

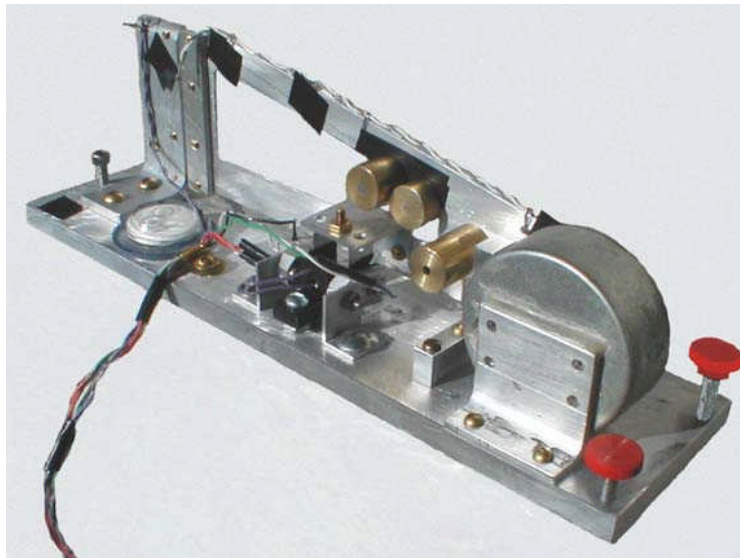
An Amateur Optoelectronic Horizontal VBB Seismometer

(Model Mk XI)

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Design revised: 12 June 2001

Web based paper was converted 12 January 2006 into a MS Word document (some text clarified).



OVERVIEW:

This document describes an amateur, designed and built, seismometer. The original design objectives of this project were: (1) to produce an instrument whose performance meets or exceeds that of a conventional long period electromagnetic velocity seismometer used for detecting regional and teleseismic events, (2) must be a small package, and (3) practical to make. The finished seismometer's overall dimensions were: 75mm wide, 300mm long and 95mm high. A horizontal component design, rather than a vertical component, was selected because it was initially determined to be easier to fabricate and maintain.

After reconfiguring the mechanics and electronics three times, a successful compromise was finally achieved. The first two configurations were force-balance accelerometers with their output signals integrated to derive a velocity signal. At high gain settings, the outputs of the accelerometers were found to be easily saturated by local cultural noise. To overcome that problem, the current configuration used a triple feedback scheme to produce a Very Broadband (VBB) output signal flat to velocity over a wide pass band. An optical displacement transducer was common to all three designs. Experiments using optoelectronics with variable apertures began in 1995, which developed into the design presented here. Optical methods of position detection based on photon counting do not have the ultimate resolution of a LDVT, variable reluctance or variable capacitance device. While this seismometer is not up to full professional VBB instrument standards, the results proved adequate for this amateur's needs. As seen in the Figures, the Opto Seismo had been modified a number of times. Several design short cuts were taken to keep the mechanical components relatively simple. Several sample seismograms, made by this seismometer, are included as Figures towards the end of the paper.

The paper provides only a very brief description of how the instrument was made. It is assumed that the reader has a basic theoretical understanding of how such mechanical devices and electronic circuits operate.

SYSTEM:

General Description:

The seismometer's pendulum traveled horizontally relative to the base, in proportion to the motion of the ground beneath it. The pendulum's displacement transducer produced three different feedback signals, which were combined to drive a feedback motor coil, also attached to the pendulum. This modified the pendulum motion, to produce a VBB velocity output signal. No additional analog response shaping filters were needed outside the feedback loop, as would be necessary to derive a velocity signal from the output of an accelerometer. The VBB velocity signal was recorded both digitally and as an analog ink tracing on paper.

VBB Response:

This important feature of the seismometer was based on the work done by Sean-Thomas Morrissey of Saint Louis University. He invented the "STM-8" VBB vertical component seismometer. An extensive description of its design, fab and calibration can be found on his Web page at: <http://www.eas.slu.edu/People/STMorrissey/index.html> Follow the links at the top of his index page. A copy of his Mathcad program, used to design and calculate the seismometer's transfer function, was down loaded from: http://www.eas.slu.edu/People/STMorrissey/etc_export Click on the Mathcad file: [tstvbb08.mcd](#). Sean-Thomas' broad in-depth knowledge regarding seismic instrumentation has been shared with subscribers of the Public Seismic Network (PSN) based in Redwood City California, starting back in Q4 of 1997. This valuable information has been archived by Larry Cochrane on the PSN's Web site at: <http://psn.quake.net/maillist.html#archives>

For VBB instrument design theory, Prof. Erhard Wielandt at the University of Stuttgart, has written an authoritative paper "Seismic Sensors and their Calibration", available on-line at: http://www.geophys.uni-stuttgart.de/seismometry/man_html/index.html

ELECTRONICS:

Theory of Operation:

Referring to Figure 1, Voltage Regulation, the power supply voltage regulators LM317 and LM337 (U1 & U2 respectively) have better than 85 dB ripple and spike rejection when fitted with 20 microfarad Tantalum capacitors. The IN4002 diodes protect the regulators from excessive voltages during power down.

Referring to Figure 2, Feedback Schematic, the system's VBB output basically begins at the displacement transducer. When horizontal ground motion causes relative movement between the suspended mass (the pendulum) and base plate, two small apertures vary in size. Energy from a common incandescent lamp L1 passes through the apertures to illuminate two photodiodes, D1 & D2. The difference in the two currents flowing through the photodiodes are detected by a low in-put current FET op-amp IC1, and converted into a voltage signal. Feedback capacitors C1 and C2 reduced high frequency feedback to 7.2 Hz. See the section titled Displacement Transducer for complimentary information. IC2 is a non-inverting amplifier with a 11X gain, used to boost the relative weak voltage signal. Together, resistor R6 and capacitor C3 acted as a 1st order low pass filter with a corner frequency set at 16 Hz, for additional noise reduction.

The acceleration signal from the displacement transducer is directed into two separate circuits. One is for the all important feedback signal, entering it through IC3. An integrator, IC4, with a time constant of 100 seconds, provided the integral feedback and is the term TI in transfer function equations. Its roll off frequency occurs at .00016 Hz, well below the built-in high pass filter found further down stream in the circuit. IC5 inverts the output of the integrator. Morrissey recommended the use of a top quality op-amp configured as a 1st order low pass filter with its RC time constant set the same as the integrator, and this would eliminate the need for IC5. This portion of the circuit also contains the proportional feedback resistor Rp, and the feedback capacitor C (consisting here of two capacitors to provide the necessary value), which are more terms in the transfer function. The combined currents of C, RI and Rp flow through the feedback coil mounted on the pendulum. Pin 6 of IC2 provides the required VBB velocity output signal. But before recording it, some additional filtering was necessary. IC6 is a buffer to prevent loading of the .007 Hz high pass filter, used to remove DC drift. Buffer IC7 prevents downstream circuit loading of the 3 Hz low pass filter, used to reduce the unwanted cultural noise to an acceptable level. The transfer function indicated an approximate 10 Hz roll off when using the selected component values, but it is the feedback capacitors on IC1 that limited the high end frequency response to 7.2 Hz. Finally, IC8 was configured as the cable driver to the signal recording device, with a fixed gain of 2.

Not shown in the electronic schematics was a simple 1:2 voltage divider between the output of IC8 and the input port of the A/D card. This prevented the A/D card from seeing an input voltage signal exceeding +/- 5 Volts.

The circuits were wired to a commercial dual linear power supply with +/- 12 VDC outputs. It was an open chassis unit that required a grounded outer metal enclosure to prevent accidental contact with the 115 VAC mains supply. Approximately 100 milliamps were drawn from each supply.

To ensure optimum performance from the op-amps and minimize circuit noise, many components had to be grounded to a common point (designated as C.P.) close to where the ground wire entered the circuit board. Those components identified in Figure 2, Feedback Schematic, had a dedicated very low impedance conductor connecting it to the C.P. All the other grounded items were connected through less direct routes.

All the ICs were installed in sockets. Filter capacitors with values less than 3 microfarads were Mylar, greater values were electrolytic unless specified otherwise. Power supply decoupling caps were ceramic. All resistors were precision metal film (1% tolerance), except for power and values greater than 1 Meg Ohm. The 100 Meg Ohm resistors R2 and R3 had 1% tolerances, and were obtained from Newark Electronics (Stock No 19C8051). Components with the reference designators Rp, RI, and C were installed in such a way to be easily replaceable during calibration.

DISPLACEMENT TRANSDUCER:

Theory of Operation:

Two apertures vary in size in proportion to the relative motion between the pendulum and base plate, in the classic push-pull arrangement. As the pendulum moves from its position of equilibrium, one aperture reduces in area as the other increases. Light from a single incandescent lamp (a common energy source) fell on two photodiodes, one located behind each of the two small variable apertures. The two photodiodes (EG&G VACTEC, P/N VTB8441B), D1 and D2, have an active area of 5.16 square mm. Each half of an aperture was attached to the side of the pendulum with the other mating half fixed to the base. With the pendulum at rest, both apertures were partially open. Photodiodes have good linearity (when compared to phototransistors), quietness and sensitivity when configured in the photovoltaic mode.

A miniature screw base incandescent lamp (Radio Shack, P/N 272-1143) L1, received its power from the +10VDC regulated supply rail via a power resistor R1. The resistor in series with the lamp reduced the current, giving the bulb an almost infinite life as well as controlling the level of light falling on the photodiodes. The use of a single centrally located lamp as a light source smoothed out power supply fluctuations, greatly reducing random high period noise as both photodiodes saw the exact same light level simultaneously.

The output voltage of IC1 varied in proportion to the displacement of the pendulum, in either direction from its equilibrium position. When a force was applied by the feedback transducer on the pendulum, the photodiodes are exposed to very small changes in light levels. A single aperture/photodiode operating on its own would produce a non-linear response to ground motion. Using two photodiodes as a differential pair gave very satisfactory results. Its accuracy highlighted problems in the measuring tool, a cheap imported micrometer. Linearity was plotted to be within 2% over a range of +/- 7 volts.

These photodiodes are VERY sensitive to the stray AC radiating from unshielded 115 VAC mains lines. Because the photodiodes were not protected by a dedicated RFI shield, a large amount of AC noise was clearly visible superimposed on the seismic signal when the instrument was being tested on the workbench inside the house. When the instrument was installed in a small surface vault approximately 12 meters away from the house, the AC interference was reduced to a level indistinguishable from the normal background cultural noise.

Construction Details:

The upper portion of Figure 3 shows how the two different photodiode block assemblies were made. The fixed half of the aperture was cut from a piece of an aluminum beverage container. Blocks of aluminum were drilled with a 3/16" drill bit to furnish a close fit with an alignment pin (more about it later), then counter-bored to 5/16" to receive a photodiode. An alignment pin was cut from a piece of #10-32UNC threaded rod. One end of it was turned down to the diameter specified in the sketch using a file, while it rotated in a drill chuck. The alignment pin temporarily located the V notch in the fixed aperture halves, while the epoxy that bonded the alum foil (with V notch) to the aluminum blocks was curing. Finally, the surfaces of the block assemblies which were exposed to the light source were painted matte black to reduce the amount of stray, reflected light. The central detail of Figure 3 shows how the moving half of the aperture was made. Another piece of an aluminum soft drink can was cut and bent to the shape illustrated. It too was painted matte black to reduce light reflection. Care was taken to not allow paint to build up in the corners of the V shaped notches.

Electrical wires were soldered directly to the lamp itself. This is a bad practice which could have permanently damaged the lamp. It is highly recommended to screw the lamp into a dedicated holder (Radio Shack P/N 272-358, Lamp Base). This holder, or lamp base, accepts any lamp with an E-5 screw base.

Set-up:

The RH and LH photodiode block assemblies were mounted on the instrument's base plate, and the moving half of the aperture attached to the side of the pendulum. See the transducer detail at the bottom of Figure 3. The ballpark distance between the two-photodiode block assemblies was 20 mm.

A simple but effective method was used to set the two apertures with nominal openings simultaneously. First, the pendulum was clamped at its center of travel using the adjustable stop screws, without the photodiodes and lamp installed. Second, to gage the openings a straight piece of wire 1 mm diameter by 50 mm long passed through both apertures at the same time. The wire had to slide snugly through both openings without rattling around. The aluminum blocks of the photodiode assemblies were adjusted to achieve the desired fit while maintaining a gap of 0.1-0.7 mm between the outer surface of the moving half of the aperture and the photodiode assemblies. To test alignments, the pendulum remained clamped in place using the stop screws. Removed the gage wire, installed the lamp and then connected it to a power supply via the power resistor R1. Peering through the photodiode holes in the aluminum blocks, the glowing lamp filament was seen through either aperture. If not, the lamp would be repositioned. Next, the photodiodes were bonded to the aluminum blocks and wires carefully soldered to their legs (because their manufacturer recommended a 240 deg C maximum solder temperature for no more than 5 seconds, to prevent damage to the package). The lamp was positioned such as to not throw a large shadow of the aperture across the active area of the photodiodes. The linearity test, described later, would indicate if a problem like this had accidentally happened.

FEEDBACK TRANSDUCER:

Theory of Operation:

The triple feedback signal from the displacement transducer caused an electric current to flow through a wire coil mounted on the end of the pendulum. The coil worked in conjunction with a mating permanent magnet attached to the base plate, generating a feedback force that modified and damped the pendulum's motion.

Construction Details:

The size of the seismometer's mass allowed for a small feedback transducer. So the transducer could be made from a 76 mm (3"), 8 Ohms, audio speaker. The paper cone/coil assembly was carefully cut away from the metal structure. A 25 mm long brass mounting screw was epoxy bonded to the center of the paper cone. The chuck of a drill press was used as a temporary holding fixture to support the brass screw, and the drilling machine's table supported the coil during the epoxy's curing cycle. This set-up kept the screw somewhat concentric and perpendicular to the coil.

The cone's supporting structure (made of metal) was removed from the magnet. A piece of masking tape was temporarily placed over the exposed magnet poles to prevent the entry of foreign material entering the gap. An aluminum angle bracket was epoxy bonded to the magnet for mounting it to the base plate.

The speaker coil was connected to the feedback board with heavy gauge wire for robustness and low electrical resistance. A break had to be made in the stiff wires at the pendulum's hinge to allow free motion of the mass. Two pieces of 36 AWG magnet wire were formed in a droopy shaped loops to bridge the gap and complete the electronic circuit.

GENERAL INSTRUMENT FABRICATION:

See photos with captions, Figures 4–8, describing the mechanical features of the instrument. It did not require any special tools to fabricate this seismometer. Access to some basic tools was all that was necessary. Knowledge of how to use these tools efficiently and safely was certainly required. The Mk XI was made out of non-ferrous, non-magnetic metals, mostly aluminum because of its corrosion resistance, lightweight, easy to work with and availability from local salvage yards. All fasteners were either brass or stainless steel. Review the Figures for additional information.

The base plate was made from 12.7mm (1/2") thick aluminum plate. It must be extremely rigid, as any flexing due to temperature changes etc can cause enough warping to throw the pendulum off center. Three leveling screws (#10-32 UNF, stainless steel) went through the base plate, one adjacent to the column and two others at the

opposite end of the plate, threaded into dedicated tapped holes. The .81mm (.032") pitch is about the coarsest thread allowable for screws so closely spaced, a finer pitch is better. Some hexagon nuts were temporarily jammed together on the leveling screw's thread so they could be held in the chuck of a drill press, whereby a slight conical point could be made on its tip using a file. Knobs were pressed onto the screw heads to assist with fine adjustments.

The pendulum was made of 1.6mm (.062") thick aluminum sheet. The area for mounting the hinges was checked for flatness with a straightedge, for reliable hinge operation. The hinge was made out of two pieces of heat-treated steel shim stock, approximately 25mm long x .05mm (.002") thick. The lower piece, subjected to an undesired compressive force, was 10mm (.40") wide and the upper piece, subjected to a tensile force, was 4mm (.15") wide. Flat pieces of aluminum 3mm (.125") thick, clamped the flexures to the pendulum and to the vertical supporting column, fabricated from a piece of aluminum angle. The inertial mass was increased to a total of 150 grams by adding several chunks of brass to increase its natural period.

BENCH-TOP ADJUSTMENTS:

The 3 adjustment screws were rotated to get the base level, helped with a spirit level. Gravity should have centered the pendulum (at the middle of its range of travel). It didn't at first. The pendulum's support column had to be corrected with shims, inserted under it. The pendulum was then gently moved side to side while observing the apertures, to verify that one was opening as the other was closing. With the pendulum at rest, the base plate was tilted until each aperture was roughly the same size, forming square approximately .5 - 1 mm on a side.

In a semi-darkened room, power was applied to the circuit with the lamp shining directly at the apertures. A digital voltmeter (DVM) was connected to pin 6 on IC1 and signal ground. The pendulum was gently moved off center for a "+" reading in one direction, and a "-" reading in the opposite direction. A voltage reading greater than 8 volts DC in either direction is desirable. The circuit, when first powered up caused the pendulum to oscillate, when it should have been steady. Flipping the two coil wires around to reverse the polarity of the coil's magnetic field stabilized the pendulum movement.

The accepted convention when reading a horizontal seismometer's seismogram is to orientate the signal trace horizontally, and is read from left to right. An upward moving seismic signal indicates an Easterly ground motion on a E-W aligned seismometer or a Northward ground motion on a N-S aligned seismometer. It is important to know the direction of ground movement when seismograms are analyzed. With the DVM connected to pin 6 on IC1 the pendulum was pushed off center in the direction to produce a "+" signal, then on the base plate an arrow was scribed pointing in the opposite direction to the pendulum movement. When installing the instrument, the arrow will point to either the North or East. The next section describes additional adjustments to the electronics, including some hardware tests.

CALIBRATION:

Determining Critical Values:

Many of the values calculated in this section, will be used in the transfer function described later.

1. Pendulum's Seismic Mass:

All of the significant parts on the pendulum assembly were carefully measured. An equivalent mass of 0.23 Kg, 120 mm from the pendulum's hinge line, was determined. This point, the center of gravity (CG) of the mass, was marked on the pendulum with a felt tip pen for later reference.

2. Displacement Transducer Linearity:

To verify the transducer's linearity, its output voltage signal was measured at a low gain part of the circuit, i.e. after IC1. Switch SW1 was toggled, whereby the output signal of IC2 went to a DVM. The feedback circuit was temporarily disabled.

In a semi-darkened room, the circuit was powered up. A leveling screw was adjusted to cause the pendulum to swing off center and gently rest against one of the adjustable stops, until an output signal over 8 volts in the "-" direction was reached. A micrometer pushed on the CG of the pendulum, for a distance significant enough to move the pendulum off the adjustable stop to get a "+" reading greater than 8 volts. A series of voltage measurements were recorded to the nearest 1/100 V every .025 mm (.001") that the CG traveled. Next, the volts/displacement data points were plotted on a Cartesian graph. All the data points formed a fairly straight line, more similar to the slightly "S" shaped line S-T Morrissey presented in the test results seen on his Web page. He pointed out that the non-linearity of

his chart was due to the micrometer's screw thread, and it appears to be the same problem with the micrometer used on the Mk XI. The test was repeated several times to verify linearity.

The data points from the previous test began falling off a little beyond 6.5 Volts. Non-linearity error was less than 2 % full scale at approximately 7 Volts. This amount of error was adequate for this amateur project. Other reasons for the data points in the "linear" portion to appear a little off-center could also be due to slight inaccuracies with the test set-up and the rounding off of the voltage readings.

3. Displacement Constant of the Displacement Transducer (r):

Two well-spaced data points that were recorded as part of the above test were selected for this part of the analysis. Both must be on the linear portion of the graph's line. For these calculations, the two data points chosen were -7.19 V and +5.89 V, spanning a total of 13.08 Volts, which calculated to be a distance of .889 mm (0.035") that the CG traveled. At pin 6 of IC1 the value for $r = (1000 \text{ mm}/0.889 \text{ mm}) \times 13.08 \text{ V} = 14,713 \text{ V/m}$. This value was rather low, so the addition of IC2 with a 11X gain increased the final displacement constant value for $r = 161,843 \text{ V/m}$

4. Motor Constant (Gn) of the Feedback Transducer:

This set-up applied a horizontal force to the pendulum. SW1 was positioned to isolate IC2 and the rest of the feedback circuit. A piece of fine cotton thread ~300mm long had one end taped to the side of the pendulum at its CG, and the other end tied to a nail in a block of wood set off to the side of the base plate. The two ends of the thread were of equal height above the bench top and far enough apart for the thread form a 90° V, when the pendulum was centered. The feedback coil was temporarily disconnected from the feedback circuit, and connected to four items in series, a 1.5 V battery, an on/off switch, a mA meter and a 10K 10-turn potentiometer.

Prior to measuring coil current, the feedback circuit was powered up and the pendulum was centered using the leveling screws to obtain 0 V at pin 6 of IC1 using a DVM. A small test mass (a paper clip) was placed at the bottom of the V in the thread, just heavy enough to deflect the pendulum towards the block of wood. Now the battery powered circuit clipped to the coil was turned on. The potentiometer steadily increased the amount of current flowing through the coil, until the pendulum was approximately re-centered (indicated by 0 volts on the DVM). No more than a few milliamps were permitted to flow through the coil; otherwise the coil could have burned out. Coil current necessary to keep the pendulum centered, was recorded, as it opposed the force exerted by the test mass. When using this method, the actual load applied to the pendulum is one half of the test mass.

The paper clip test mass measured 0.00043 Kg. and the re-centering current was 0.00039 Amps. So the load on the pendulum was $0.00043/2 = 0.00021 \text{ Kg}$. The motor constant, Gn, is defined in units of Newton/Ampere (N/A).

$$N = m \times a = 0.00021 \times 9.8 = 0.00206$$

$$G_n = N/A = 0.00206/0.00039 = 5.277 \text{ N/A}$$

At the completion of this test, the coil was re-connected to the feedback circuit, and toggle switch SW1 was set to normal operation.

5. Mathematical Analysis:

Downloaded the Mathcad file of S-T Morrissey (same as the hard copy of the worksheet he has on his Web page) and opened it up using "Mathcad Standard 2000" to calculate the response of the Mk XI. The following values were substituted for the ones found in the terms on S-T Morrissey's work sheet:

$$r = 161,843$$

$$M = .23$$

$$C = .0000235$$

$$R_p = 2,000,000$$

$$R_I = 100,000$$

$$G_n = 5.3$$

$$R_f = 8$$

$$T_I = 100$$

$$T_o = 2.5$$

The following values resulted after all the number crunching:

$$\text{Zeta} = .71$$

$$T_n = 96$$

$$\text{Closed loop velocity signal output: } V/m/s = 1848$$

The plotted curve for the velocity response curve showed the top end response rolling off at approximately 10 Hz. System VBB velocity signal output at IC8 (having a 2X gain): V/m/s =3696

6. System Damping Test:

This test was performed in a semi-darkened room with the feedback circuit powered up. The pendulum was lightly tapped using a narrow strip of paper as a hammer, not displacing the pendulum much more than 1 mm. The response was monitored in real time on the seismic signal's display device. The trace was seen moving away from its normal neutral position, returning to the neutral position with a slight overshoot.

INSTALLATION:

Site Preparation:

The seismometer's adjustable feet (screws) rested on 3 pieces of smooth plate glass, 25 mm x 25 mm x 3 mm thick, bonded with tile grout to the surface of a cast cement slab. The polished surfaces of the glass allowed the screws to slide easily as the instrument's base expanded or contracted in response to thermal changes, which is a potential noise source. Prior to bonding glass pieces to the slab all types of erratic noise, both long and short period, was observed in the data.

Cement, one of the easiest materials for an amateur to work, was used for the pier. The pier was not exposed to direct sunlight, because any warming effect can induce tilting. Frosts and ground water changes in or on the earth surrounding the pier was a source of unexpected background noise and tilting movements. The ideal situation would have been to cast the pier directly on a clean exposure of bedrock. Instead, the seismometer resided on a cast slab of cement on top of 200+ meters of glacial till, over bedrock. The pier was enclosed within a small surface vault made with cement block walls and a plywood lid lined with insulation. Floor and blocks were sealed to prevent moisture entering into the space occupied by the seismometer and electronics. Instrument did not visually straddle any cracks in the slab.

Pendulum required protection from unwanted drafts and convection currents, which exist in any location. So a lightproof cover was made to go over the seismometer, but resting on the cement slab and not touching any part of the seismometer. A simple 5-sided box was made out of Styrofoam sheet 25 mm thick, fully glued along its mating edges with any crack stuffed full of fiberglass insulation to prevent air leaks (drafts). Its internal dimensions were roughly 15 mm larger than any protruding feature on the seismometer. When installed correctly, the Styrofoam box helped to stratify the air trapped inside. Yet it took additional fiber glass insulation to minimized/eliminate the thermal convection currents that formed under the cover.

Initial Alignment and Adjustment:

Because the seismometer did not have any pendulum locking mechanism, it was carried while tilted at a 45° angle along the sensitive axis, so the pendulum rested against one of its stops. Over several months, some experimentation occurred with the alignment of the sensitive axis, to find the quietest direction. For a N-S alignment, the pre-scribed direction arrow on the base plate pointed North or East for an E-W alignment. The velocity VBB output voltage signal went positive (+) when the ground moved either North or East.

With the seismometer installed on the glass pieces and the sensitive axis correctly aligned, the base plate was leveled with a DVM connected to pin 6 of IC1 via SW1. It is easier to perform this task with the feedback signal detached. The pendulum will re-center quicker when using its natural period of 2.5 seconds, than waiting 96 seconds with the feedback on. After waiting for a minute for the electronics to settle down, a base plate leveling screw was adjusted until the DVM read 0.0 ± 0.3 volts. The opaque cover was temporarily installed over it now, along plus the outer thermal insulation. After a couple of hours another voltage reading was taken after the air had stabilized around the seismometer. When re-leveling was necessary, the cover was lifted just high enough to access the desired leveling screw, to obtain 0.0 ± 0.3 volts. Finally, duct taped the foam cover to the slab (not allowing it to touch the seismometer). Toggle switch SW1 was re-set to send the seismic signal through the feedback circuit, after all adjustments were completed.

Removing the lightproof foam cover to gain access to the leveling screws exposed the displacement transducer's phototransistors to large uneven levels of ambient light. Ambient light shadows falling directly on the photodiodes were difficult to recognize and compensate for. With hindsight, it would have been advantageous to have made a small opaque cover that went over the displacement transducer only. It would not need to be completely lightproof, and if attached to the base plate, must not interfere with the operation of the leveling screws.

SAMPLE SEISMOGRAMS:

See seismograms made with the Mk XI starting at Figure 9. The majority of the seismograms were created using Larry Cochrane's SDR and WinQuake computer programs, including his 16 bit A/D card. Digital filtering, available with WinQuake, enhanced events by removing undesirable noise. Pass band limits are specified beneath each seismogram. High pass filter settings had a 6th order roll-off, and the low pass filters had a 12th order roll-off.

See the top of each WinQuake seismogram for additional information regarding an event's origin time, date, coordinates, distance and magnitude. Note: all events were detected with the seismometer's sensitive axis aligned E-W. Earthquake information was preliminary, provided by the NEIC's (USGS) Near Real Time Earthquake List, obtained via the WWW.

CONCLUSION:

The seismometer's overall performance was very satisfactory. The displacement transducer, though not as responsive as desired at the high frequency end, had good sensitivity towards the lower frequencies. Electronic circuits appeared to be very stable and reliable.

Whenever the seismometer was placed in the vault (instrument was frequently removed for circuit tweaks etc), for several times a day during the first week of operation, the output signal exhibited some odd long period noise, seen as a random spontaneous disturbance more noticeable during the quieter evening hours. The noise would predictably disappear after a few days, so it was assumed it was the instrument settling in and nothing to do with the weather or other influences. Most long period noise sources were environmental (ground tilt); i.e. thermal effects of the sun on the vault, weight of snow/rain on the ground, a neighbor parking an automobile near the instrument, people walking near the vault. Winds blowing on an adjacent fence and shrubs caused the greatest ground tilting. Data recording began immediately after powering up the seismometer, but 2 - 12 hours elapsed before the instrument thermally stabilized and convection currents subsided enough for the detection normal background noise levels.

The electronic components selected for this instrument are expected last for many years, if they are well protected from the elements. The lamp's life expectancy is thousands of hours since it was driven by a regulated DC voltage and drive current limited by a power resistor, R1. Periodic inspection of the instrument and electronics occurred every few months to ensure they were not sitting in a pool of water or providing food and shelter to a family of bugs, plus a slight re-leveling of the instrument may have been necessary then to re-center the displacement transducer.

FUTURE PROJECTS:

1. Motorize the sensitive axis leveling screw to remotely re-center the pendulum, without having to disturb the thermal insulation when trying to monitor the voltage at pin 6 of IC1.
2. Photodiodes are high impedance devices that are very prone to stray AC electrical noise. They, along with IC1 & IC2, need to be enclosed in some type of metal box (Faraday cage) that is electrically connected to the seismometer's base plate and chassis ground. The output signal from IC2 would then pass through a shielded wire to IC3 on the Feedback circuit board.

ACKNOWLEDGEMENTS:

Special thanks to Sean-Thomas Morrissey of Saint Louis University for sharing the details of his work on the STM-8 VBB seismometer through the Public Seismic Network (PSN), and for making available a copy of the Mathcad file used for calculating the performance of the STM-8. The author is grateful to Chris Chapman for reviewing a previous revision of this paper and offering many valuable suggestions that helped to improve the performance of the displacement transducer, and to clarify portions of the document's text.

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WORLD WIDE WEB (WWW) SITES:

Application Bulletin AB-34, MFB Low Pass Filter Design Program.
<http://www.burr-brown.com/applications/>
Trump, B., and Stitt, R. M.

Burr-Brown Corp., Tucson AZ.
See Filter Pro. It is a DOS program for designing several types of low pass filters, from 1st to 8th order. Another feature of it plots the theoretical response. Component selection is discussed.

Broadband Vault Construction.
<http://www.iris.edu/passcal>
The IRIS Consortium under the title "Index of Services" (upper left of screen), click on "Manuals", next click on "PASSCAL Field Manual", then go to section 11.2 for the above title. Document has general information on vault construction.

Guidelines for Installing Broadband Seismic Instrumentation.
<http://www.seismo.berkeley.edu/seismo/bdsn/instrumentation/guidelines.html>
Uhrhammer, B., and Karavas, B. UC Berkeley Seismological Laboratory, CA.
Explains clearly the two largest influences on broadband instrument performance, i.e. pier construction and thermal insulation around the pier and instruments.

Guidelines for Engineering Works at Remote Seismic Stations. Application Note #42
<http://www.kinometrics.com/appnotes.html>
Trnkoczy A., Kinometrics, Inc., Pasadena, CA.
Document has general information on vault construction.

Manual of Seismological Observatory Practice (1979 Edition).
<http://www.seismo.com/msop/msop79/msop.html>
Global Seismological Services (GSS), Golden, CO.
An out-of-print publication, scanned and now available on the WWW. Most of the information is obsolete and irrelevant. Contains a lot of information about site selection and vault construction.

Public Seismic Network (PSN)
<http://psn.quake.net>
Cochrane, L. Redwood City, CA.
Web site contains many informative articles regarding amateur built instruments, with links to others. Site has enough info for anyone wanting to build his or her own, complete, seismograph station.

The STM-8 Leaf Spring Seismometer.
<http://www.eas.slu.edu/People/STMorrissey/index.html>
Morrissey, S-T. St. Louis University, Department of Earth and Atmospheric Sciences, MO.

An amateur (?) built VBB seismometer with a multiple feedback configuration. It achieves an effective operating period greater than 150 seconds, its performance near equals that of professionally built instruments.

ELECTRONIC PART SUPPLIERS:

Digi-Key Corporation
 701 Brooks Ave. South
 Thief River Falls, MN 56701-0677
 Order phone line: 1-800-334-4539

Newark Electronics
 Sales branches in almost all U.S. states. See your local phone book for nearest location.
 Catalog request phone: 1-800-298-3133, extension 48

FIGURES:

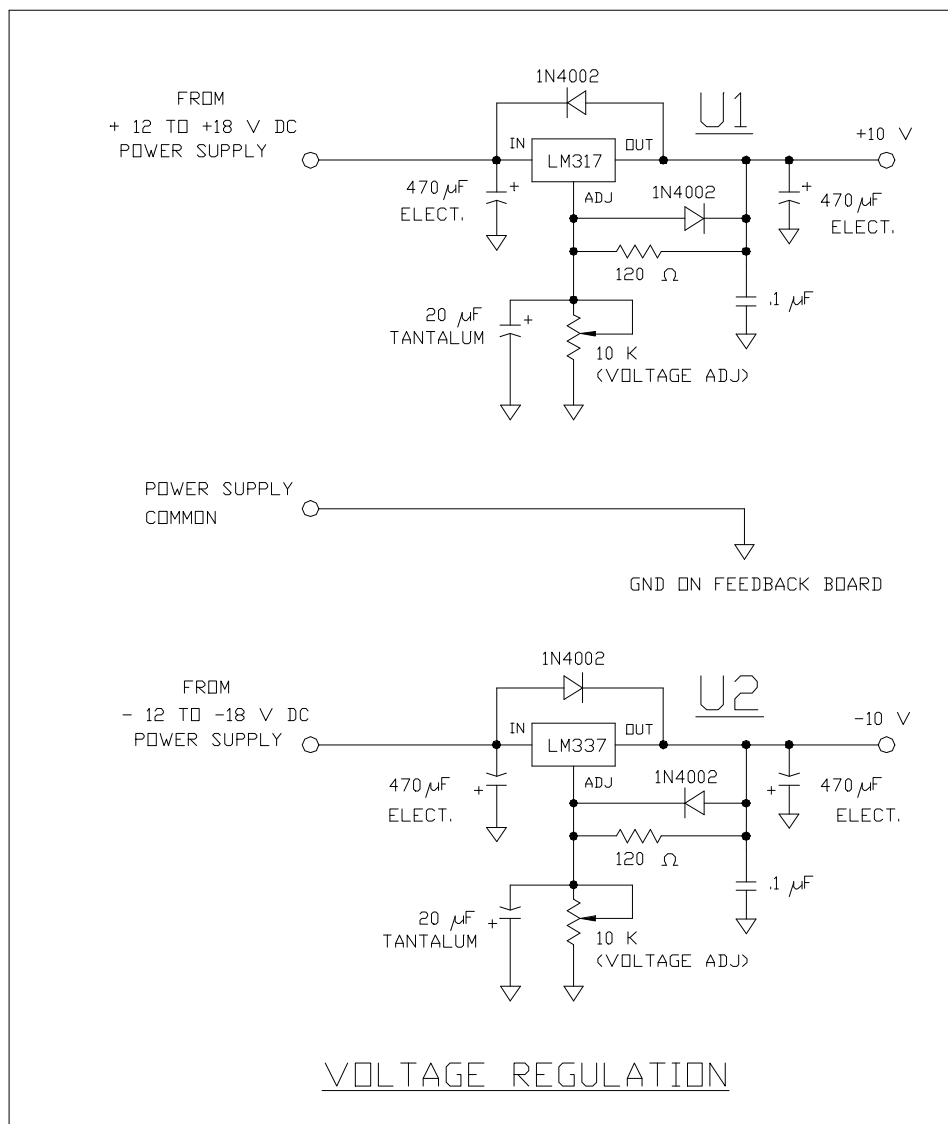


Figure 1

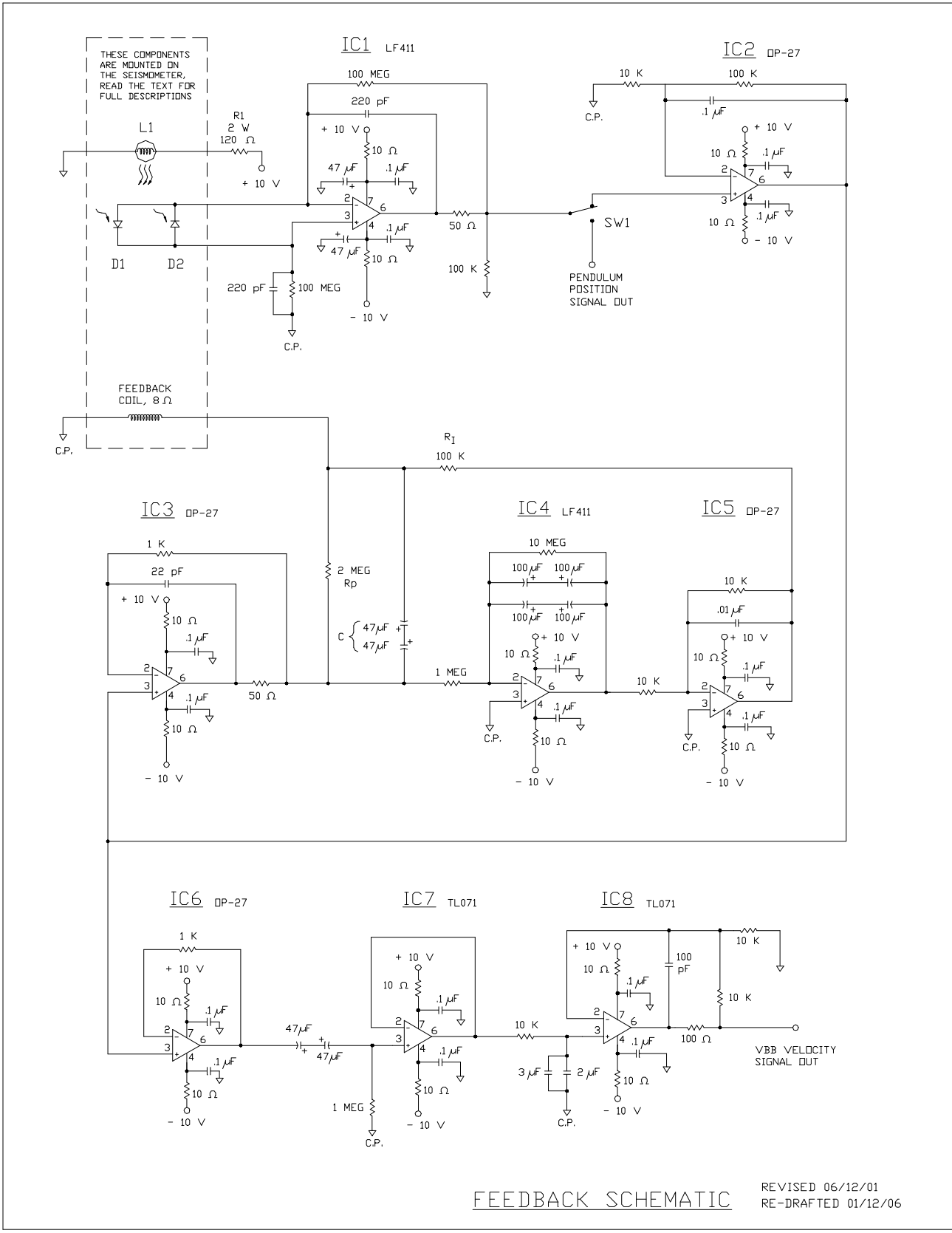


Figure 2

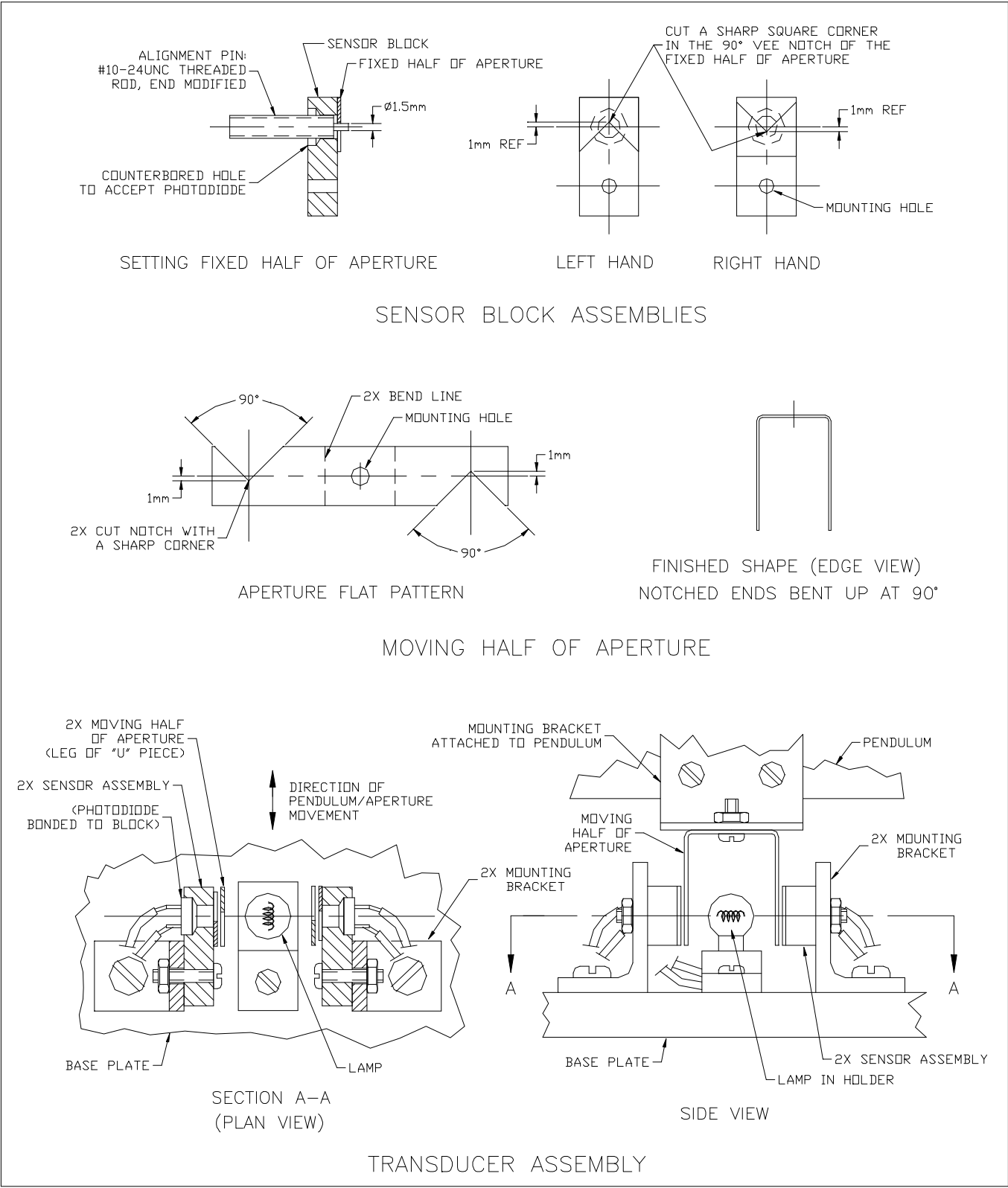


Figure 3

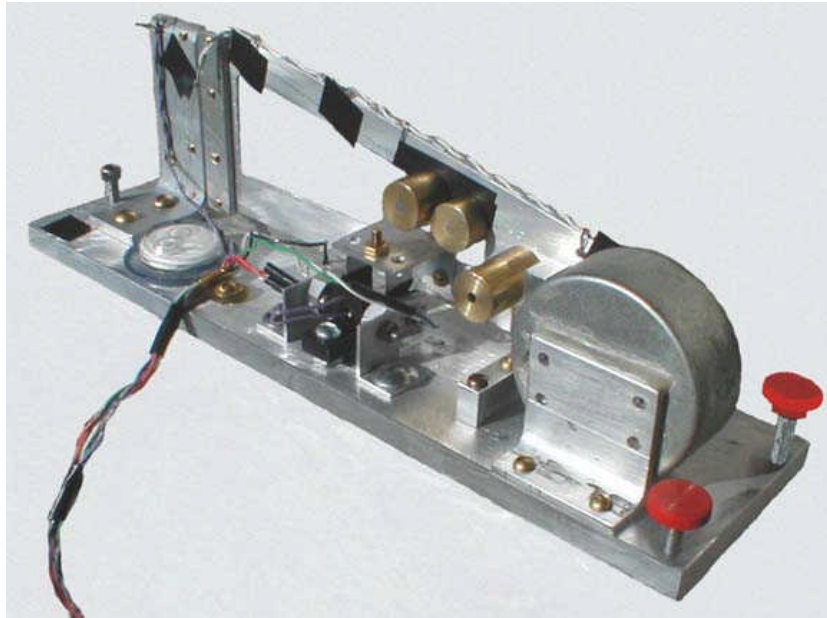


Figure 4

This overview shows the main features of the instrument. The feedback magnet is located at the extreme right hand end of the pendulum. The cylindrical gold colored objects on the pendulum are the brass seismic masses. Below them on the base is the displacement transducer. Left of it on the base is a bulls eye spirit level, used numerous times when leveling the instrument during calibration.



Figure 5

Feedback coil and magnet. Note how the coil is mounted on a sub-plate to facilitate alignment of the coil with the gap in the magnet. Clearly shown in this photo is the adjustable stops. Brass masses also protrude from this side of the pendulum for balance.

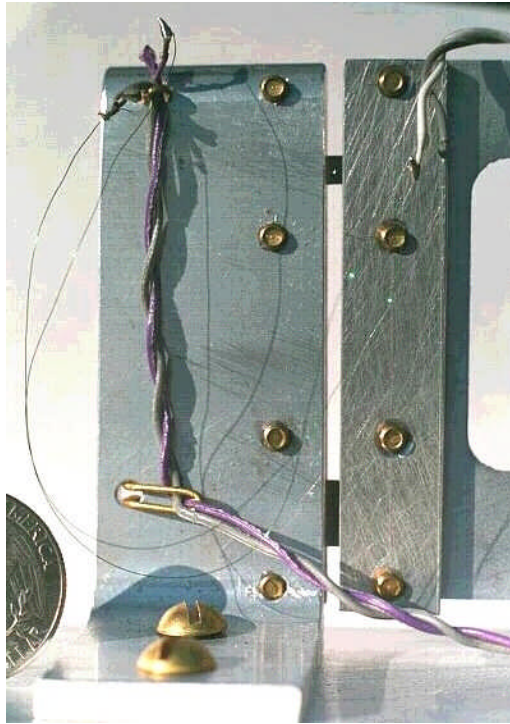


Figure 6

The hinge comprises of two pieces of thin spring tempered metal shims, visible in the narrow vertical slit. Observe how the two heavier coil wires fall short of bridging the hinge gap. Lighter pieces of 36 AWG magnet wire actually cross the gap, as they are more flexible.

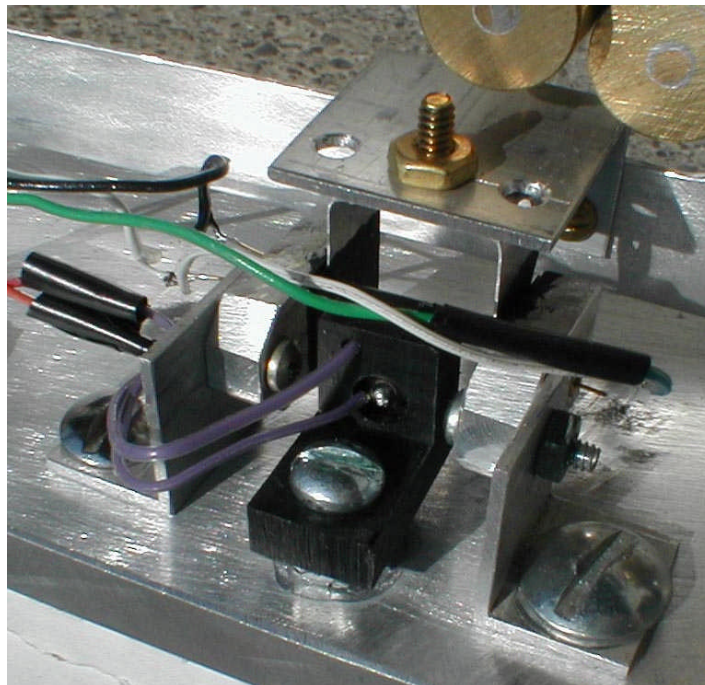


Figure 7

The displacement transducer. You can see the moving half of the aperture fixed to a bracket mounted on the side of the pendulum. The two sensor block assemblies are mounted to base plate with small angle brackets, and the lamp is installed between them.

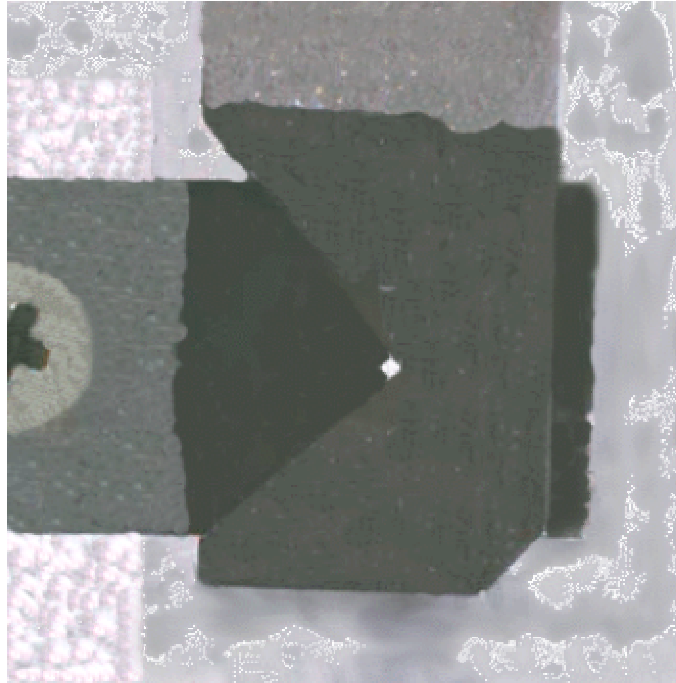


Figure 8

This photo has been obviously touched up to show what the aperture looks like. The moving half of the aperture is in front of the sensor block assembly. The metal surfaces around the opening were painted matte black to reduce reflections of stray light.

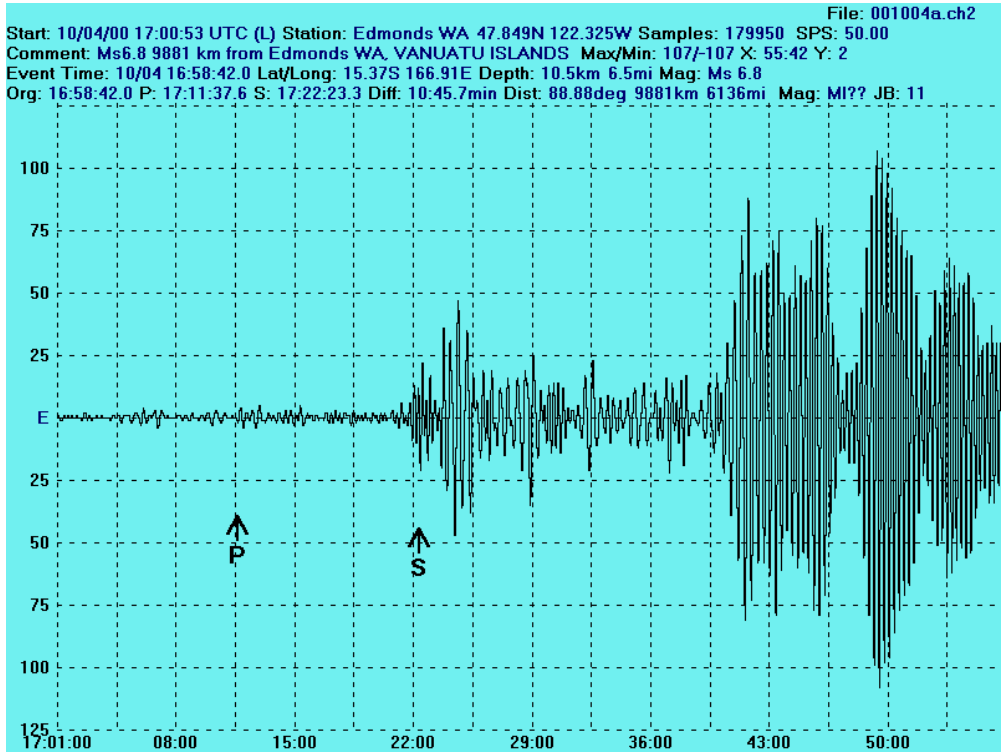


Figure 9

Seismogram pass band filtered .03 - .07 Hz

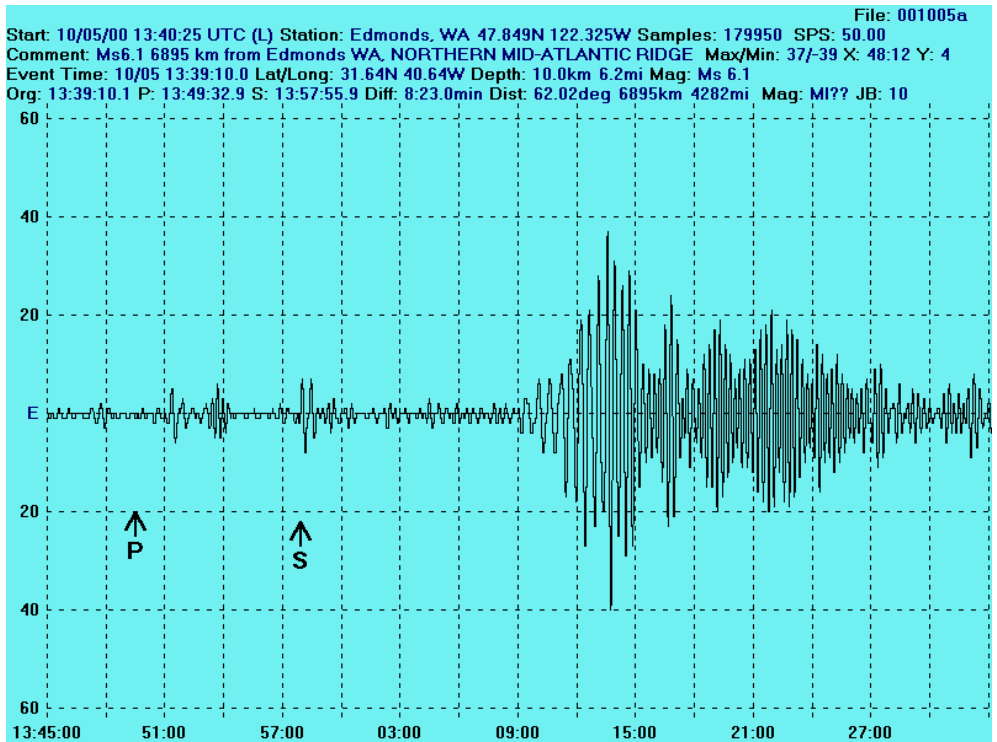


Figure 10

Seismogram pass band filtered .03 - .07 Hz

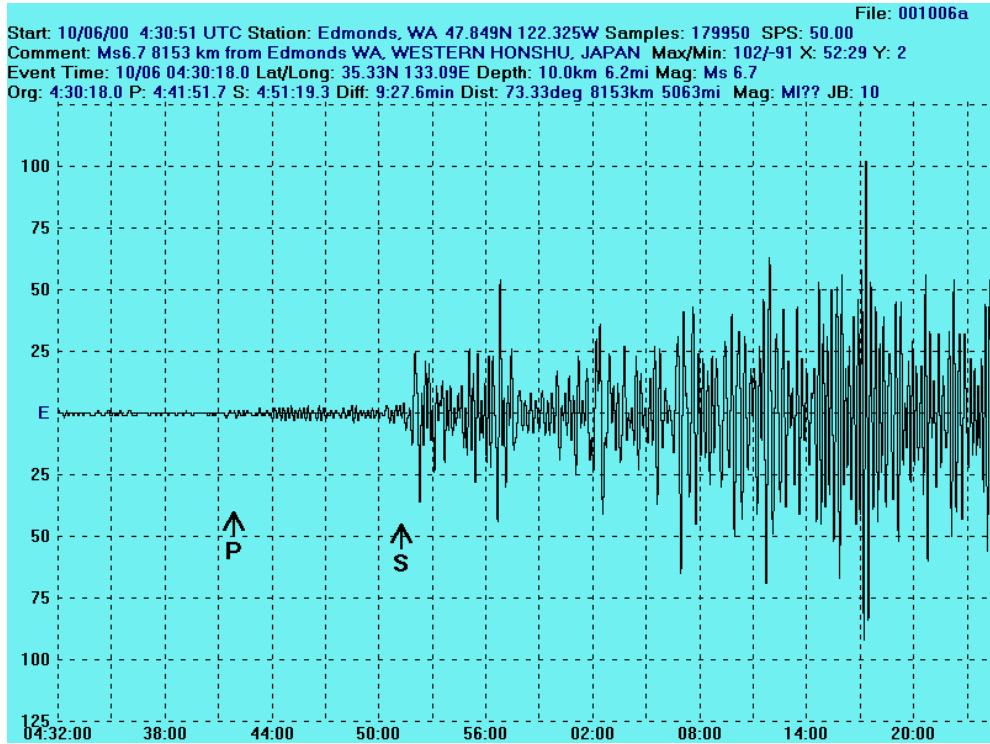


Figure 11

Seismogram pass band filtered .02 - .08 Hz

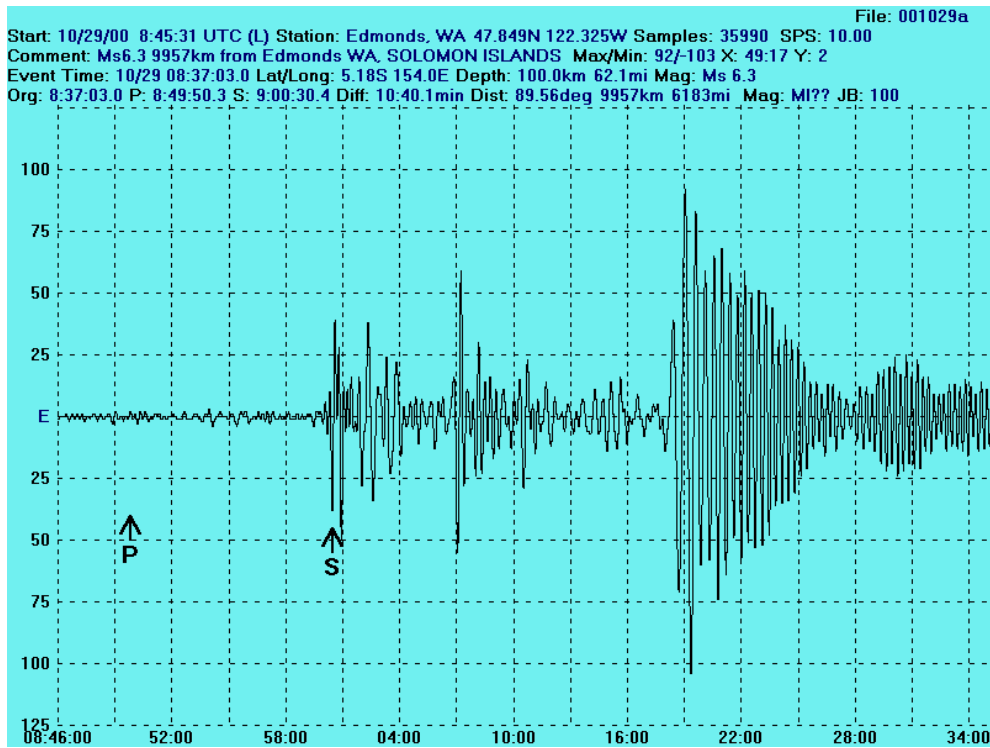


Figure 12

Seismogram pass band filtered .02 - .07 Hz

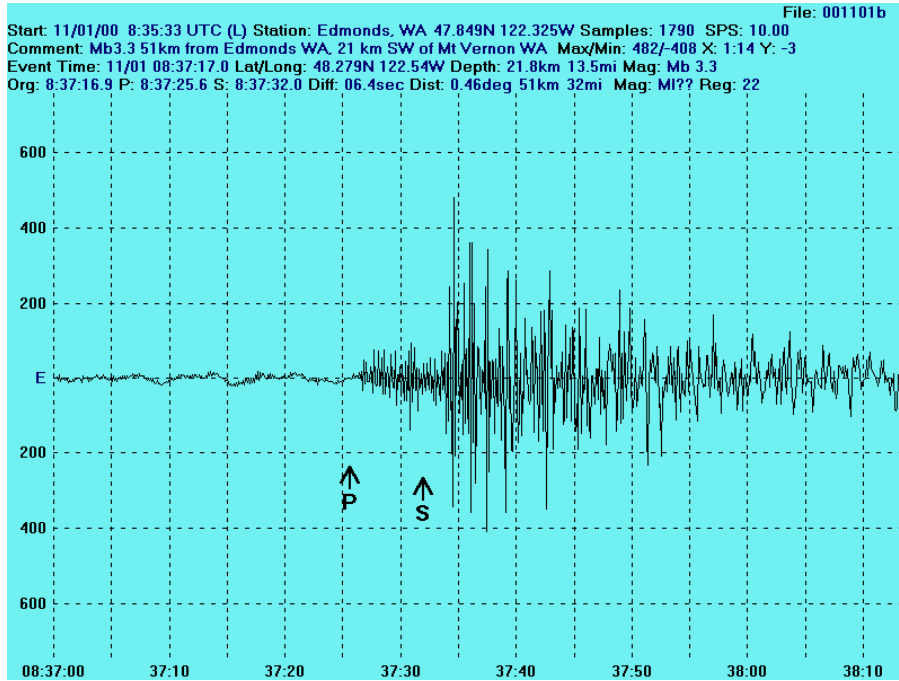


Figure 13

Seismogram pass band filtered .01 - 5 Hz

This is the raw signal from a local Md 3.3 event. The horizontal pendulum was pointing almost directly at the epicenter to the North. Not good for P wave detection, yet at least the instrument remained stable with no indication of signal saturation.

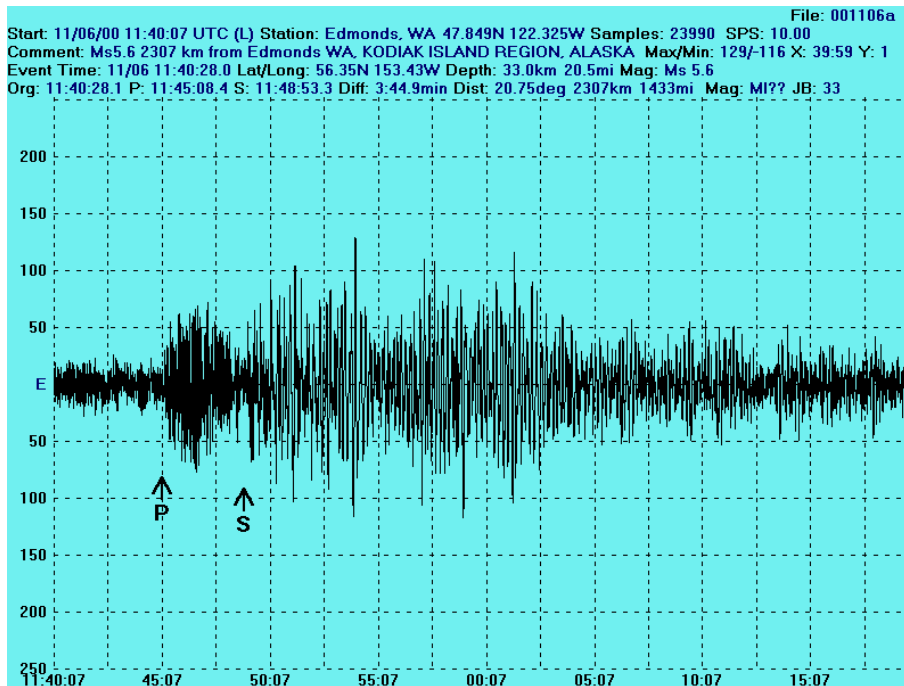


Figure 14

Seismogram pass band filtered .01 - 5 Hz

This is the raw unfiltered signal. See Seismograms 7 & 8 for additional seismograms of the same event.

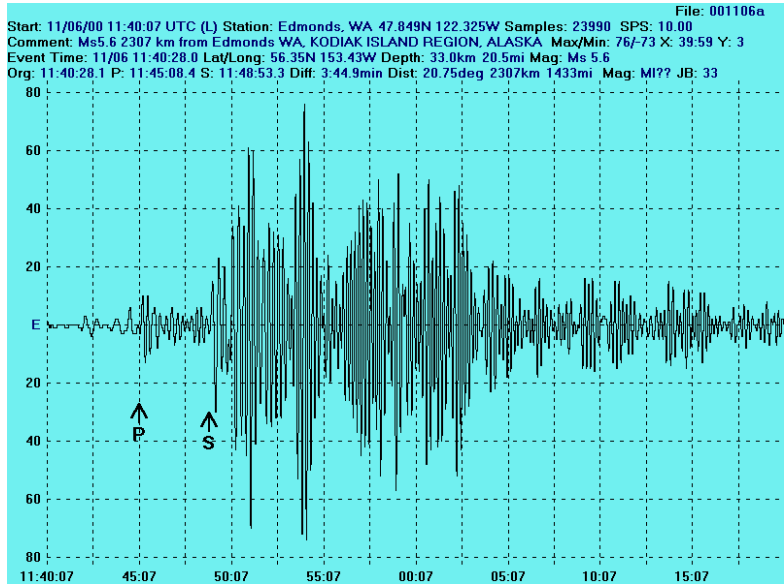


Figure 15

Pass band .02 - 08 Hz

This is the narrow band presentation of the event shown in Seismogram 6 above. It is a good example of the benefits of digital filtering.

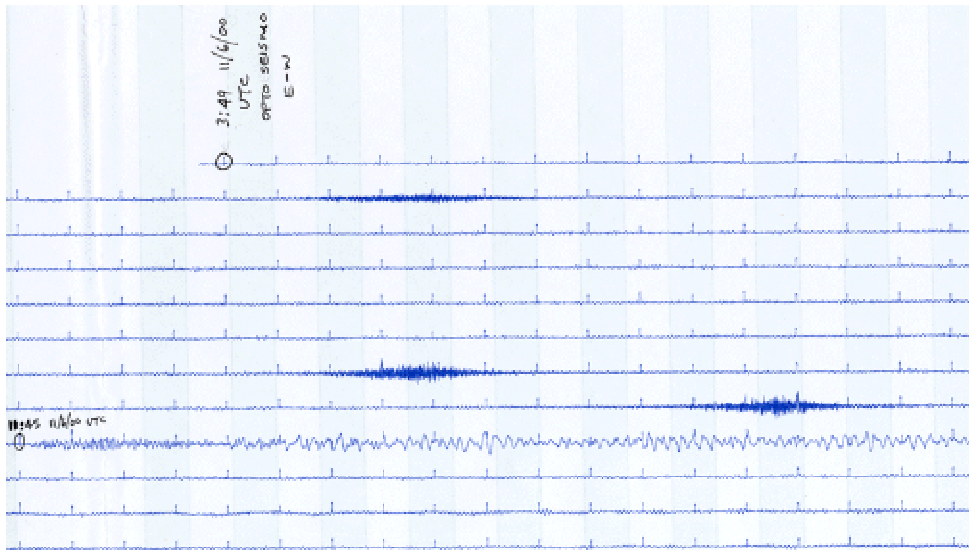


Figure 16

Seismogram pass band filtered .0085 - 8 Hz

The seismogram is a conventional ink on paper recording (made on the back side of faint ruled computer printer paper) of the event shown on Seismograms 6 & 7 above. It is only a small portion of the full tracing, showing the first few minutes of the Ms 5.6 Kodiak Island event, 3/4 ths of the way down the page. The small vertical hash marks are spaced at one minute intervals, and the horizontal lines are spaced 60 minutes apart. The lens shaped blobs of high frequency noise are trains that passed by the seismometer approximately 1 kilometer to the west. This seismogram shows the normal background noise at this site, at least during the quieter evening hours. There is some long period noise visible, but in cold weather this noise disappears and the lines straighten out. Overall the instrument's stability is very satisfactory considering it had a horizontal pendulum. Many of the events presented on this Web page had some significant train noise filtered out.

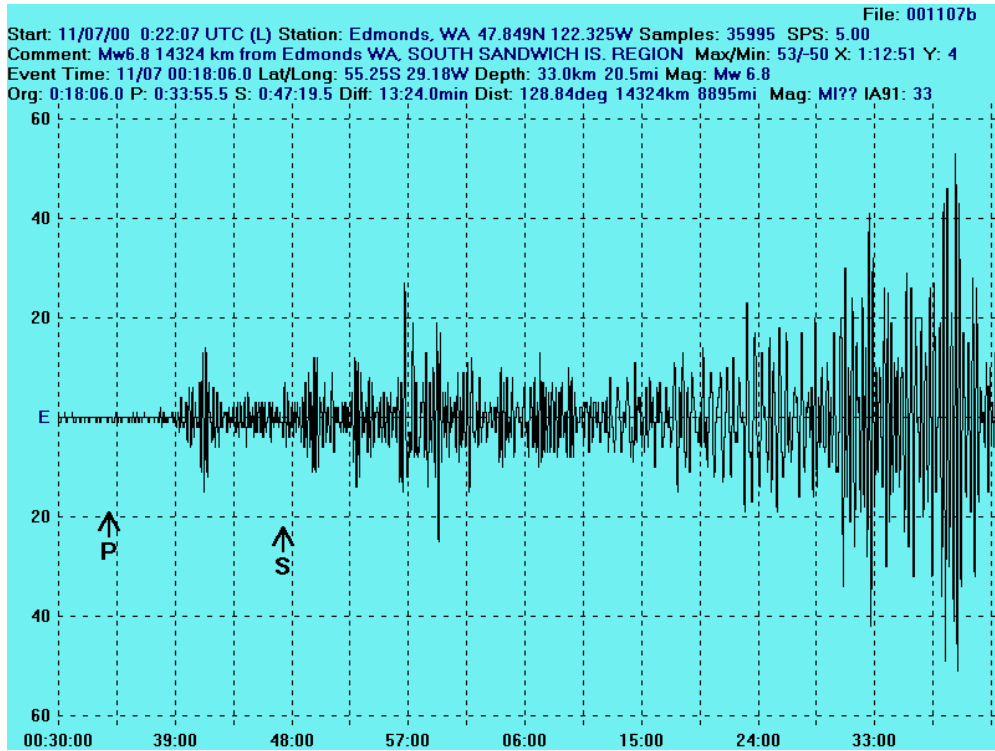


Figure 17

Seismogram pass band filtered .02 - .08 Hz

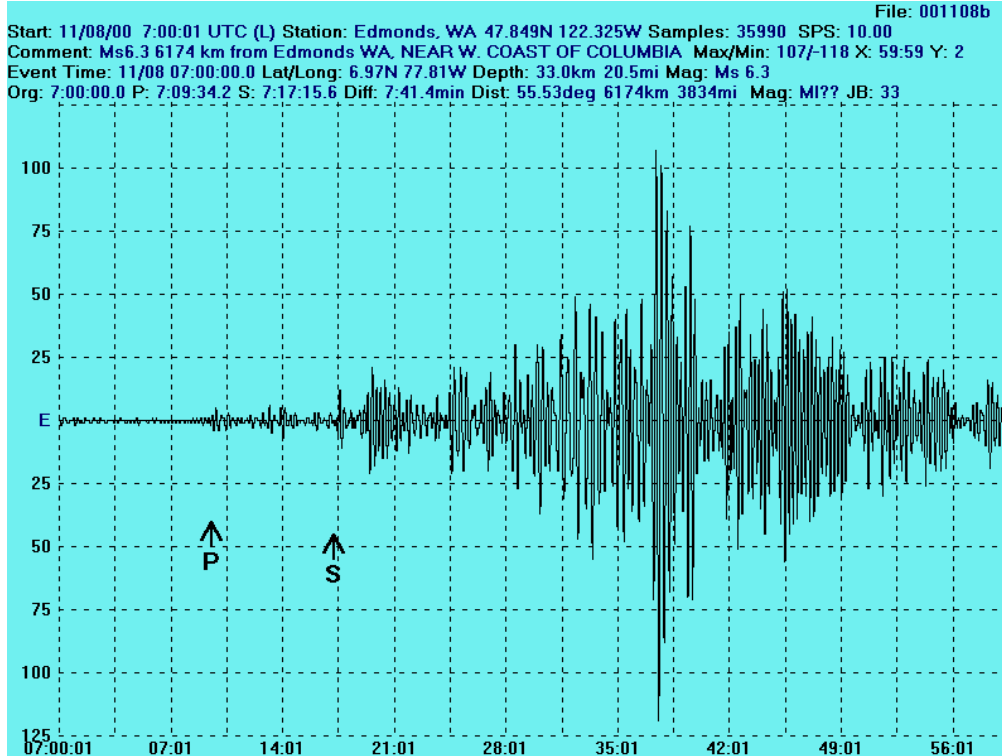


Figure 18

Seismogram pass band filtered .03 - .08 Hz

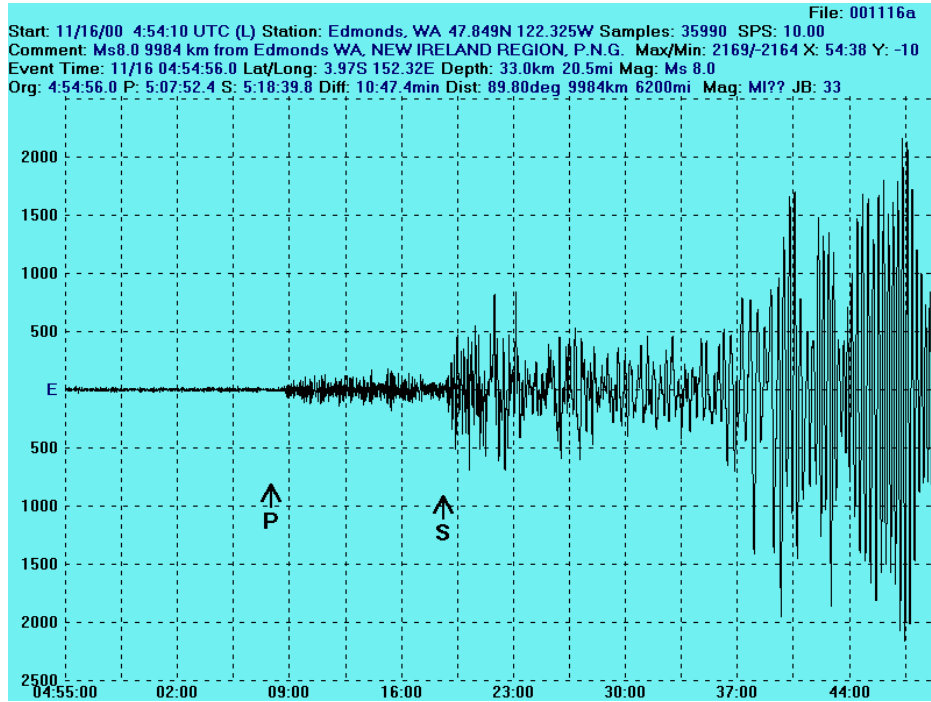


Figure 19

Seismogram pass band filtered .01 - 5 Hz

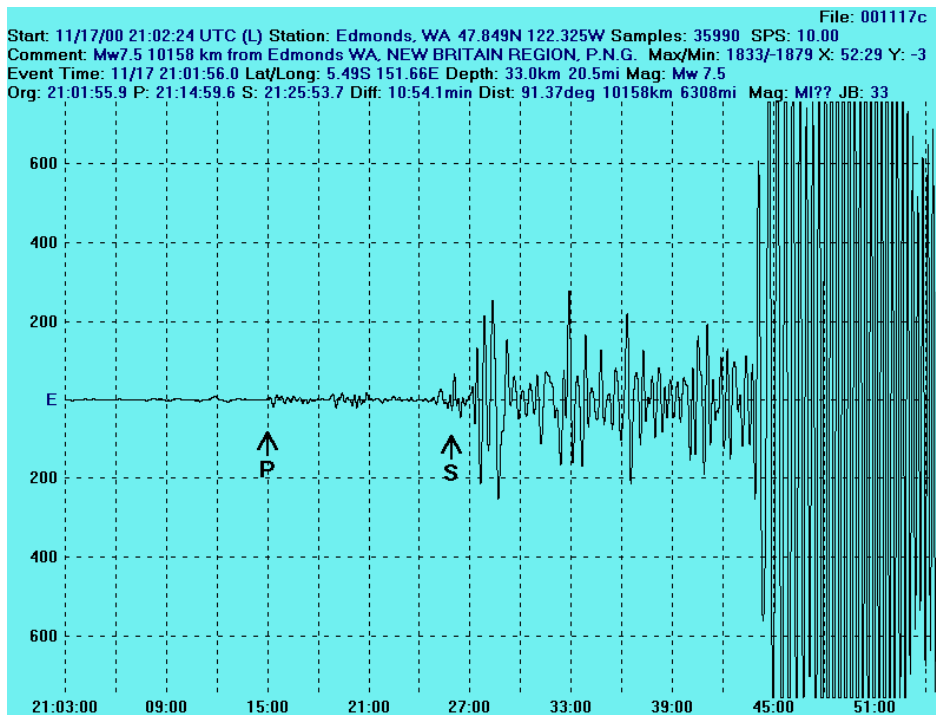


Figure 20

Pass band .01 - .07 Hz

An event in the same general locality as the event recorded in Seismogram 11. Increased the Y-scale to clearly show the P wave.

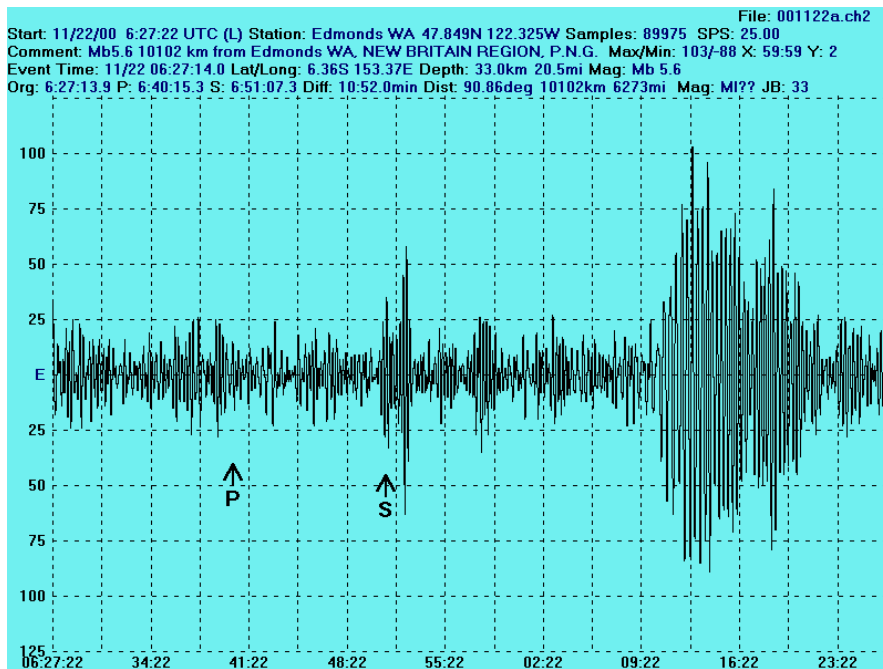


Figure 21

Seismogram pass band filtered .04 - .08

This seismogram was made using additional analog filtering. A non-inverting op-amp (gain 20X), followed by a 3rd order .1 Hz LPF with a Bessel response, was placed in the circuit between the seismometer output and the input to the A/D card. The instrument's resolution, with the additional low pass filtering, was good enough to detect the Mb 5.0 event shown above, which originated in the same general location as the event shown in Seismogram 11. The surface waves are clearly noticeable, extending beyond the background noise

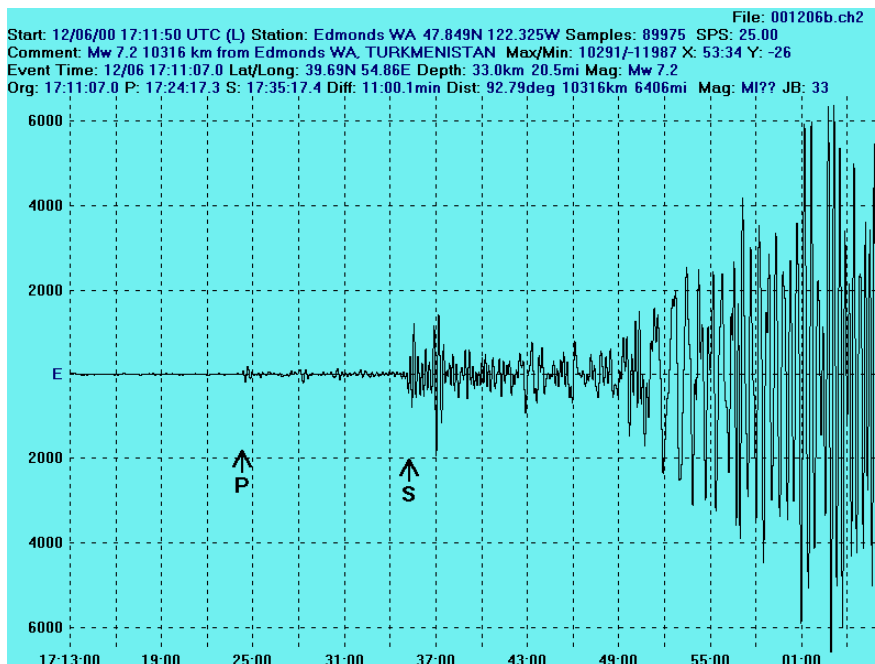


Figure 22

Seismogram pass band filtered .01 - .08 Hz

This seismogram was also made using the additional 3rd order .1 Hz LPF inserted in the circuit.

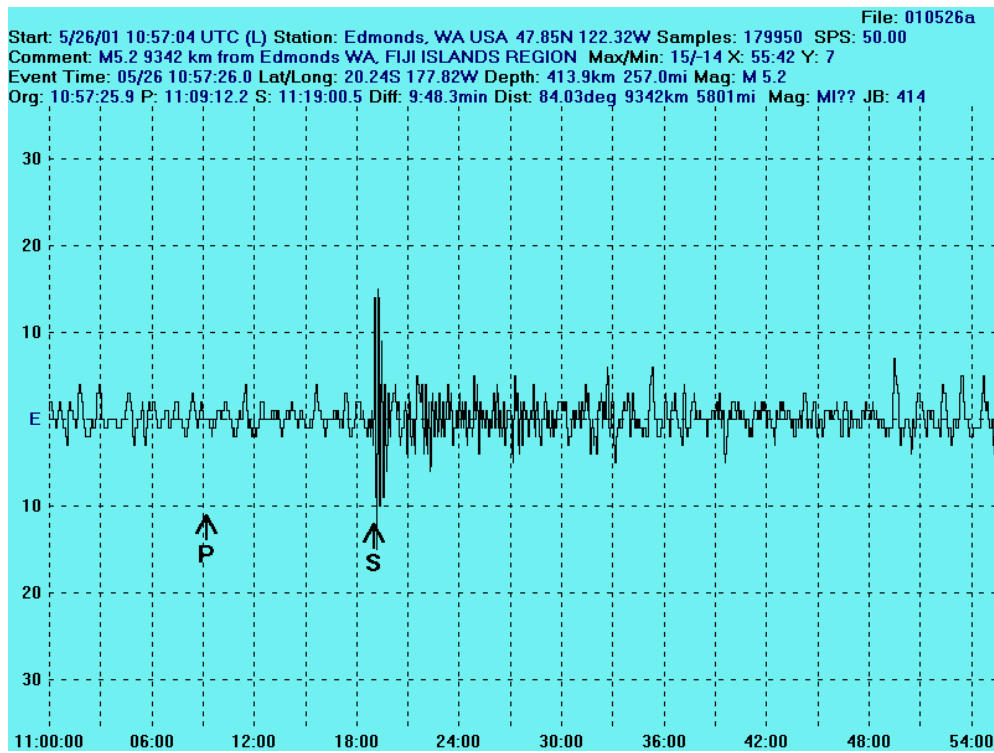


Figure 23

Seismogram pass band filtered .01 - .10 Hz
 WinQuake's digital filtering stripped out a large portion of unwanted instrument and environmental noise, revealing
 an otherwise obscure event