Calibrating the Inyo FBV Seismometer

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It is quite possible to build and operate the Inyo without knowing its exact calibration. So long as the mechanical and electrical specifications are followed reasonably closely you could expect to have a velocity response which is within 10-20% of the values predicted by the Loop7 spreadsheet. High quality commercial instruments usually have their velocity responses specified to within ±1%, although it is still expected that they will need to have their calibrations checked occasionally.

It should be possible to measure the response of the Inyo to an accuracy of 1% and by properly selecting a number of its resistors, to closely achieve a particular response by design. Once calibrated, two main factors act to alter its calibration during operation, the temperature sensitivity of the forcing-coil magnet, causing a sensitivity increase of about 0.12% (1200ppm) per ℃ and the temperature coefficient of the derivative-branch capacitor which causes a sensitivity decrease of roughly 0.025% (250ppm) per ℃ at temperatures above 20℃ and more like 0.05% (500ppm) per℃ in the region below 20℃. But, with relatively constant temperature, the Inyo should be able to maintain its calibration reasonably well over a considerable period of time.

It is customary for each seismic station to report the calibration factors for its instruments and to update that information whenever recalibration is done. Similarly for the Inyo data to be scientifically useful, it will be necessary to know and report its calibration results.

We will consider two types of calibration problems. The first, which is the more difficult, is to assemble a new instrument to accurately match a desired response curve. Easier, is measuring the V/m/s *generator constant* of an operational instrument.

What performance should I want?

It is probably best to start from the top end and set up the maximum peak velocity which the instrument can record without clipping. A suggestion, based on the peak clipping level of some professional broadband instruments would be to aim to handle peaks of 1.5cm/sec. That should allow it to handle local quakes up to about magnitude 5 and regional quakes up to about magnitude 7. The low gain channel can be used either to drive a 24-bit digitizer or to provide a large-motion, less sensitive channel for use with 16-bit digitizers. We will make the 10 Volt maximum signal on the low-gain channel correspond to 1.5×10^{-2} m/s.

So, with a 24-bit digitizer, one count will represent 0.015 m/s ÷ 8,388,608 counts, or 1.788 nm/s. Note that we are using the peak value of the ground motion, not peak-to-peak, so that the maximum count value available from a 24-bit 10Volt digitizer will be $2^{24} \times ½$ or 8,388,608. Half the D/A range is for positive signals and half will be for negative. In the proposed design a 16-bit 10V D/A would also clip at 1.5cm/sec but with a maximum count value of 32,768. In that case one count would equal 0.015m/s ÷ 32,768counts or 458 nm/s.

For 16-bit digitizers you will additionally want to make use of the high gain output which was designed to have a sensitivity 50x greater than its low gain counterpart. On the high gain channel 1 count of a 16-bit 10V digitizer will therefore equal 0.015m/s ÷ 50 ÷ 32,768 which is 9.16 nm/s, or about 1/5 the bit sensitivity we would see when using a 24-bit digitizer. This is still quite adequate to resolve any ground motions greater than the seismic background in all but the very best sites.

Going back to the low gain channel we recall that the mid-band response was designed to be 10V ÷ 0.015 m/s or 667 V/m/s. In the proposed design, that signal is obtained by amplifying the output of the feedback loop by a factor of 2, so that, measured at the loop output, the desired generator constant of the feedback loop, A_g will need to be 333 V/m/s. If you want to match the generator constant seen in some commercial instruments of 750 V/m/s, you could design A_g for 375 V/m/s, though that would come at the slight expense of reducing the clipping level from 1.5 to 1.33 cm/s.

The instrument velocity response will be approximately flat between the low and high corner frequencies. The low corner frequency F_L was set at 1/50 Hz, which seems to be a good compromise between the instrument's ability to see weak ground motions from distant quakes and its ability to reject the effects of varying spring temperature. The high corner frequency, F_H with a value of 30Hz is chosen to be able to accommodate most of the higher frequencies generated by local quakes.

Choosing component values:

When initially assembling the seismometer a number of measuring instruments are useful or necessary:

First, a means of accurately measuring resistors is essential. Depending on the quality of the available ohmmeter or resistance bridge it may be necessary to correct its calibration by measuring a standard resistor whose resistance is in the general vicinity of the resistor being measured. When checked against a standard resistor, a good-quality digital multimeter should be adequate for most measurements. A useful resistance standard can be obtained by using 0.1% metal film resistors, generally available from parts distributors for a dollar or two each. In some cases it might be reasonable to simply use 0.1% resistors in the instrument in places where their values are critical to the calibration. That has the additional advantage that the 0.1% parts can be obtained having stock values which are closer to the values required, and their temperature coefficients of resistance will often be lower than those typically found in 1% components.

Capacitors also should be measured, though that is harder, since most inexpensive capacitance meters are not very accurate. When using one, check the manufacturer's specifications. I have seen 3 and 4-digit capacitance meters whose accuracy was only guaranteed to be 3 or 4% for some measurements. One approach to getting more accuracy would be to have one of the 10μF capacitors measured with a high-quality capacitance meter and then use that as a standard to correct measurements made with a cheaper one.

Some sort of weighing scale will also be needed, one with a range of 0-200g and an accuracy of ±0.1g or better. And finally a micrometer or micrometer head will be useful when measuring the displacement sensor sensitivity.

Different circuit elements will contribute different amounts to the calibration errors. Capacitors will probably introduce some of the larger errors as they are not commonly available with tight tolerances, while resistors may be easily obtained with tolerances of ±1% or better. Also significant is the forcing coil coefficient, Gn, which will depend on the coil winding characteristics, the magnet strength and the steel armature properties, all of which will initially be somewhat uncertain. The displacement sensor sensitivity may also be slightly uncertain, though its effect on the instrument performance will be less significant, so long as its value is known reasonably well. Finally, it will be important to know the boom mass and mass distribution, which will mostly depend on the coil weight and the boom construction details.

In general, the desired response curve may be obtained by selecting various resistor values to compensate for variations in the capacitors, the forcing coil Gn value and the boom mass characteristics.

Referring to the schematic, the various resistors have different effects.

Original Inyo

R9 adjusts the feedback loop's generator constant, its V/m/s in the mid-frequency region, compensating for variations of Cd, Gn and M_0, the boom mass.

R3 sets the frequency of the inverse filter high-frequency zero, F_{FH} , and compensates for any inaccuracy of C1.

R4 sets the span of the inverse filter, which affects the low-frequency loop gain--not a calibration issue, but one which is possibly related to the resulting amount of low frequency waveform distortion and drift.

R2 can adjust the overall effective sensor gain, r_t, to the desired value, compensating for variations in the displacement sensor circuit sensitivity and for the effects of the choices for R3 and R4.

Ri is determined by the temperature range over which the instrument is intended to operate and it also affects the low corner frequency of the instrument response. Its value must be low enough for the integrator to be able to handle the maximum expected temperature variations, but high enough to not introduce excessive long-period noise from the integrator circuit. As a starting point, Ri could be chosen to allow operation over a temperature range of ±15°C.

After Ri is determined, R5 sets the low corner frequency of the instrument response, correcting for the tolerance of Ci and the choice of Ri.

Rp removes any resonant peaking at the instrument's low corner frequency and is a function of that frequency and the feedback loop's generator constant.

The output amplifier circuits can be assumed to be accurate within a percent or two, but may be checked and trimmed if desired. The gain of the low-gain output amplifier is given by R27/R23, which is nominally 2.004. The low gain-output is amplified by an additional factor given by R12/R14, [Inyo-2 R12/R16] nominally 50, resulting in an overall gain of 100.2 at the high-gain output. These gains multiply the loop generator-constant and determine the overall instrument generator-constants at the low and high-gain '+' output terminals. Note that the 'LOW - ' output terminal is only used for providing a balanced signal to a 24-bit differential-input digitizer.

Measurements:

It will be helpful to first measure the capacitors making up Ci and Cd as well as C1, as their values will be used in the calibration process. Then the boom mass, M_0, the displacement sensor gain, R_{sensor}, and the forcing coil constant, G_N, should be measured.

First, the instrument may be assembled without the spring and the effective boom weight measured by means of a sensitive scale, arranged to support the beam so that it is level, at a point which is the same distance from the pivot as the center of the coil/magnet. That gives M_0. When using particularly flexible (Kapton) flexures, watch to be sure that without the spring, they aren't flexing downward too much during the measurement.

To measure the sensor gain, remove jumpers JP1 and JP2 and unplug the connection to the forcing coil. Arrange for the boom to seek its upper stop, either by installing and adjusting the spring or by means of an external spring such as a rubber band gently lifting the boom. Mount a micrometer or micrometer head to press down on the boom at the same distance from the pivot as the center of the coil. Mount the micrometer so that it can move the boom over its vertical range. Starting with the boom approximately centered, connect a meter to the 'POS ERR' output, pin 7 and turn on the electronics. After the voltage stabilizes, using the micrometer, move the boom in steps in both directions from center over about half its range, approximately ±0.4mm or ±0.015", while recording the micrometer readings and corresponding output voltages. The slope of the data curve at its zero-volt point (change in voltage/change in position in mm) should be approximately 12.5V/mm, which, multiplied by R6/R29 (nominally 1/10), will give the value of r_{sensor}.

G_N can be measured with the instrument assembled and operating normally. First record the coil resistance, Rc, and the measured value of Ri. Attach an accurate voltmeter to the

"CENT FORCE" output, pin 6, and turn on the seismometer. Balance the boom if necessary and after it stabilizes, record the voltage, V_{CF}. Then place a 500mg weight on the top of the boom at the same distance from the pivot as the center of the coil. If necessary, any approximately 500mg non-magnetic object whose weight is accurately known, such as a #6 brass washer, may be used instead of a 500mg standard weight. After the output on pin 6 settles, record the new voltage. The coil constant Gn = W/ δV_{CF} * 0.00981* (Ri+Rc) N/A, where W is the test weight value in grams.

For example, if adding a test weight of 0.50g results in an output voltage change of 3.86V with Ri = 12,000 Ohms and Rc = 50 Ohms, then Gn = (0.5/3.86) x 0.00981 x (12,000+50) = 15.31 N/A Or for greatest accuracy you could multiply that by R21/R18, as measured, instead of assuming a nominal ratio of 1.0 .

Recalibration

This can be done occasionally to determine if the instrument generator constant has changed to any significant degree.

There are two approaches to performing this calibration, mechanical and electrical.

Mechanical calibration can be performed with a specialized shaker table, oscillating vertically with an accurately known amplitude. It is extremely important that no tilting occur along with the vertical motion as that can introduce serious errors, though it is somewhat less of a problem with vertical seismometers. The magnetic fields surrounding magnetically driven shakers can completely invalidate the measurements, and must be eliminated. In general this approach is not likely to be successful unless one has access to specialized seismometer test equipment. http://bnordgren.org/seismo/Shaker01.pdf

Alternatively, vertical position steps may be applied and the recorded data processed to reveal the generator constant.
See: http://www.lennartz-electronic.de/MamboV4.5.2/downloads/CT-EW1.pdf

A beam-balance type scale may also be used so long as it is capable of supporting the weight of the instrument. With the instrument resting on the weighing platform, the beam is smoothly but quickly moved between two closely spaced stops causing the seismometer to experience a vertical step in displacement of accurately known amplitude. See: http://bnordgren.org/seismo/cal_exer.JPG In this picture of an Inyo and an STS-2, pieces of cardboard are being used as flexures to restrain any accidental horizontal motion of the scale platform. The resulting data are then analyzed using Erhard Wielandt's program DISPCAL to report the instrument sensitivity.

An index to a number of pages relating to instrument calibration is at:
http://www.lennartz-electronic.de/MamboV4.5.2/index.php?option=com_content&task=category&sectionid=8&id=41&Itemid=68

For simple recalibration it is only necessary to have a voltage source which can produce a sine wave with frequency in the range of 1/10 to 1 Hz and having an accurately known voltage of several volts, along with a means of accurately measuring the resulting seismometer output voltage. The voltage measurements can possibly be made with the same A/D setup planned for recording the outputs of the operational instrument. ....

Appendix:

Parts cross reference - Original Inyo to Inyo-2
Part and pin numbers are all the same except for:

	Original Inyo Rev 1.13	Inyo-2 Rev. 2.0
J3-2	Sensor - 3 Cb	Sensor - 2 Cb
J3-3	Sensor - 2 Ca	Sensor - 3 Ca
P2-3	Sig. A	Out Low -
P2-4	Sig. B	Out Low +
P2-5	Sig. Gnd	Out Hi +
P2-10	N/C	Gnd
	R14	R16
	R16	R14
	U3A if JP4 2-3	U3A
	U3A if JP4 1-2	U9A