

An Amateur, Vertical Component, Broadband Seismometer (Model MkXVIII)

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SUMMARY

This paper describes an amateur designed vertical component seismometer with a broadband (BB) response flat to velocity between .05-10 Hz. It featured a capacitive displacement transducer, a feedback transducer to modify and damp the pendulum's motion, plus a small DC electric motor to compensate for long-term mechanical drift of the displacement transducer. The suspended seismic mass was packaged in a rigid airtight housing to reduce its susceptibility to barometric pressure changes. Post filtering the raw data exposed the presence of long period (LP) waves from teleseismic events, having magnitudes greater than 5.6 from most places on earth.

INTRODUCTION

For its relative ease to design and fabricate, a horizontal component seismometer fitted with an electromagnetic transducer to produce an electrical signal proportional to ground velocity, is an attractive choice. Unfortunately, the transducer's increasingly weaker signal towards the lower frequencies makes it undesirable for the detection of long period waves from teleseismic events, and the horizontal component is quite susceptible to ground tilting. A capacitance displacement transducer, on the other hand, has excellent low frequency sensitivity and when mounted on a vertical motion pendulum (an inertial spring mass type), has good immunity to ground tilting. Controlling the pendulum motion with a multi-path feedback signal improved linearity and broadened the response while providing a velocity output signal.

Initially, a couple of older homemade horizontal seismometers having capacitive transducers were the "test beds" for developing the electronic circuit design, the configuration of the transducer plates and the motorized re-centering feature. The horizontals were very sensitive to ground tilting and responded accordingly to noise from numerous sources, i.e. nearby foot traffic, wind, rain, frost heave or barometric fluctuations interacting with the local geology. It was obvious that a vertical component would be better suited for a suburban backyard.

Compared to the horizontal designs, the vertical seismometer required two additional features. A spring suspension system to counterbalance the force of gravity acting on the seismic mass and a rigid airtight housing to protect the suspended mass from atmospheric fluctuations. Implementing the extra requirements was not trivial and was considered as separate projects unto themselves. Designing, fabricating and adjusting the MkXVIII took approximately 3-4 times longer than for any of the horizontal seismometers. End results, indicated by the sample seismograms presented later in this document, were encouraging.

The following pages of texts and images offer only a brief description of the final design. It is assumed that the reader has already acquired some basic understanding of mechanics and electronics.

MECHANICAL DESIGN

This section describes the main mechanical features of the seismometer and their contribution to the overall system. See the section titled ELECTRONICS, for a description of its circuits. Because the seismometer's component parts were built in a non-metric country, linear dimensions will be specified in either inches or millimeters.

Being a true "amateur" project, design complexity was limited to the equipment and materials readily on hand in the home garage or available from local hardware stores and salvage yards. Besides having a selection of powered hand tools, more powerful machinery like a mill/drill machine, metal cutting band saw and a 3" metal lathe (hobby type) assisted with cutting and shaping of the thicker materials. Slotting holes with round files combined with shimming compensated for less than ideal machining techniques and limited tooling (cutters etc). To save time and materials, several of the MkXVIII's mechanical components were salvaged from older homemade seismometers.

INSTRUMENT ENCLOSURE

Protecting the suspended seismic mass from variations in barometric pressure required a rigid airtight housing. A cost-effective solution was a piece of rigid ABS plastic tubing 180 mm OD x 500 mm long x 10 mm wall thickness.

Certainly not the correct material for a major structural member requiring resistance to long term creep, but it proved satisfactory for the task. Its circular cross section ensured ambient air pressure changes were spread uniformly around the entire diameter of the tube. This meant that the internal mechanism did not rest on a flat plate subjected to warping as the external air pressure changed, it did however complicate the design of the internal mechanism. See Figures 1 through to 4 for images of the enclosure. The tube was deliberately cut 150 mm longer than required, in case a larger suspension of an improved design had to be installed at some time in the future.

A disc of 5 mm thick clear Plexiglas sheet was fully bonded to one end of the tube with silicone adhesive. On the opposite end of the tube was the access port. Since the tube was cut to length by the vendor on a chop saw, its surface finish was too rough for a gasket to seal against. Rubbing the end of the tube on a sheet of 400-grit emery paper supported by a flat plate removed most scratches while maintaining a flat end surface. A thin coating of epoxy was squeegeed over the sanded surface, filling the scratches and allowed to cure leaving a smooth glossy surface. Four ¼-20 UNC metal machine screws were pinned and epoxy bonded to the OD of the tube for mounting the access plate.

Another piece of 5 mm thick Plexiglas formed the access plate, with electrical conductors passing through its central area. Signal carrying wires were soldered to the ends of short pieces of brass wire installed in close fitting holes drilled in the Plexiglas. Exposing the coax center conductors for the one-centimeter length of the feed-through appeared to work OK (had no appropriate means of verifying signal cross talk anyway). A drop of epoxy was applied to each piece of brass wire to seal out air. Cork gasket material 1.5 mm thick sheet, cut to size with a box knife, was coated on both sides with a very thin layer of petroleum jelly (Vaseline), for an airtight seal between tube and plate. Hand tightened knurled nuts and washers secured the plate to the tube assembly.

Longitudinal and lateral movement of the frame inside the tube was controlled by two pieces of 3 mm thick aluminum, epoxied to the floor of the tube. One piece of aluminum was notched to receive the forward foot of the mechanism and the second piece had a central hole to engage a retractable pin. Gravity kept things in place vertically.

Two chunks of 25 mm thick aluminum, containing three ¼-20 UNC coach head bolts for leveling the instrument, were epoxied to the under side of the tube. Fixed to the top of the tube was a carrying handle and a small circular spirit level. The finished tube assembly was washed with detergent in warm water to remove loose clinking plastic particles held by static electricity before being masked with tape and sprayed painted.

FRAME

Figures 5 through 9 are photos of the internal frame and pendulum. Aluminum is not normally chosen by professional instrument designers for structural components [1], but the availability of an assortment of scrap material stored under the workbench made its use unavoidable for most of the mechanism. The metal frame could not be fastened directly to the plastic tube because of different thermal coefficients, it could only rest on three feet. One foot was threaded into a piece of alum plate at one end of the frame and two screws in an inverted V arrangement were threaded in a plate at the opposite end.

Captured between the 3 mm thick alum side plates was the mounting plate for the pendulum hinges, feedback transducer magnet assembly, center plate of the displacement transducer and the fixed end of the suspension springs. Parts deliberately had thick rigid cross sections wherever possible to add mass and thermal inertia [2]. Circular spirit level shown in Figure 5 was permanently bonded to the end of the frame for reliable leveling when making repeatable adjustments.

The enclosure was leveled prior to installing the mechanism. Next the leveling screws were adjusted on the frame, to level it inside the enclosure. Note: a separate plate (colored black in several photos) with three of its own screws, provided a temporary way of holding the frame level while working on it outside of the enclosure.

PENDULUM AND SPRING SUSPENSION

Overall length of the pendulum was approximately 275 mm. Non-magnetic materials had to be used on the pendulum, because the feedback transducer's magnet was attached to the frame. Maintaining vertical openings within the pendulum's framework reduced the risk of rising or descending air convection currents striking surfaces that could upset the pendulum's equilibrium.

Between 2 mm thick alum side plates was a block to attach four crossed hinges (flexures) for connecting the pendulum to the frame. Flexures of hardened 0.002" thick phosphor bronze, cut in strips 5 mm wide x 10 mm long were held in place with finger clamps, see Figure 9 for a partial view. Heat-treated stainless steel shim stock (feeler strip) could have worked as well.

A cross bar for attaching the suspension springs, had three brass studs protruding from it. Upper stud carried the bulk of the seismic mass, 0.36 Kg of brass, and the lower two studs received the free ends of the suspension springs. Optimum location for where the suspension spring contacted the cross bar was just forward of the pendulum's center of gravity, i.e. towards the displacement transducer. At this point, the two inner vertical flexures were kept in slight tension by the weight of the pendulum. The two horizontal outer flexures were in tension due to the direction of the spring force.

An aluminum plate carried portions of both transducers. The lower of the two outer displacement transducer plates was bonded to it, and a central hole in the alum plate received the brass mounting stud of the feedback transducer. Some trim weights were also attached to the plate.

Counterbalancing the force of gravity on the pendulum/seismic mass was accomplished by using two common hacksaw blades, 1/2" wide x 10" long. Over the years the cheapest blades have been found to possess some of the best spring properties. Both blades were used "as is" out of the box, and conformed into a collapsed C shape. Lower end of the blades were attached to a hinged plate, with a screw through their pre-made holes. Downward pointing brass studs on the cross bar in the middle of the pendulum went through the hole in the upper free end of each blade.

The hinged plate pivoted about a dowel pin pressed into each side, that aligned with holes drilled in the frame's 3 mm thick side plates. Screwed to one edge of the hinged plate was Z shaped arm, with a swivel nut inserted in the upper overhanging arm. Threaded into the swivel nut and supported by a thrust bearing pressed into another plate beneath the hinged plate, was a piece of 6-32 UNC threaded rod with a Nylon worm gear. A small 12-volt DC motor coupled to a 1000:1 ratio gearbox fitted with a worm, rotated the threaded rod to raise or lower the hinged plate on command. This movement added or subtracted some force to the lower end of the attached springs, causing the pendulum to raise or lower. Long term weakening of the suspension spring and short-term temperature fluctuations effecting the spring modulus, easily disturbed the pendulum's equilibrium, requiring some compensation.

When the displacement transducer's signal exceeded a pre-determined offset voltage level after a long period of integration, the motor was activated. Long period integration eliminated false triggering during the detection of large microseisms, wind noise and seismic events. Pendulum was returned to null at a rate slightly slower than the lagging response of the feedback circuit's integrator output signal (observed when the seismometer is correctly leveled). A voltage feedback resistor set optimum motor speed. Complementary power boosting transistors were configured to form a dead band within plus or minus 0.6 volts of null. When the amplified signal of the transducer reached the dead band on either side of null, the output voltage of the transistors quickly dropped off to a level insufficient to drive the motor. Then the integrator's lagging output could catch up and drift into the dead band, placing the pendulum very close to null without any dithering. Automatic re-centering meant that the thermal insulation surrounding the instrument did not get disturbed.

Before installing the mating fixed portions of the transducers to the frame, the pendulum's free end could travel up and down +/-5 mm, with a natural frequency of 1.0 Hz. The pendulum oscillated freely for over 6 minutes before its amplitude diminished to 10% of its initial height. After the seismometer was operational (transducers fully intact but no feedback signal), air trapped in the narrow gaps of the transducers damped the pendulum's motion, taking ~80 seconds to reach 10% of the initial amplitude, when released. Equivalent seismic mass for the pendulum assembly was calculated to be 0.588Kg, centered at a point 192 mm from the flexures.

No method for locking the pendulum remotely was provided. If the seismometer had to be carried, it was tilted to one side at a shallow angle, causing the pendulum to lift until two of the displacement transducer's plates rested together.

FEEDBACK TRANSDUCER

An electrical feedback signal flowed through a voice coil suspended from the pendulum, see Figures 5, 6 & 8. The coil, working in conjunction with a permanent magnet attached to the alum frame, applied a driving force proportional to ground acceleration that both modified and damped the pendulum's motion. Transducer linearity directly effected the accuracy of the final output signal.

Sean-Thomas Morrissey utilized a large 12" off-the-shelf audio speaker for a feedback transducer, as an alternative to building something from scratch, on his unique STM-8 design [3]. Off the shelf audio speakers can perform reasonably well, as long as they are not expected to control too much mass. A low resistance speaker voice coil has a low generator constant (calculation of the feedback transducer's generator constant, G_n , will be discussed later in this paper), so a custom-made feedback transducer was created for the MkXVIII. No information will be presented here regarding how to design such transducers. Please read Sean-Thomas Morrissey's e-mail postings archived on the Public Seismic Network (PSN) web site for instructions pertaining to their design and how he custom made his own. The MkXVIII's feedback transducer was constructed as follows.

Figures 6 and 8 partially show some of its mechanical details, identifiable in the photos as the green lump. Starting with the magnet assembly, it went together like this. Two large 75 mm OD ceramic ring magnets retrieved from a couple of old microwave ovens were epoxy bonded between two mild steel plates 50 mm x 80 mm x 13 mm thick, forming the magnetic return path. Screwed to the center of the lower plate was the inner pole piece, along with some tapped holes for attaching the assembly to the frame's aluminum side plates. Upper plate was the outer pole piece, having a 27 mm diameter hole centrally located and concentric with the inner piece, to receive the moving voice coil. The inner pole piece previously mentioned was a 1/2" diameter mild steel bolt, its head turned down to 17 mm diameter. Top of the head was flush with the top of the upper plate, with a uniform gap of 5 mm between the inner and outer pole pieces.

A voice coil was made from a piece of 25 mm OD ABS plastic tube, plugged at one end with another piece of ABS. The plugged end was gripped in the chuck of a small lathe and a broad groove was then turned into the outside surface of the tube. Drilled a hole through the center of the plug in which a brass mounting screw was installed. Holding the screw in a lathe chuck, the ABS plastic bobbin was slowly rotated until enough 34 AWG enameled magnet wire was

wound on to equal 300 ohms resistance. Both loose ends of the magnet wire were cut to a length of 500 mm, later trimmed and soldered to more rigid wire conductors after the voice coil was mounted to the pendulum.

Thoroughly cleaned out the magnet gap by sliding around a piece of pliable vinyl electrical insulation tape. Forcing the sticky side of the tape against the inside surfaces of the gap, captured loose magnetic particles, flakes of paint, lint, hair and dead skin. Repeated this process several times to ensure cleanliness. A large piece of tape was temporarily placed over the exposed poles and gap to prevent dirt and metallic particles from re-entering. Tape was removed at final assembly with the coil.

DISPLACEMENT TRANSDUCER

Most professional seismometers and accelerometers appear to use a variable capacitance displacement transducer in a half bridge configuration. Wanting to ensure decent performance from a crude homemade instrument, a full bridge, or symmetric differential capacitive (SDC) transducer [4] was selected. Compared to a half bridge, an SDC transducer has double the sensitivity, a well defined null position and does not require a very precise symmetric oscillator. Its main drawback is the need for two variable capacitors and a precise method for differentiating their output signals. A variable capacitance transducer is also quieter electronically and more sensitive than a linear voltage displacement transformer (LVDT) transducer, and perhaps easier to make.

SDC transducers consist of two separate transducers rigidly coupled together to move as a single unit. Each transducer forms a branch of the bridge circuit. Refer to Figures 5, 8, 10 & 11 regarding how this concept was applied to the MkXVIII. Responding to a displacement of the seismic mass, i.e. some amount of detectable motion between the pendulum and base plate, each transducer must output a signal of opposite polarity to the other. In regards to the MkXVIII, each outer plate comprised of two separate active areas, facing towards the center plate. Back to back active areas on the center plate were joined electrically together, but not to the adjacent active areas on the same side of the center plate. An active area on one of the outer plates was joined electrically (cross-linked) to the active area on the opposing outer plate of the other transducer. When one of the outer plates, consisting of two active areas, got closer to the center plate, one half of the center plate received a stronger positive signal and the half of the center plate received a stronger negative signal, providing a true differential output. Fairly fine 40 AWG coax wire carried the modulating signal from the oscillator circuit to the outer plates. These coaxes easily flexed where they bridged the gap at the pendulum's hinges.

A three-plate transducer design balanced out the electrostatic forces acting between the plates. Viscosity of the air trapped between the plates posed a significant problem by damping the pendulum's motion. A pattern of "vent" holes was uniformly distributed across all plates of the transducer. Size of gaps between the plates and vent hole diameters had to be carefully considered for an acceptable sensitivity. Critical aspects of half bridge capacitance transducer designs were covered in a paper by Jones & Richards [1] and a out of print book written by Baxter [5], but the information was still applicable to the full bridge SDC design.

Flexing a signal cable can generate noise, so the center plate (modulated signal receiver) was fixed to the base framework and the two outer plates (modulated signal transmitters) were attached to the moving pendulum. Rigid, heavily shielded coaxes connected the center plate's active areas to the electronics. The outer plate's active areas overlapped those on the center plate, allowing for some very slight, unavoidable off-axis motions without noticeably effecting sensitivity.

A sine wave oscillator with stable amplitude is important for the SDC transducer's sensitivity, but not as much as for a half bridge. An EXAR XR-8038 function generator providing a sine wave output with a total harmonic distortion (THD) of 2-3% and similar tolerance for the frequency stability was acceptable. Relatively cheap and readily available high performance op amps with moderate slew rates easily handled the selected sine wave excitation carrier frequency. Precision DC operational amplifiers have increasing noise towards the lower frequencies, so operating the transducer with a reasonably high AC frequency reduced the 1/f noise problem.

The capacitor plates should have been a non-corrosive grade of brass or stainless steel finished with a special surface treatment, but were actually made from 1/8" thick FR-4 (PCB) type material coated on both sides with a layer of 1 oz, 0.0014" thick, copper foil. Relied on the board's manufacturer to have applied some type of corrosion inhibitor to the exposed copper. Material was cut to shape with a saw and a Dremel Tool fitted with an engraving bit defined the active areas by making isolation grooves 1-2 mm wide through the copper layers. Plate details are presented in Figure 11.

Copper layers, left intact over much of the outer plate's back surface, acted as a protective ground plane. Mounting screws shorted the ground plane to the seismometer's metal structure. Outer braided jackets of the modulating signal's coaxes were soldered to the copper ground planes, tying the seismometer and the electronics' metal enclosure to the same voltage potential.

The actual active area for each of the two separate displacement transducers was calculated to be 1192 square millimeters, excluding the area of the 5 mm and 8 mm diameter air vent holes. Nominal gaps between the center and outer plates measured 1.0 mm. Parallelism between the center and outer plates were within 0.08 mm at the extremes of pendulum travel. Air viscosity was less of an issue when the total vent hole area was greater than 15% of the total plate area (i.e. active area + vent hole area) for the given nominal gaps. Sensitivity was not adversely compromised.

ELECTRONICS

The electronic circuits were modularized according to their unique function within the overall system, for conveniently swapping out a board for an upgrade. There were three separate hand-wired boards, the Displacement Transducer Circuit Board, the Feedback Circuit Board and the Transducer Re-centering Circuit Board. Power came to the circuit boards from an off-the-shelf +/-12 VDC dual linear supply (1 amp per side). Most of the op amps, being reasonably cheap for their rated performance, consumed their share of the power. Measured totals were 96 mA from the positive supply and 84 mA from the negative supply. While running, the DC re-centering motor drew an additional 48 mA from either supply. The Displacement Transducer Circuit Board was mounted in its own aluminum project box, and the Feedback Circuit Board shared space with the Transducer Re-centering Circuit Board in another metal project box.

Circuits were constructed using metal film resistors with 1% tolerances, for all values up to 1 meg ohm. Larger values were carbon types with 5% tolerances. All power decoupling caps and feedback cap values under .01 microFarad were ceramic, all others >.01 mF were polyester. The circuits were built on perforated boards with sockets for all ICs. To reduce power rail noise, the power pins on all op amps were wired directly, or via 20-Ohm resistors, to a common point on the output pins of the voltage regulators.

For grounding, there was a small piece of adhesive backed copper foil 3 mm wide by 20 mm long attached to the underside of the perf board, centered between the rows legs of each socket. Decoupling caps and other components associated with the op amp requiring grounding were soldered to the piece of foil. Each foil was wired directly to a common ground point on the circuit board, no daisy chaining. Any flux residues built-up on the circuit board between conductors were scraped off the board as best as possible, to reduce potential signal leakage.

Please note; the author has had no formal electronics training, but gained the appropriate skills and knowledge after several years of building similar experimental projects.

DISPLACEMENT TRANSDUCER CIRCUIT BOARD (DTCB)

Adjustable voltage regulators U1 and U2 (see Figure 12) filtered and stepped down the voltage from the common supply, providing the circuits with +/-10 VDC. With 10 mF Tantalum capacitors connected to the regulators, better than 65dB ripple and spike rejection was possible. The IN4002 diodes protected the regulators from excess voltages during power down.

Function generator U3 produced a sine wave output signal at 5.4 KHz. Signal was filtered and buffered by op amp U4 with a 4X gain to increase P-P value. An audio transformer T1 (Digi-Key P/N 237-1121-ND) had 600-600 ohm center tapped coils which were referenced to ground for DC common-mode voltage rejection. The secondary coils produced two modulating signals, 180 degrees out of phase with each other and connected to the active areas on the SDC's outer plates, PA and PB, per the diagonally opposing pattern (described earlier in the paper) shown in Figure 13.

Op amp U5 is a zero-crossing detector referenced to ground for converting the AC sine wave into a sharp square wave, oscillating from 0 to +10 volts. Because the demodulator's analog switch U8 required a lower triggering voltage, a divider dropped its peak to +3.8 volts max. The active areas on the capacitor's moving center plates, PC and PD detected the modulated voltage signal's amplitude and phase, in proportion to its displacement in either direction from their null position. Op amps U6 and U7, both high impedance follower amplifiers at unity gain, drove guards (the coax shields) to reduce stray input capacitance for additional sensitivity. The input pins to these op amps were bootstrapped for circuit stability. Their outputs were fed into the analog switch U8, a demodulator synchronized with the sine wave signal from U4, monitoring the modulated voltage of each half cycle. Op amp U9 is an instrumentation amplifier (in-amp) with a 72X gain boosted the weak differentiated signal from the SDC. Op amp U10, a 34 Hz LPF, attenuated high frequency circuit noise prior to exiting the board.

Coax audio cables, half a meter long, were soldered to the SDC and connected to the circuit board via RCA phono plugs. The outer shields of the two outer plate's coaxes were attached to chassis ground. Due to the high frequency signals in this circuit, the metal structure that surrounded the SDC and the boards' metal enclosure (for RFI shielding) were connected to earth ground on the 115 VAC power supply via a low resistance conductor.

FEEDBACK CIRCUIT BOARD (FCB)

Adjustable voltage regulators U1 and U2 (see Figure 12), including their associated components were duplicated on this board to supply filtered +/- 10 VDC to the circuit.

Referring to Figure 14, op amps U11 and U12 together form an inverse filter. Appearing in some published articles written by Erhard Wielandt, was a feature labeled "inverse filter" [2] or "integrator" [6], shown attached to the displacement transducer in block diagrams representing the electronic circuitry of the STS-1 VBB seismometer. Erhard Wielandt kindly provided (via personal communications, 17 February 2003) the following explanation for this unique filter: "You want to have a high loop gain in the passband but due to unavoidable delays in the closed loop, the system may oscillate if high gain is maintained at high frequencies. So the loop gain has to be frequency-dependent, increasing towards

low frequencies. (It is anyhow frequency-dependent, but only with the inverse first power of frequency; you may want it to increase with a higher inverse power.) One way to realize this is to insert an integrator or quasi-integrator after the displacement transducer, another is to insert a filter whose response is inverse to that of the mechanical sensor. The latter option would be most appropriate when the mechanical sensor has a short free period. Since the closed-loop response is mainly determined by the feedback path, there is some freedom in choosing the response of the forward path, and the practical differences between the options are not dramatic." A circuit diagram closely matching the above description was uncovered in a paper by Wielandt [7], which was referenced in a paper by Wielandt and Streckeisen [8]. The inverse filter for the MkXVII had unity gain, to avoid feedback problems occurring within the filter's closed loop.

Signals passed through the unity gain differential amplifier U11, on their way to U12, a 2nd order Sallen-Key high pass filter (HPF) with unity gain, a Butterworth response and a corner frequency set at approximately 10 Hz. When a signal frequency exceeding 10 Hz went through the HPF, U12's output reached unity. The output of U11 dropped to zero voltage when the input voltage from U12 equaled the input voltage from U10, which occurred at frequencies greater than 10Hz.

The multi-path feedback circuit followed a schematic published by Sean-Thomas Morrissey for his vertical component VBB seismometer, the STM-8 [3]. His circuit design was based on a similar circuit found on Streckeisen STS-1 & STS-2 VBB seismometers. Multi-path feedback is a combination of differential and integral feedback signals flowing through the feedback transducer mounted on the pendulum. The differential signal dominates across the passband of interest, decreasing towards the lower frequencies where the strength of the integral signal increases. Reading the papers by Morrissey and Wielandt is highly recommended for their discussions on this subject. Resistor R_p and capacitor C provided the proportional feedback. The combined currents of R_p , C and R_I flowed through the feedback coil, modifying the pendulum motion for a BB velocity response. The capacitor, designated C, was a combination of individual Mylar caps soldered together in parallel.

U13 inverted the acceleration signal before it entered a composite integrator with unity gain, comprising of U14 and U15. The RC time constant of the 10 Meg resistor and the 2.7-microFarad capacitor at 27 seconds is the mathematical term T_I used in later calculations. A composite integrator [9] takes advantage of the high input impedance of a FET op amp combined with the DC output accuracy of a BJT op amp. Op amp U16 buffered this branch of the circuit when the displacement signal was monitored with a DVM. The Transducer Re-centering Circuit also monitored the displacement signal at pin 6 on op amp U15.

Buffer U17 prevented down stream loading of a .003 Hz (333 seconds) high pass filter that removed unwanted DC signal drift. Finally, op amp U18 with a 2X gain to drive a capacitive load created by a 30-meter long coax cable connecting the seismometer to the data logger, a PC fitted with an internal A/D card.

TRANSDUCER RE-CENTERING CIRCUIT BOARD (TRCB)

The TRCB was mounted inside the same metal enclosure that housed the FCB, sharing the FCB's two voltage regulators that were a duplication of U1 and U2.

This circuit constantly monitored the voltage level and polarity of the displacement output at pin 6 on op amp U15. Referring to Figure 15, op amps U19A and U19B buffered the circuits from the effects of the long period integrator (LPI), formed by the 2 meg resistor and 2X 1500 mF caps. The LPI's time constant of 1500 seconds, or 25 minutes, was enough to smooth out voltage spikes that would have constantly triggered the motor into action.

Op amps U20A and U20B are voltage comparators, to output >8 volts whenever the LPI exceeded voltage levels of +/-1.3 volts. Their high state outputs turned on transistor Q1, driving the input of a LM555 timer U21 low. For the next 52 seconds, the output of U21 remained high, causing transistor Q2 to activate a DPDT relay. One pole of the relay, REL 1A, drained accumulated voltage away from the large capacitors to re-set the LPI.

A momentary push button switch SW1 mounted on the metal enclosure was used at any time to manually override the function of the LPI, by driving the input of U21 low. As a visual indicator, an LED mounted on the outside of the metal enclosure lit up whenever the re-centering circuit was activated.

Like U19A, op amp U22 constantly monitored the voltage and polarity at pin 6 on U15. Power transistors Q3 and Q4 boosted the current output of op amp U22 to drive the DC motor at over 50 mA. Once activated, the relay pole REL 1B connected the motor MOT indirectly to the feedback circuit. By being able to track the circuit's polarity, the motor rotated in a direction necessary to null the displacement transducer. The 68K-feedback resistor increased the drive voltage to the motor for optimum speed. At the end of a 52-second timed cycle, the motor was once more isolated from the rest of the circuit.

BROADBAND VELOCITY OUTPUT SIGNAL

The accepted standard is to have a positive voltage signal coming from the vertical component seismometer when the ground moved upward. Lightly pushed down on the pendulum (equivalent to the ground moving upward) to verify a positive voltage signal at pin 6 on U10, U16 and U18. Initially a negative voltage signal resulted, requiring the wires to pins 1 and 2 on U8 to be reversed. Powering up the circuits again caused the pendulum to violently oscillate, but reversing the wires to the feedback coils restored stability.

Not shown in the electronic schematics was a simple 1:2 voltage divider, installed between the output of U18 and the A/D card, thus preventing it from receiving a voltage signal exceeding its rated input of +/- 5 volts.

TRANSFER FUNCTION

SYSTEM RESPONSE

The transfer function is a mathematical statement that describes the relationship between the input, a set of predetermined parameters, and the output of the system. Calculating a system's output can be a very difficult task. Fortunately the Mathcad file compiled by Morrissey for his STM-8 was made available for downloading [10], thereby saving a great deal of time and effort. Mathcad Standard 2000 software opened the file on a local PC. The STM-8's values were substituted with different ones, as you can see in Appendix A (Mathcad work sheet) at the end of this paper. Numerous values were tested for C, Rp, RI and TI, before settling on those below for an acceptable response:

Input parameters:

r = 152,559 V/m (this value was determined per the method explained below)
M = 0.588 Kg
C = 0.000017 Farads
Rp = 2 M Ohms
RI = 22 K Ohms
Gn = 20 N/A (this value was determined per the method explained below)
Rf = 300 Ohms
TI = 27 seconds
To = 1.0 seconds

Calculated system response:

Zeta = 0.76 (damping)
Tn = 20 seconds (closed loop natural period)
V/m/s = 1,739 (max sensitivity)

The plotted curve for the velocity response showed the high frequency end rolling off above 20 Hz (see Appendix A), but this was reduced to 10 Hz by the inverse filter, which is still an adequate range for the intended goal of teleseismic event detection.

DISPLACEMENT TRANSDUCER CONSTANT: V/M

The transducer's displacement constant Volts/Meter (V/M), was determined by measuring the voltage at pin 6 of op amp U10, as the pendulum was moved in approximately 0.0005" (0.0127 mm) increments about its null position, from one maximum voltage level to the other. A micrometer's spindle contacted the center of the seismic mass, a point located on the moving plate of the displacement transducer, 192 mm from the flexures. The collected voltage/displacement data points were then plotted on graph paper. Pushed the pendulum for a distance of 0.004" (0.1016 mm), well within the linear portion of the displacement transducer and roughly centered about the null position. Over this shorter measured distance the SDC transducer produced a total output of 15.5 volts, which equaled 152,559 V/M. Looking at the plotted data points, transducer linearity exceeded 85% of the range of travel, in either direction from null. Note: additional amplification of the seismic signal in later circuits caused signal saturation well before the linear range of the transducer was exceeded.

GENERATOR CONSTANT: Gn

This test set-up applied a small vertical force to the pendulum. First, the mechanism was leveled and the transducer roughly centered. Temporarily disconnected the feedback coil from the electronic circuit board and connected a DVM to pin 6 of op amp U10. Connected a 1.5 V battery, an on/off momentary switch, a mA meter (another DVM) and a 10K potentiometer in series with the feedback coil. Powered up the circuit, and then energized the re-centering motor with a power supply to null the transducer for 0 V at pin 6 of U10. Placed a small test weight of known mass at the center of the seismic mass (192 mm from the flexures), which was heavy enough to deflect the pendulum downwards over 0.5 mm. Now the battery circuit was turned on and the 10K potentiometer adjusted until just enough current flowed through the coil to null the displacement transducer, indicated by ~0 volts on the DVM connected to pin 6 of U10. Did not allow more than a few milliamps to flow through the coil, otherwise the coil could have burned out. Recorded the amount of current necessary to null the transducer as the test weight exerted its force.

The test mass was a paper clip measuring 0.0004331 Kg. Re-centering current was measured as 0.00021 Amp.

The generator constant, Gn, is defined in units of Newton/Amperes (N/A).

$N = \text{mass} \times \text{accel.} = 0.0004331 \times 9.8 = 0.004244 \text{ N}$

$G_n = N/A = 0.004244/0.00021 = 20.2 \text{ N/A}$

SEISMOMETER VAULT

Vault coordinates: Latitude: 47.849 N, Longitude: 122.328 W, Elevation: 110 meters

The seismometer was installed in a small surface vault squeezed between a 1.5-meter tall hedge and a 2-meter high wooden fence, in the backyard of a house located in a noisy urban environment. Vault was separated from bedrock by a 1.8 meter thick layer of unconsolidated backfill (16+ years of settling) and 200+ meters of glacial till.

Long period noise occurred when northerly or southerly winds struck the E-W aligned hedge and fence. Major levels of short period noise came from the N-S aligned railroad tracks located one kilometer west of the vault, where on an average day, twenty to thirty freight trains passed by. Large bodies of water to the west, the Pacific Ocean at a distance of 160 kilometers and the eastern shoreline of Puget Sound just west of the railroad tracks, generated noise (microseisms) with periods of 4-15 seconds, peaking in the autumn/winter months.

Inside the vault was a small rectangular pier, measuring 450mm wide x 800mm long x 250mm thick, cast from a 50/50 mixture of sand and cement (no aggregate) poured directly onto compacted earth. Styrofoam sheet, 75mm thick, isolated the pier from the vault's, 203mm thick, hollow concrete block walls. A hollow insulated plywood roof was hinged off one of the block walls to permit access to the vault's interior from the top. Styrofoam insulation 25mm thick lined the internal wall surfaces and 50mm thick sheets covered the external surfaces of the concrete block walls.

Under each leveling screw of the seismometer was a piece of smooth glass plate 40mm x 40mm x 5mm thick for reducing thermal noise and torsion forces necessary to operate the screws. Metal enclosures at chassis ground housing the electronics, were electrically connected to a common point on the metal enclosure of the dual power supply plugged into the 115 VAC mains outlet mounted on the inside wall of the vault.

Setting up the seismometer in the vault required adjustment of the three leveling feet using the spirit level on top of the enclosure. A momentary switch installed on the electronics' enclosure was briefly pressed to manually override the long period integrator for precise centering of the transducer using the internal motor. The re-centering cycle was activated manually several times, until the monitored output voltage of the integrator came within +/- 0.75 VDC.

Over the entire instrument (excluding electronics) was a polystyrene foam cover. The intent was to stratify the temperature of the air trapped inside the enclosure, minimizing convection currents. Five rectangular shaped pieces of 25mm thick sheet were permanently bonded together with wood glue. Seams were sealed with a second bead of adhesive to properly fill all gaps. Cable bundle from the seismometer passed through a snug fitting notch cut in the lower edge where it contacted the pier, at one end. The cover provided absolutely no RFI shielding for the transducer.

Output signal of the displacement transducer drifted enough to require a re-centering adjustment cycle to restore optimum performance once every 3-6 days, depending on outside temperatures. A temperature change of roughly 1.8 degrees C inside the plastic enclosure was sufficient to cause re-centering, recognized on the seismograms as a very large amplitude wave that slowly diminished back to normal behavior in approximately five minutes.

DATA PROCESSING

Collected data through an 8 channel, 16 bit, A/D card installed on the motherboard of a Gateway 486 DX2 66 MHz personal computer. Larry Cochrane of Redwood City, California USA, manufactured the card, model PSN-ADC-12/16 Rev 2. The card had a temperature-controlled oven for the clock crystal and a WWV time correction feature accurate to within +/-20 milliseconds when locked onto an appropriate frequency provided by a short wave radio receiver. One channel recorded the raw output signal (0.05-10 Hz passband, defined by the seismometer's internal filters) for detecting high frequency (short period) local and regional events. A second channel recorded data passband filtered at 0.007-0.10 Hz (high end controlled by a 3rd order 0.10 Hz Bessel LPF) for detecting long period teleseismic events.

Data was displayed and saved using Seismic Data Recorder (SDR) software, release 2.71, a DOS program written by Larry Cochrane that was loaded on the Gateway computer. Data was collected at a rate of 50 samples per second, time and date stamped by the software. Seismic events files were saved in PSN format for later analysis, at a lesser sampling rate for manageable file sizes.

WinQuake software, release 2.8.7, also written by Larry Cochrane, is a Windows based program used for analyzing the data files created with the SDR software. Features include distance calculations, FFT graphic displays, data filtering, data integration and much more.

SAMPLE SEISMOGRAMS

Attached to this paper are several seismograms (saved as GIF images using WinQuake software) starting at Figure 16. A portion of an on-line seismogram from station COR, Figure 18A, is compared to the seismogram from the MkXVIII, Figure 18B, since they were both at roughly the same distance from the event. The seismograms were made during the relative stormy months of January and February of 2004.

RESULTS

Without the appropriate test equipment and skills suitable for determining the instrument's sensitivity and noise levels, visual comparisons were made with near real time seismograms accessible on the WWW. Nearest on-line station displaying LP Z-axis data was PGC (operated by the CGS) located 124 km to the NW in Sidney BC, Canada. In a field adjacent to their facility, a Guralp CMG-3ESP BB seismometer provided data passband filtered to 0.01-0.07 Hz. Their noisy site produced seismograms with signal to noise ratios similar to the MkXVIII. Comparisons made with a Streckeisen STS-1 VBB seismometer at station COR (USGS), located 360 km to the south in Corvallis Oregon, proved more valuable. COR's LP seismograms were passband filtered at 0.01-0.05 Hz with high gain, to daily display many small teleseismic events. During favorable local weather conditions, the MkXVIII successfully detected several of the same small events.

Background noise levels on seismograms from the MkXVIII during an average day typically appeared to be 4-5 times higher than the levels shown on seismograms from COR. Lower noise levels may be encountered during summer when calmer weather conditions prevail. Difficult to compare data from an instrument supported by unconsolidated earth with one residing on solid bedrock sited some distance away.

CONCLUSIONS

Time spent to design, build and calibrate the mechanical assemblies totaled over 80 hours. Manually wiring electronic components on three perforated circuit boards, attaching hardware to the metal enclosures and system debugging/fine tuning was an extra 30 hours. Raw materials and electronic components had cost roughly \$250.

Quality of the instrument's construction, seen in the enclosed photos, left something to be desired. Loose hanging wires draped across the pendulum, including the long suspension springs, no doubt had resonances that contributed noise to fall within the frequency range of interest. Moving the mechanism without a mass lock may have slightly damaged the flexures, creating additional noise.

Limiting the instrument's low-end response to 0.05 Hz was a nuisance. If it had a full VBB response, a high order 0.05 Hz LPF could have effectively removed much of the annoying microseisms (above 0.07 Hz) to display LP data in greater detail, e.g. station COR. Attempts to broaden the response of the instrument from its current configuration to a lower frequency resulted in nasty humps forming at the ends of the velocity response plot, indicating circuit instabilities and non-linearity. To improve performance, the pendulum requires a mechanical natural period exceeding 5 seconds. Reduce the seismic mass to 0.3 Kg, held in equilibrium with a feedback transducer having a generator constant greater than 20 N/A. However the MkXVIII's overall performance, though nowhere near that of a professional seismometer, exceeded personal expectations.

ACKNOWLEDGEMENTS

The author is indebted to the late Sean-Thomas Morrissey who for several years generously shared his professional knowledge and experiences regarding seismometer theory, operation and installation, with subscribers to the Public Seismic Network (PSN), particularly the construction details of the STM-8. Professor Erhard Wielandt must be thanked for his mentoring and explanation of the inverse filter, an important feature that is not routinely discussed in the general texts.

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SUGGESTED READING

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Usher M. J. & Guralp C., 1978. *The design of miniature wideband seismometers*. Journal of Geophysics, **48**, 281-292.

FIGURES



FIGURE 1

THE MkXVIII SESIMOMETER

(White colored rule is approx. 30 cm long. Centimeter graduations can be seen along its near edge)



FIGURE 2

ACCESS PLATE WITH WIRE FEED THROUGHS, ON THE END OF THE ENCLOSURE



FIGURE 3

PLAIN END PLATE (CLEAR PLEXIGLAS) ON THE ENCLOSURE



FIGURE 4

EMPTY ENCLOSURE, ACCESS PLATE REMOVED

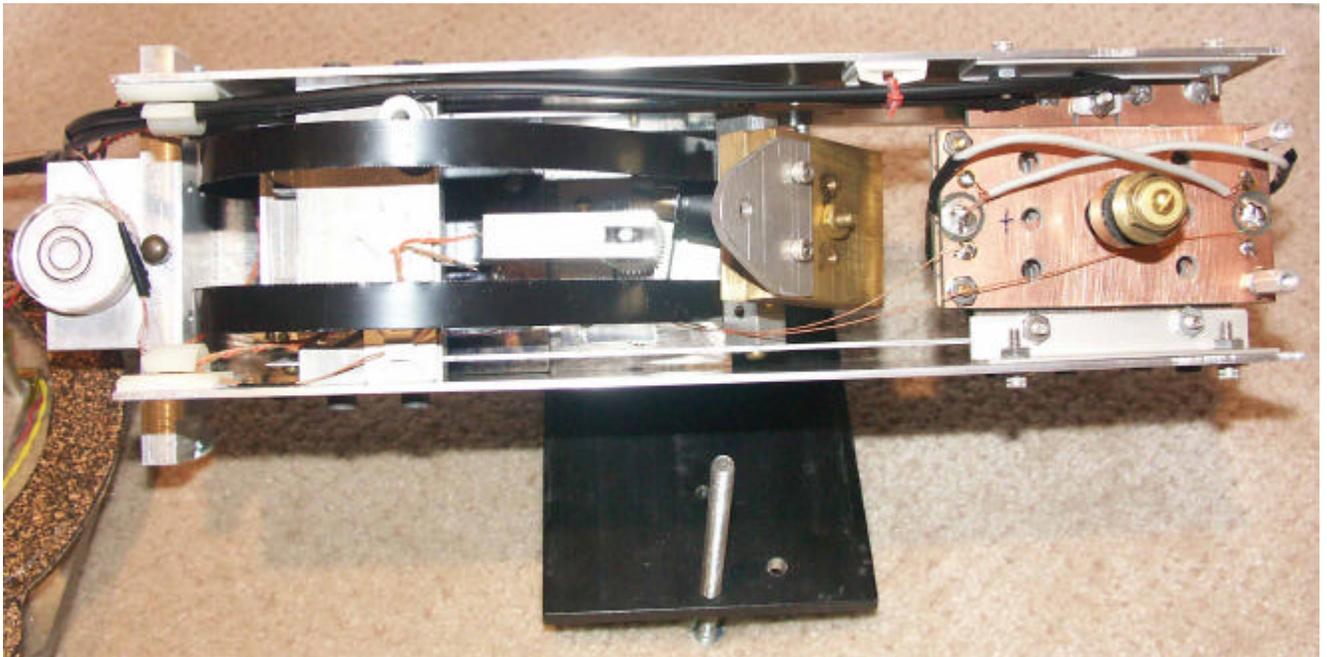


FIGURE 5

TOP VIEW OF THE INTERNAL MECHANISM

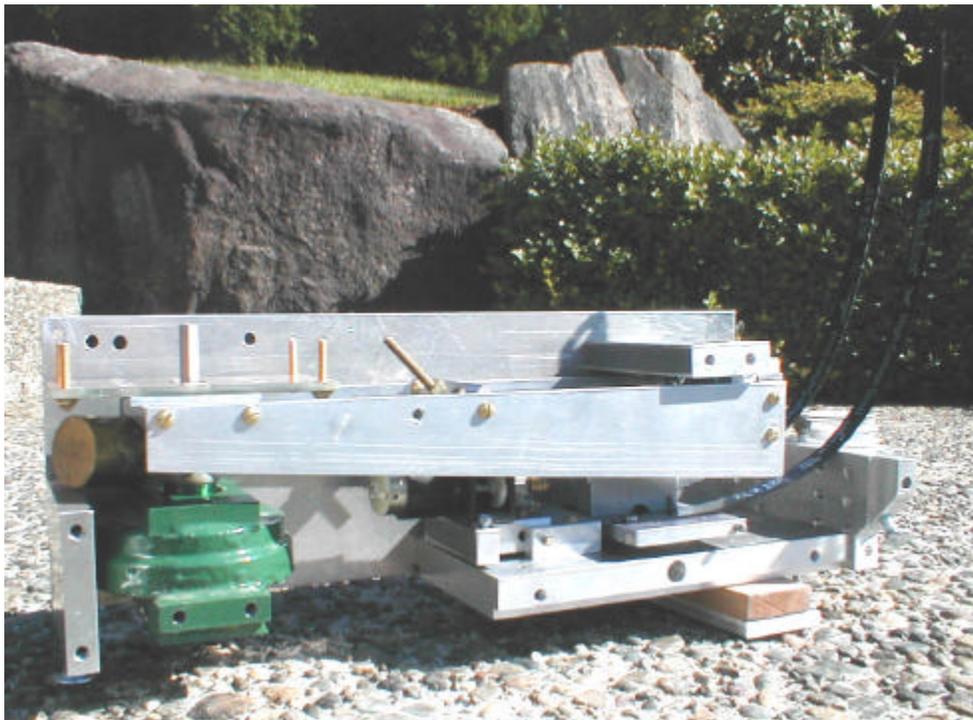


FIGURE 6

SIDE PLATE REMOVED, EXPOSING MECHANICAL DETAILS

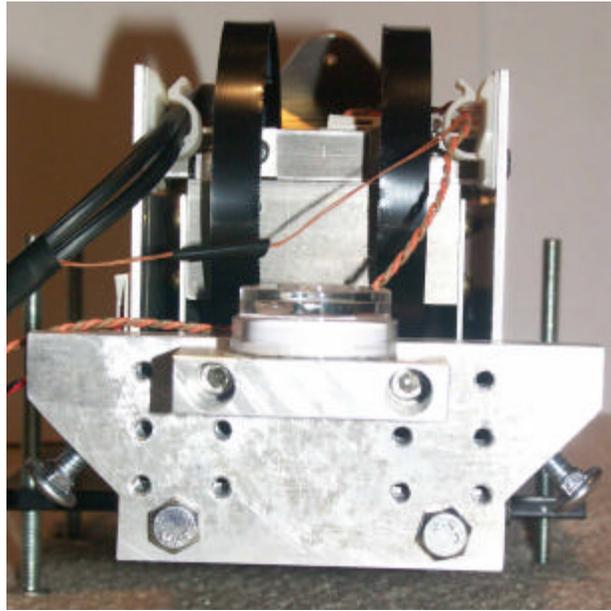


FIGURE 7

SUSPENSION SPRING END OF THE MECHANICAL ASSEMBLY

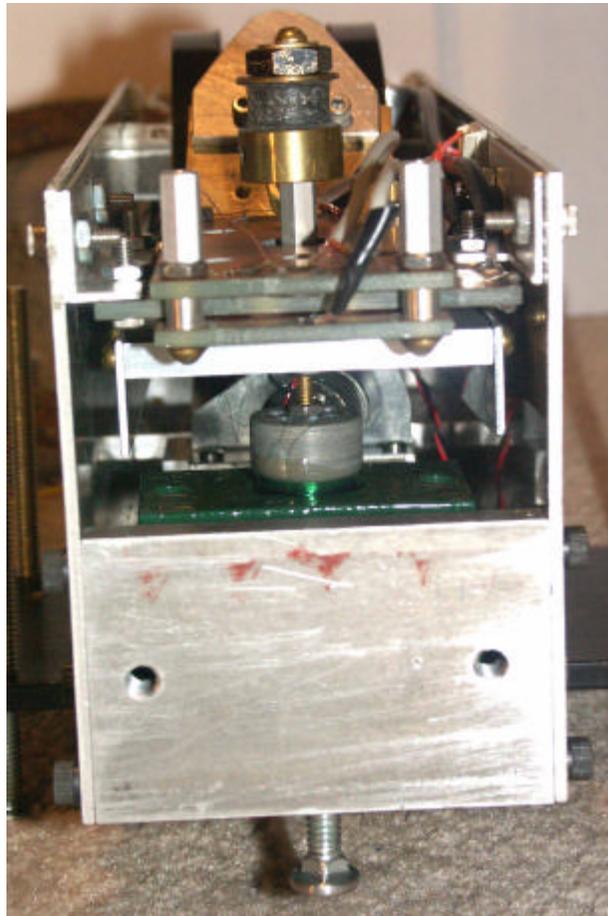


FIGURE 8

TRANSDUCER END OF THE MECHANICAL ASSEMBLY

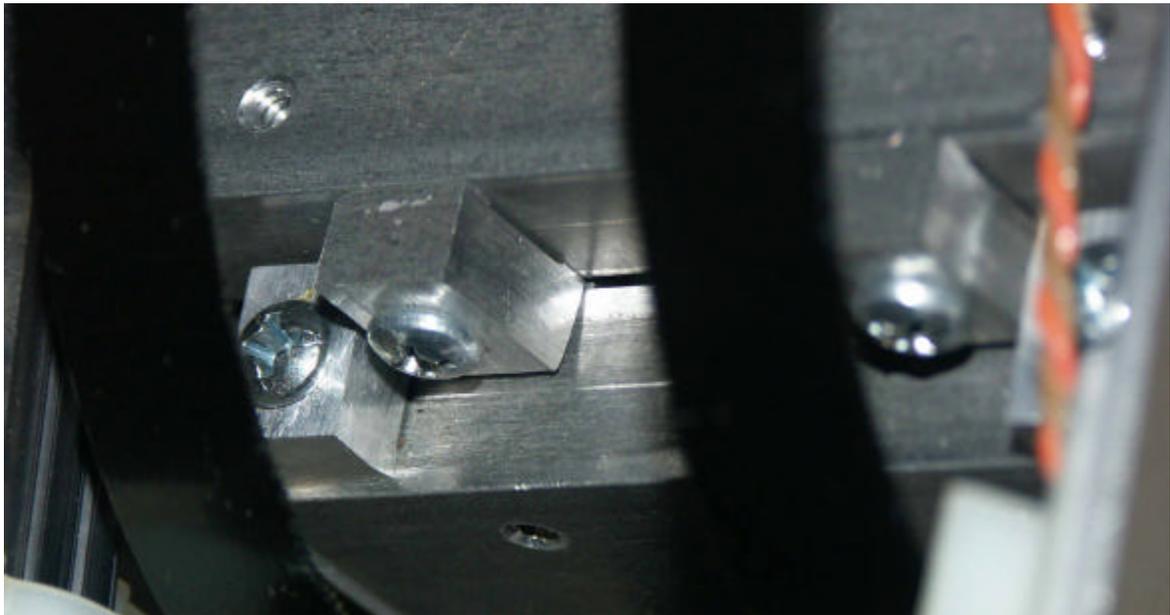


FIGURE 9

PENDULUM HINGE AND CLAMPS

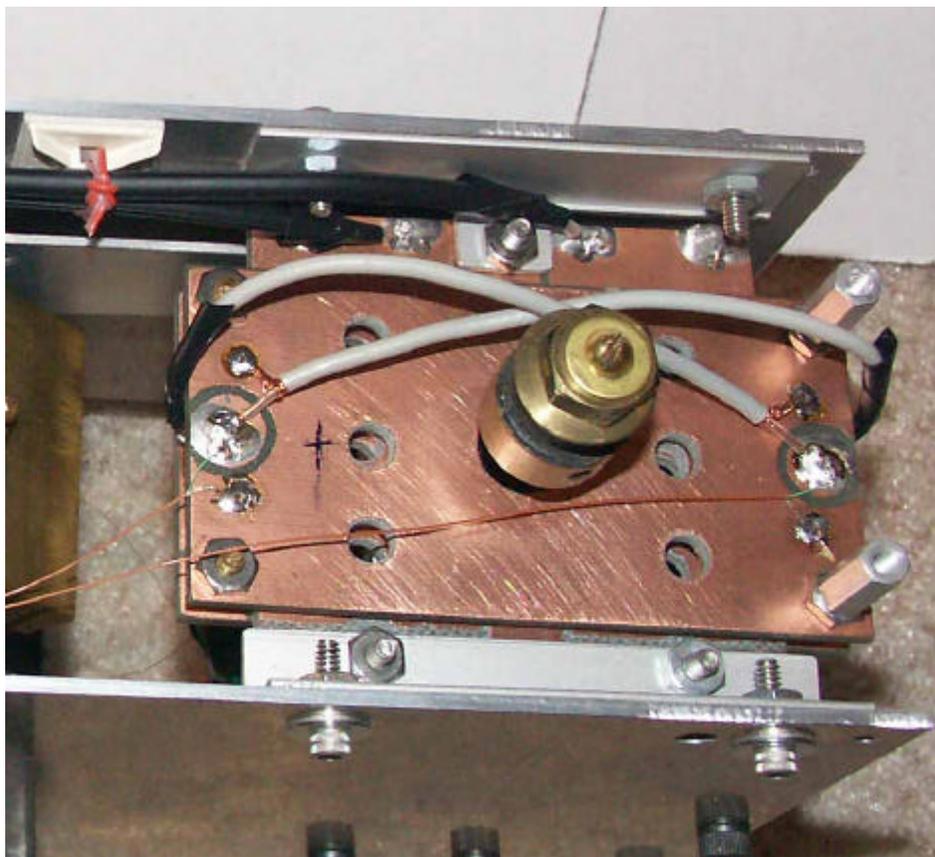
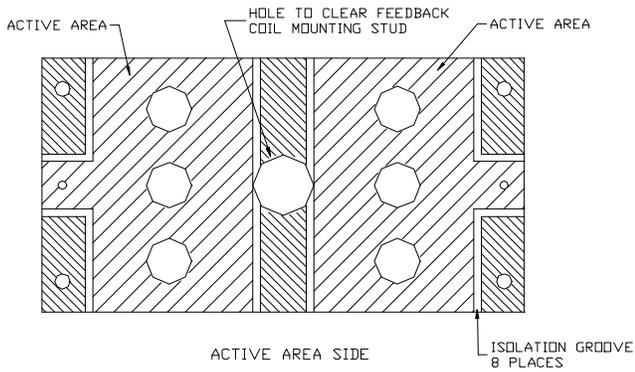
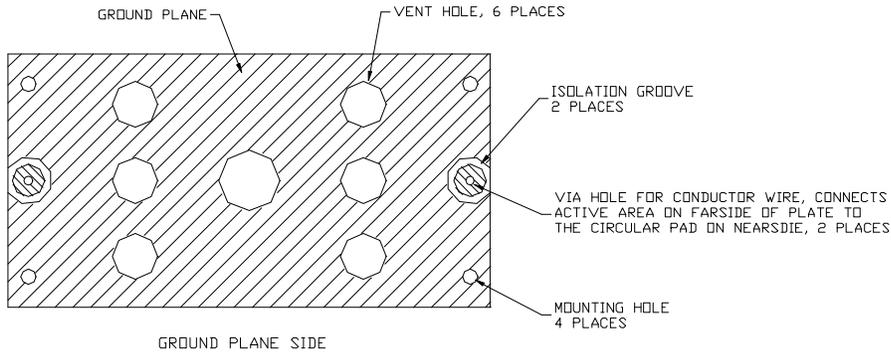
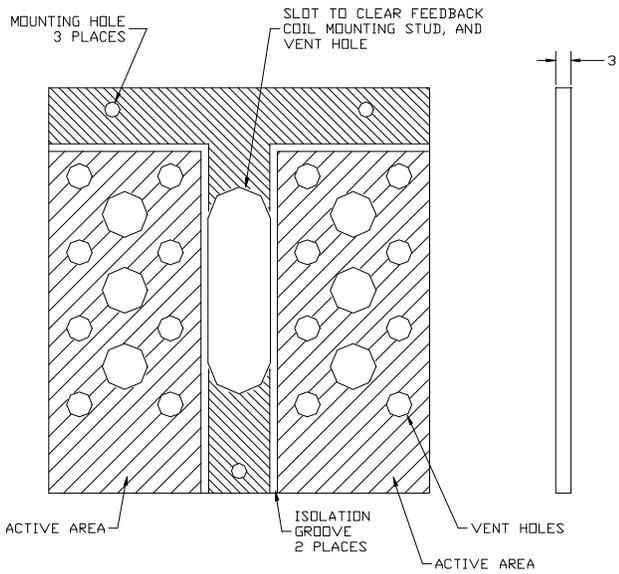
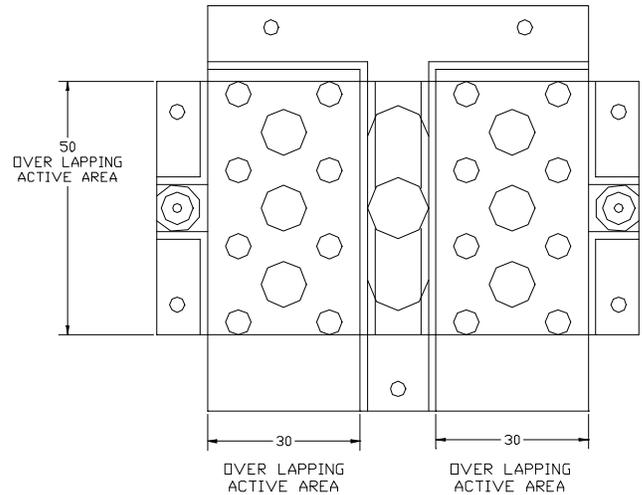


FIGURE 10

TOP VIEW OF THE DISPLACEMENT TRANSDUCER



OUTER PLATE
(2 REQUIRED)



(ACTIVE AREA/ISOLATION GROOVE PATTERN IS IDENTICAL ON BOTH SIDES OF THIS PLATE)

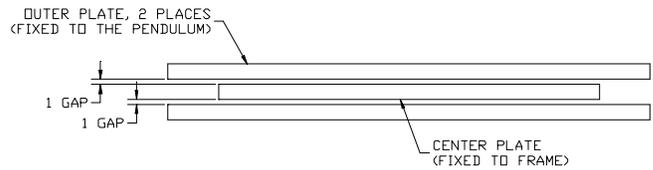
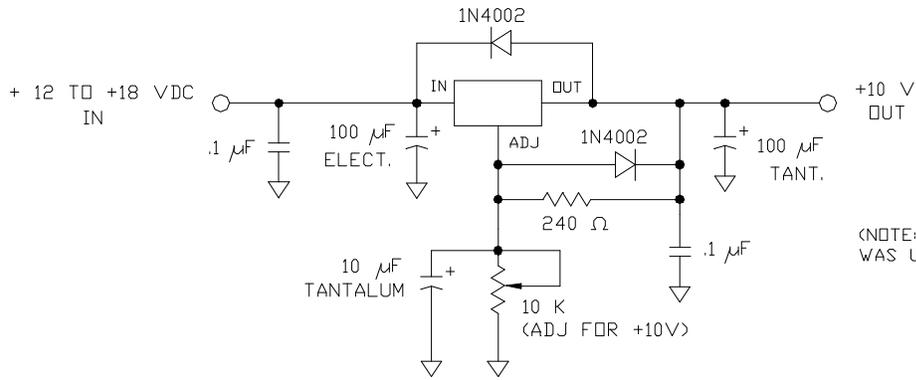


PLATE ASSEMBLY

(ONLY THE PLATES ARE SHOWN FOR CLARITY
NO MOUNTING HARDWARE SHOWN)

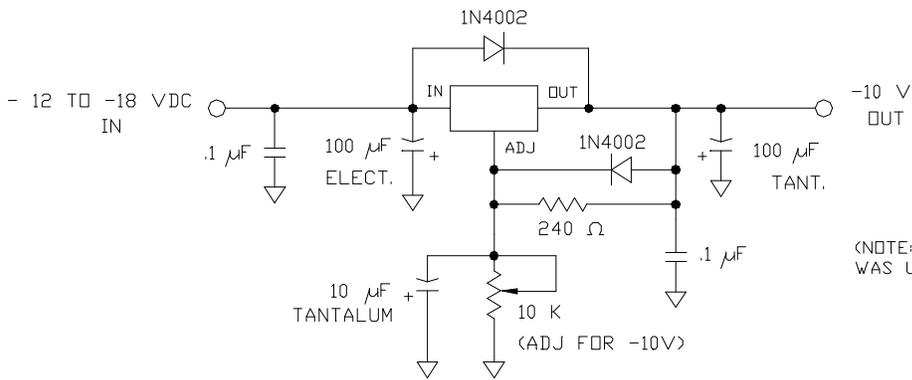
FIGURE 11
CAPACITOR PLATE DETAILS

REVISED 30 DECEMBER 2003



(NOTE: THIS VOLTAGE REGULATOR WAS USED ON THE DTCB AND FCB)

U1
LM317



(NOTE: THIS VOLTAGE REGULATOR WAS USED ON THE DTCB AND FCB)

U2
LM337

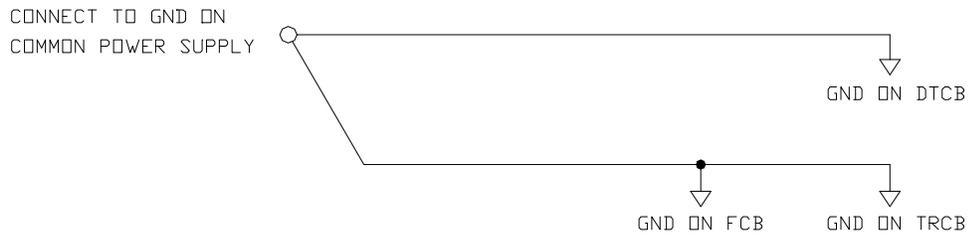


FIGURE 12
VOLTAGE REGULATOR CIRCUITS

REVISED 30 DECEMBER 2003

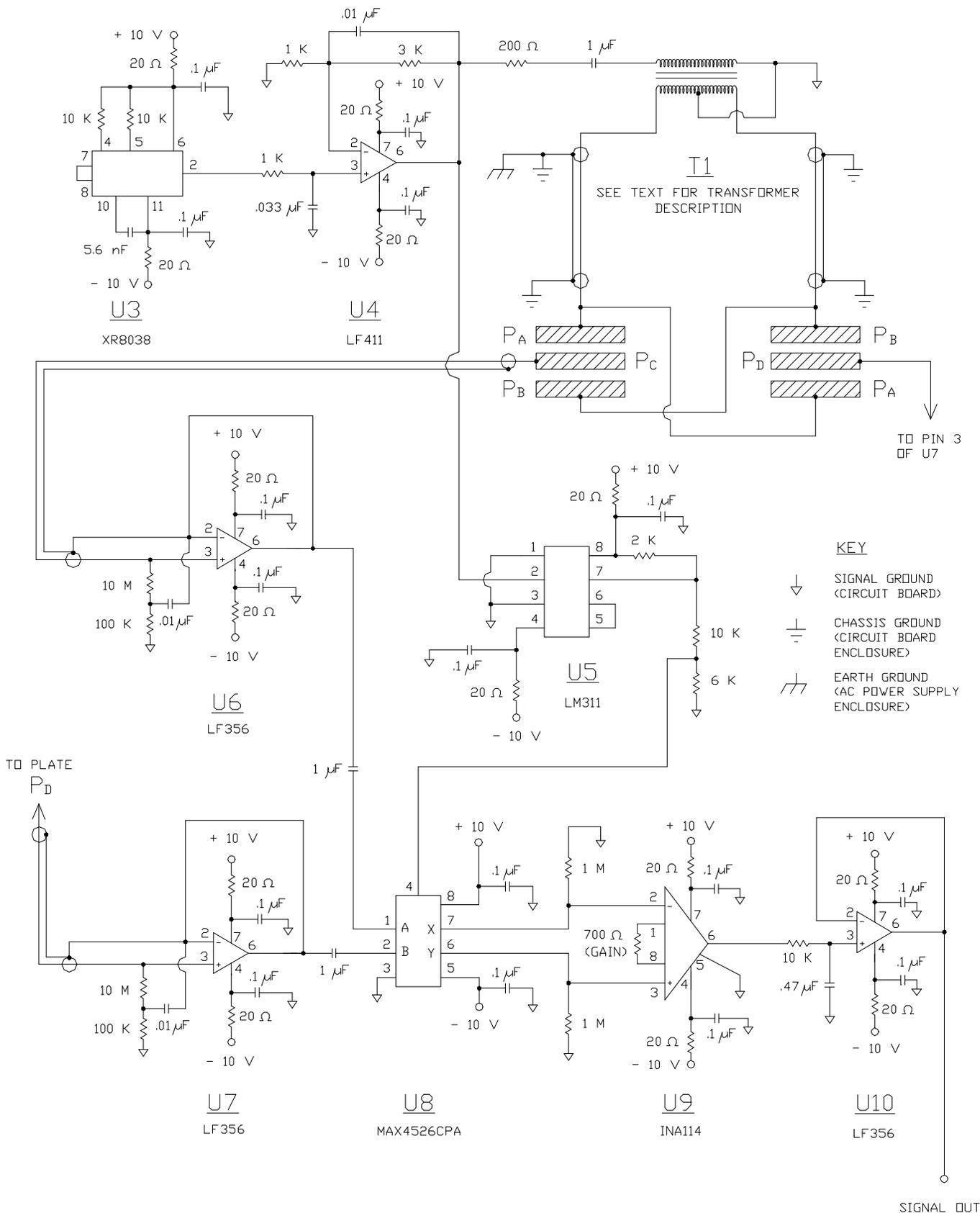


FIGURE 13
 DISPLACEMENT TRANSDUCER CIRCUIT BOARD (DTCB)
 REVISED 30 DECEMBER 2003

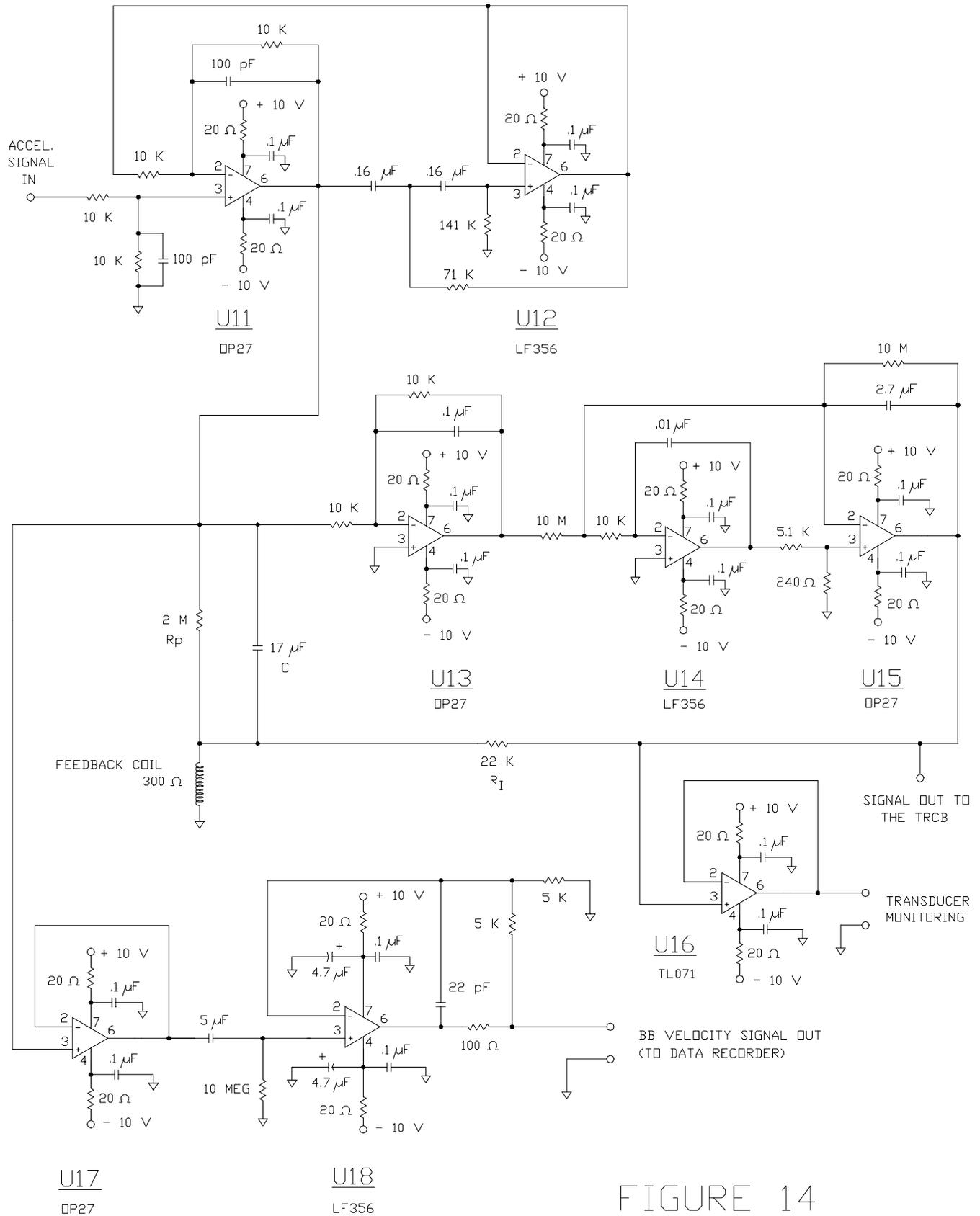


FIGURE 14
 FEEDBACK CIRCUIT BOARD (FCB)
 REVISED 30 DECEMBER 2003

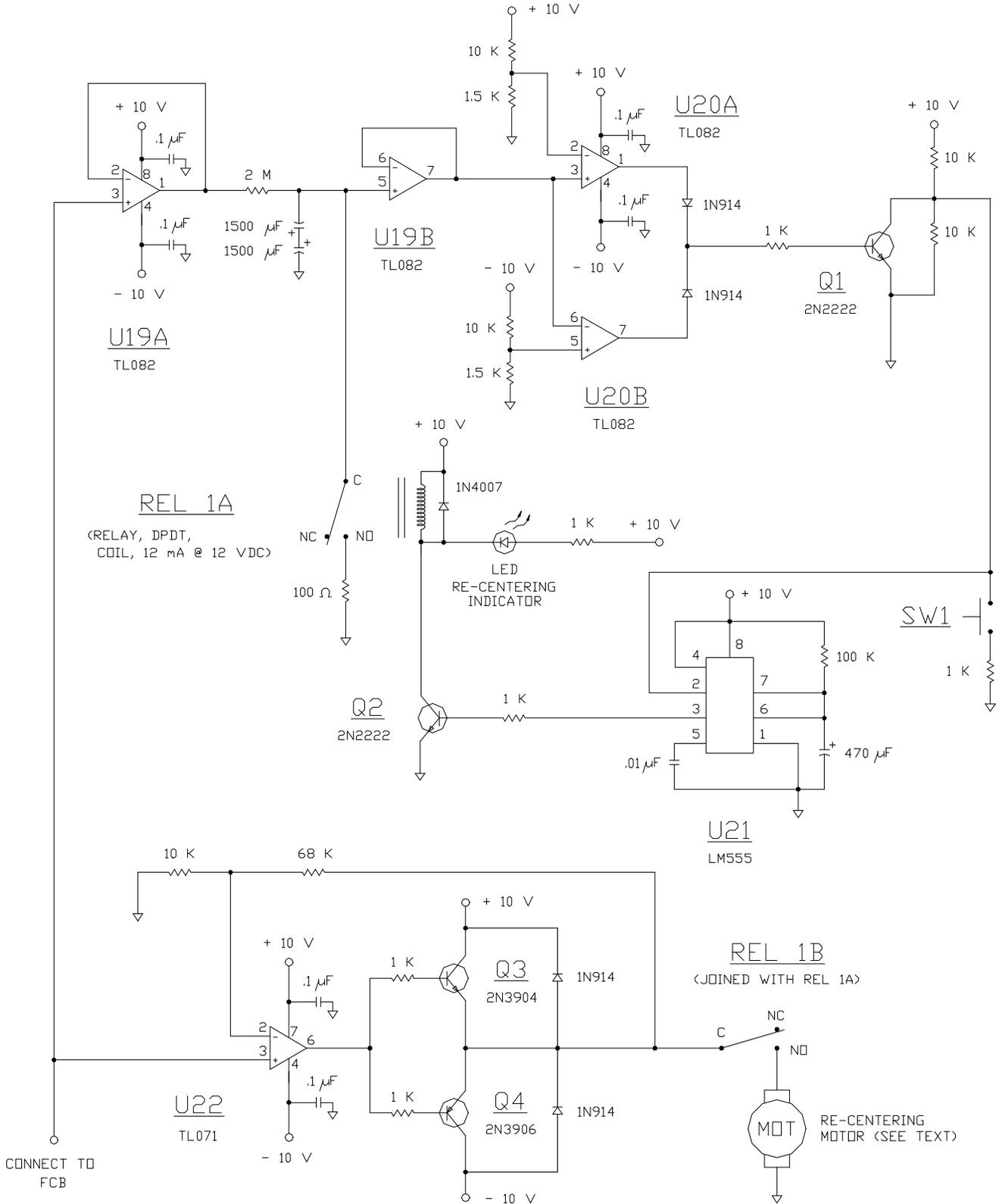


FIGURE 15
 TRANSDUCER RE-CENTERING CIRCUIT BOARD (TRCB)

REVISED 30 DECEMBER 2003

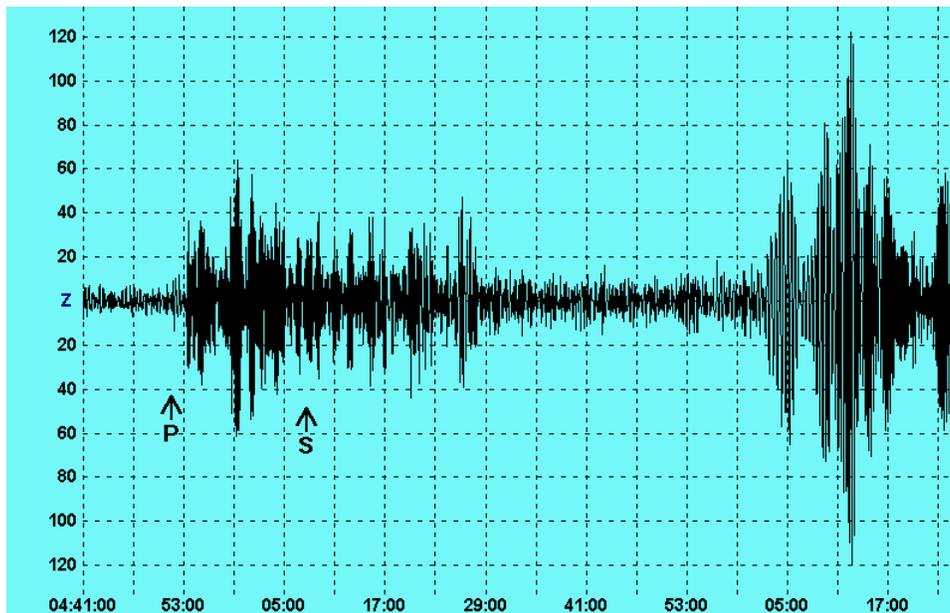


FIGURE 16
SEISMOGRAM: SOUTH INDIAN OCEAN, Mb 6.1

Origin date and time: 2004/01/11, 04:32:49 UTC
 Event coordinates: 36.68° S, 53.19° E, 10 km deep
 Distance: delta = 168°, 18,720 km
 Passband: 0.03-0.10 Hz, 16th order roll-off at each end.
 UTC time indicated across the bottom of the seismogram. Vertical grid spaced at 6-minute intervals.

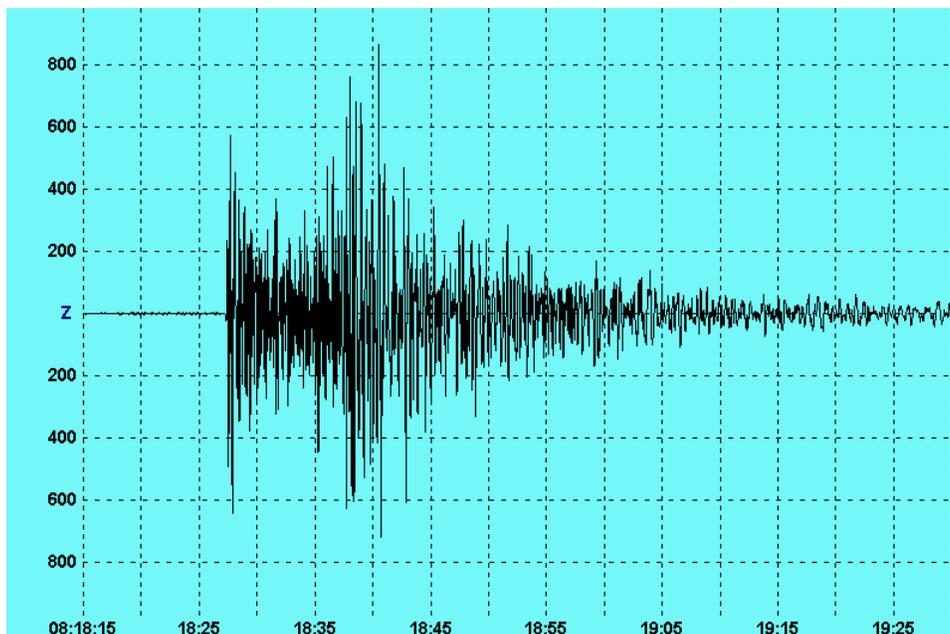
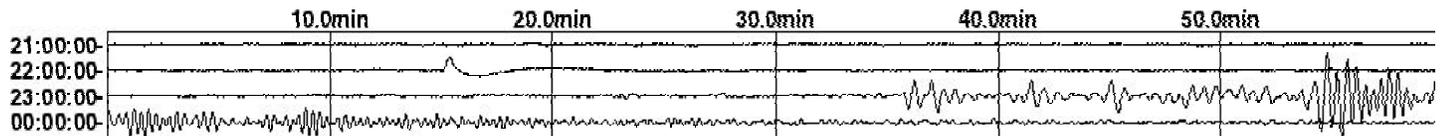
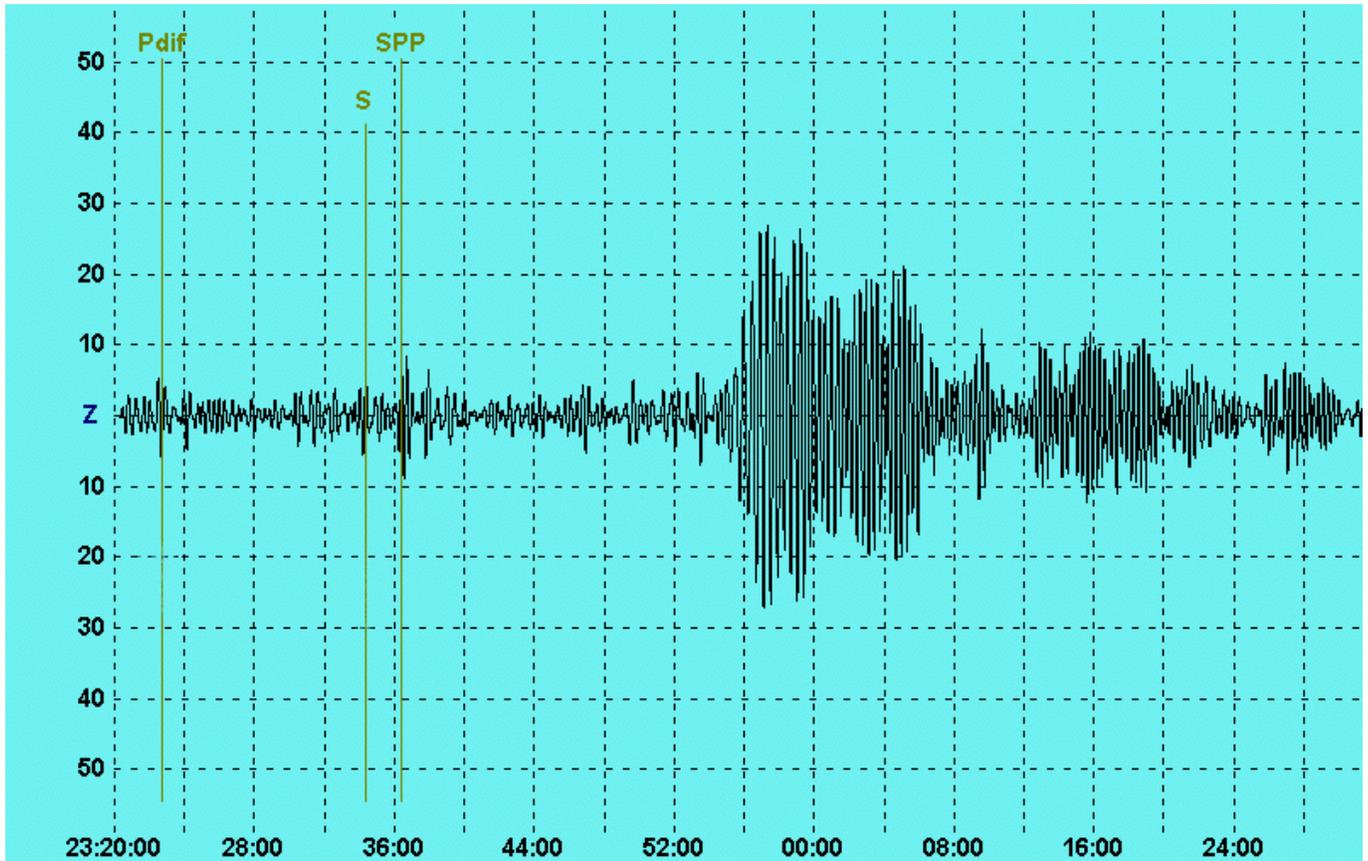


FIGURE 17
SEISMOGRAM: SEATTLE-TACOMA AREA, WASHINGTON USA, Md 3.6

Origin date and time: 2004/01/16, 08:18:18 UTC
 Event coordinates: 47.57° N, 122.58° W, 54.5 km deep
 Distance: delta = 0.325°, 36.1 km
 Passband: 1-10 Hz, 16th order roll-off at each end.
 UTC time indicated across the bottom of the seismogram. Vertical grid spaced at 5-second intervals.



(A)



(B)

FIGURE 18
SEISMOGRAM: IRIAN JAYA, INDONESIA, Mw 5.8

Origin date and time: 2004/02/03, 23:09:30 UTC
Event coordinates: 3.72° S, 140.34° E, 33 km deep

Figures 18A and 18B compare the performance of a VBB seismometer at a low noise site, to that of the MkXVIII. Both seismometers located at a similar distance from event. The MkXVIII has the higher passband filters.

FIGURE 18A: ON-LINE SEISMOGRAM FROM STATION COR, CORVALLIS OR, USA
Station COR, Corvallis Oregon. Delta to event = 97.1°
Streckeisen STS-1 VBB vertical component seismometer, seismogram low pass filtered to 0.05 Hz.
UTC time indicated across the top of the seismogram.

FIGURE 18B: SEISMOGRAM PRODUCED BY THE MKXVIII SEISMOMETER, EDMONDS WA, USA
Distance: delta = 97.6°, 10854 km
Passband: 0.033-0.06 Hz, 10th order roll-off at each end.
UTC time indicated across the bottom of the seismogram. Vertical grid spaced at 4-minute intervals.
Comments: Waves Pdif and SPP (?) appear on both seismograms at approximately the same time.

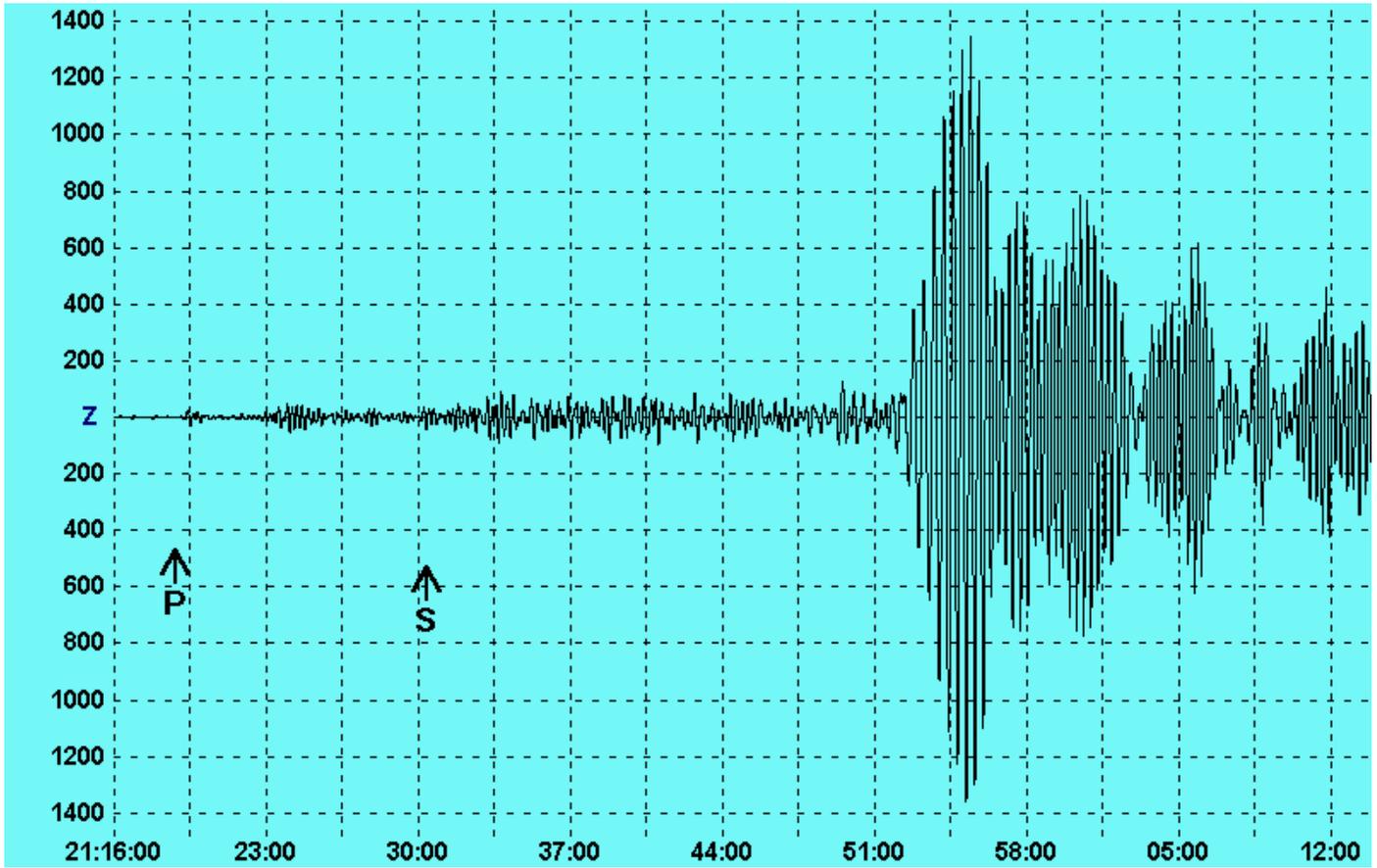


FIGURE 19
SEISMOGRAM: IRIAN JAYA, INDONESIA, Mw 6.8

Origin date and time: 2004/02/05, 21:05:02 UTC

Event coordinates: 3.59° S, 135.55° E, 10 km deep

Distance: delta = 100.8°, 11206 km

Passband: 0.03-0.07 Hz, 6th order roll-off at each end.

UTC time indicated across the bottom of the seismogram. Vertical grid spaced at 3.5-minute intervals.

Generalized Equation:
$$Y_i := \frac{1}{G \cdot C} \cdot \frac{s_i \cdot (1 + s_i \cdot C \cdot R_F)}{(s_i)^4 \cdot \left(\frac{R_F}{r \cdot G}\right) + (s_i)^3 \cdot \left(\frac{1}{r \cdot G \cdot C}\right) + (s_i)^2 + s_i \cdot \left[\frac{(S\omega_0)^2}{r \cdot G \cdot C} + \frac{1}{C \cdot R_p}\right] + \frac{1}{C \cdot R_I \cdot T_I}}$$

Setting Constants: $k := \frac{1}{G \cdot C}$ $n := (C \cdot R_F)$ $a := \frac{R_F}{r \cdot G}$ $b := \frac{1}{r \cdot G \cdot C}$ $c := \frac{(S\omega_0)^2}{r \cdot G \cdot C} + \frac{1}{C \cdot R_p}$ $d := \frac{1}{C \cdot R_I \cdot T_I}$

$i := 1, 2, \dots, 600$ $f_i := 10^{(i-300) \cdot 0.01}$ $\omega_i := 2 \cdot \pi \cdot f_i$ $s_i := j \cdot \omega_i$ $s_{200} = 0.6283i$

Evaluating:
$$A_i := k \cdot \left[\frac{s_i \cdot (1 + s_i \cdot n)}{(s_i)^4 \cdot a + (s_i)^3 \cdot b + (s_i)^2 + s_i \cdot c + d} \right]$$

$vel_i := \text{Re}(A_i \cdot s_i)$ $\text{maxv} := \text{max}(vel)$

Ref. line, V/m/s: $\text{maxv} = 1.7395 \times 10^3$

Marking effective periods: $F_I := \frac{1}{T_I}$ $F_n := \frac{1}{T_n}$

