Seismometers & Accelerometers:
Are you using the right sensor for the job?

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Abstract

How do you decide what is the best type of sensor for your application? Is a "broadband" sensor always the best choice? Is a short period seismmometer useful? How good are modern accelerometers and geophones? Is there one system that can do everything? In this paper we explore the relative benefits and deficiencies of a range of sensor types and technologies, and how to record the signals from these sensors to capture all of the relevant frequency and amplitude data for your application.

Sensors and recording equipment have come a long way in the last 40 years. Refinement of old techniques and the development of new approaches for detecting motion over the range of earthquake frequencies have created a range of products that can be confusing, and with digital sensors combining recording equipment with sensing elements also in the mix, it has become difficult to distinguish which products have the right performance for the application at the right price.

This paper looks at several sensor technologies: passive elements (geophones), active elements (force feedback, electrochemical, modified response geophones), various types of accelerometers (MEMS, feedback coil, optical interferometry), as well as how these pair with various types of recording systems; to discover a set of criteria for selecting the right equipment for each monitoring application. Applications include: structural monitoring, ambient vibration surveys, blast monitoring, aftershock monitoring, regional seismic monitoring networks, and global earthquake monitoring networks.

Keywords: instrumentation, earthquake, sensors, technology, noise, dynamic range

EARTHQUAKE SENSOR EVOLUTION

The first seismograph was a device that measured the physical displacement of the ground using a sprung mass on a pivot. To make devices smaller required measuring the change in displacement over a smaller distance, and thus the velocity sensor was born. Although more compact, strong motions still caused the velocity sensors to clip, so a further differential measurement of ground motion was required, and the accelerometer came into being.

For decades, accelerometers have had the reputation of being insensitive and only good for recording moderate to large earthquakes at close range, but as with all technology, accelerometer performance has improved with time. In fact, many earthquake sensors have improved to the point that we can no longer record their full range of ground motion with a single analogue-to-digital converter. To understand sensor performance we first need to understand how data is recorded. As seismologists we tend to base our instrumentation decisions on simple numbers in technical specifications and data sheets, but we really need to understand what these numbers mean to decide whether a particular sensor or recorder can perform the intended function.

DIGITAL RECORDING AND DYNAMIC RANGE

Almost all observatory-grade seismic recorders use 24-bit or 32-bit analogue to digital converters (ADCs), although the useful range of currently available of 32-bit ADCs is limited to the lower 24 bits – the other 8 bits are digital noise.

24-bits equates to 16,777,216 counts of recording range. If the average (RMS) noise level is just **one** count out of this range, then the dynamic range of recording is defined as:

$$20\log10(16777216/\mathbf{\underline{1}}) = 144.5\text{dB}$$

The USGS ANSS guidelines[1] require that the dynamic range of a data acquisition unit should be ≥24-bits, based on the RMS noise compared to the RMS of the zero to peak signal of a sine wave, which would be:

$$20\log10(8388608/\mathbf{\underline{1}}/\sqrt2) = 135.5\text{dB}$$

Whichever way that dynamic range is defined, there is still only 1 count of noise, and the full scale range is still ±8,388,608 counts.

You will often see very large dynamic range numbers quoted for digitisers, even when based on the ANSS method. This is possible when the RMS value of the noise is less than one count. It is possible to have less than one integer count of noise because the RMS value is an average over a number of samples. A small reduction in the fraction of a count has a huge impact on the dynamic range number, but in practice it means very little. For example:

$$20\log10(8388608/\mathbf{\underline{0.5}}/\sqrt2) = 141.5\text{dB}$$

$$20\log10(8388608/\mathbf{\underline{0.1}}/\sqrt2) = 155.5\text{dB}$$

Apart from the digitiser noise levels we need to consider sensor noise levels. A typical ADC input range is 40 Volts peak-to-peak, so a single count in a 24-bit range is equivalent to 2.3µV. One of the first things to look at is the electronic noise level of the sensor is over the bandwidth of interest. Noise increases with frequency, so another way sensors and recorders can be quoted with high dynamic range figures is by looking at a very low frequency band or recording data at a low sample rate.

In all sensor testing a 6-channel or 12-channel Kelunji EchoPro seismic recorder with 24-bit ADCs was used. Data was recorded at 100 samples per second (sps), giving a bandwidth of DC to 40Hz (after FIR filtering). The ANSS requirement for digitisers recording frequencies up to 30Hz is 123.4dB, and the EchoPro has a dynamic range of 131.5dB at 100sps and 123.3dB at 500sps.

SENSORS TESTED

A range of velocity and acceleration sensors were tested over a period of more than 12 months at the Geoscience Australia (GA) seismic vault at Toolangi in central Victoria. The makes and models of sensors tested included:

- Guralp CMG-6T-1 1Hz velocity seismometer
- Guralp CMG-5TC ±2g accelerometer
- Silicon Designs MEMS ±2g accelerometer
- White Industrial 1Hz geophone
- Lennartz LE-3Dlite MKII seismometer
- Trillium Compact 20s posthole seismometer
- Silicon Audio 203P broadband posthole accelerometer

Results from these sensors were also compared to the GA equipment operating at the vault, which comprised a Quanterra Q330-HR digitiser, a Streckeisen STS-2 (120s to 10Hz) broadband seismometer, and a Geotech PA22 ±2g accelerometer. An electro-chemical sensor was also to be compared, but there were some reliability issues and the sensor was subsequently excluded from the testing process.

PROCESSING DATA & RAW RESULTS

Several earthquakes and blast events were studied during the sensor comparison, and background noise levels were also studied to compare sensor noise levels at the quietest seismic vault within practical range of the Seismology Research Centre. The vertical channel of each sensor was primarily used for sensor comparison. Most magnitude values stated are in MLv (local Richter magnitude, calculated from the vertical channel of calculated displacement of signals 2Hz and above).

Data viewing, conversion and filtering was performed using the eqWave software.

COMPARING THE 5TC, MEMS, 6T-1 AND 1HZ GEOPHONE
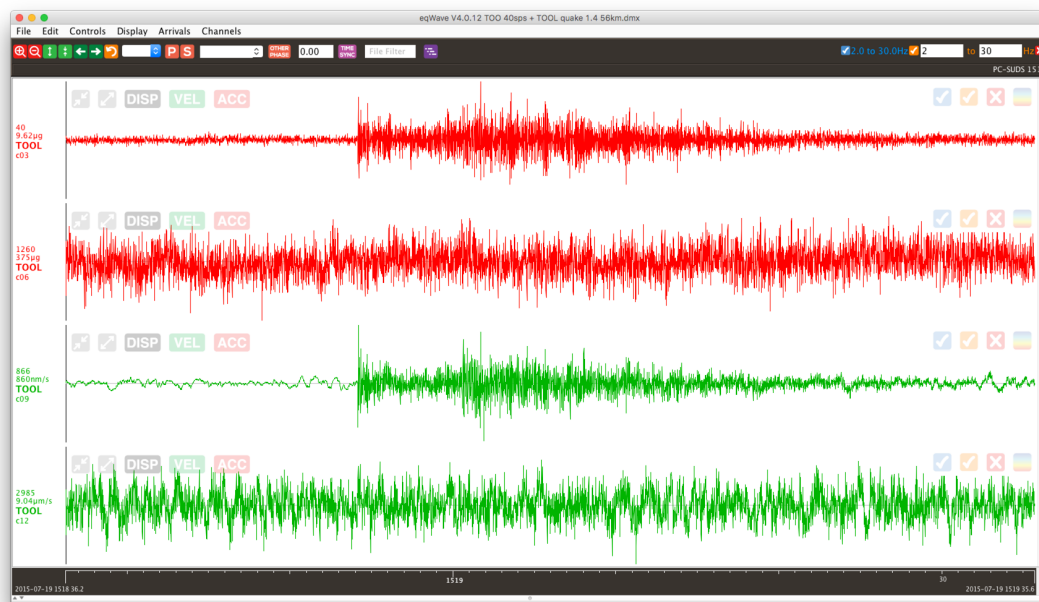
2015 July 20, magnitude 2.3 at 208km range
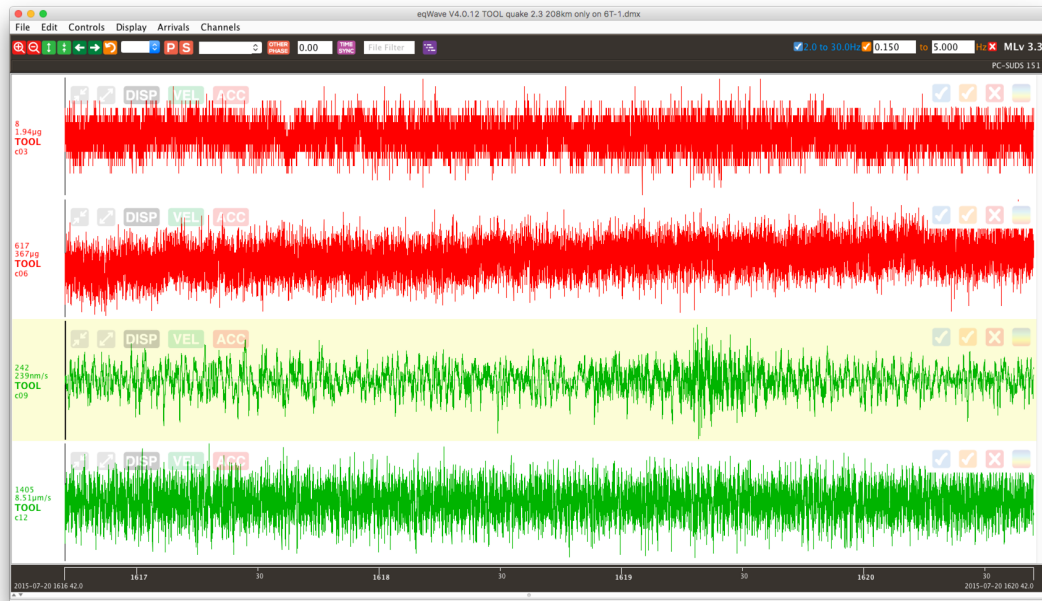
top-bottom: vertical channel of 5TC, MEMS, 6T-1, 1Hz geophone

This earthquake (image above) was only visible on the 6T-1 seismometer. Filtering the data (image below) from 2-30Hz revealed this local event more clearly on the seismometer, but nothing was apparent on the 5TC or MEMS accelerometers, nor on the 1Hz blast-monitoring spec geophone. The peak value on the 6T-1 was 209nm/s with an average background noise level at the time of around 90nm/s in the 2-30Hz band. The S-wave is just discernable on the filtered 5TC accelerometer data, but it would not be noticeable without the seismometer for reference.
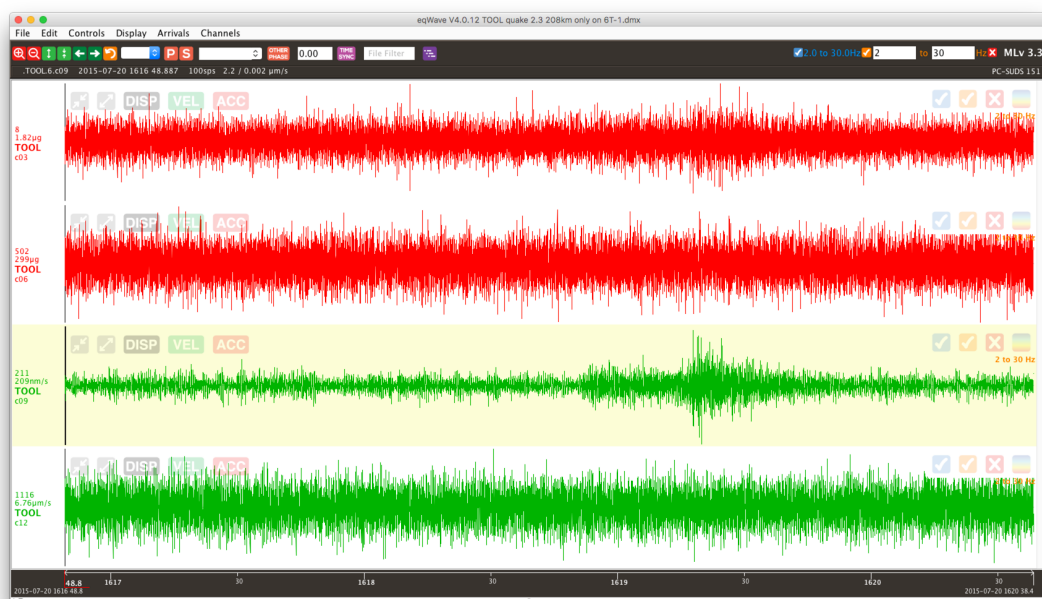
top-bottom: vertical channel of 5TC, MEMS, 6T-1, 1Hz geophone, filtered 2-30Hz

2015 July 19, magnitude 1.4 at 56km range

top-bottom: vertical channel of 5TC, MEMS, 6T-1, 1Hz geophone

This earthquake was much smaller but much closer and was clearly visible on the 5TC accelerometer and 6T-1 seismometer without any waveform filtering. The signal to noise ratio for the two Guralp sensors was quite similar. The time of this event was 1518 UTC, or 1:18am local time, a quiet time of day; ideal for comparing sensor background noise levels. The STS-2 was sampled at 40sps, so comparing the 1-20Hz bandwidth reveals the following sensor noise levels:

- 0.95 micro g (5TC)
- 205 micro g (MEMS)
- 0.056 μm/s (6T-1)
- 4.88 μm/s (geophone)
- 0.005 μm/s (STS-2)

The STS-2 shows that the station noise is well below any of the other sensors tested, indicating that these numbers are true sensor noise levels in this frequency band.
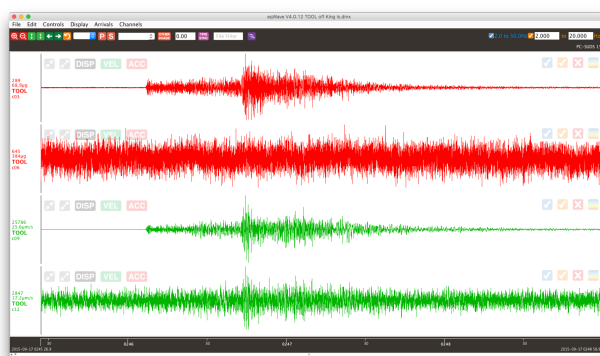

During the period of testing no event generated sufficient ground acceleration to appear above the noise level of the MEMS accelerometer. Only one event, a magnitude 4+ at a distance of around 300km, generated sufficient ground motion to appear above the noise level of the 1Hz geophone (left).

At this point the testing of the MEMS accelerometer and 1Hz geophone ended and testing moved to comparing the Lennartz 1Hz seismometer with the Guralp 6T-1. Although the Lennartz uses a similar technological approach to the 1Hz geophone, it was developed with earthquake monitoring in mind, not for blast monitoring.

COMPARING THE 6T-1 and LE-3Dlite MKII

2015 October 9, magnitude 1.3 at 60km range
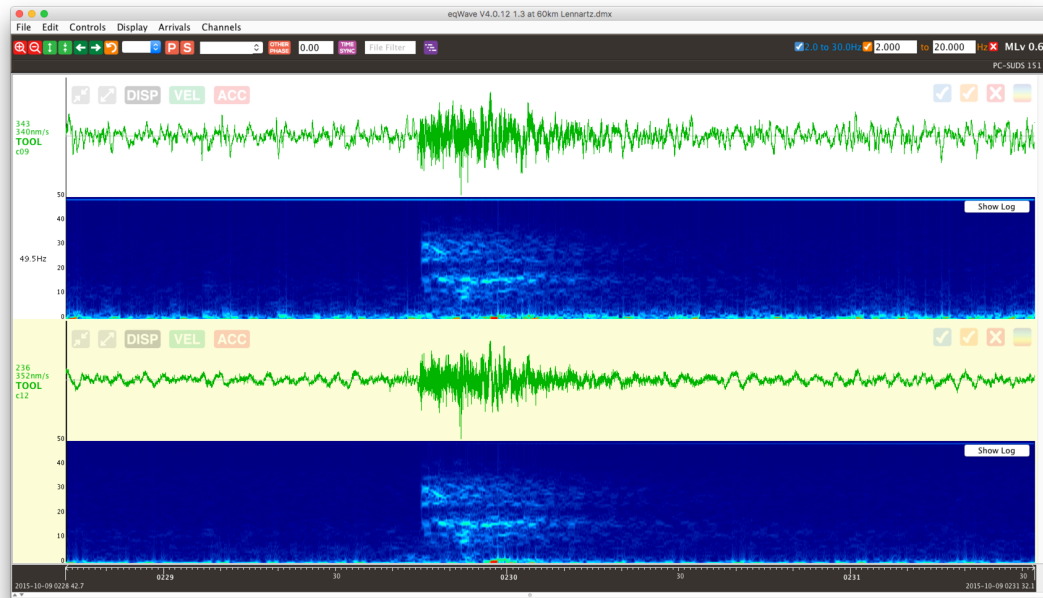
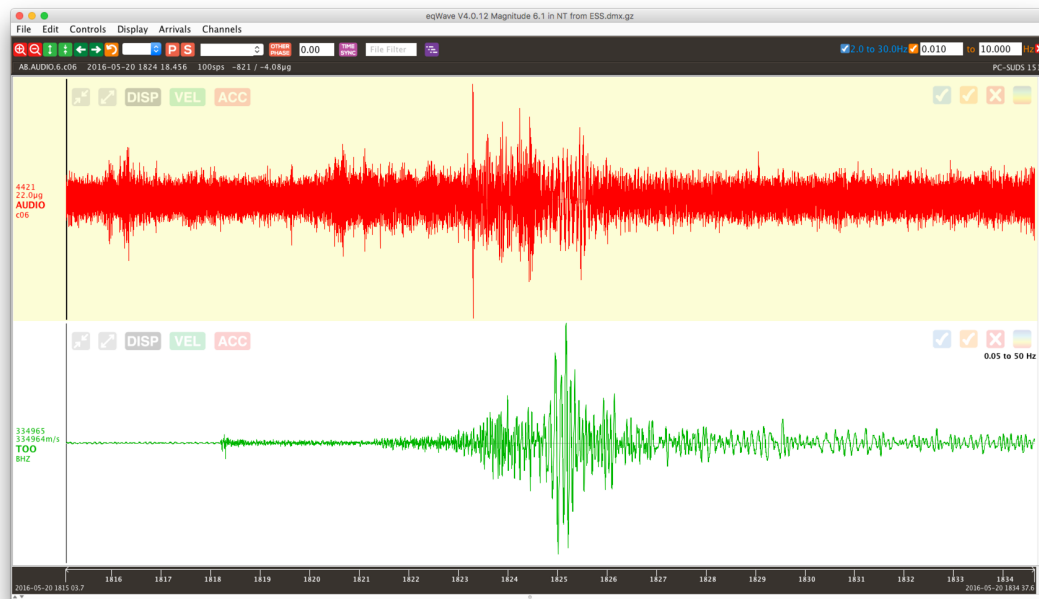*top: vertical channel of 6T-1, bottom: vertical channel of LE-3Dlite MKII*

At about half the amplitude of the July 19 event, the traces above show the similarity of the 6T-1 and LE-3Dlite MKII sensors. As can be seen in the spectrograms below each trace (image above), the 6T shows a lot more low frequency content at and below 1Hz compared to the MKII (note: since testing, the MKIII was released and improves on this low frequency performance). This is not surprising given the different designs of the sensor components, but for the intended purpose (local earthquake monitoring over the 1-100Hz band) their performance is satisfactory.
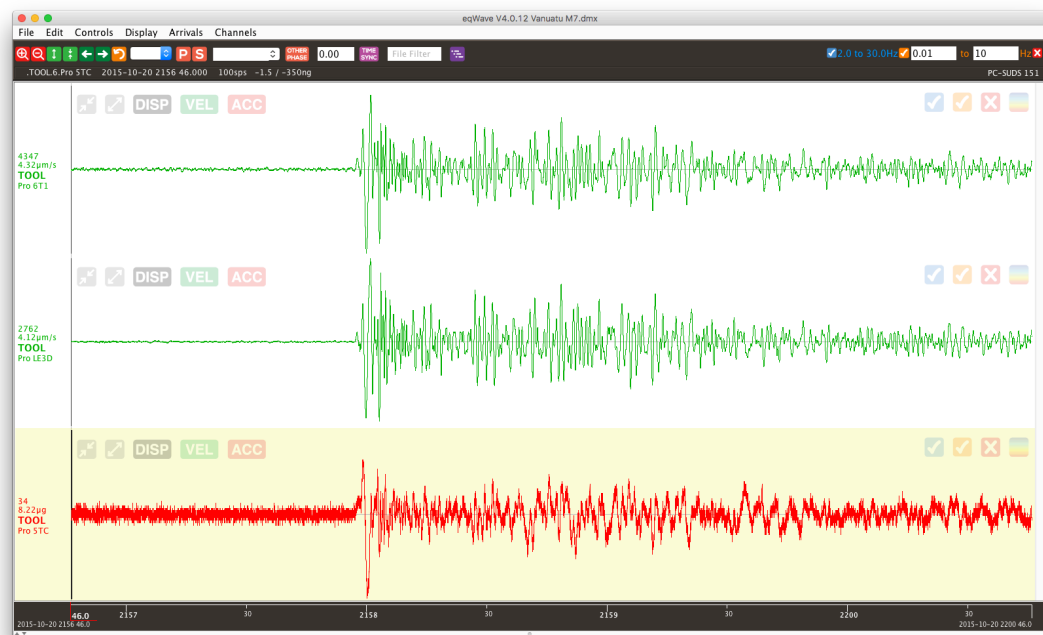
This is not to say that the MKII cannot detect low frequency signals. The event above shows the recording of a magnitude 7 earthquake in Vanuatu (about 3300km range) on the 6T-1 (top), MKII (middle) and even the 5TC accelerometer (bottom).

EVALUATING THE BROADBAND OPTICAL ACCELEROMETER

### 2016 May 20, magnitude 6.1 at 2800km range

top: vertical high gain acceleration channel of 203P at SRC office
bottom: vertical channel of STS-2 at Toolangi vault

Upon receiving the 203P optical broadband accelerometer evaluation unit, it was set up in our office and left overnight as a basic functionality test. Within hours of being set up we were fortunate enough to have recorded the largest earthquake in Australia in 19 years, with its epicenter about 100km west of Uluru. As can be above, the raw acceleration trace was not particularly inspiring when compared to the recording from the STS-2 at Toolangi, even considering its noisy office location.
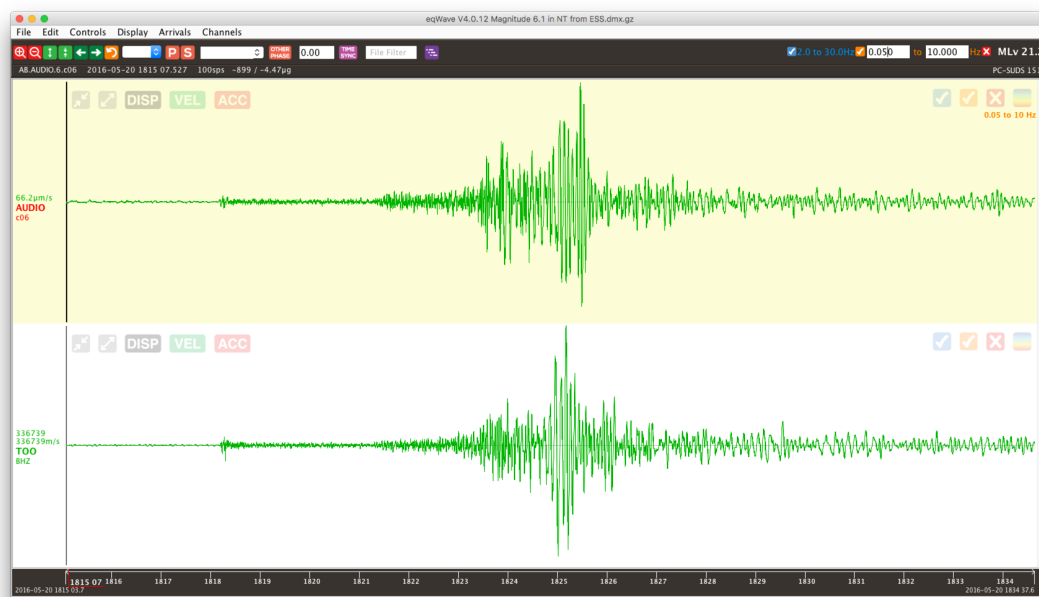

Although, once converted to velocity and filtered from 20-seconds to 10Hz (to match the energy content visible on the STS-2), the traces were surprisingly similar. An impressively comparable result from an accelerometer in a noisy urban environment.

Indeed, after the 203P was taken to the Toolangi vault, it continued to perform comparably to the STS-2 in detecting low frequency signals, so the next test was to evaluate its performance at high frequencies for monitoring local earthquakes.
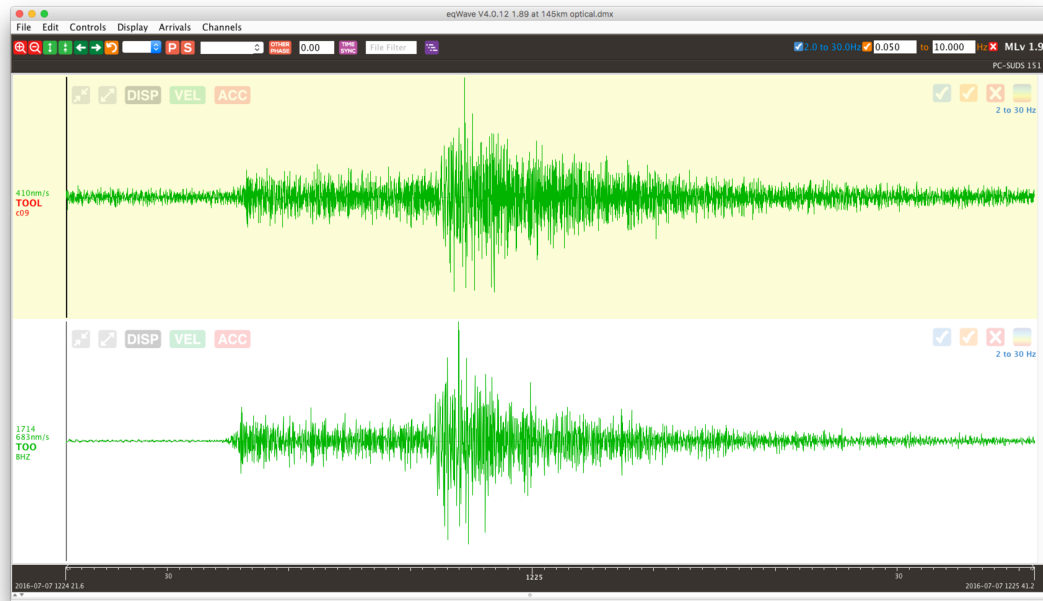
top: velocity conversion of 203P, bottom: STS-2 (both filtered 2-30Hz)

The earthquake above, a magnitude 1.9 at 145km, appeared clearly on the 203P above a background noise level of around 30 nm/s, compared to the STS-2 noise level of around 9nm/s (filtered 2-30Hz). The Trillium Compact 20s sensor was then installed with a different 203P sensor, and several earthquakes reviewed.
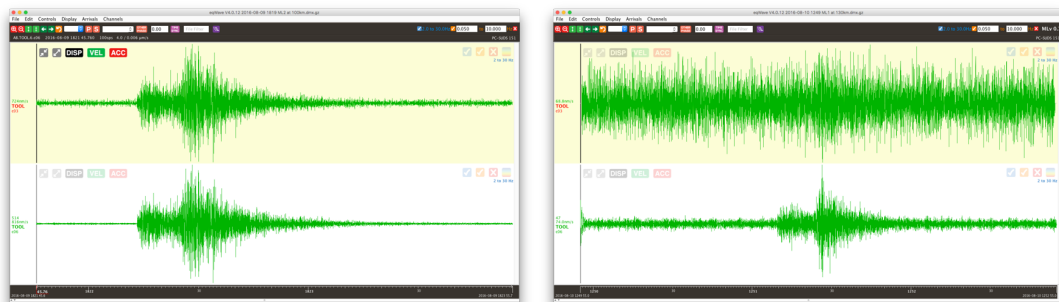
top trace: velocity conversion of 203P, bottom trace: Trillium Compact
left: MLv2.0 at 100km range, right:MLv 1.0 at 130km (all filtered 2-30Hz)

The Trillium and 203P both clearly recorded a magnitude 2 earthquake at 100km (left image), but a magnitude 1 earthquake at 130km (right image) was not visible above the high frequency noise of the broadband accelerometer.

CONCLUSION

The use of MEMS accelerometers does have a place in earthquake seismology as a companion to a weak motion velocity sensor. There is sufficient overlap in ground motion measurement between a velocity sensor and a seismic-grade MEMS accelerometer to increase the dynamic range of recording to around 200dB[2], something that has not been possible with any single sensor (and is certainly not possible with a single 24-bit ADC). MEMS accelerometers are robust and appropriate for use in near field blast monitoring and in structural monitoring where motions below 1000µg are considered unimportant.

Similarly, geophones are relegated to blast monitoring applications, with low frequency performance possible but only at relatively high levels of motion. As such they cannot be considered appropriate for local earthquake monitoring.

When done properly, a geophone-based seismometer can produce similar real-world results to a traditional seismometer, as evidenced by the performance of the Lennartz LE-3Dlite MKII compared with the Guralp 6T-1. They are very similar in price, with the Guralp having a slight low frequency performance advantage, offset by a physical size and power consumption penalty.

On paper the new Silicon Audio 203P optical broadband accelerometer seems to be the answer to the ultimate one-sensor-fits-all solution, with a ±2g output and a parallel high gain output that when recorded through a high gain amplifier (tested at a gain of x16, and converted to velocity) can give the 200dB dynamic range of a combined sensor system. Unfortunately it is let down by noise in the critical 1-30Hz band, making it only slightly more sensitive to small local earthquakes than a traditional feedback accelerometer like the Guralp 5TC. It does provide excellent value for low frequency monitoring applications, particularly due to its small size and the robust nature of the design that has almost no moving parts.

The Trillium Compact 20s sensor performed as a useful reference, and it compared favourably to the STS-2 in low frequency performance, if slightly noisier.

Noise is an important factor in sensor choice, but the biggest effect on noise is the choice of recording location. Most of the results presented in this paper were generated at a well-engineered, remotely-located underground purpose-built seismic vault. This is not typical of most seismic installations, where a compromise is often required because a geologically suitable location may be inaccessible or may not offer the required communication or power amenities.

A modern ±2g accelerometer will suffice for most near-field vibration monitoring applications (particularly aftershock surveys), but additional sensitivity can be achieved using a traditional short period velocity sensor - at the expense of peak motion clipping.

For regional monitoring (detecting events within about 600km of a station) short period seismometers are still the best value option. Longer period response velocity seismometers like the Trillium Compact 20s or the 30-second Guralp 6T or 40T may be more appropriate for larger networks where a low frequency data is required for moment magnitude calculation.

The optical interferometry accelerometer may be an economical option for portable array applications where long period monitoring is required but site conditions may not be ideal. Some basic data processing is required to reveal the data that is otherwise immediately apparent on broadband velocity sensors.

While processing data for this paper it became obvious that more automated data processing is required to make analysing this type of accelerograph data practical. This initiated a campaign to focus on improving the unit conversion aspects of the waveform software used so that seismologists can use data from new technology sensors in more familiar ways.

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(2) Pascale, A., (2009) Using MEMS accelerometers for earthquake monitoring, Australian Earthquake Engineering Society website article; aees.org.au