Velocity Sensor Mega Test: a Noise, Response, and Value Equation

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Abstract

As feedback accelerometer performance improves, short period velocity sensors are becoming less common in near field microseismic monitoring networks. The cost of short period sensors is increasing, making them almost as expensive as medium period seismometers. As low cost electronic hobby kit seismographs emerge, it begs the question as to whether short period sensors still offer value for money.

With so many sensors on the market today it's hard to know which will perform the task based purely based on technical specifications. A sensor may say that it has a flat response down to a particular frequency, or a very wide dynamic range, but unless you consider a number of factors you may end up with a sensor that only records a very narrow range of events, or possibly end up spending a lot of money collecting data that requires pre-processing before it can be analysed.

This paper presents the results of testing several short period (>1Hz) velocity sensors (vertical components only) at the Toolangi seismic vault. Sensors tested include: three passive geophones (1Hz, 2Hz and 4.5Hz); two 1Hz sensors that use passive geophones with electronic period extension and amplification; and a feedback current coil-based 1Hz seismometer. In balancing performance and cost, the best value comes from the traditional 2Hz geophone, particularly when paired with modern high resolution amplifiers and digitisers.

Keywords: seismic, instrumentation, velocity, sensors, short period seismometer

Introduction

As broadband sensor slowly reduce in price and accelerometer performance improves, short period velocity sensors are becoming less common in earthquake monitoring networks. The cost of short period sensors is generally increasing, making some of them almost as expensive as medium period seismometers. This begs the question as to whether modern short period sensors still have a place in earthquake monitoring networks. The Seismology Research Centre has almost exclusively used short period sensors for earthquake monitoring and alert networks for over 40 years, and the ease of data processing and clarity of signal makes them perfectly suited to detecting local earthquake activity. While short period sensors are more affordable than broadband sensors and more sensitive than accelerometers, they will remain the tool of choice.

There are so many sensors on the market today that it's hard to know which will perform the task based purely on technical specifications. A sensor may say that it has a flat response down to a particular frequency, or a very wide dynamic range, but unless you consider a number of factors you may end up with a sensor that only records a very narrow range of events, or possibly end up spending a lot of money collecting data that requires a lot of pre-processing before it is useful.

This paper presents the results of testing several velocity sensors (vertical components only) at the Toolangi seismic vault. Sensors tested included: three passive geophones (1Hz, 2Hz and 4.5Hz); two 1Hz sensors that use passive geophones with electronic period extension and amplification; and a force-feedback pivot-coil 1Hz seismometer. It was hoped that the 4.5Hz geophone-based hobby kit seismograph would be available for the comparison, but it arrived too late for installation at the vault.

An optical interferometry 0.03Hz (30 second) seismometer was also tested, but isn't classified as a short period sensor in the terms of this study, so will be excluded from the discussion of results. So too the permanent on-site STS2 120-second broadband seismometer.

Comparative Costs

The cost of the tested sensors covers a wide range. When considering these sensors in triaxial sensor packages, the lowest cost sensor which uses 4.5Hz passive geophones is priced at **$500**. The next higher in price is a 1Hz sensor based on 10Hz geophone elements with electronic low frequency (LF) amplification, priced at around **$2500**. The 2Hz passive geophones as a triaxial package in a housing comes in at around **$4000**, followed by a 1Hz sensor based on 4.5Hz geophones with electronic response modification at **$6000**. Next was the active 1Hz seismometer at **$10000**. The most expensive triaxial short period sensor - whose design has remained unchanged for 40 years - is a passive 1Hz sensor which is currently priced at a staggering **$12000**!

It should be noted that there are 30+ second period seismometers available at lower cost than some of these short period sensors, starting from around $8000, but in micro-seismic networks much of this low frequency signal would need to be filtered out in normal processing. This may be an operational issue for data processors, which will be explored below.

Sensitivity

A velocity sensor's output is measured in V/m/s (Volts per metre per second) and the higher the number the more sensitive it is. A passive sensor is one that does not require power to operate, and as such the output from purely mechanical systems tend to be quite low (e.g. 28.8V/m/s for the 4.5Hz geophone, 78.74V/m/s for the 2Hz, and 180V/m/s for the 1Hz). These passive signals can be amplified in the recorder when used at quiet locations, and in this test higher gains were used to better test self-noise levels of the sensors at a very quiet underground seismic vault.

The active sensors have their own amplifiers, so their sensitivities tend to be in the hundreds or thousands of V/m/s. Again, these signals were amplified for noise testing.

Test Setup

The sensors were connected to two recorders, named TOOL3 (a 3-channel logger) and TOOL4 (a 4-channel data logger), both sampling data at 250sps, giving an effective signal bandwidth of DC to 100Hz (the recorder's FIR filter starts attenuating signal from about 80% of the Nyquist frequency). Channel codes in the recordings equate to the following sensors:

- TOOL3 CHE: LF boosted 10Hz geophone for 1Hz flat response
- TOOL3 CHN: LF boosted 4.5Hz geophone for 1Hz flat response
- TOOL3 CHZ: 1Hz+ passive geophone
- TOOL4 CHE: 4.5Hz+ passive geophone
- TOOL4 CHN: 2Hz+ passive geophone
- TOOL4 CHZ: 1-50Hz active seismometer
- (TOOL4 CHO: 30s-80Hz optical seismometer – reference only)

As the 10Hz based sensor had a 0-5V output with a 2.5V zero offset, a gain of x4 was the maximum gain possible on the TOOL3 recorder's ±20V input. A gain of x16 was used on TOOL4 to get the best noise figure for the lowest output sensor (the 4.5Hz passive geophone).

For transparency, at the time of the test, the SRC had a commercial interest in selling the 1-50Hz active seismometer. All other models are sensors purchased by SRC from the suppliers on the open market without any commercial distribution arrangements.

Sensors (l-r): 4.5Hz and 2Hz passive geophones (on circular plate), 1Hz active seismometer, optical sensor under foam box, LF boosted 10Hz & 4.5Hz geophones, and 1Hz passive geophone

An Early Exit

The sensors were initially set up in an office environment for configuration tests before being deployed to the vault. The noise levels in the office were such that it was difficult to see much difference in sensitivity, apart from the 10Hz geophone based sensor which appeared to have a relatively high level of self noise.

This was further highlighted once installed at quiet the Toolangi vault. The peak noise level over the 100Hz bandwidth for this sensor was around ±3µm/s, over 20 times higher than most of the other sensors. The largest earthquake recorded during the test period, a magnitude 3.3 at a distance of 200km from the test site (less than 3 days after testing began!), registered S-wave peak amplitudes of around 5µm/s on the other sensors, but no discernible signal was visible on the 10Hz geophone based sensor.

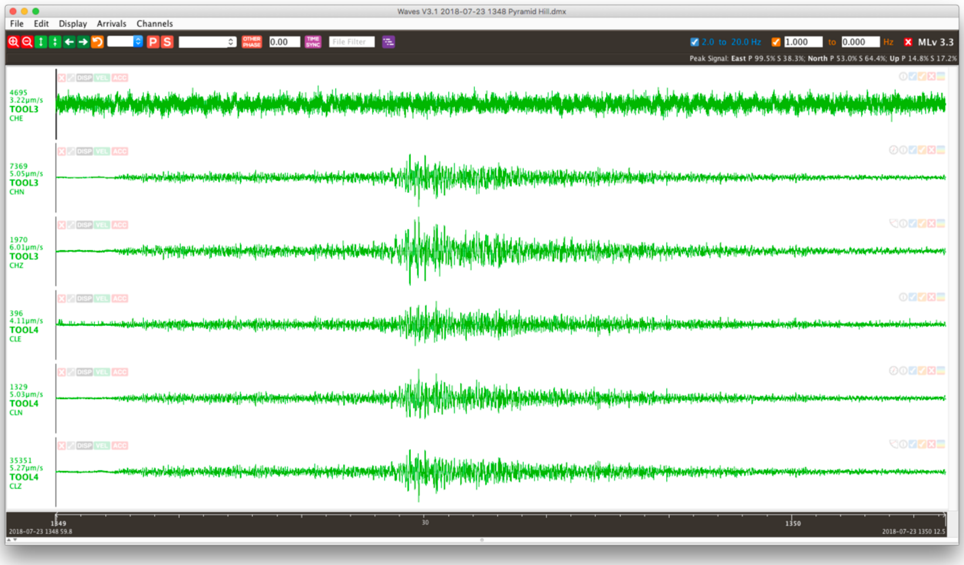

Figure 1: 10Hz geophone based sensor (top channel) shows no discernible signal Note that all channels above are scaled to a common peak amplitude

The sensor was later checked to ensure it was actually working (which it was). The sensor is designed for blast monitoring, and it does have a linear amplitude response when shaken at 1Hz, but only at high amplitudes. Despite being specified with a high gain output for an output range of 25.4mm/s (the standard unit has 254mm/s range) there was no benefit to sensitivity, implying a poor amplifier design. This sensor was deemed unfit for purpose and is excluded from further discussion of results.

Comparing the Passive Geophones

As we are interested in sensitivity of short period sensors, this distant moderate magnitude earthquake is a good event for comparing sensor performance. We first compared the purely mechanical sensors. These sensors have low noise but also low signal levels so often need to be amplified to reveal their sensitivity potential. With such small signal levels, they also need to have good cable shielding, an issue that was not sufficiently addressed in the test setup, resulting in small spikes and 50Hz AC mains power noise visible in the data when looking at small signal levels.

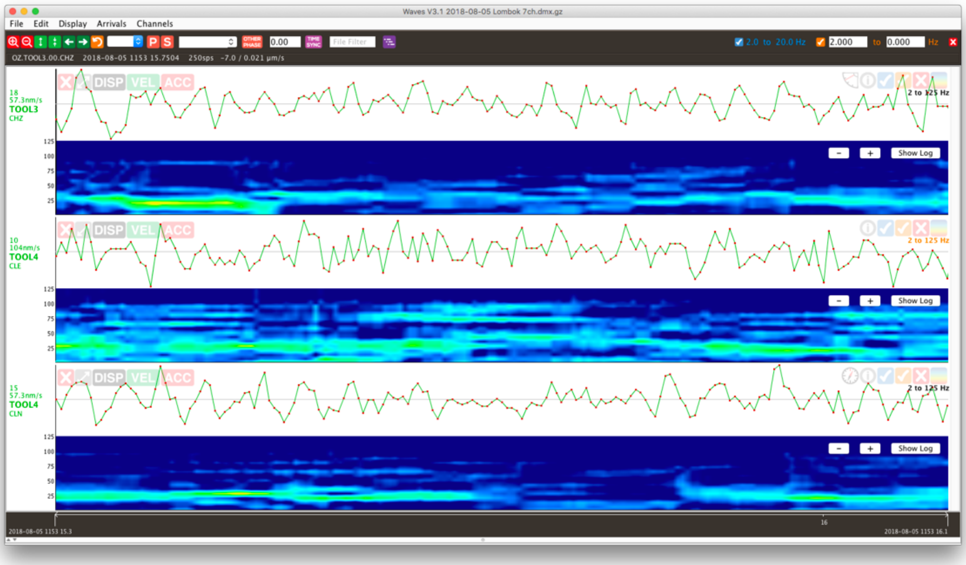

Figure 2: Background noise of passive sensors; 1Hz (top), 4.5Hz (middle) and 2Hz (bottom)

Figure 2 above shows the 4.5Hz sensor (middle trace) displays realtively more high frequency energy due to its insensitivity to low frequencies, but the 4.5Hz sensor had a peak noise level (~104nm/s) twice that of the 1Hz and 2Hz sensors (~57nm/s).

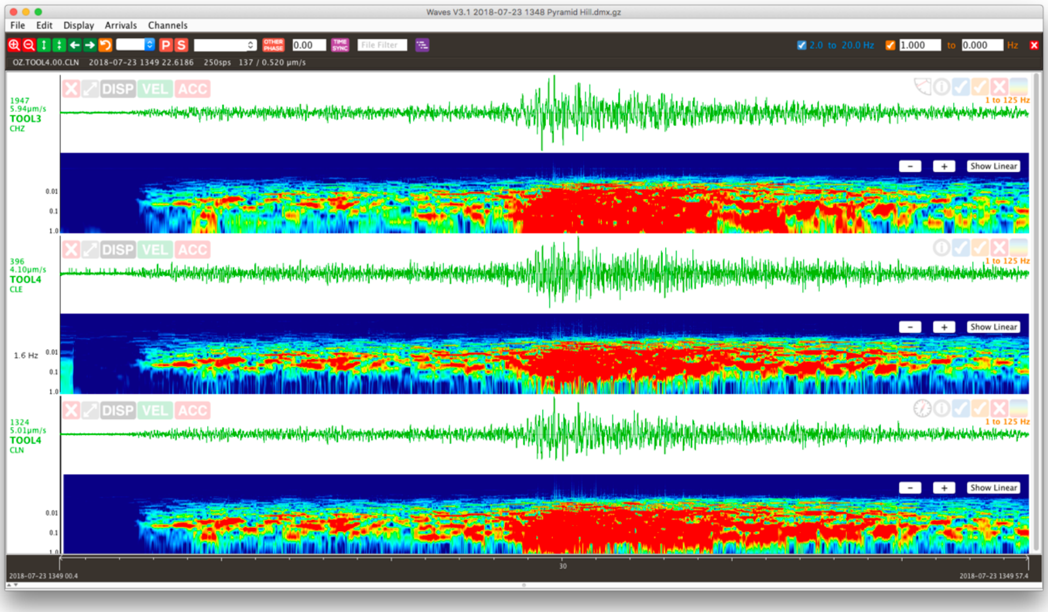

Figure 3: log spectrograms; 1Hz (top), 4.5Hz (middle) and 2Hz (bottom)

As shown in the spectrograms above, the 1Hz sensor shows high energy levels recorded down to 1Hz (bottom of first spectrogram), and the insensitivity of the 2Hz and 4.5Hz sensors to low frequencies are obvious. The absence of low frequency energy, particularly on the 4.5Hz sensor, resulted in slightly lower peak amplitudes.

Comparing the 1Hz Sensors

For all the electronic wizardry that has gone into developing active seismometers with 1Hz frequency response, there doesn't seem to be a particular benefit in performance other than requiring less amplification by the recorder.

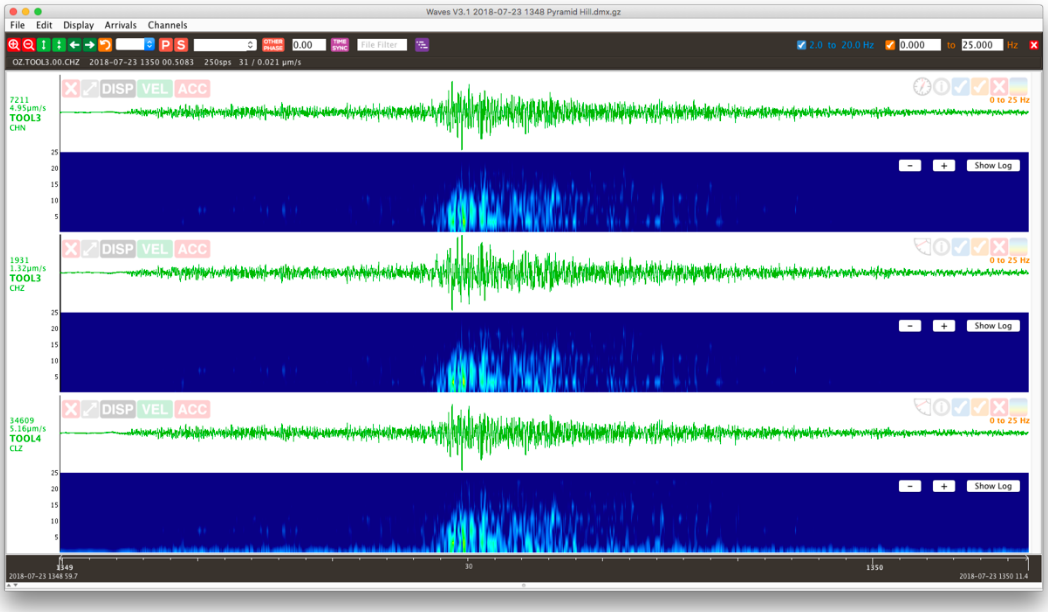

Figure 4: linear spectrograms; passive (top), amplified 4.5Hz (middle) and pivot coil (bottom)

Looking at the same magnitude 3.3 earthquake at 200km range again, the three 1Hz seismometers have practically identical recordings (ignoring the varied polarity). The force feedback pivot coil sensor shows more low frequency content below 1Hz, but the site noise measurement is no better than the passive sensor.

Value For Money

Eliminating the modified 10Hz blasting geophone and 4.5Hz passive geophone based on their relative insensitivity, we are left with four short period sensors to consider for local earthquake monitoring. To recap, the approximate costs of **triaxial** units of these sensors in AUD are:

- 2Hz passive geophones **$4K**
- 1Hz electronically amplified 4.5Hz geophones at **$6K**
- 1Hz feedback seismometer at **$10K**
- 1Hz passive sensor at **$12K**

From our passive sensor comparison we know that the 2Hz sensor performed well against the 1Hz, and at a third of the price offers good performance for the price. Of the active sensors, the high quality low frequency boosting of the 4.5Hz geophones resulted in identical performance to the 1Hz seismometer, at almost half the price.

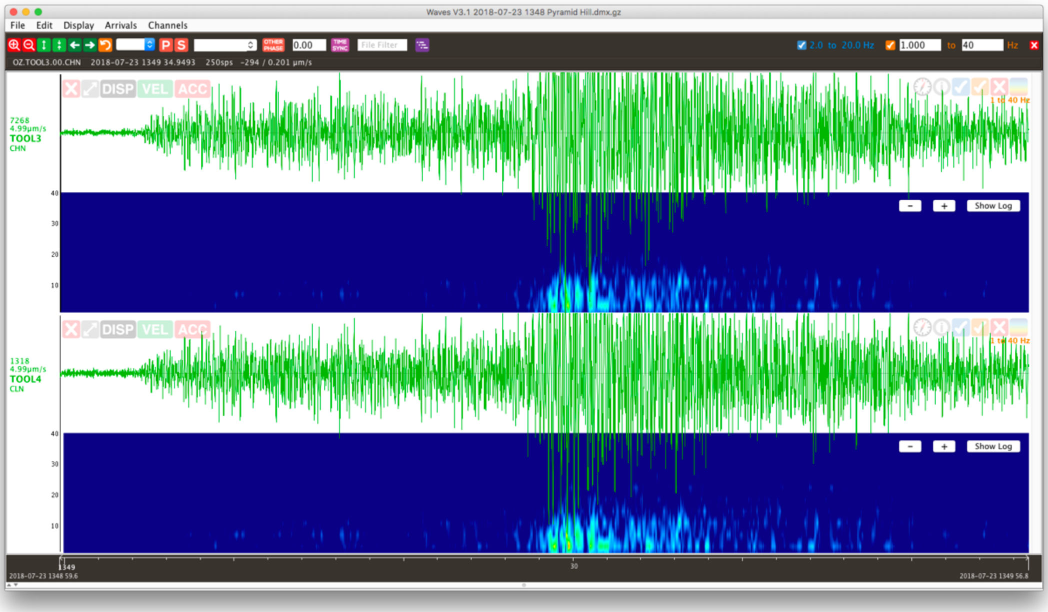

Figure 5: 1Hz active seismometer (top) compared to 2Hz passive geophone (bottom)

Looking at the same earthquake again, we compare these two sensors in more detail. The pre-event noise level in the recording is around 0.1µm/s on both sensors. Remember that these sensor were on different recorders at different gains, so to compare performance effectively we need to evaluate a typical configuration.

The 1Hz sensor would normally be used at a gain of x1, although this sensor has a clip level of 70% of the recorder's input range, resulting in a clip level of 17.5mm/s. The 2Hz sensor at a gain of x16 has the same signal level at the site noise floor as the 1Hz would at a gain of x1 (about ±30 recorder counts), and would clip at the recorder's full scale input at about 16mm/s. Here too we find equivalent performance.

Portability

As short-period sensors are often used in portable applications such as aftershock monitoring, or large node arrays where many instruments are transported and deployed by less experienced staff or students, a robust sensor is important.

Although not specifically tested in the course of researching this paper, years of experience have demonstrated the relative reliability of the various configurations. Small geophone-based sensors (both passive and low-frequency boosted) tend to be the most robust, able to take rough treatment without issue.

The pivot-based active sensor can sometimes have a component stuck if transported roughly, which can often be addressed with a tap, but is an issue that can be easily missed by inexperienced users.

The large-mass passive 1Hz geophone is reliable, but needs to transported in a particular orientation to avoid the masses knocking around, and the size and weight of this sensor, particularly in triaxial form, makes it impractical most of the time.

Short Period vs Broad Band

Although vault-spec broadband seismometers still cost many tens of thousands of dollars, some modern portable broadband sensors can be found for $8K to $12K, providing low frequency performance that often covers the frequency band of short period sensors. It is tempting to consider purchasing broadband sensors for the added flexibility for other applications, but if the primary purpose of your application is looking at local earthquakes within about 500km of your seismograph, then paying two or three times as much for a sensor may be uneconomical.

The other consideration is that when used for local earthquake monitoring, broadband sensor data needs to be filtered to display small high frequency local events that are otherwise lost in high amplitude the long period oscillations; and the additional filtering steps in data analysis to review triggers and pick arrivals.

Modern Accelerometers

As explored in a previous paper (Pascale, 2016) modern accelerometers can achieve similar noise performance to short period seismometers. A similar issue to using broadband sensors arises – the need to perform data conversion and filtering before the data is easily analysed. The cost of these modern accelerometers is higher than the 2Hz passive geophone (at around $5.5K) and they tend to draw significant amounts of power, but they do have a greater dynamic range as they clip at ±2g or higher.

Their range becomes an advantage if a magnitude 5+ earthquake occurs within about 30km of a seismograph – a velocity sensor would likely clip, but an accelerometer could record a magnitude 6+ earthquake at the same distance before clipping.

Conclusion

Frequency response, sensitivity and noise levels all need to be considered carefully when selecting a sensor. A 1Hz specification can be misleading, particularly if the sensitivity is unusable; and a low sensitivity specification may not be a limiting factor if the sensor can be operated at a high gain without amplifying its noise.

Of the sensors tested, the 2Hz passive geophone, when recorded at high gain on a high dynamic range recorder, appears to be a compelling option in the limited choice of short period seismometers available today. With practically equivalent performance to 1Hz sensors for local earthquake monitoring applications, it seems illogical to spend 50% to 200% more on the alternatives, particular when these other sensors cost almost as much as medium period seismometers.

The physical durability, compact form factor, and the power consumption benefits of using the 2Hz passive geophone makes it the best choice of short period seismometer for local earthquake and aftershock monitoring applications.

REFERENCES:

Pascale, A. (2016) Seismometers & Accelerometers: Are you using the right sensor for the job?, Asian Seismological Commission General Assembly, Paper 86.