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Teaching Geophysics with a Vertical-Component Seismometer

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Earthquakes are some of the more dramatic expressions of the dynamics of our planet. The sudden release of stress built up slowly by tectonic or volcanic processes often has far-reaching consequences, and can be measured (in classrooms) around the world. This is one reason why designing and building seismometers has been a popular activity,[1,2] and why different versions of "Seismometer in Schools" projects thrive in the United States, Australia, and Europe. We present a cheap, robust, and easy-to-build seismometer—called the TC1 —to measure seismic displacements in the vertical direction. Its components are easy to obtain and assemble, yet the resulting instrument is accurate enough to record earthquakes from around the globe. The parts list and building instructions of the TC1 seismometer are freely available online. Alternatively, a complete kit can be purchased for around US$300. Assembling the system naturally introduces students to a number of concepts in physics and engineering, while upon completion seismic recordings trigger discussions about the dynamics and internal structure of the Earth. The discussions are fostered by service learning and shared in the network of TC1s called the Z-NET.

The TC1 seismometer

The following describes in broad strokes the components of the TC1. Detailed instructions, including the Bill of Materials, on how to build a TC1 seismometer are available online at http://tc1seismometer.wordpress.com/.

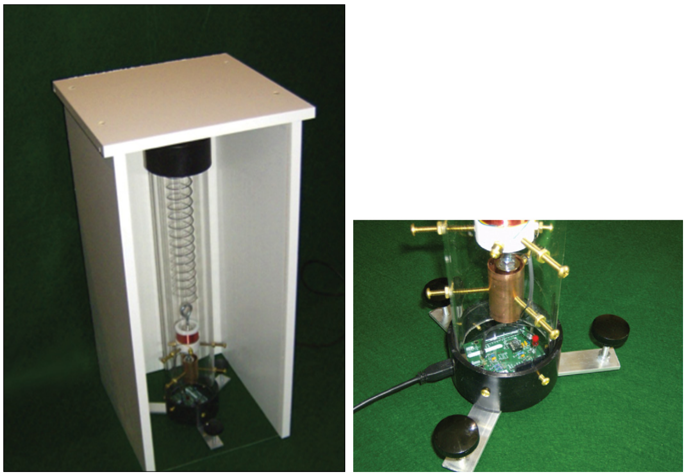

Fig. 1. Left: Photograph of the TC1 seismometer, based on a magnet and Slinky toy spring. Right: a close-up of the bottom of the induction coil, the damping system of a magnet inside a copper tube, and the NERdaq recording system.

• *Spring, mass, coil, and magnet*

At the heart of the TC1 seismometer is a harmonic oscillator composed of a mass on a spring, inside a clear-plastic frame with legs (Fig. 1). Ground motion moves the frame, but the inert mass resists movement. Our spring is a Slinky® toy with a natural period around 1 s, and the mass a neodymium magnet. The magnet is positioned inside a handmade coil consisting of many wraps of narrow-gauge copper wire and which is attached to the frame. When the frame is disturbed by ground motion, the magnet on the spring moves relative to the coil, which leads to an induced current in the coil.

• *Magnetic damping*

To isolate seismic vibrations from the ringing of an excited harmonic oscillator, we damp the system. Historically, seismometers were damped using friction from a viscous fluid (such as oil), but here we use magnetic damping with a second magnet suspended well below the first magnet on the spring. This second magnet is positioned inside an isolated copper tube, attached to the frame. When the sensor is perturbed, the second magnet induces eddy currents in the copper tube that counteract the motion of the spring/mass.

The digital acquisition system

Like all modern seismometers, the TC1 uses a wide dynamic range digital recording system. Our system is named the NERdaq. We have constructed a simple system consisting of an analog stage with an integral high-cut filter followed by a 10-bit analog-to-digital converter (ADC) that is heavily oversampled. Oversampling is simply the technique of heavily averaging a noisy stream of digital samples to produce a slower stream with greater effective resolution.[3] Figure 2 is a graphical representation of the steps that make up the NERdaq.

The analog side of the system consists of an op-amp that provides a gain of about 800 together with a simple high-cut filter that starts to roll off at about 2 kHz. This unusually high cut-off frequency provides noise to the ADC input that makes oversampling work.

The digital side is based upon the popular, inexpensive open-source Arduino hardware, in our particular case the Arduino Uno. This system supports 10-bit ADC conversion at 9600 samples per second (sps). We use an averaging window of 2048 samples, which is stepped by 512 samples to provide an output sample rate of 18.78 sps. This heavily averaged output has an effective resolution of about 16 bits (although system noise uses up one or two bits of resolution). The data

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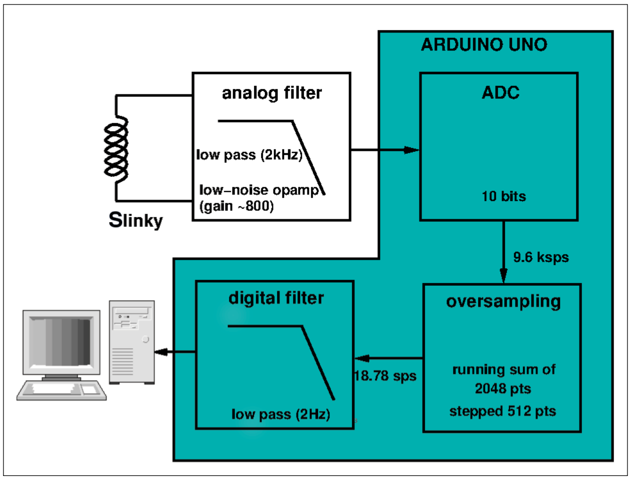


Fig. 2. Block diagram of the NERdaq interface between the raw analog signal and computer.

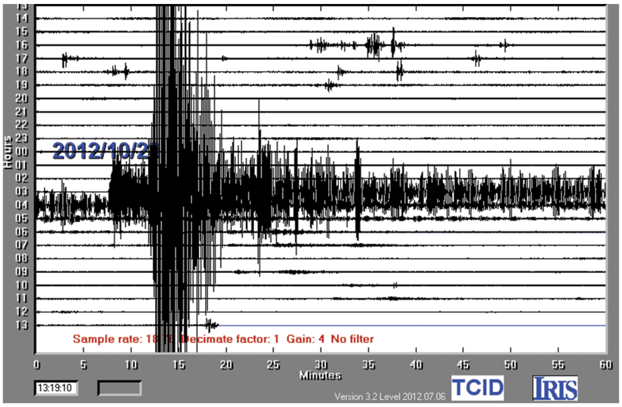
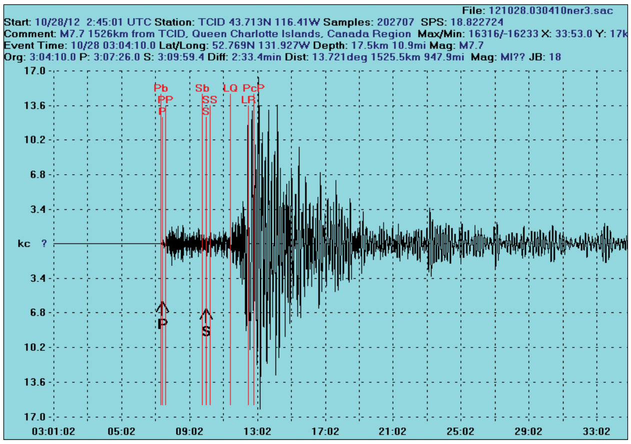


Fig. 3. Snapshot of the seismic data recorded on station TCID in Eagle, ID, on Oct. 28, 2012, when an earthquake struck off the west coast of Canada at 03:04:08 UTC.



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                                                     File: 121028.030410ner3.sac
Start: 10/28/12  2:45:01 UTC Station: TCID 43.713N 116.41W Samples: 202707  SPS: 18.822724
Comment: M7.7 1526km from TCID, Queen Charlotte Islands, Canada Region  Max/Min: 16316/-16233 X: 33:53.0 Y: 17k
Event Time: 10/28 03:04:10.0 Lat/Long: 52.769N 131.927W Depth: 17.5km 10.9mi Mag: M7.7
Org: 3:04:10.0 P: 3:07:26.0 S: 3:09:59.4 Diff: 2:33.4min Dist: 13.721deg 1525.5km 947.9mi  Mag: Ml?? JB: 18
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Fig. 4. Part of the seismic data from Fig. 3 that contains the signal from an earthquake located off the west coast of Canada. The different seismic waves arriving in Idaho have been annotated.

stream is then subject, in software, to three digital filters:

1) a low-pass minimum-phase filter at about 2 Hz to reduce noise,
2) a band-boost filter that enhances the signal between 10 and 20 s to highlight short-period surface waves, and
3) a high-pass filter with a 30-s cutoff to remove drift.

The first filter introduces an impulse delay of about 0.4 s, which we judged tolerable. The other filters have little effect on the high-frequency P-wave arrival.

The system is implemented on a printed-circuit daughterboard that couples directly to the Arduino Uno (although the analog part is simple enough to wire by hand). The latest version of the TC1 has the NERdaq built into the bottom part of the sensor case, with its output fed via USB to the host computer.

• *Amaseis*

Once signals are filtered and converted from analog to digital in the NERdaq, we display the seismogram on a PC with software named Amaseis, written by Alan Jones for the IRIS "Seismometers in Schools" program.[4,5] While originally written for the AS-1 vertical seismometer and its "black box" interface, the TC1 system seamlessly operates with Amaseis. On the same computer, timing accuracy is ensured with a free version of software called AboutTime.[6]

Classroom seismology

Once the TC1 is completed, exciting seismic records such as in Fig. 3 are quite common. These are a starting point for inquiries in a number of concepts in seismology, supporting lessons about the Earth's subsurface structure and processes. We encourage the students to enroll for an automated warning system such as the one run by the United States Geological Survey (USGS), so that students are notified when significant earthquakes have occurred.

• *Earthquake identification*

When students observe an anomalous signal on their sensor, an email or text message from the USGS can confirm (or deny, if this was a "bump" of the instrument) the recording is from an earthquake. Figure 4 shows the data that contain the main energy recorded from an earthquake with magnitude 7.8 off the west coast of Canada from Oct. 28, 2012, at 03:04:08 UTC. Annotated are the *predicted* main arrivals of different seismic waves, based on a spherically symmetric model of the Earth.[7] We used Larry Cochrane's Winquake software, but (freeware) alternatives with similar capabilities, such as Obspy and Amaseis, are available. Most obvious is the prediction and the onset in the data of the fastest seismic wave (the primary or P-wave is marked with a single "P") followed by the slower secondary or S-wave, and seismic waves that bounce off the surface and main interfaces of the Earth (core, mantle, crust). Seismic waves that travel along the Earth's surface (so-called Rayleigh, LR, and Love waves, labeled LQ) make their way from Canada to the TC1 station in Idaho as slower, but more energetic, signals. The predicted seismic phases overall match the data, which means that the approximation of a spherically symmetric Earth structure is not bad at all. In fact, it is the small deviations from this approximation that seismologists use in seismic tomography to unravel the details of the Earth's subsurface structure.[8]

• *Finding the epicenter with the TC1 network*

To estimate the epicenter of an earthquake, schools can first compare the arrival of the P-wave at various stations. The earlier the arriving P-wave, the closer a station is to the epicenter. While this can provide a first-order estimate with a large network, students can then try to identify arrival of the secondary wave (S-wave). The time difference between the S- and P-wave (S–P) from an earthquake recorded at a specific station determines the distance from that station to the epicenter (Fig. 5). Students can then draw a circle with a radius that equals this S–P distance on a map. The earthquake could lie anywhere on this circle, but similar epicentral distance circles from two more TC1 schools uniquely define the epicenter.

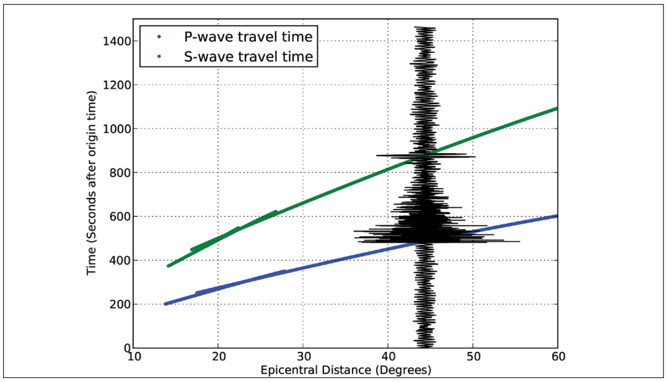

Fig. 5. Seismogram with predicted P- and S-wave arrival times in blue and green, respectively. This is overlaid onto a P- and S-wave travel-time plot for epicenters from 0 to 60°. At 43°, the S – P-wave travel time matches the curves.

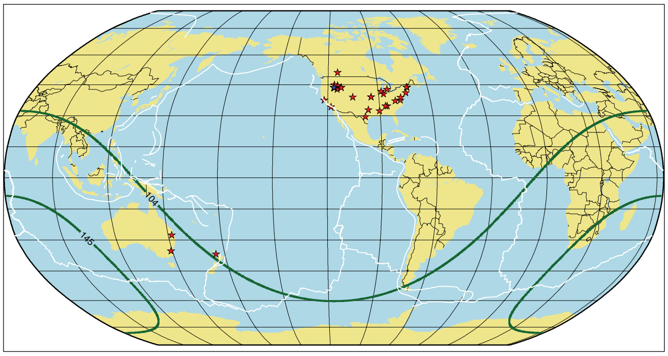

Fig. 6. World map with the members of the Z-NET indicated by stars. The 104° and 145° contours outline the P-wave shadow zone for station TCID (blue star). Because of the drop in P-wave speed in the liquid outer core, TCID does not record direct P-waves from this region.

• *Service learning and the Z-NET*

Student engagement through hands-on learning is a productive learning strategy that integrates well with service learning: the promotion of student learning through relevant community service. In this case, students learn seismology by building a seismometer, helping a K-12 teacher set it up in his or her classroom, and then teaching K-12 students about the subject matter. As a result, undergraduate students have been mentors for institutions of secondary education. Now, some 50 TC1s populate the planet in our network called the Z-NET (pronounced "zed-net," Fig. 6). If the TC1 user marks each epicenter of the earthquakes it records on this map, it will not be long until tectonic plate boundaries are outlined by these marks.

Conclusions

The robust TC1 seismometer, easy to build and understand, acts as a gateway to learning the underlying physics of the sensor. Topics such as inertia, (damped) harmonic oscillators, induction, and eddy currents are brought to the fore. in the assembly phase. Upon completion, the end-product of earthquake recordings sparks discussions about the physics of the Earth, including plate tectonics, structure of the deep Earth, and geohazards.

Acknowledgments

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