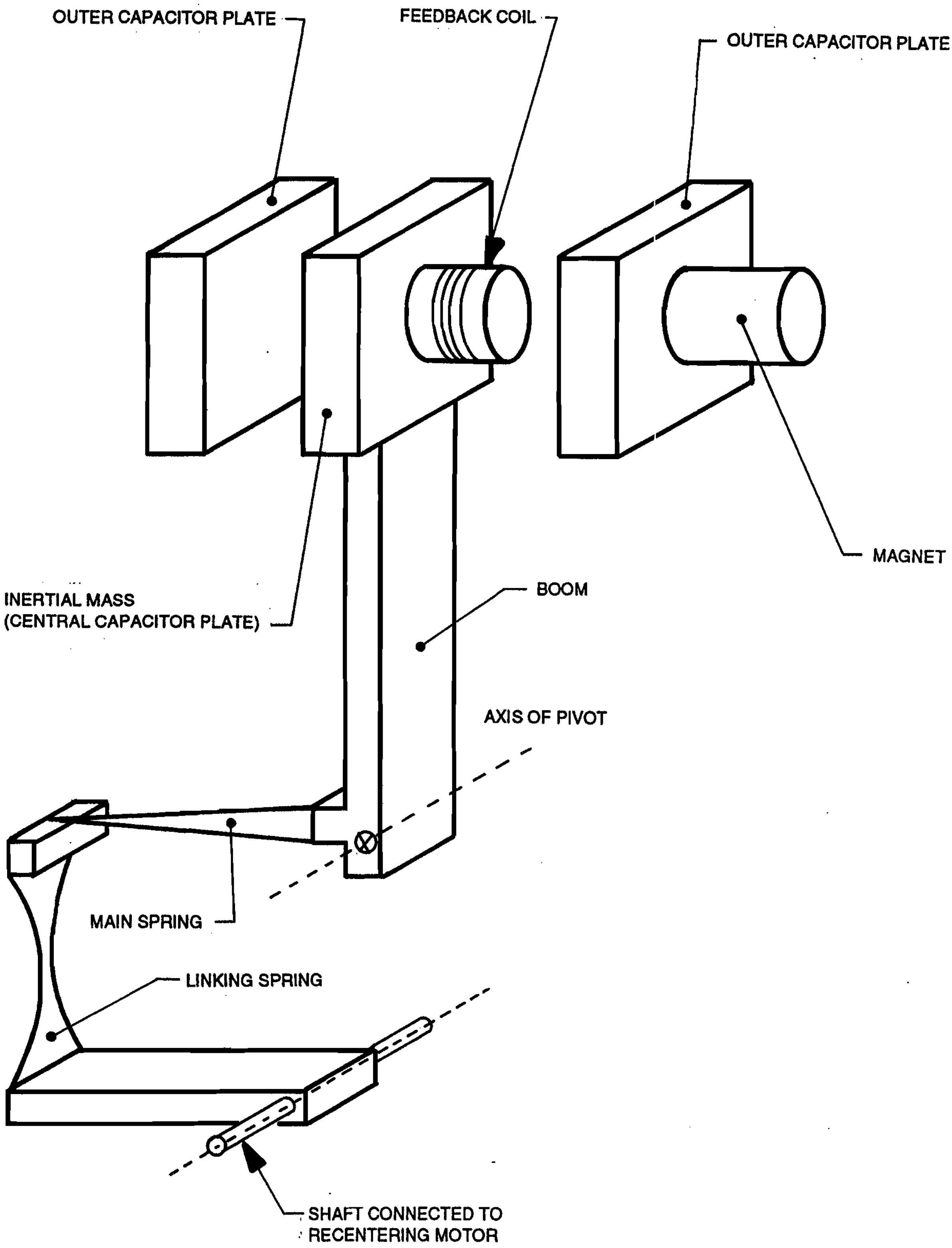


FIGURE 12 Basic Elements of Horizontal Component Seismometer

FIGURE 13 Downhole Electronics Unit

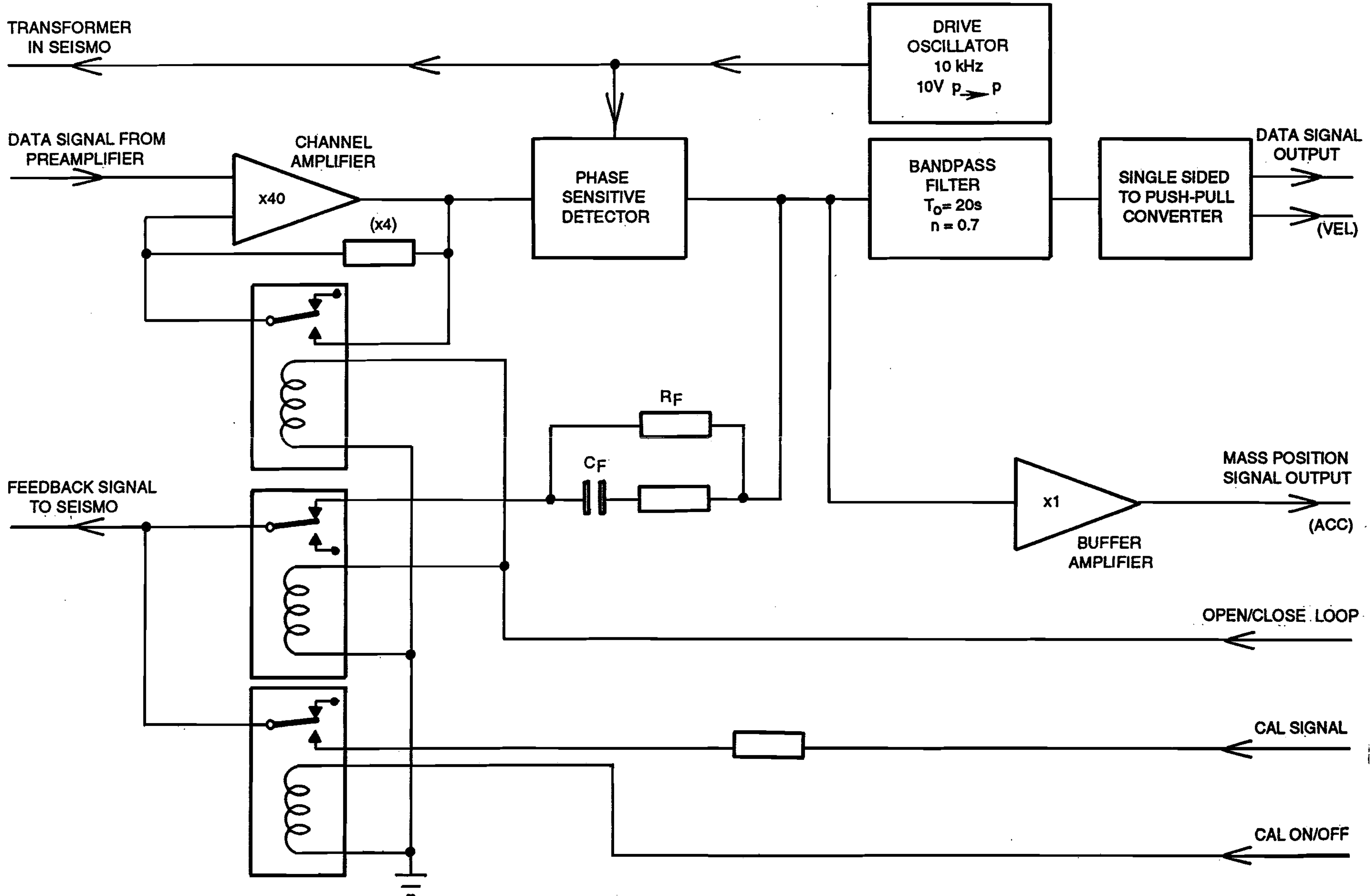


FIGURE 14 Block Diagram of Electronics Unit (one channel)

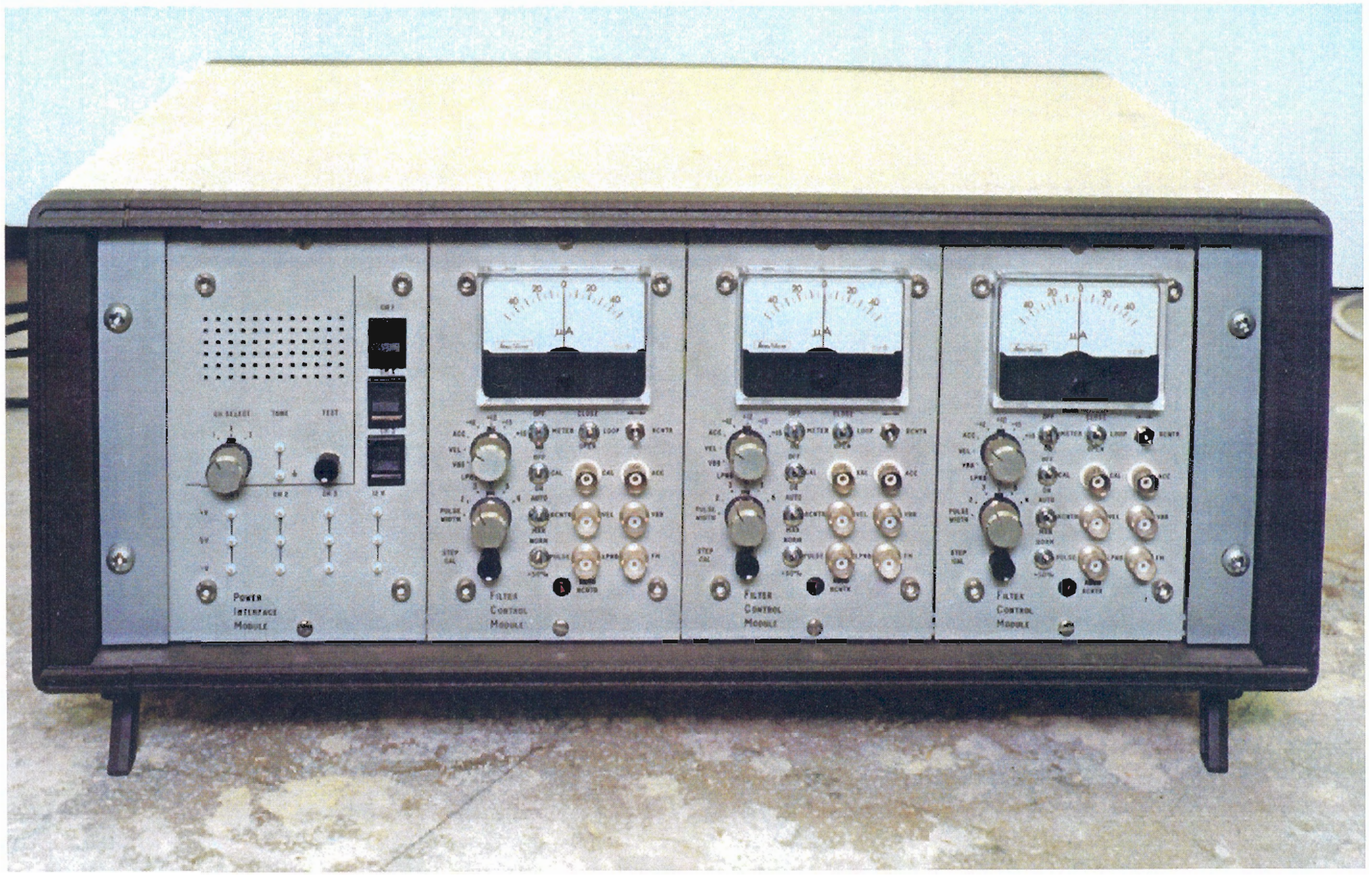


FIGURE 15 Surface Electronics Unit

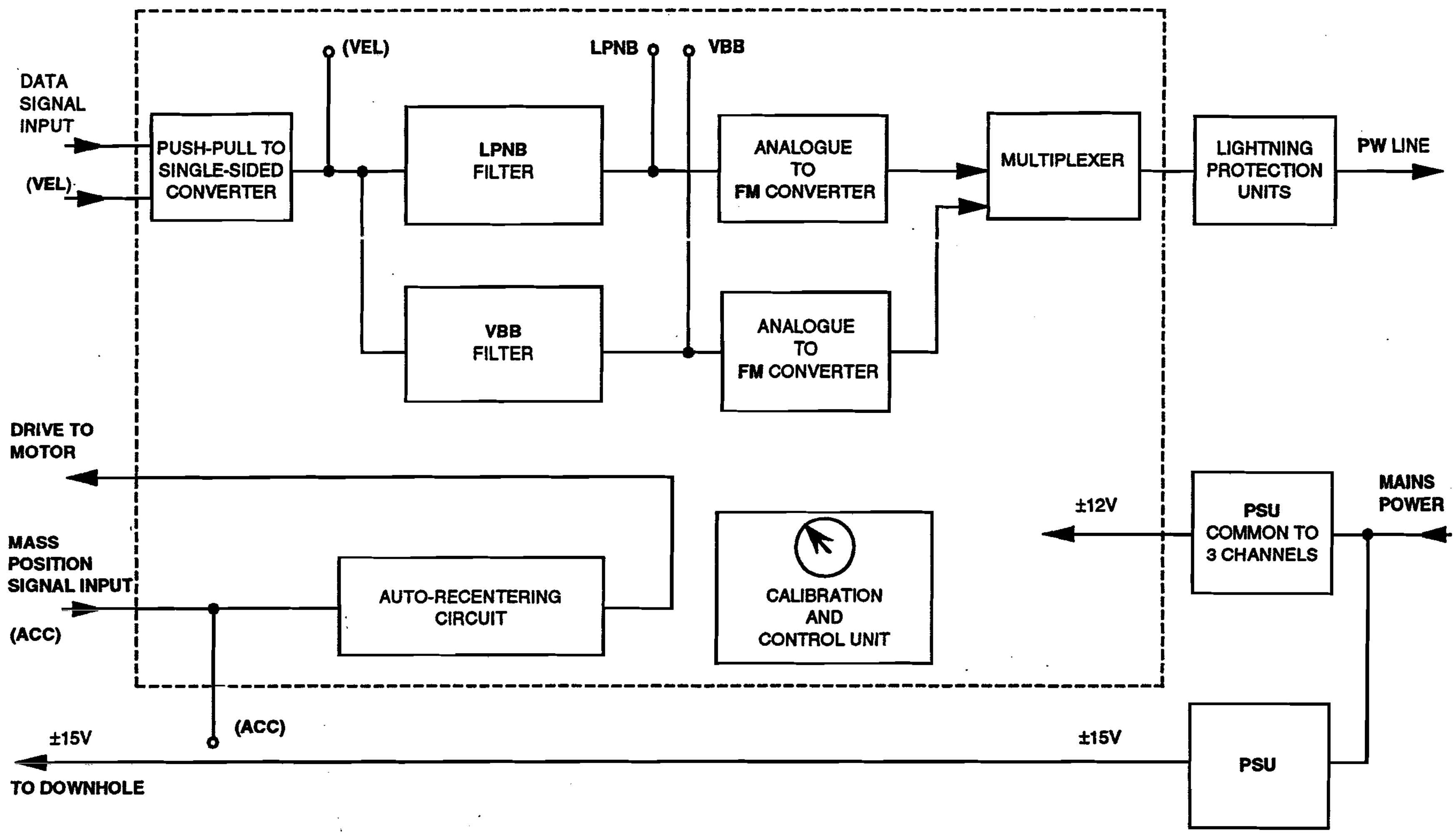


FIGURE 16 Block Diagram of Single Channel of Surface Electronics Unit

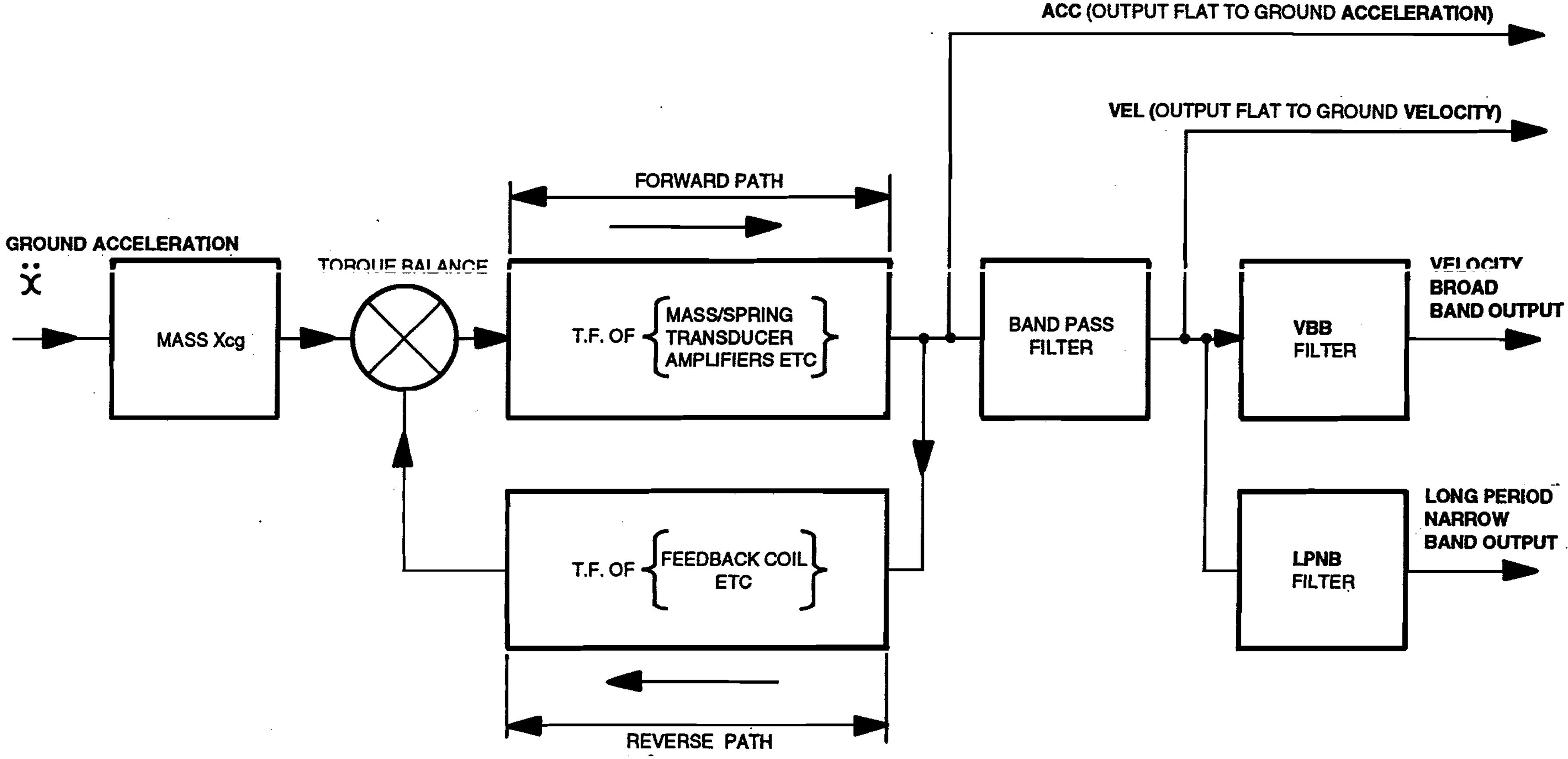


FIGURE 17 Block Diagram of Signal Circuits

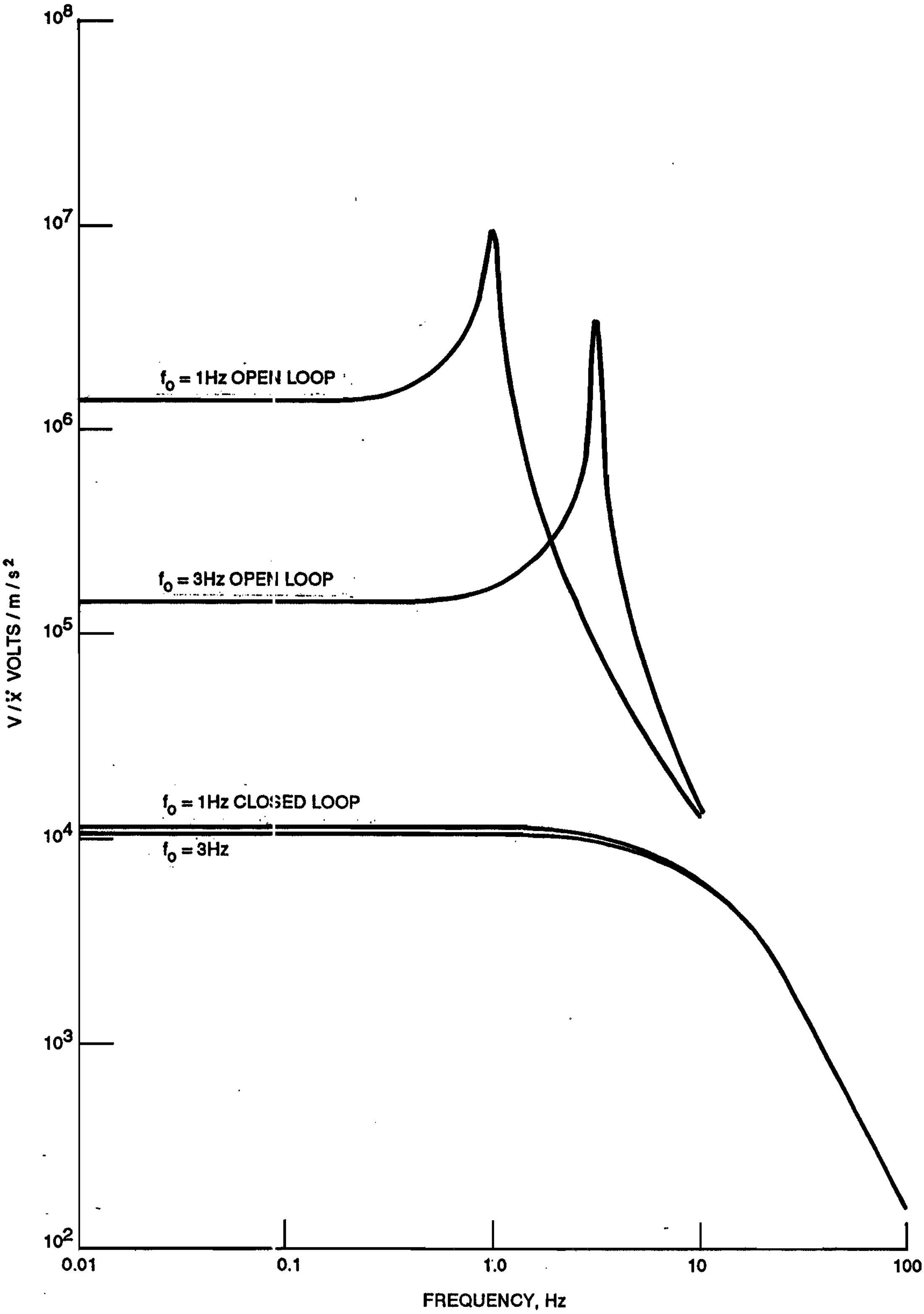


FIGURE 18 ACC Outputs Open and Closed Loop, f_0 =1Hz and 3Hz

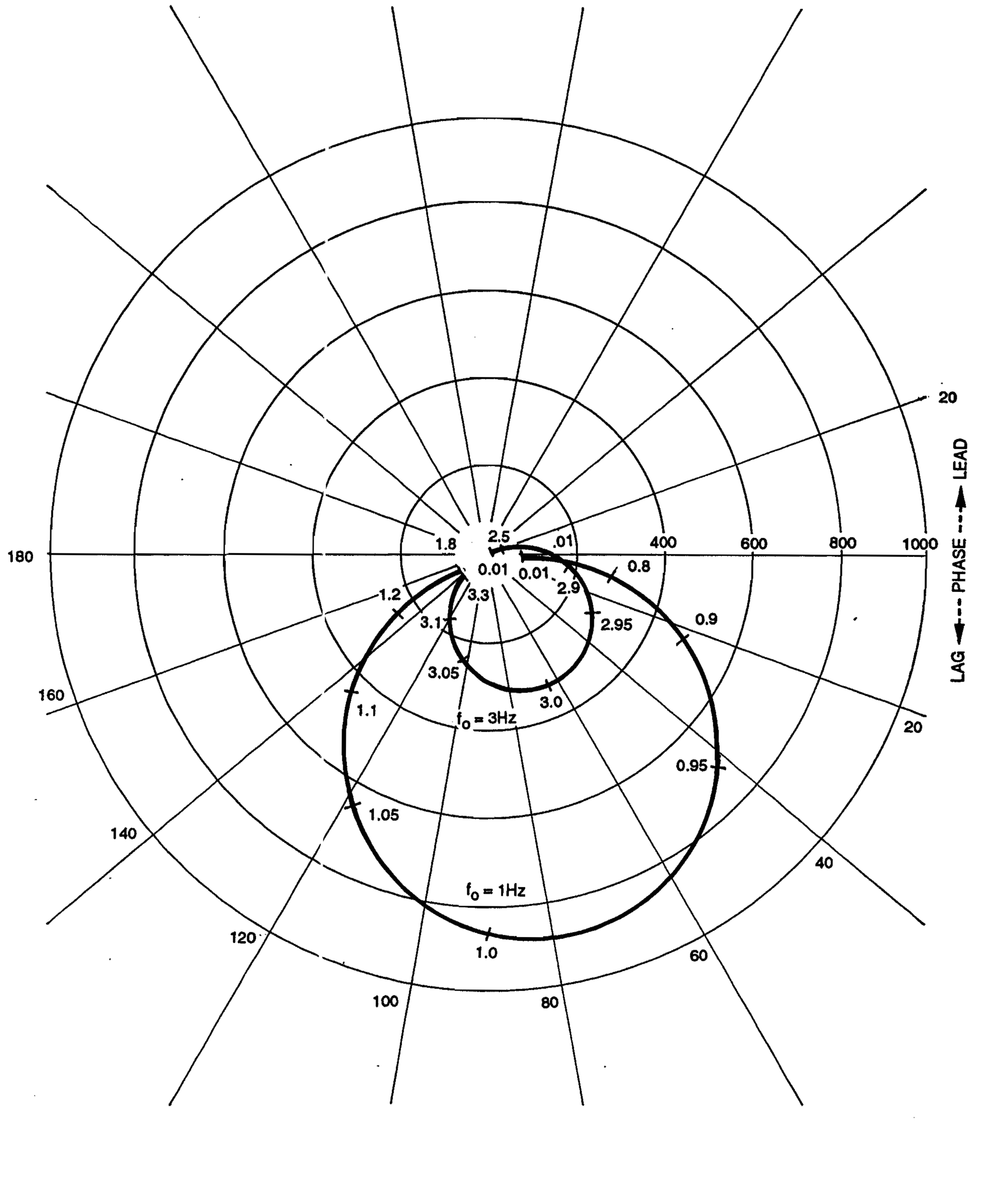


FIGURE 19a Nyquist Diagram for f between 0.01 Hz and 1.5 Hz (for $f_o = 1$ Hz) and f between 0.01 Hz and 3.3 Hz (for $f_o = 3$ Hz)

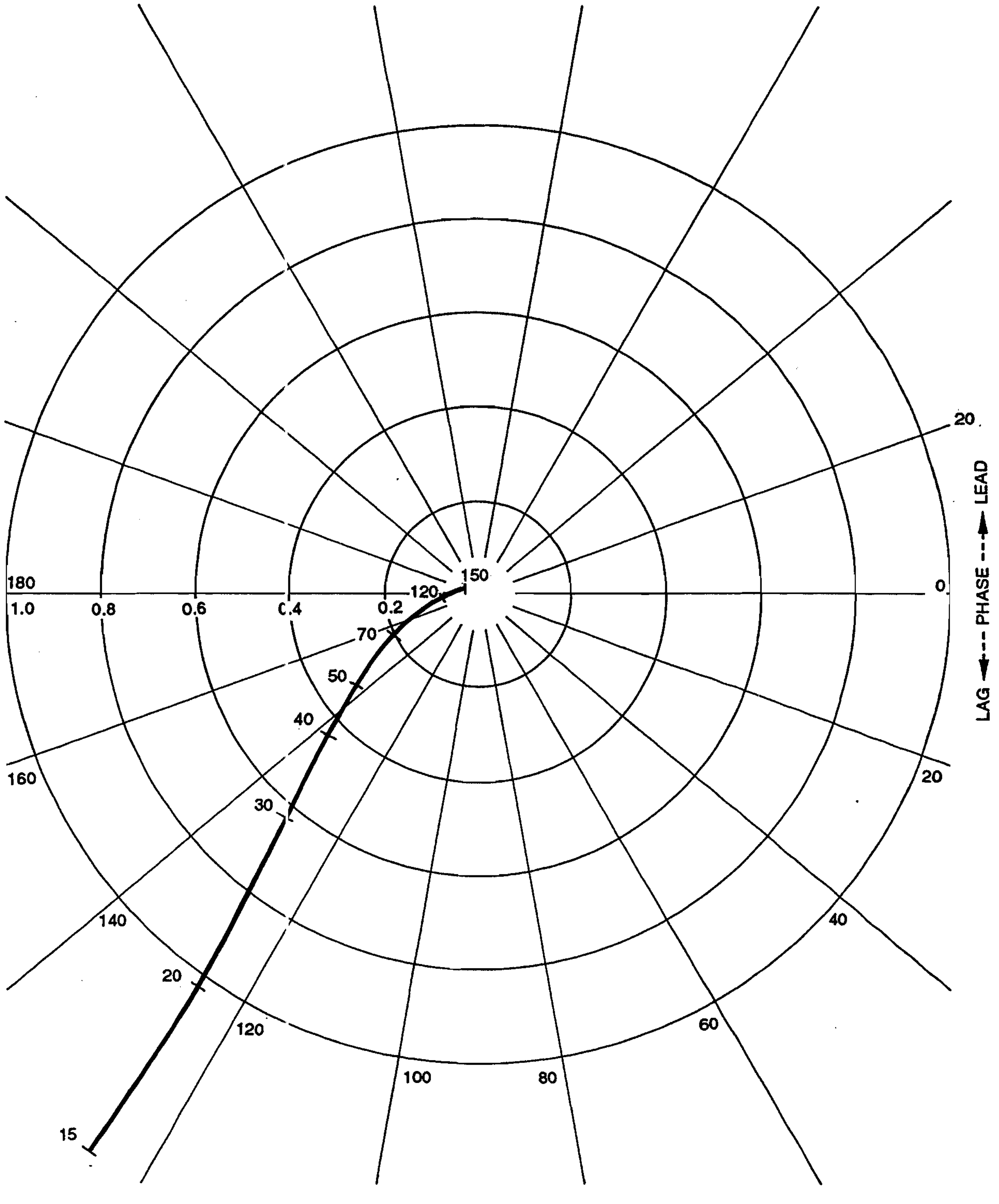


FIGURE 19b. Nyquist Diagram for f between 15 Hz and 150 Hz for both $f_O = 1$ Hz and for $f_O = 3$ Hz (Identical)

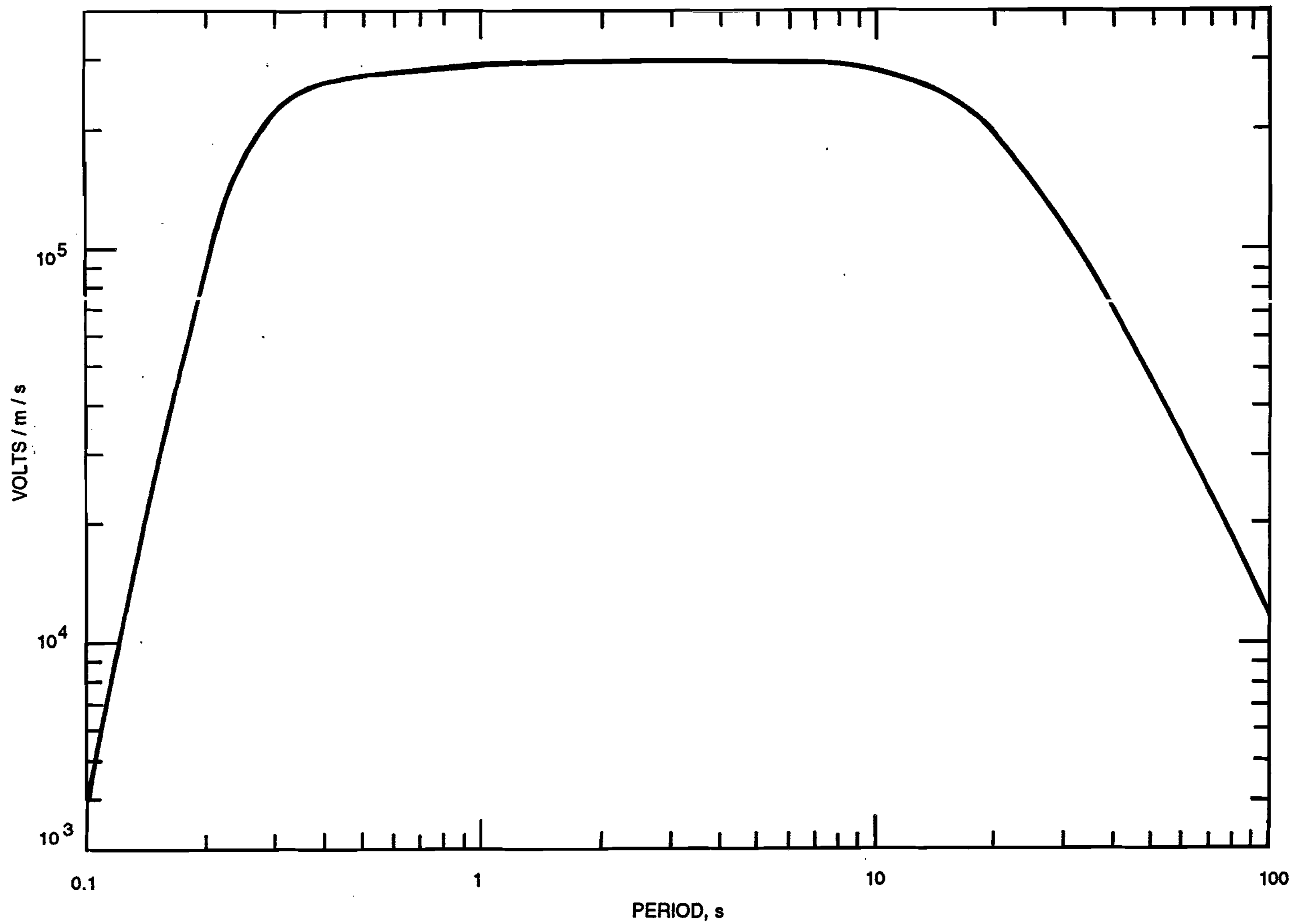


FIGURE 20 VBB Response to Ground Velocity at Surface Electronics Unit

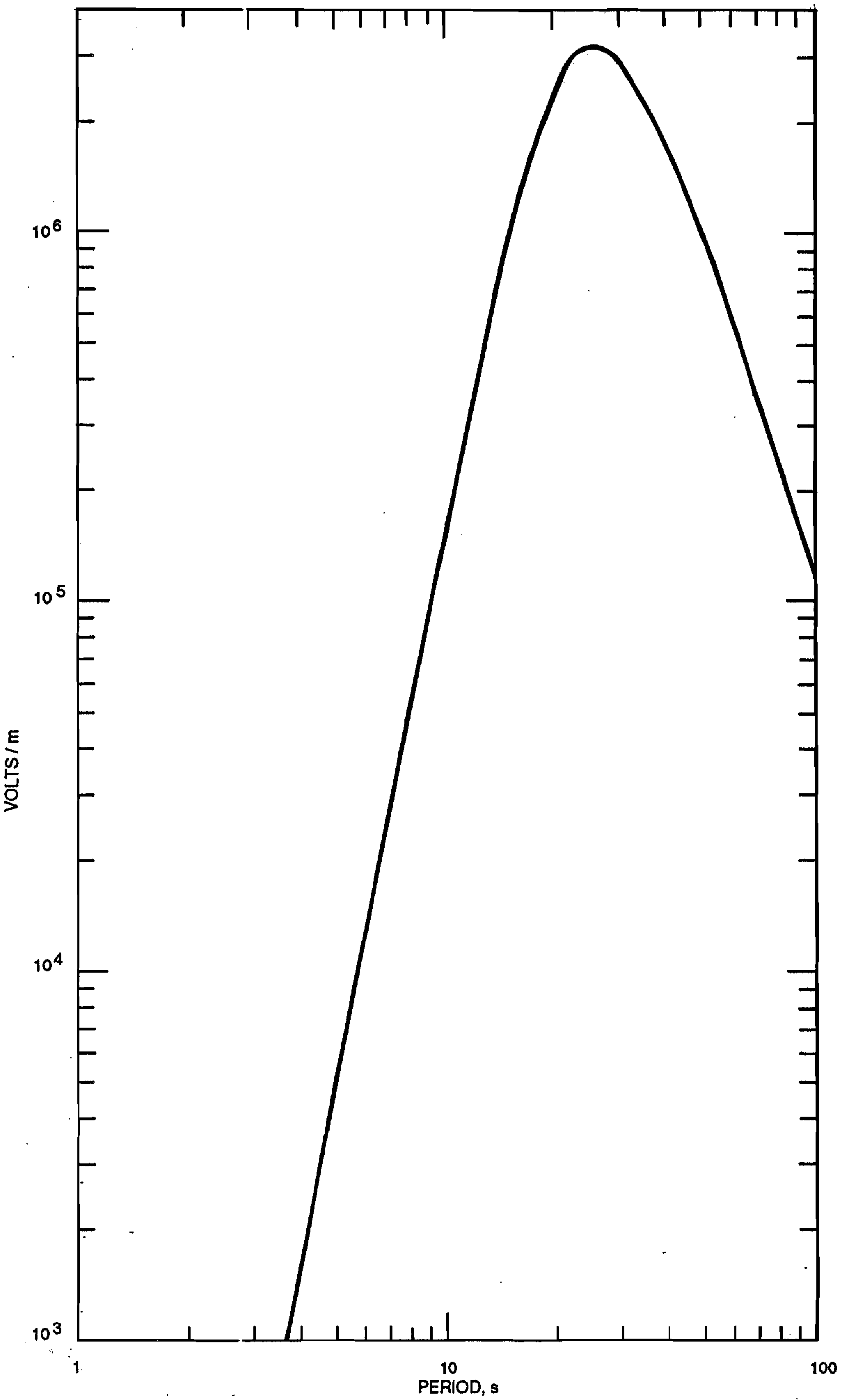


FIGURE 21   LPNB Response to Ground Displacement at Surface Electronics Unit

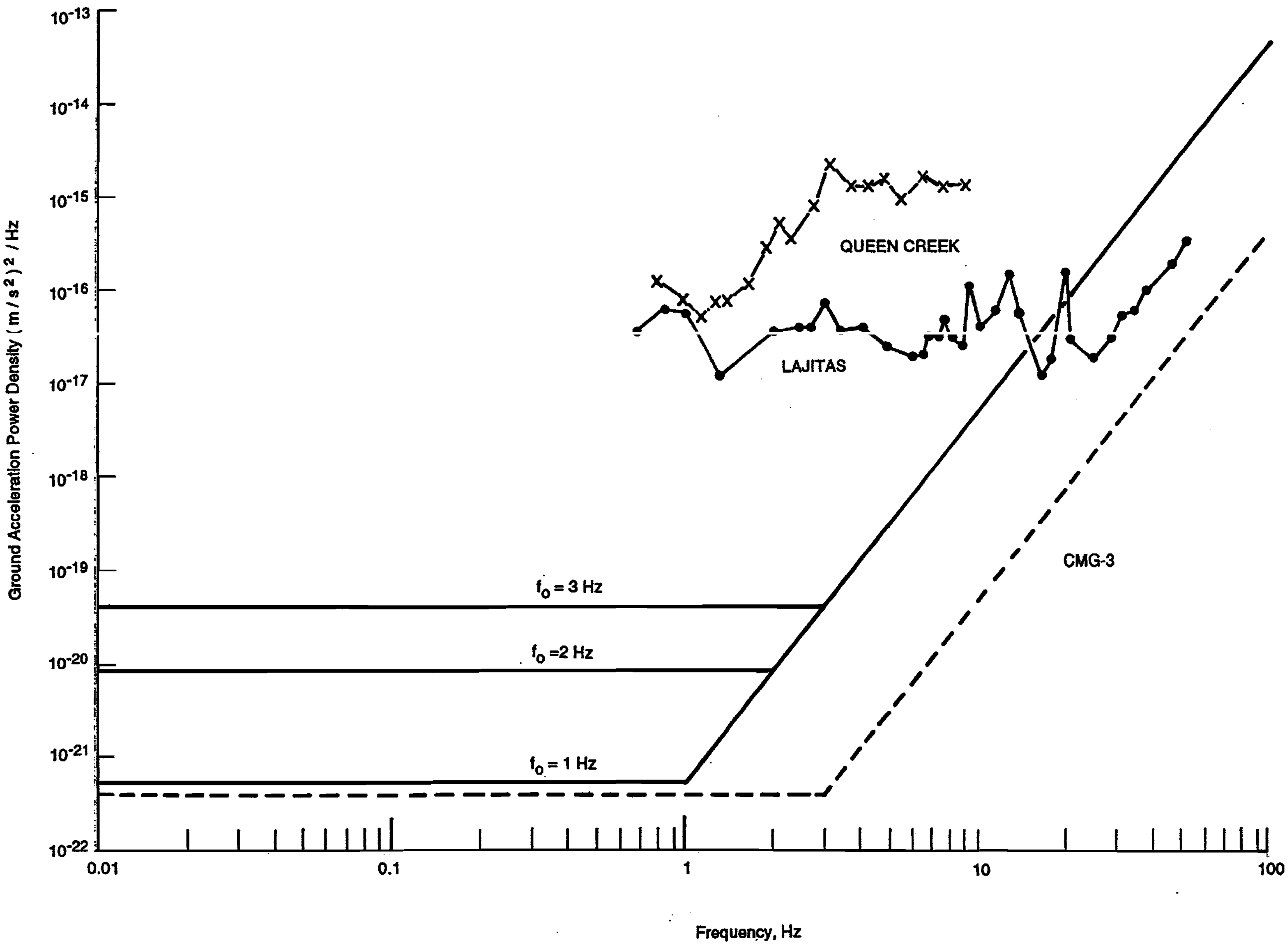


FIGURE 22 Variation of Transducer Noise with Suspension Natural Frequency and High Frequency Seismic Noise at Queens Creek and Lajitas.

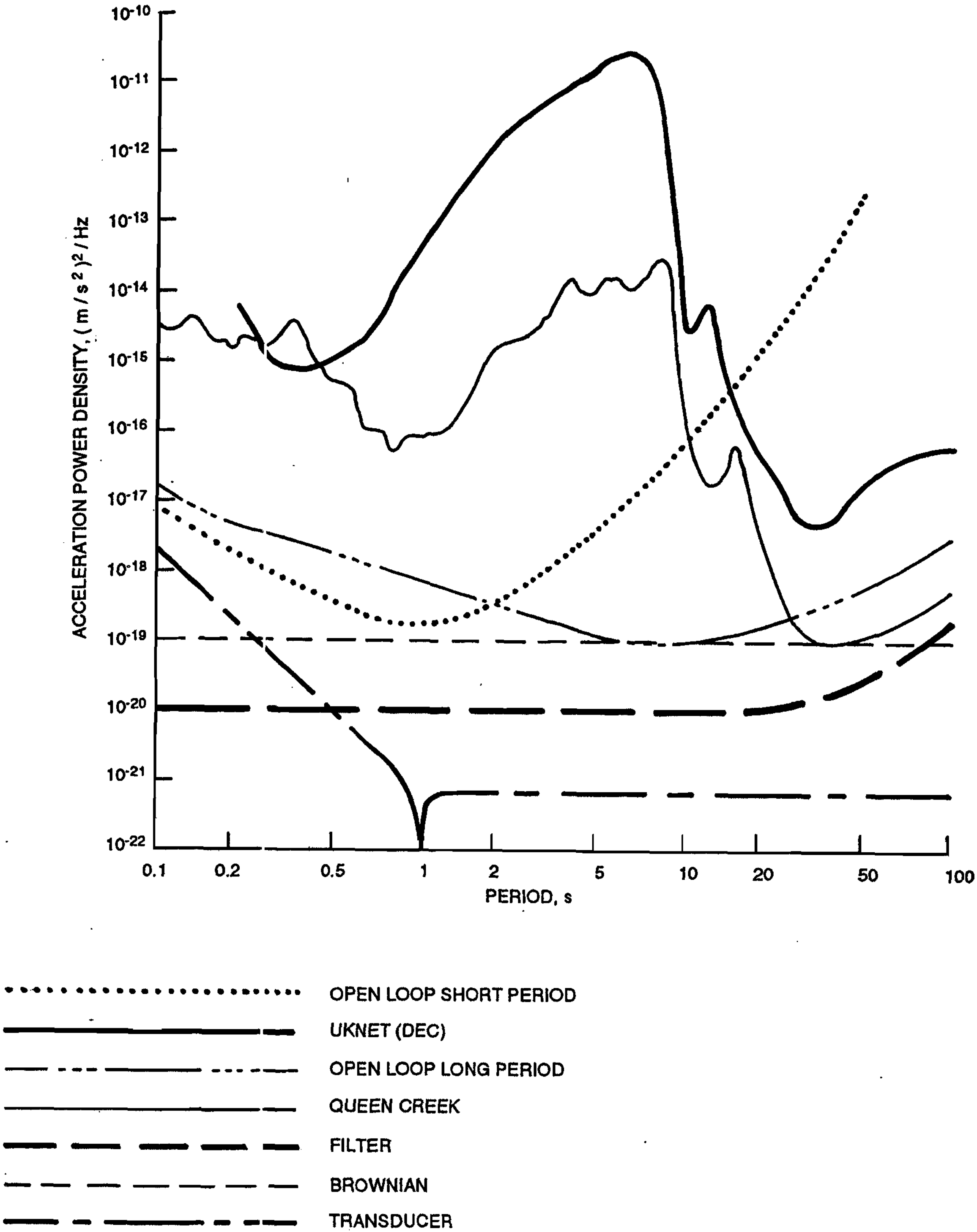


FIGURE 23 Instrument Noise and Seismic Noise Acceleration Power Density Spectra

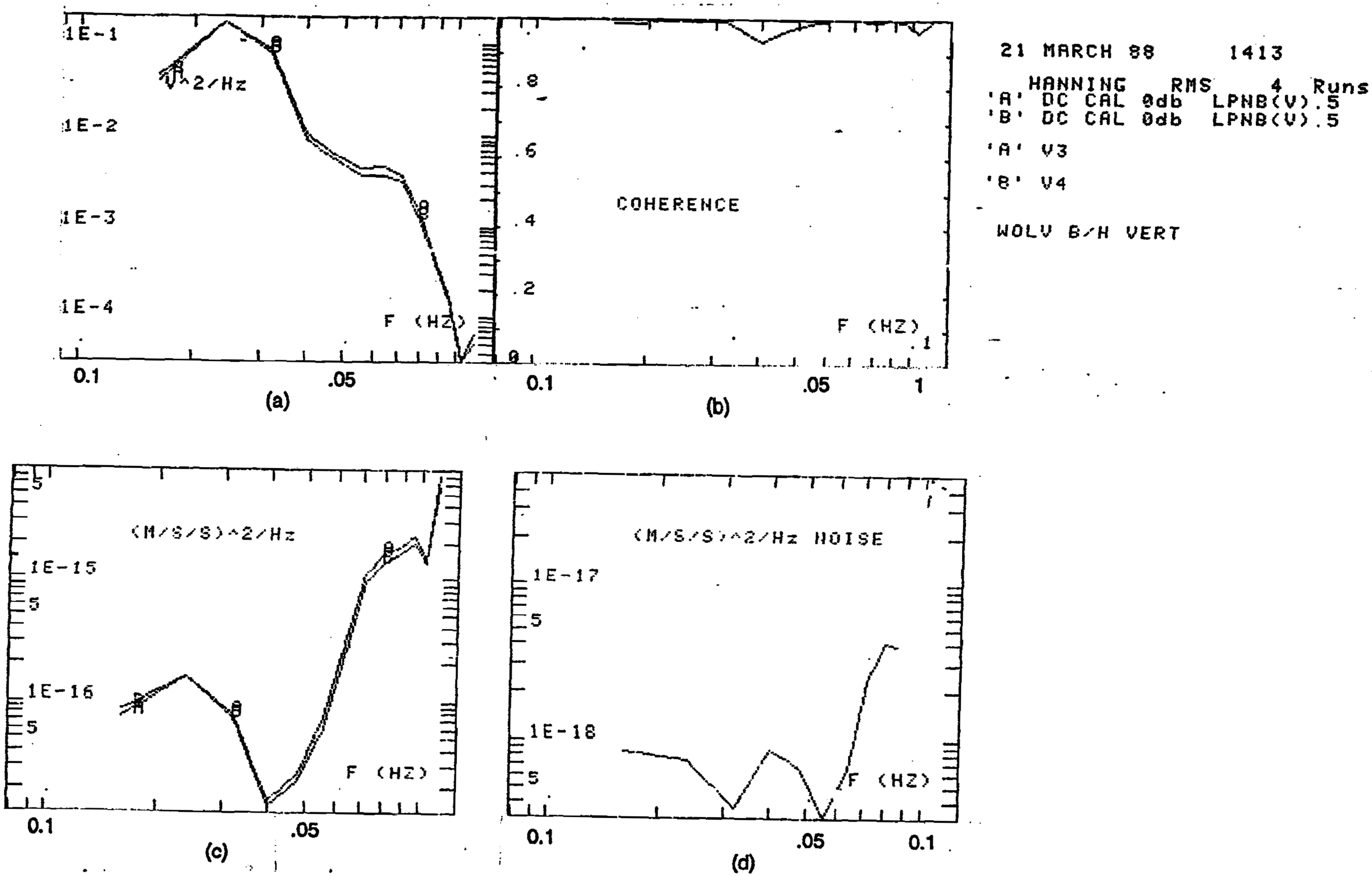


FIGURE 24. Typical Noise Run

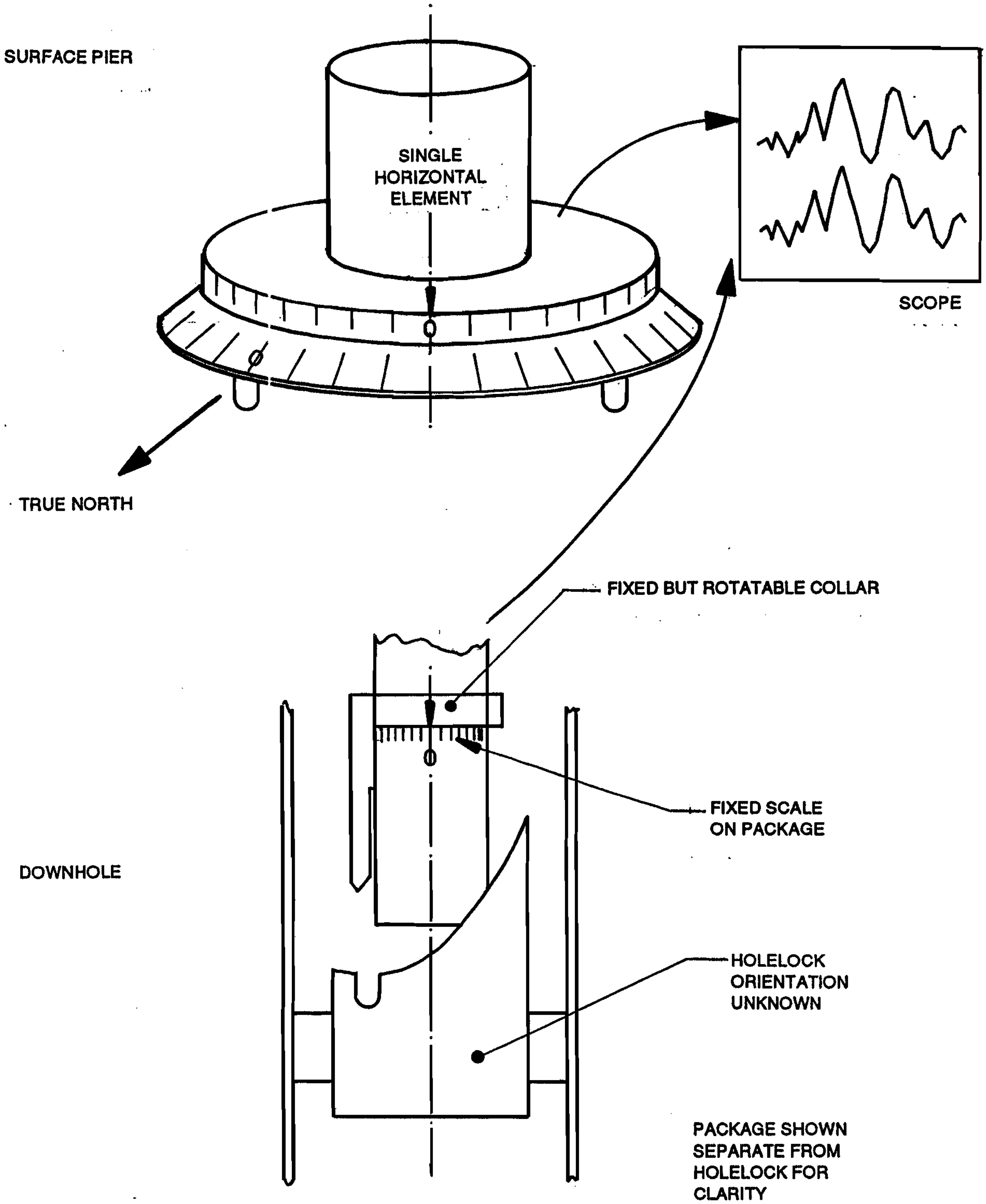


FIGURE 25. Package Orientation Using 6 sec Microseisms from Velocity Broad Band Output

27 NOV 86 0923

HANNING RMS 4 Runs
'A' DC CAL 0db VBB (H).5
'B' DC CAL 0db VBB (H).5

'A' LINE 2 H5 BOREHOLE BOTTO
M
'B' LINE 7 H1 TURNTABLE.

HOR COMPARE AT WOL. ALIGNM
ENT OF BOREHOLE SEISMOS REPE
AT AGAINST TURNTABLE ON SURF
ACE. BOTH FACING N/S

Date 27 NOV 86 1041
OVERLOAD

100°

27 NOV 86 1041

F(Hz)	COH SQUARED	PHASE
.120	.999632	.8
.160	.999615	.5
.200	.999365	.0
.240	.999317	-.2
.280	.999792	.0
.320	.999018	-.3
.360	.997997	.2
.400	.998461	.4

AVERAGE COHERENCE SQUARED IS
.9991

27 NOV 86 1045

F(Hz)	COH SQUARED	PHASE
.120	.999485	.2
.160	.999832	-.4
.200	.999539	-.0
.240	.997353	-1.4
.280	.999631	.5
.320	.999836	.7
.360	.999196	.2
.400	.999542	-.5

AVERAGE COHERENCE SQUARED IS
.9993

27 NOV 86 1050

F(Hz)	COH SQUARED	PHASE
.120	.999787	-.0
.160	.999644	-.2
.200	.999598	-.3
.240	.999708	-.0
.280	.999692	-.2
.320	.999412	.5
.360	.999317	-.5
.400	.999251	-.8

AVERAGE COHERENCE SQUARED IS
.9995

Date 27 NOV 86 1057
OVERLOAD

101°

27 NOV 86 1057

F(Hz)	COH SQUARED	PHASE
.120	.999812	-.2
.160	.999459	-.1
.200	.999801	-.2
.240	.999904	-.1
.280	.999982	-.0
.320	.999849	.1
.360	.999521	.3
.400	.999156	.3

AVERAGE COHERENCE SQUARED IS
.9996

27 NOV 86 1100

F(Hz)	COH SQUARED	PHASE
.120	.999961	-.1
.160	.999931	-.1
.200	.999823	.0
.240	.999861	.1
.280	.999949	.4
.320	.999877	.6
.360	.999803	.6
.400	.999640	.1

AVERAGE COHERENCE SQUARED IS
.9998

27 NOV 86 1105

F(Hz)	COH SQUARED	PHASE
.120	.999900	.1
.160	.999977	.2
.200	.999959	.1
.240	.999941	.1
.280	.999818	.1
.320	.999784	.0
.360	.999735	.5
.400	.999743	.6

AVERAGE COHERENCE SQUARED IS
.9998

FIGURE 26 Computer Output of Coherence for Alignment using Microseisms.

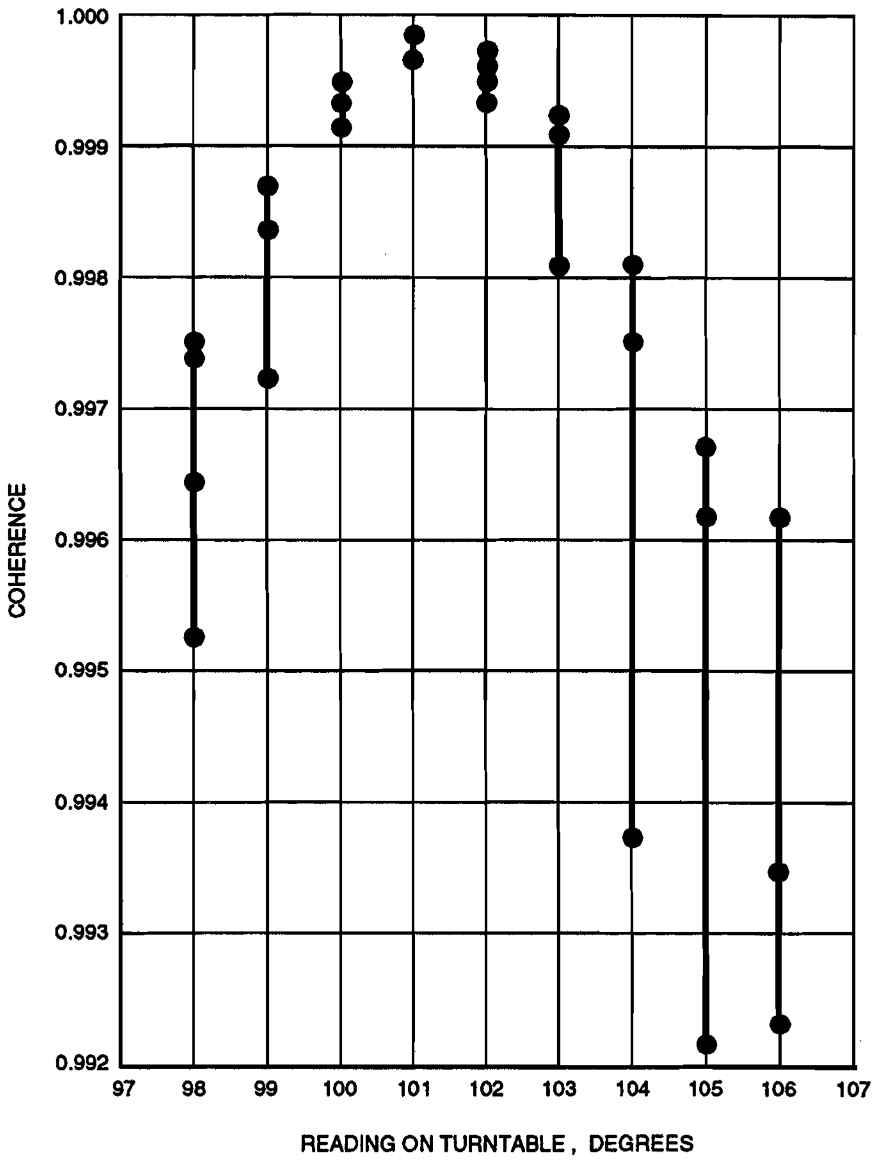


Figure 27 Coherence between Surface and Borehole Seismometers using Turntable.

6060/BURCH/27

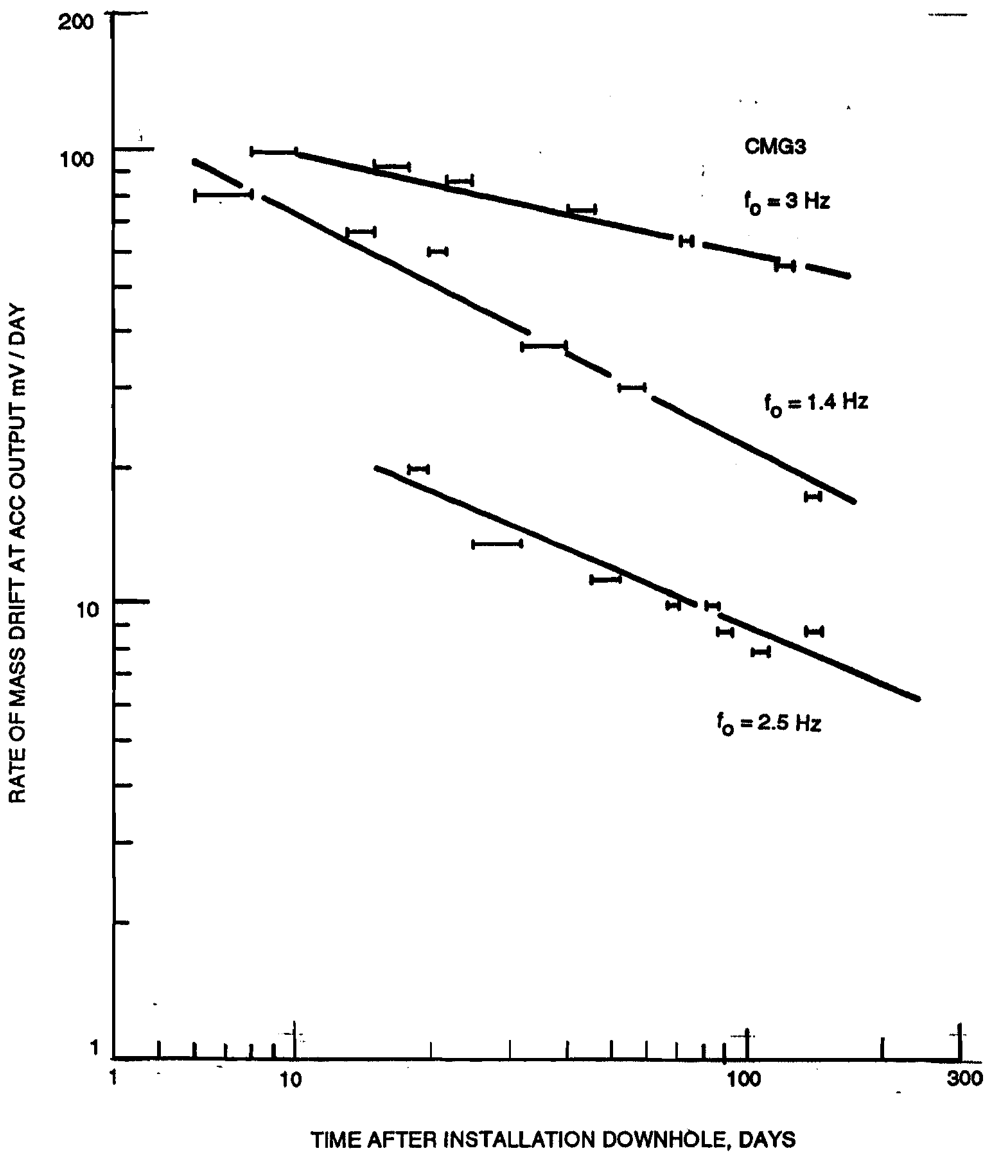


FIGURE 28 Rate of Drift of the Mass of the Vertical Component Seismometer Downhole as Measured at the ACC Output

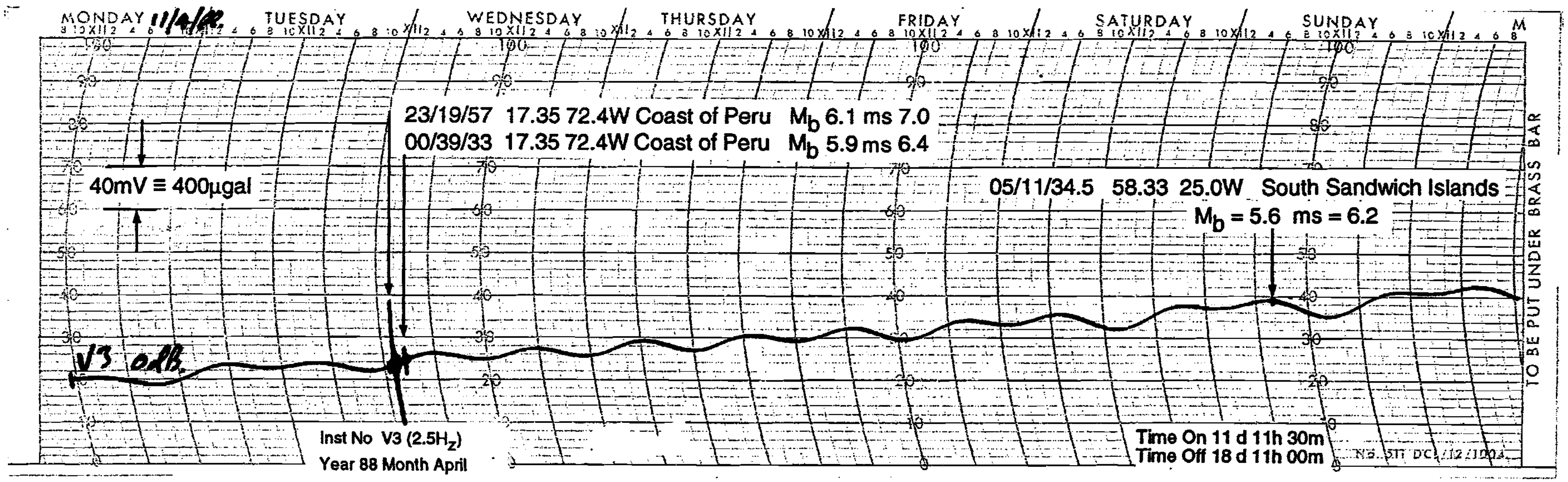


FIGURE 29. Low Pass Filtered ACC Output Showing Drift of Inertial Mass

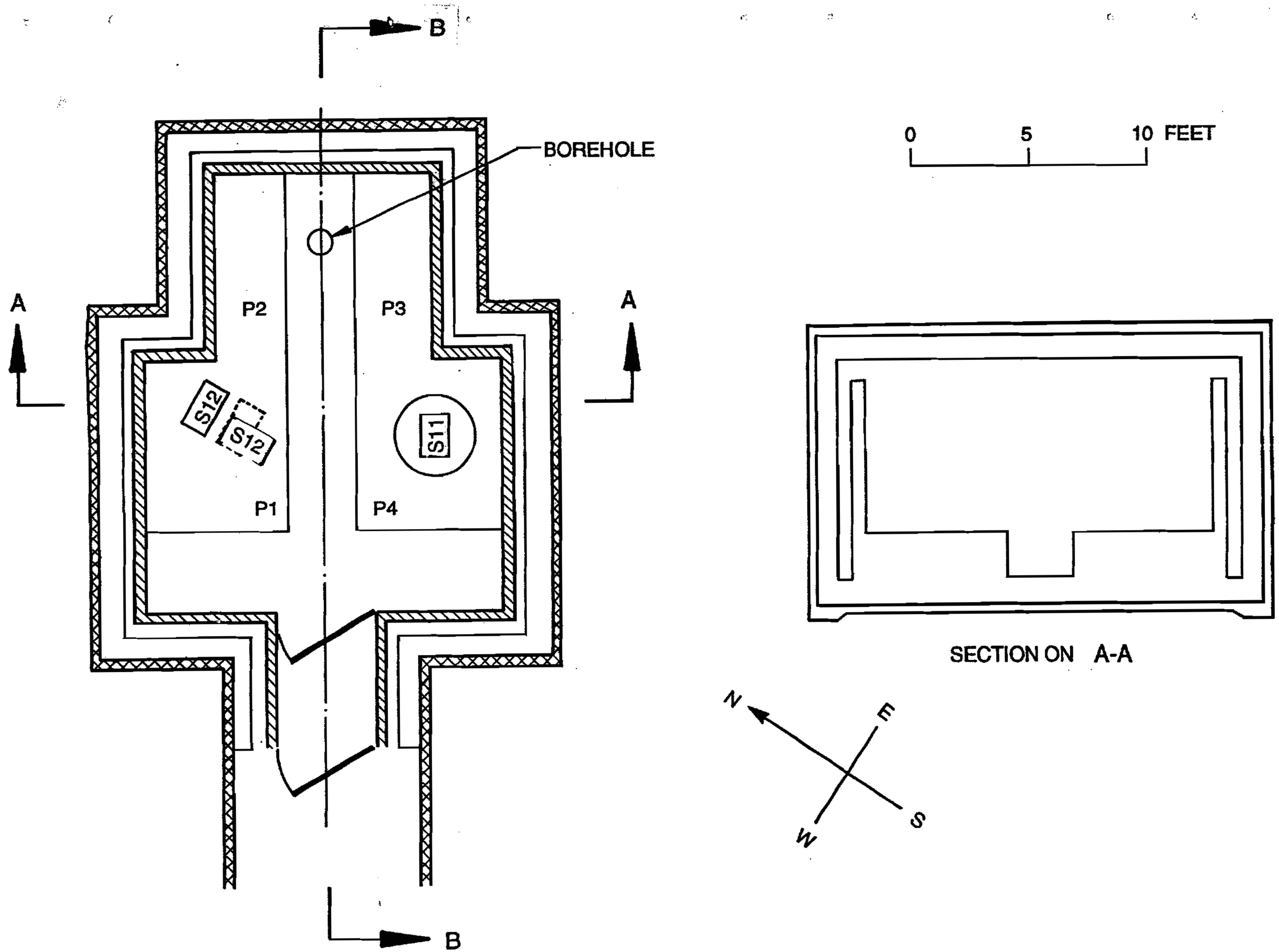
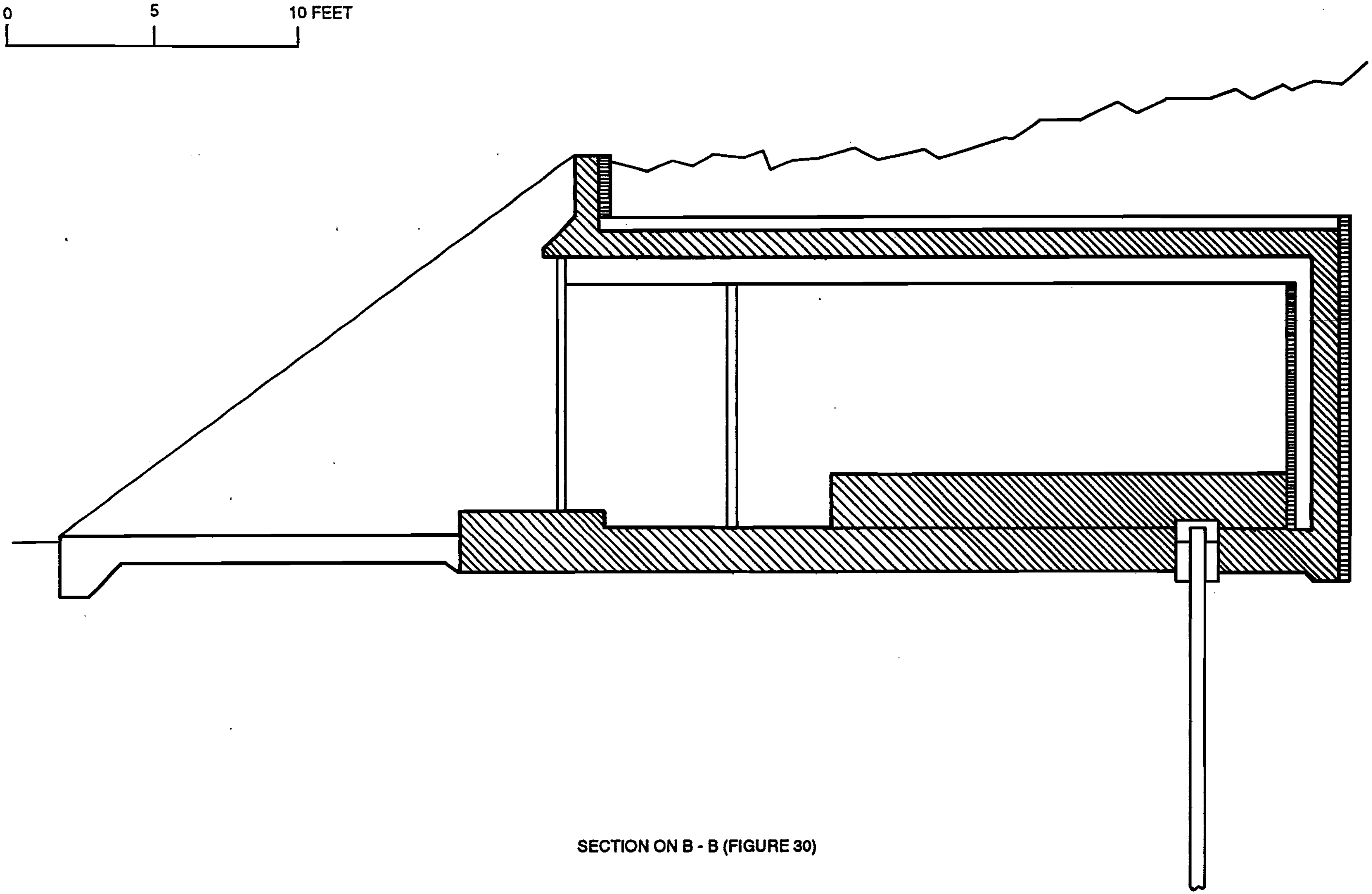


FIGURE 30 Wolverton Vault



SECTION ON B - B (FIGURE 30)

FIGURE 31. Wolverton Vault

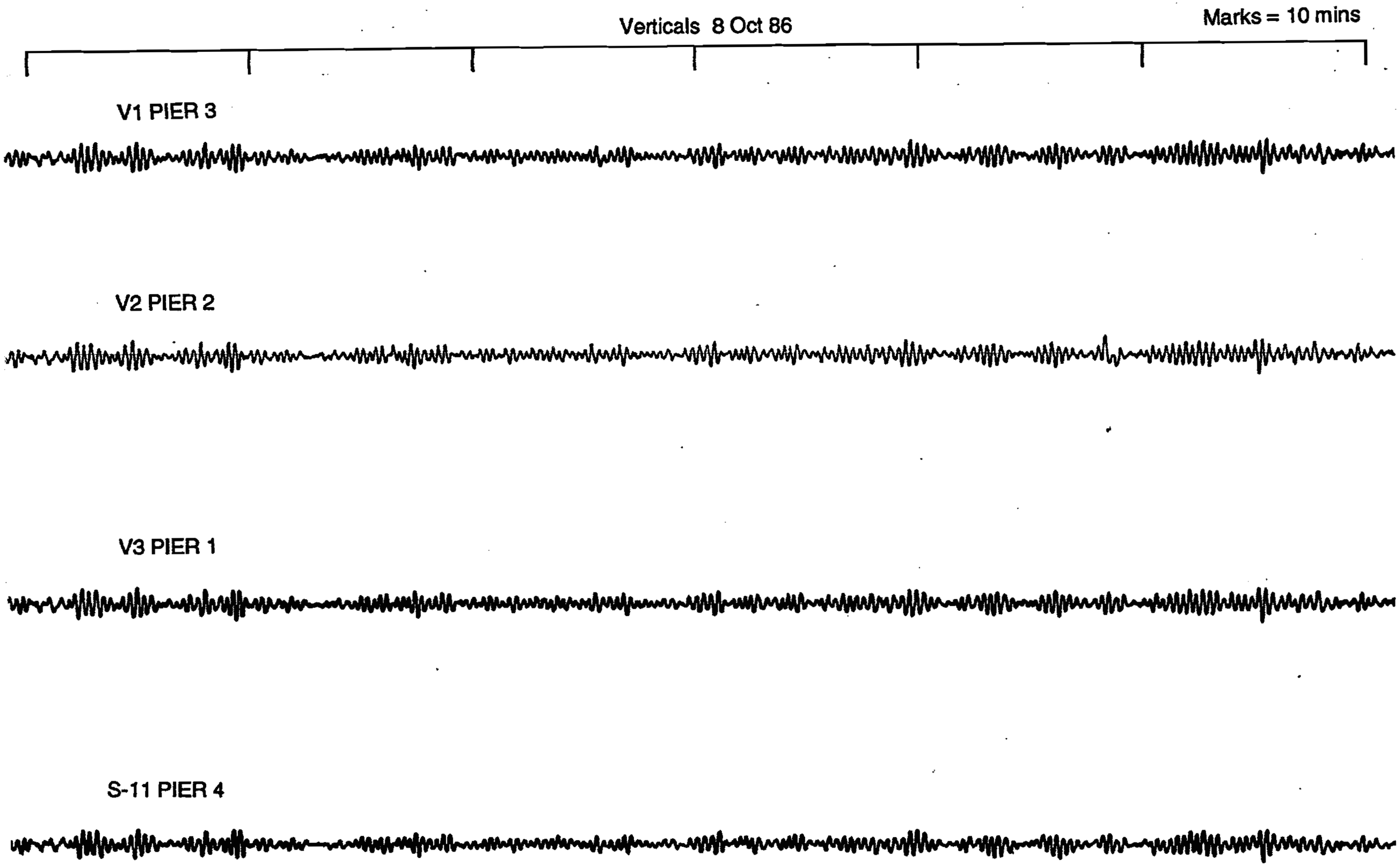
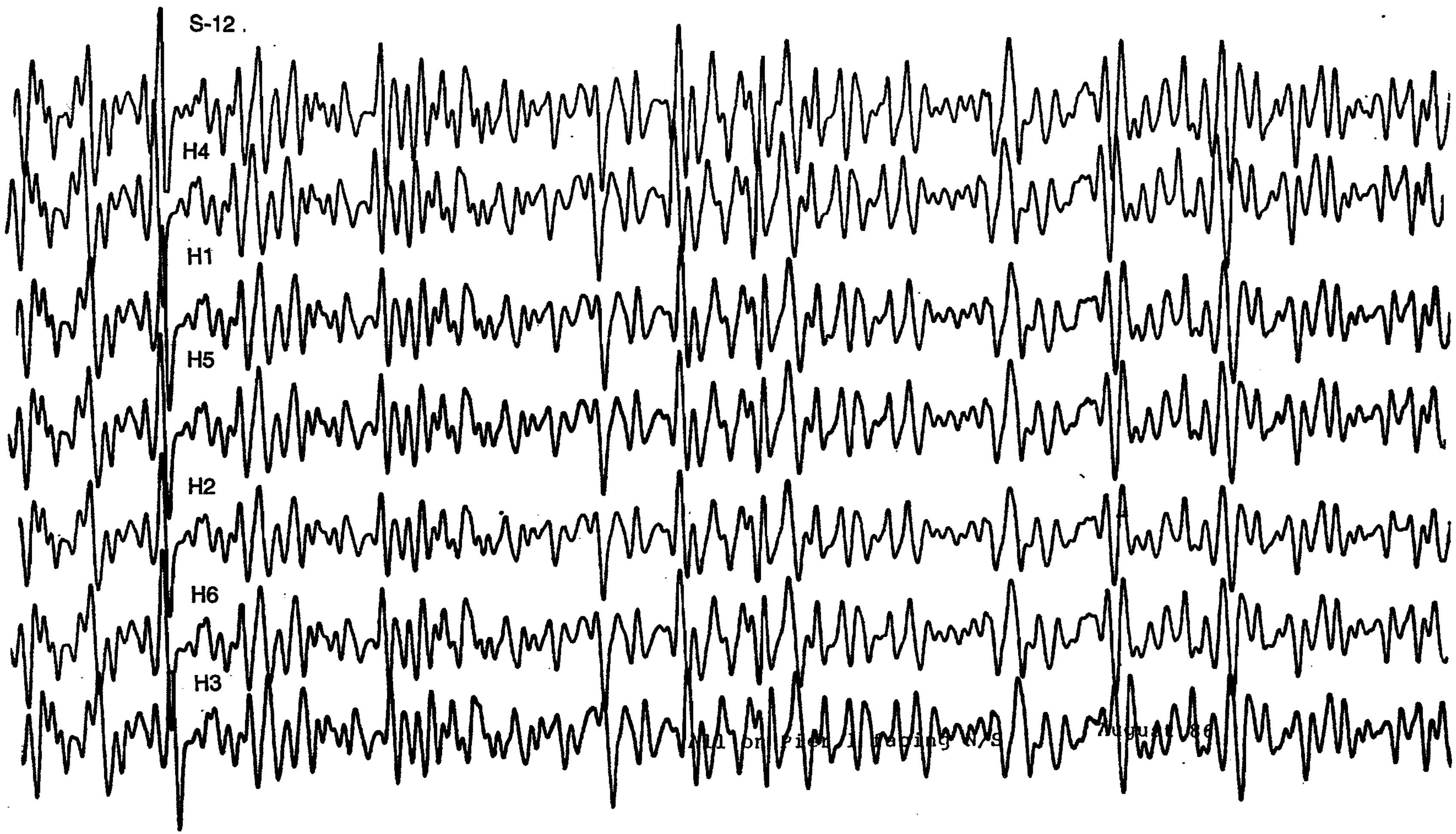


FIGURE 32 Distribution of Four Vertical Component Seismometers on Separate Piers during Windy Conditions



ALL ON PIER 1 FACING N/S AUGUST 86

FIGURE 33. Seven Seismometers aligned North /South on Pier 1 (Windy).

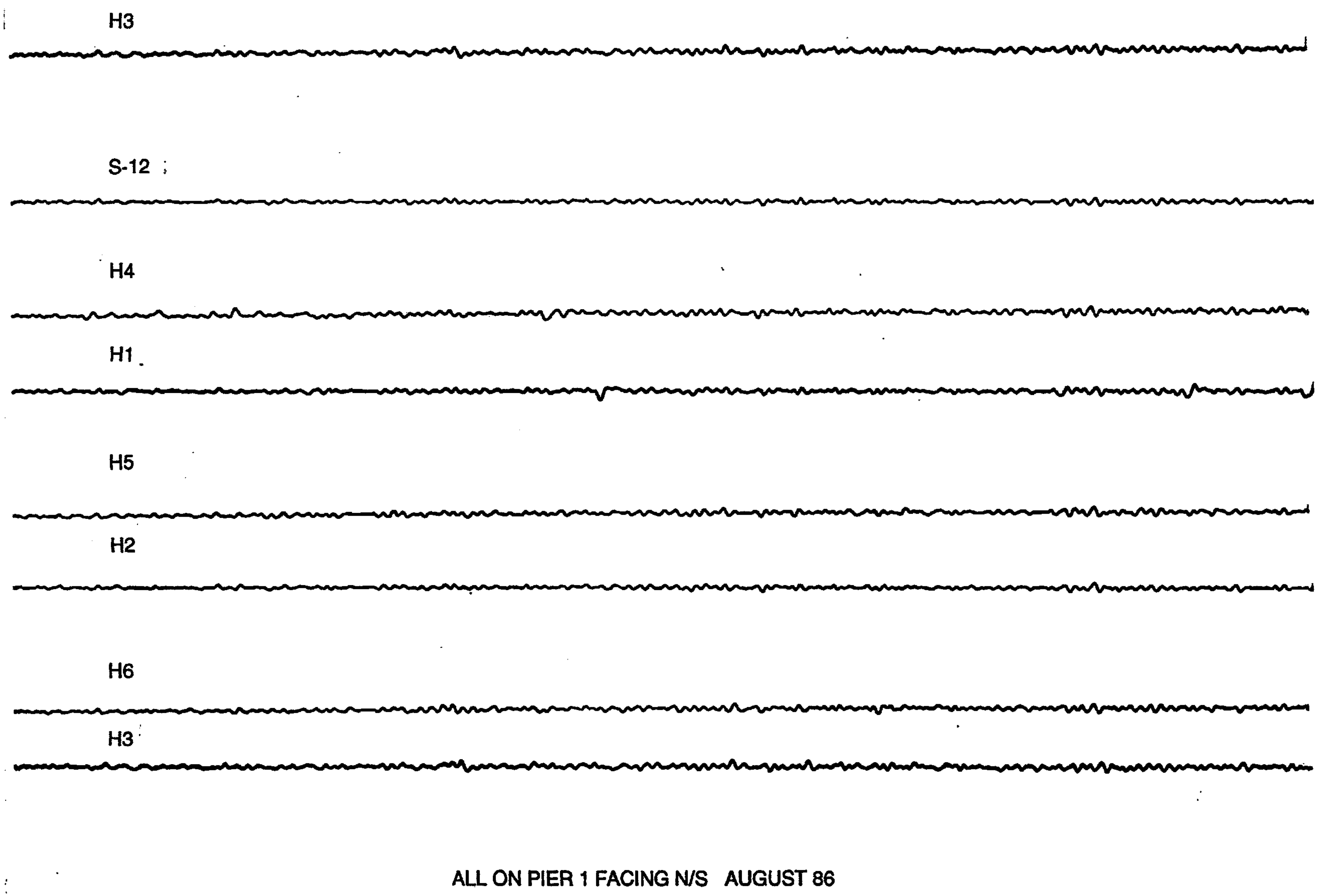


FIGURE 34. Seven Seismometers aligned North /South on Pier 1 (Calm Conditions).

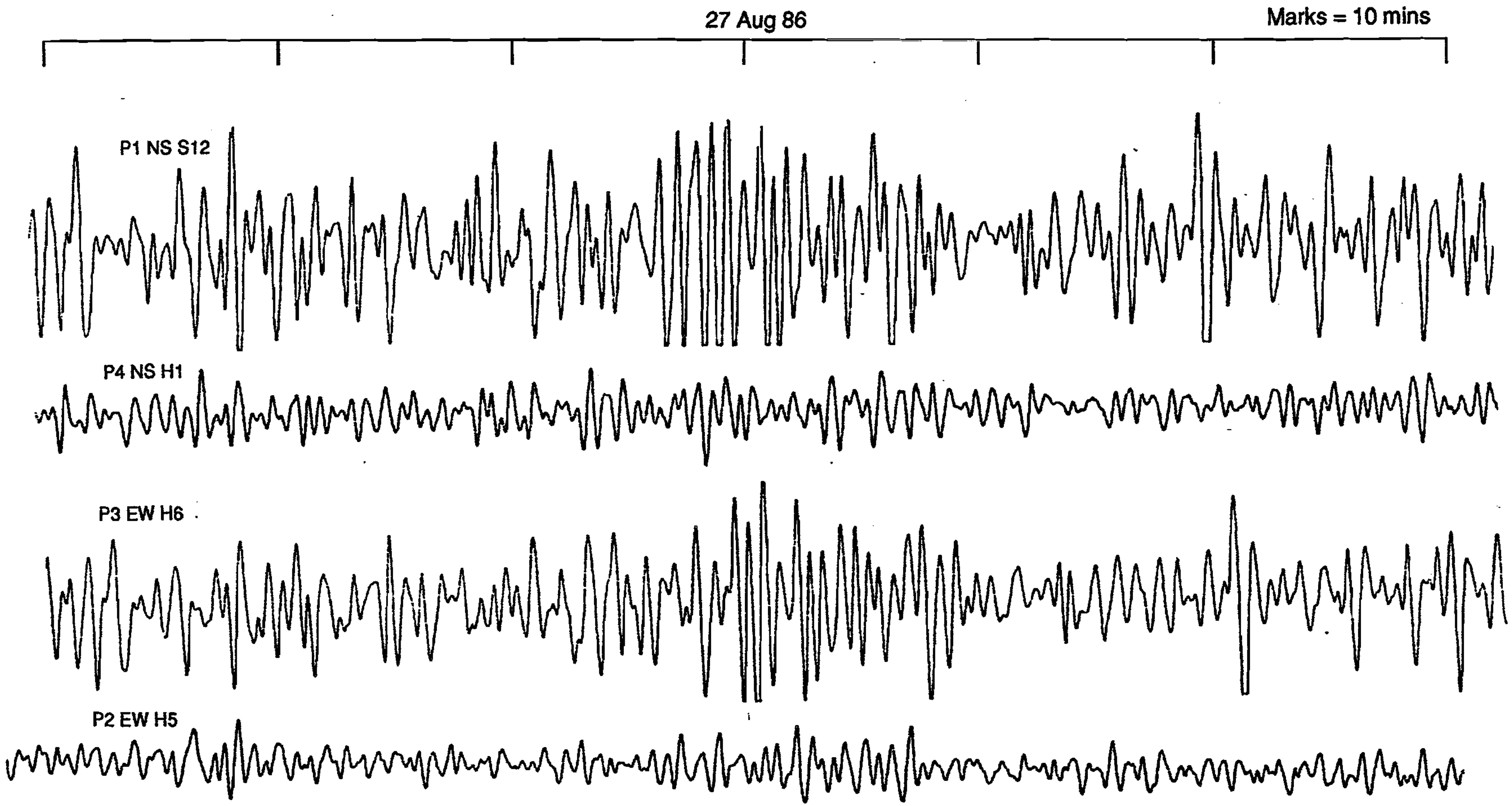


FIGURE 35 Worst and Best Signals from Surface Piers for North/South and East /West Alignment during Windy Conditions

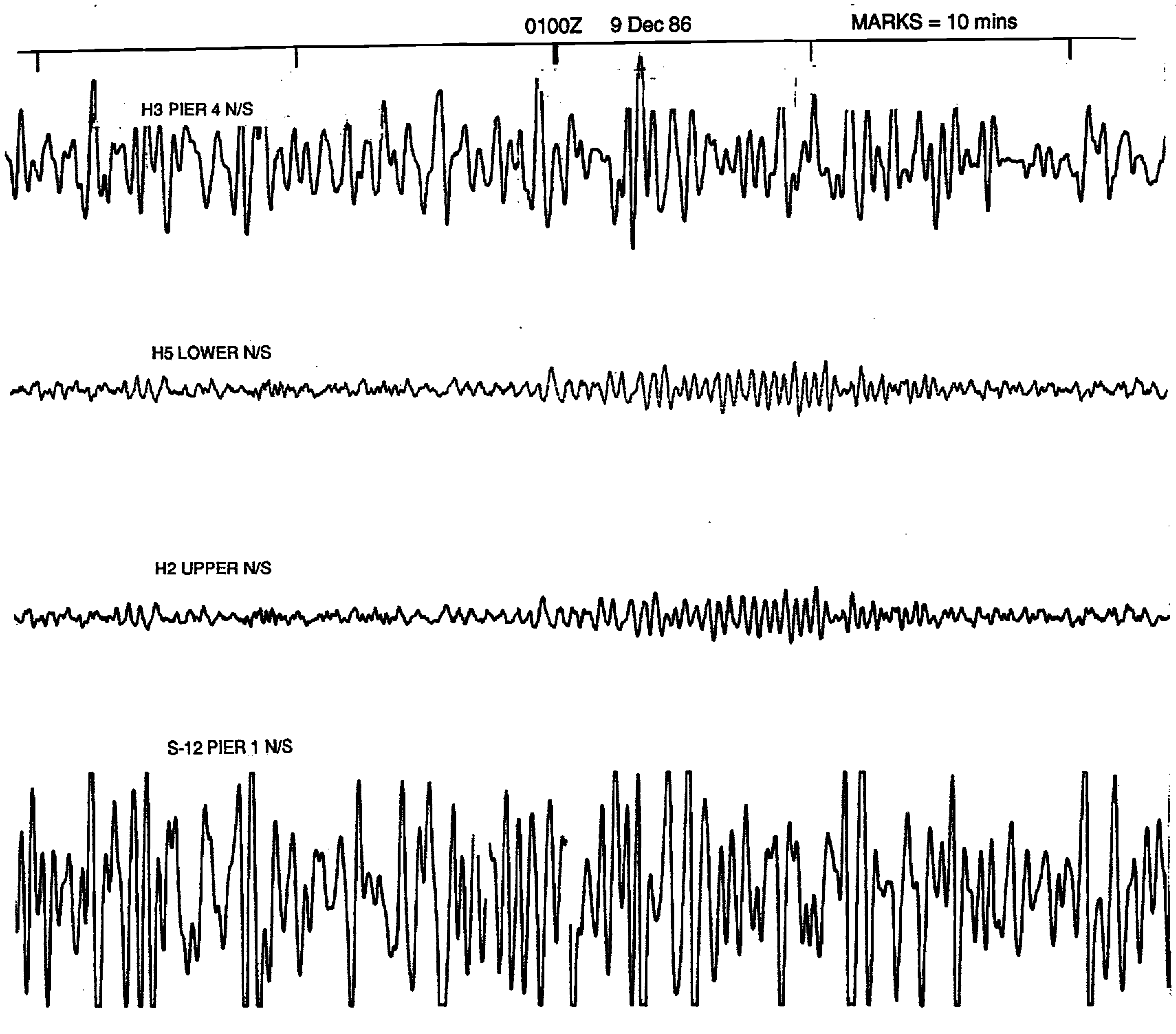


FIGURE 36 Comparison of Surface and Downhole Traces during Windy Conditions.

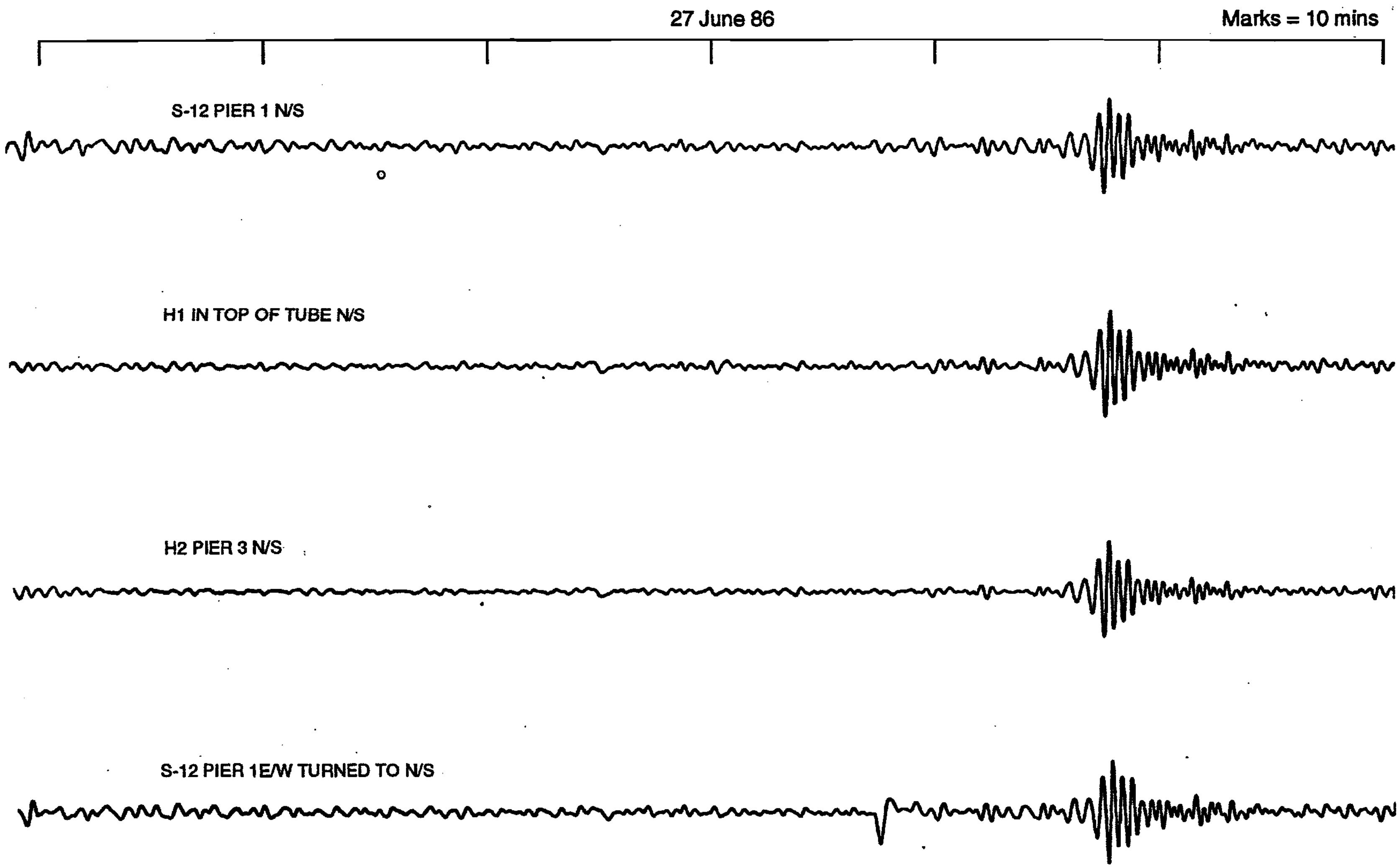


FIGURE 37 Weight Lift 'Glitch' on Conventional LPNB Trace

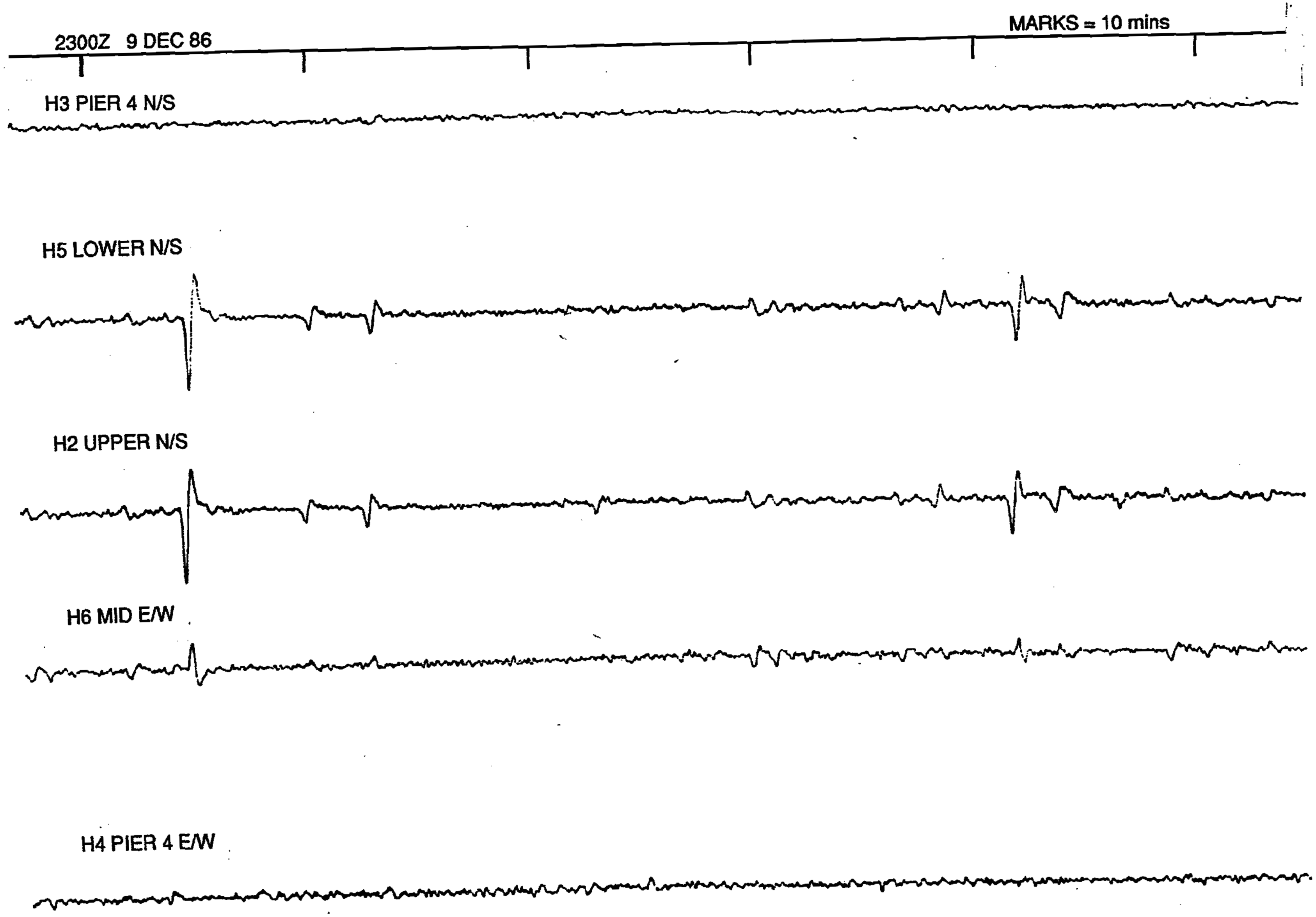


FIGURE 38 Weight Lift Glitches on Downhole Horizontal Component Traces

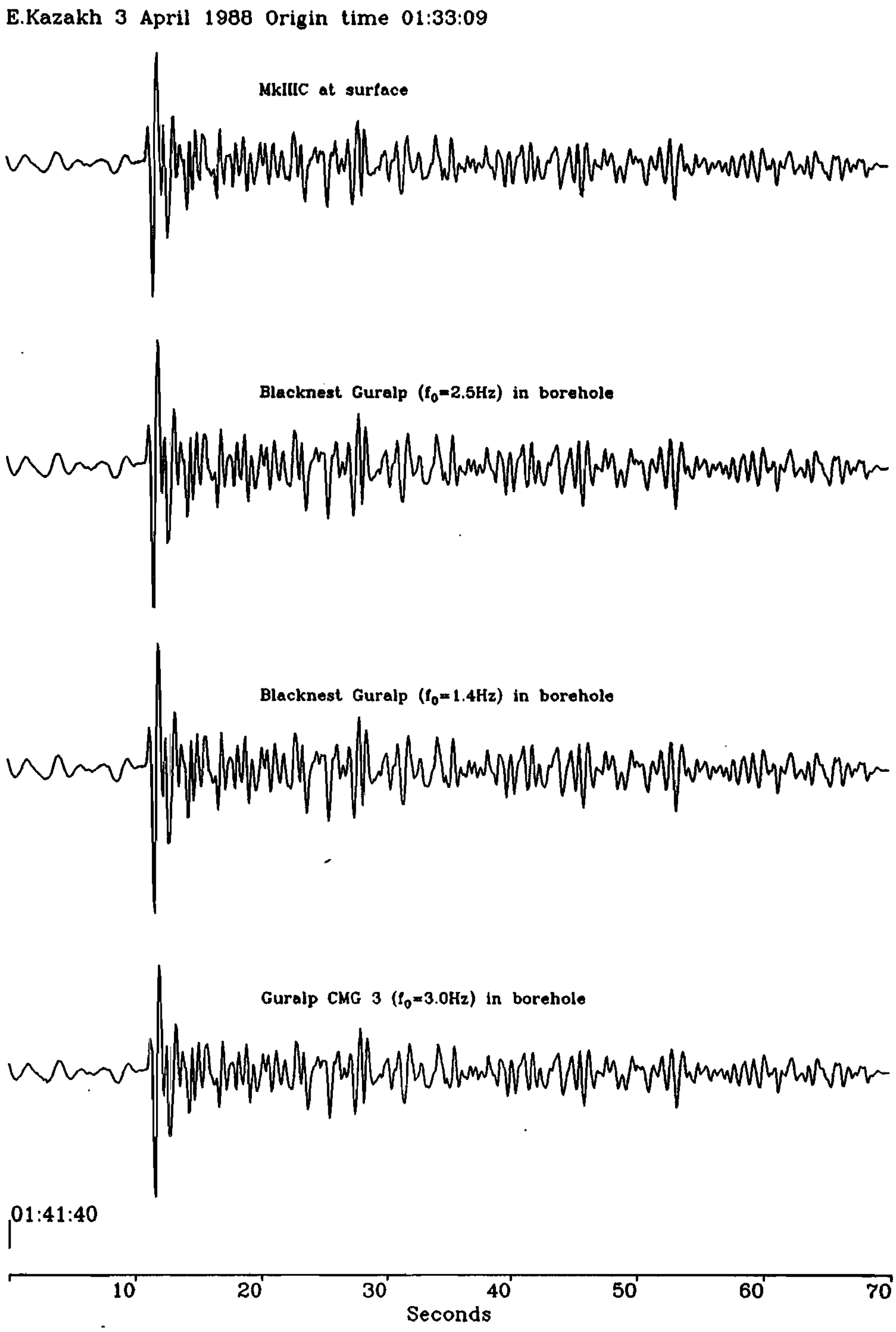


FIGURE 39 Comparison of SP Seismograms Derived from the VBB using three Vertical Component Seismometers in the Borehole and One at the Surface.

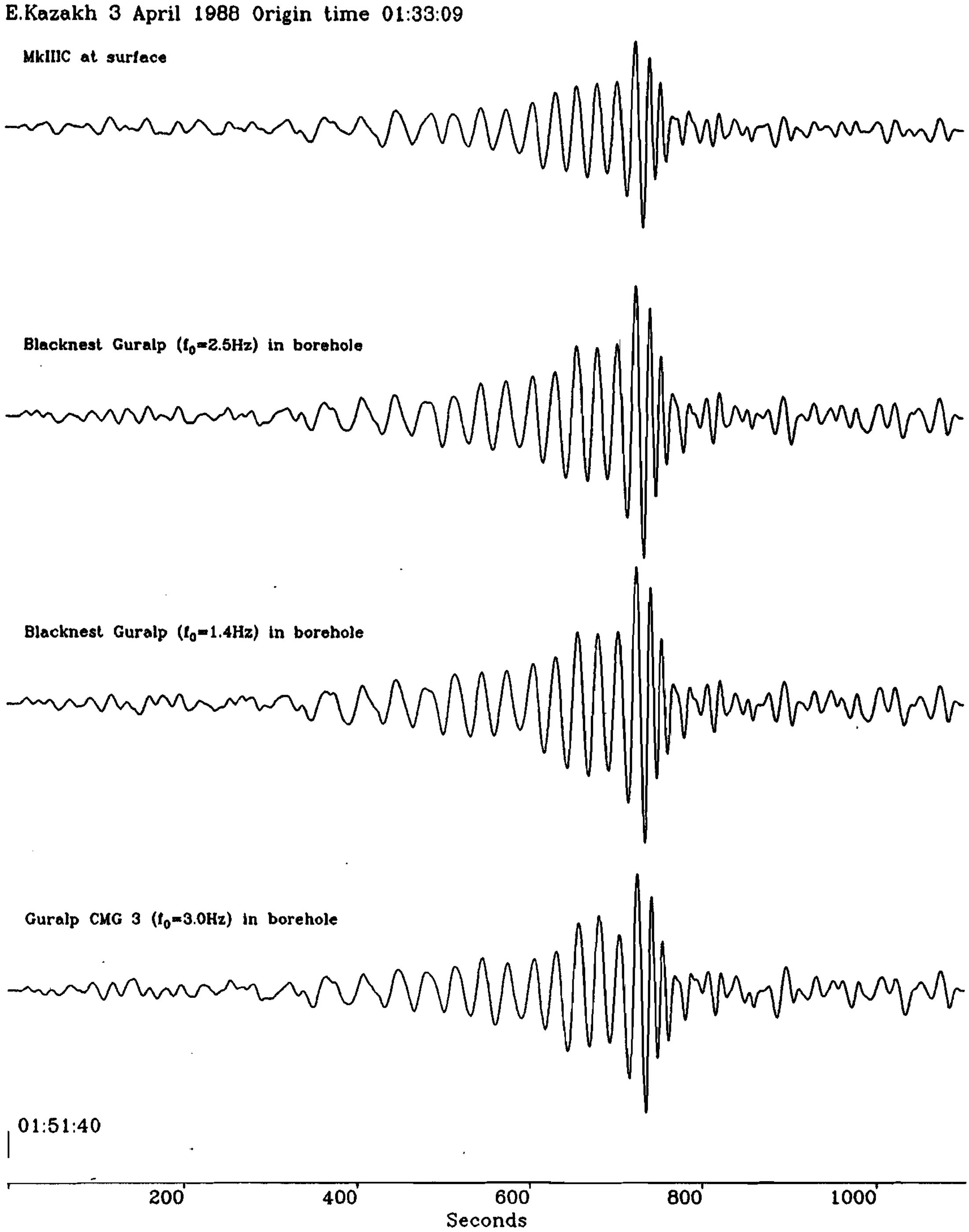


FIGURE 40 Comparison of LP Seismograms Derived from the VBB using three Vertical Component Seismometers in the Borehole and One at the Surface.

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