Long-Period Earthquake Recording Using a 2 Hz Geophone With Inverse Response Correction

A field study evaluating whether useful long-period earthquake motion can be recovered from a conventional 2 Hz moving-coil geophone when compared with broadband seismic sensors.

This research demonstrates that a conventional 2 Hz geophone can contain recoverable long-period earthquake information well below its nominal natural frequency when the sensor response is known, the recording system has sufficient dynamic range, and digital inverse response correction is applied.

Researcher: John Giles
Organization: Seismic Source

Test Location: Ponca City, Oklahoma Area
Recording Period: Multi-year field comparison
Primary Equipment: Sigma 3 Seismograph, 2 Hz Geophone, Broadband Seismic Sensors

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Test Objective

A long-term field test was conducted to evaluate how well a conventional 2 Hz moving-coil geophone could record earthquake signals when compared with broadband seismic sensors.

The primary objective was to determine whether useful long-period seismic information exists in the output of a 2 Hz geophone at frequencies substantially below its nominal natural frequency, and whether that information can be recovered through digital inverse filtering.

Particular attention was given to long-period earthquake energy extending to approximately 30-second periods, or about 0.033 Hz.

Test Setup

The test system consisted of a 2 Hz geophone and multiple broadband seismic sensors installed at the same test location in a remote area of Oklahoma.

All sensors were placed on the same concrete slab inside a barn. This arrangement provided a common foundation and helped ensure that the instruments were subjected to substantially the same ground motion.

The remote location was selected to minimize interference from traffic, industrial activity, and other sources of cultural vibration.

The instruments continuously recorded seismic activity for more than two years. During this period, the system captured both distant large earthquakes and smaller regional and local earthquakes.

The broadband sensors served as the reference instruments because their mechanical and electronic response extends to much longer periods than that of a conventional 2 Hz geophone.

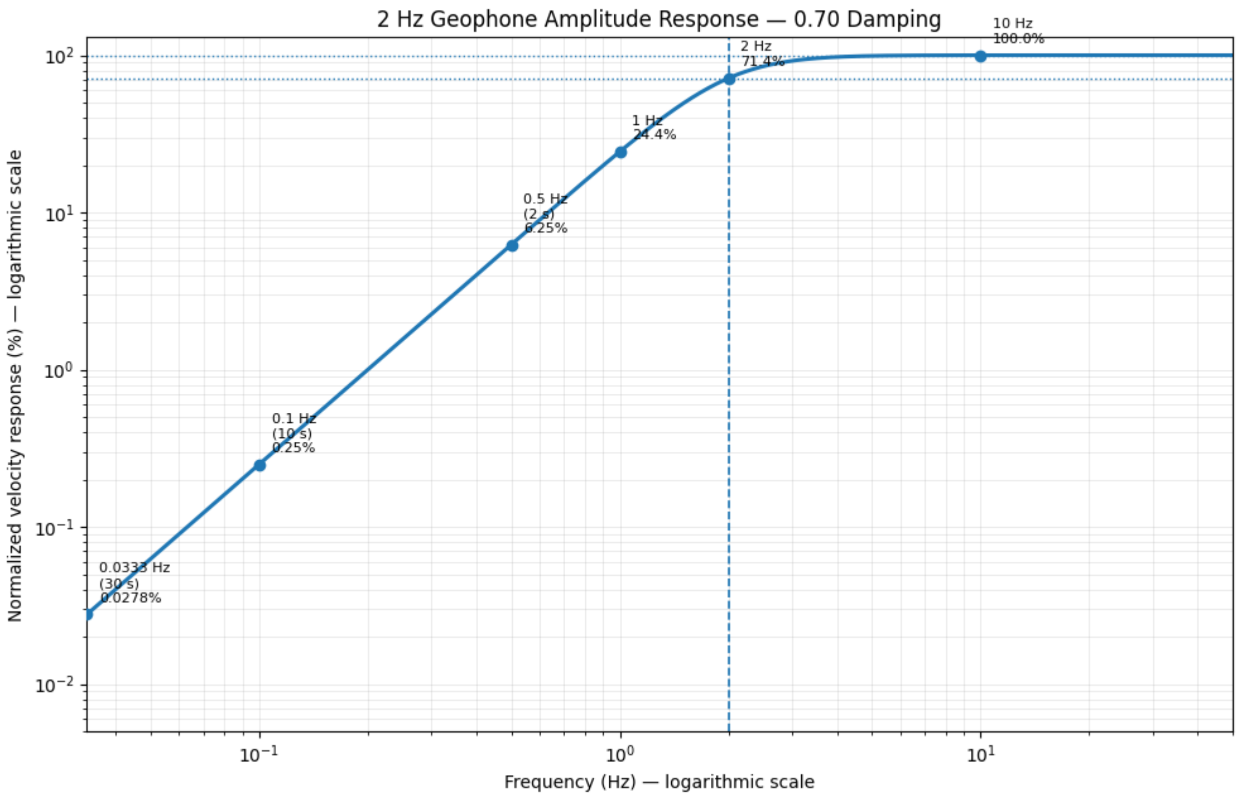
Expected Response of the 2 Hz Geophone

A conventional 2 Hz geophone is normally considered a velocity sensor whose useful flat response begins near its 2 Hz natural frequency. Geophones roll off at approximately **12 dB/octave** (40 dB/decade) below their natural frequency.

For a geophone with approximately 0.7 damping, the output at 2 Hz is roughly 70% of its higher-frequency velocity sensitivity. Below the natural frequency, the response decreases rapidly, approximately proportional to frequency squared.

As a result, the theoretical response at very long periods becomes extremely small. At a 30-second period, corresponding to approximately 0.033 Hz, the raw sensitivity of an ideal 2 Hz geophone is only a very small fraction of its nominal sensitivity.

For this reason, earthquake signals containing strong long-period motion are often essentially invisible in the uncorrected geophone waveform.



A few useful points from the curve:

- **2 Hz:** 71.4% response
- **1 Hz:** 24.4%
- **0.5 Hz (2 s period):** 6.25%
- **0.2 Hz (5 s):** 1.00%
- **0.1 Hz (10 s):** 0.25%
- **0.0333 Hz (30 s):** only **0.0278%**

Observations from Large Earthquakes

The difference between the raw 2 Hz geophone data and the broadband sensor data was particularly apparent during larger earthquakes.

In many events, the broadband instruments clearly recorded the long-period earthquake waveform while very little, or in some cases essentially no recognizable earthquake signal, could be seen directly in the raw 2 Hz geophone data.

This initially gives the impression that the 2 Hz geophone is not detecting the long-period motion.

However, the absence of a clearly visible waveform in the raw data does not necessarily mean that the information is absent. Instead, the signal has been strongly attenuated by the known mechanical transfer function of the geophone.

Inverse Response Correction

The recorded 2 Hz geophone data was digitally corrected using an inverse filter based on the geophone's frequency response.

The inverse filter compensates for the attenuation produced by the geophone below its natural frequency. At long periods, where the mechanical response of the geophone is very small, the digital correction applies correspondingly large gain.

Following this correction, long-period signals that were nearly invisible in the original waveform became clearly observable.

One of the most significant results of the test was that the inverse-filtered 2 Hz geophone waveforms matched the broadband sensor recordings remarkably well during many of the larger earthquake events.

The waveform shape, timing, and long-period motion observed after correction closely followed the signals recorded independently by the broadband instruments.

This indicates that the moving-coil geophone was physically responding to ground motion far below its nominal 2 Hz natural frequency, even though the mechanical response had attenuated the signal to a very low level in the raw recording.

Information Exists Below the Natural Frequency

The results demonstrate an important distinction between sensor response and the actual presence of seismic information.

The 2 Hz natural frequency should not necessarily be interpreted as a hard lower-frequency limit below which no useful information is recorded.

Instead, the geophone behaves as a predictable mechanical filter.

Provided that:

- the geophone transfer function is known,
- the acquisition electronics have sufficiently low noise,
- the recorder has adequate dynamic range,
- the original waveform is recorded without inappropriate filtering or clipping, and
- the signal remains above the combined sensor and electronic noise floor,

the attenuated low-frequency information can potentially be recovered digitally.

In this test, useful earthquake information was recovered at periods extending many times longer than the nominal 0.5-second natural period of the 2 Hz geophone.

Regional and Local Earthquake Performance

An additional and somewhat different result was observed for smaller regional and local earthquakes.

Earthquakes of approximately magnitude 3 and smaller occurring within a few hundred miles of the test location were frequently recorded very clearly by the 2 Hz geophone.

In many of these cases, the seismic arrivals appeared stronger or more easily identifiable on the 2 Hz geophone than on the broadband sensors.

This behavior is reasonable because nearby smaller earthquakes generally contain a greater proportion of their useful signal energy at higher frequencies than distant large earthquakes.

These frequencies fall within or above the natural-frequency region of the 2 Hz geophone, where its sensitivity is high and relatively flat.

The broadband sensors are designed to provide extremely wide frequency response, including very long periods, but that does not automatically mean that they will provide the strongest or cleanest representation of every local high-frequency seismic event.

For nearby earthquakes, the combination of the 2 Hz geophone's sensitivity, coupling, acquisition electronics, and frequency response can produce an excellent signal-to-noise ratio.

Significance of the Test

The two-year comparison suggests that a high-quality 2 Hz geophone combined with a sufficiently capable digitizer may have a much wider practical seismic bandwidth than would be assumed from its nominal natural-frequency specification alone.

For conventional seismic exploration, the geophone may simply be treated as a sensor with a usable response beginning near its natural frequency.

For earthquake monitoring, however, the complete sensor and recorder system should be considered.

The geophone continues to produce a physical response below resonance. The response becomes progressively smaller, but it follows a predictable transfer function. If the signal is recorded with adequate fidelity, digital inverse-response correction can recover a significant portion of the attenuated low-frequency ground motion.

The field comparison with broadband sensors provides direct experimental evidence of this behavior.

Conclusions

The long-term Oklahoma test produced several important observations.

A conventional 2 Hz geophone showed very little visible raw response to the long-period components of some large earthquakes, particularly at periods extending toward tens of seconds.

After applying an inverse filter based on the geophone response, those same recordings produced long-period waveforms that closely matched the simultaneously recorded broadband sensor data.

This demonstrates that the long-period earthquake information was present in the geophone recording even though it had been strongly attenuated by the sensor's mechanical response.

The test also demonstrated that the 2 Hz geophone performed extremely well for regional and local earthquakes. Events of approximately magnitude 3 and smaller occurring within a few hundred miles frequently produced strong, easily identifiable signals and in some cases appeared better defined on the geophone than on the broadband instruments.

These results indicate that the nominal 2 Hz natural frequency of a geophone should not be viewed as an absolute low-frequency cutoff. Instead, it defines the mechanical response of the sensor. When that response is accurately characterized and the recording system provides sufficient low-noise dynamic range, inverse filtering can extend the useful recovered bandwidth to periods far longer than the geophone's natural period.

The following data shows some of the results of this testing.

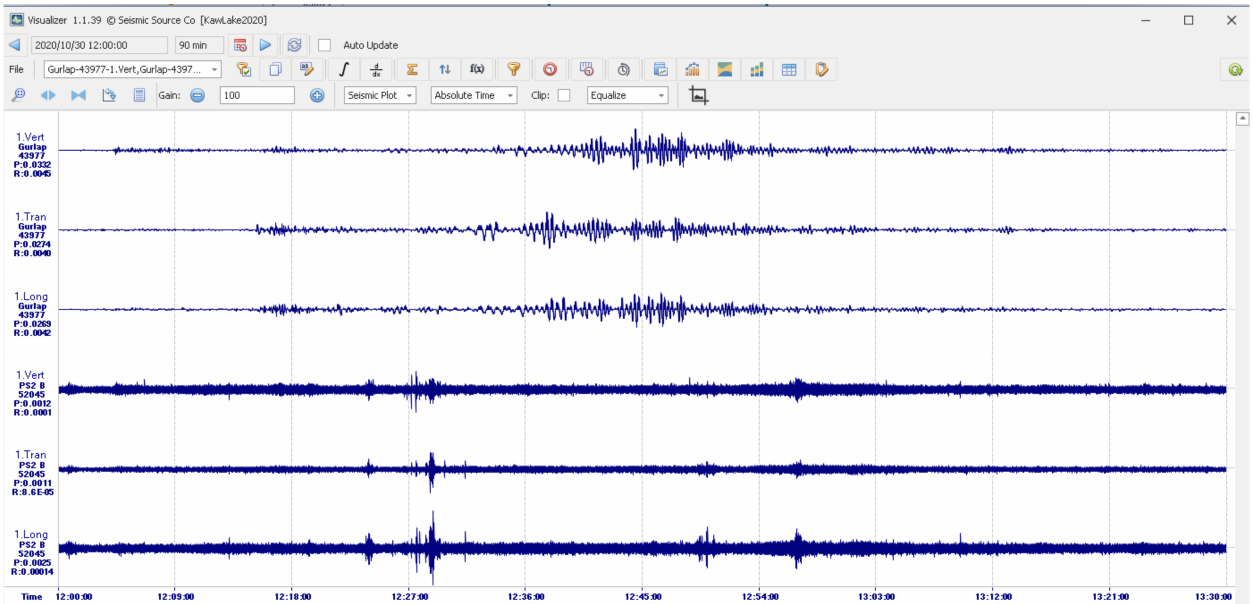
Sigma3 low noise 32 bit seismograph was used for the data collection

Sunful PS2 – 2Hz geophone with nominal sensitivity of 22 volts/Meter/second sensitivity was used for all recordings

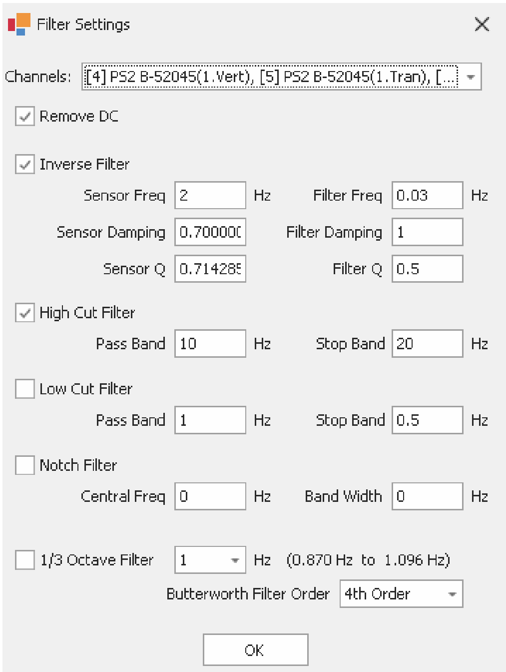
Mag 7 Greece 10-30-2020

Raw Signals from Guralp 40T and Sunful PS2 – 2Hz geophone

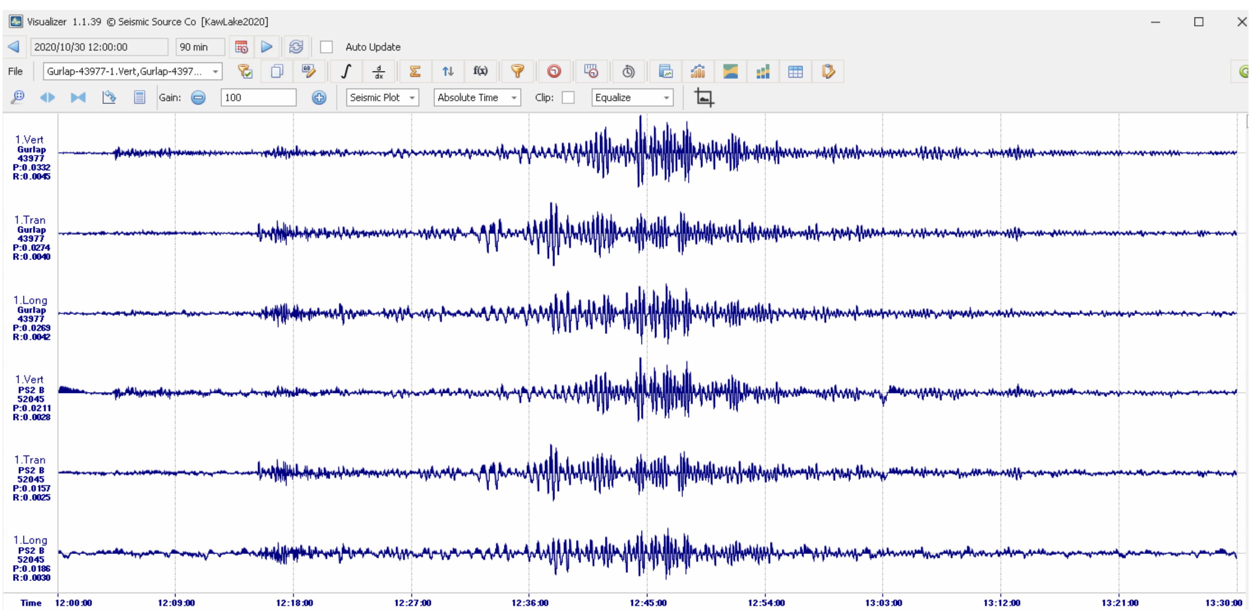
Recorded in Ponca City



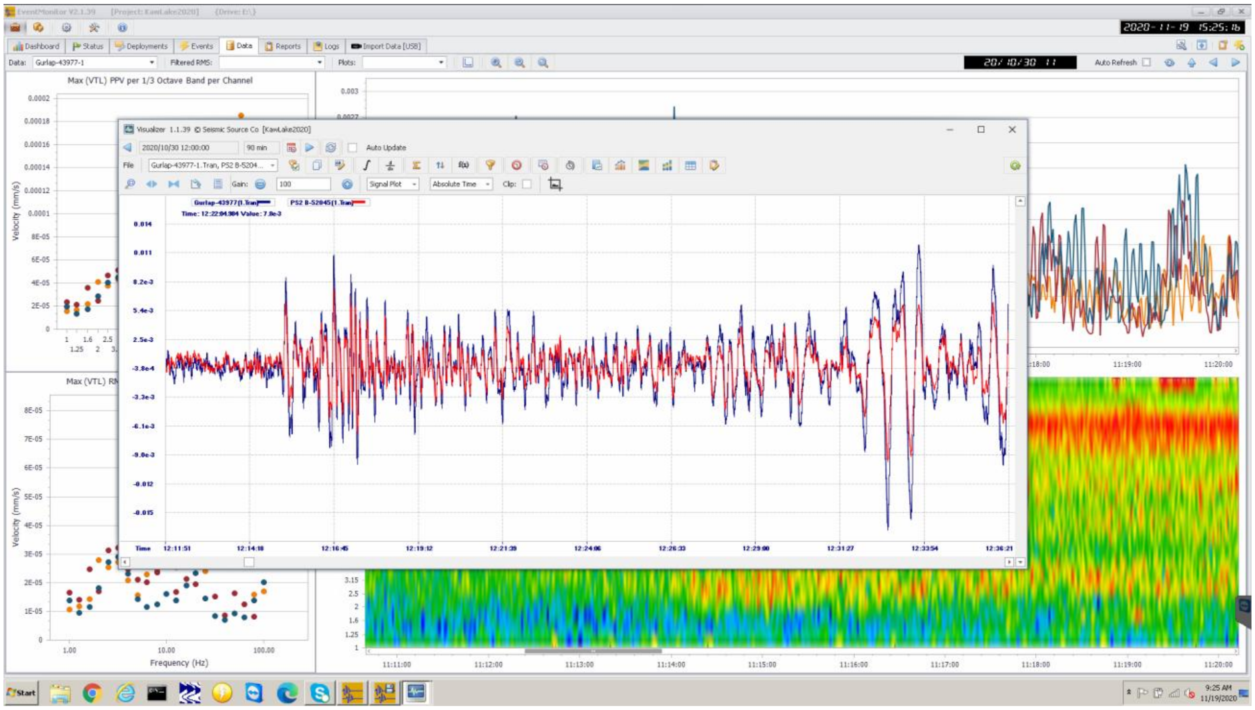
Apply Inverse Filter to PS2



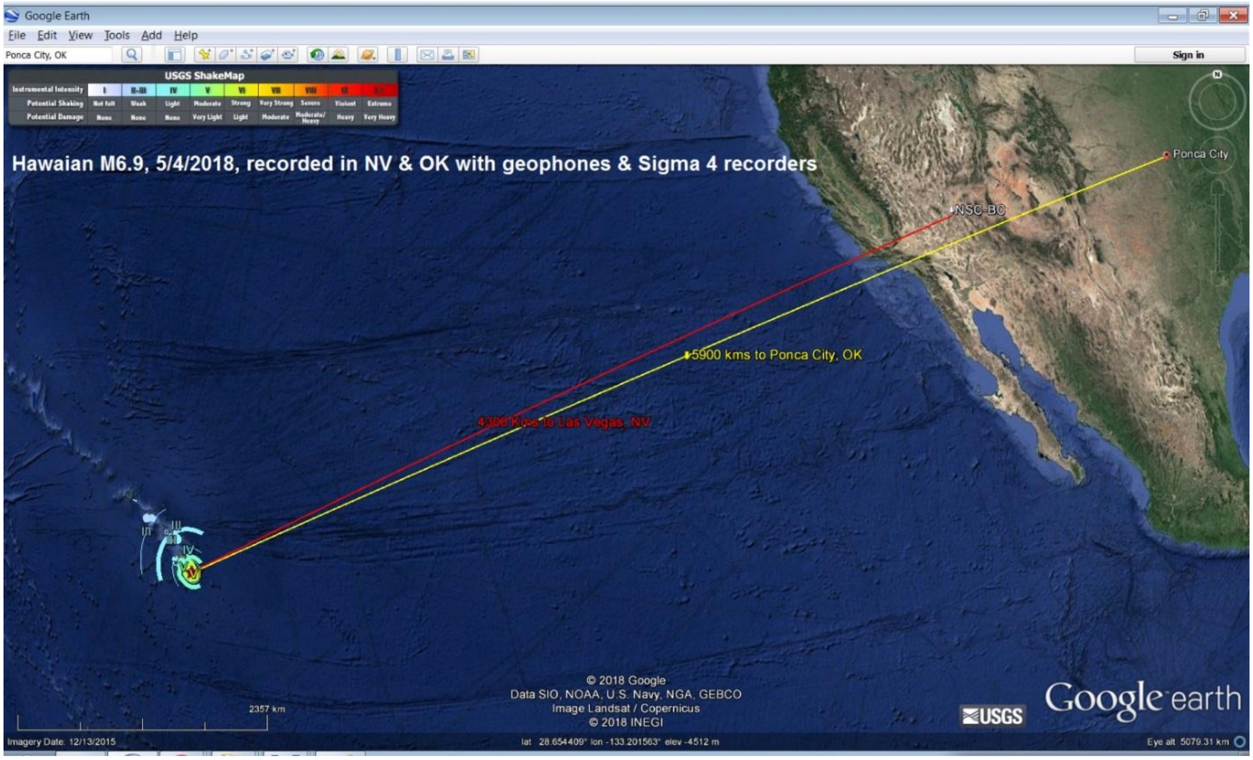
After Inverse Filter

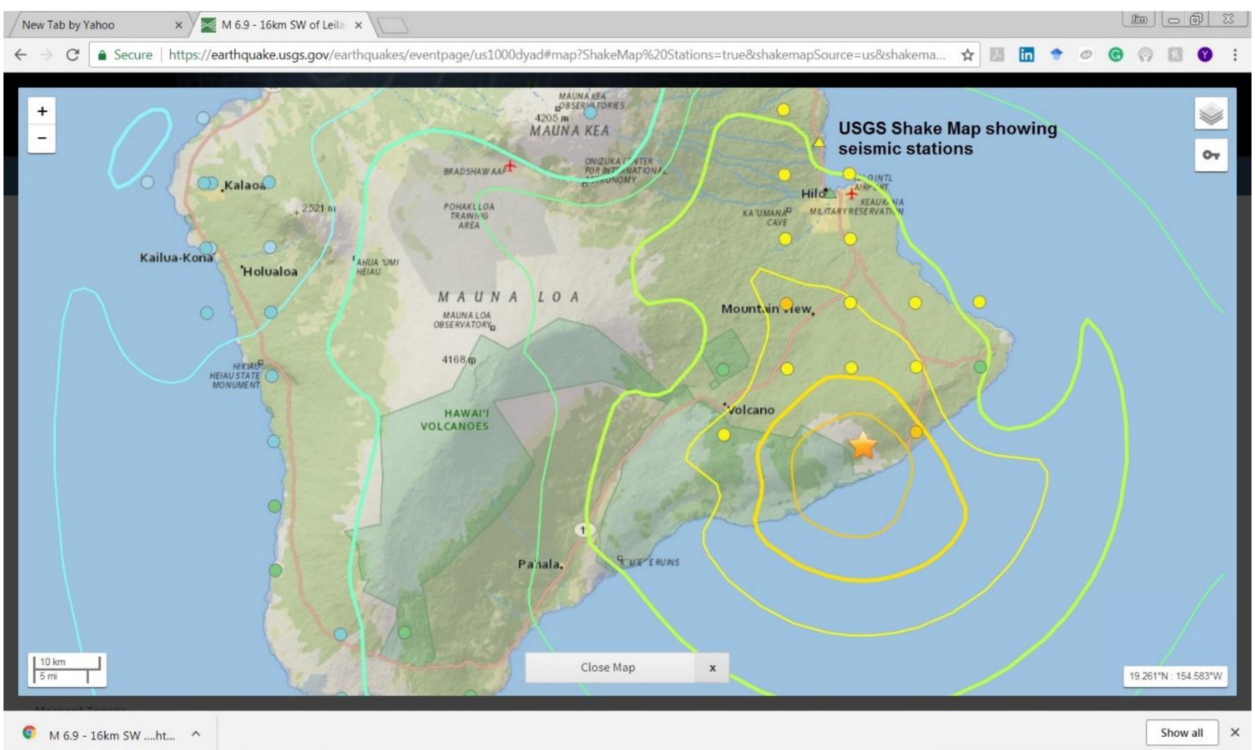


Zoom in on Transverse Axis on Guralp and PS2 after inverse filter



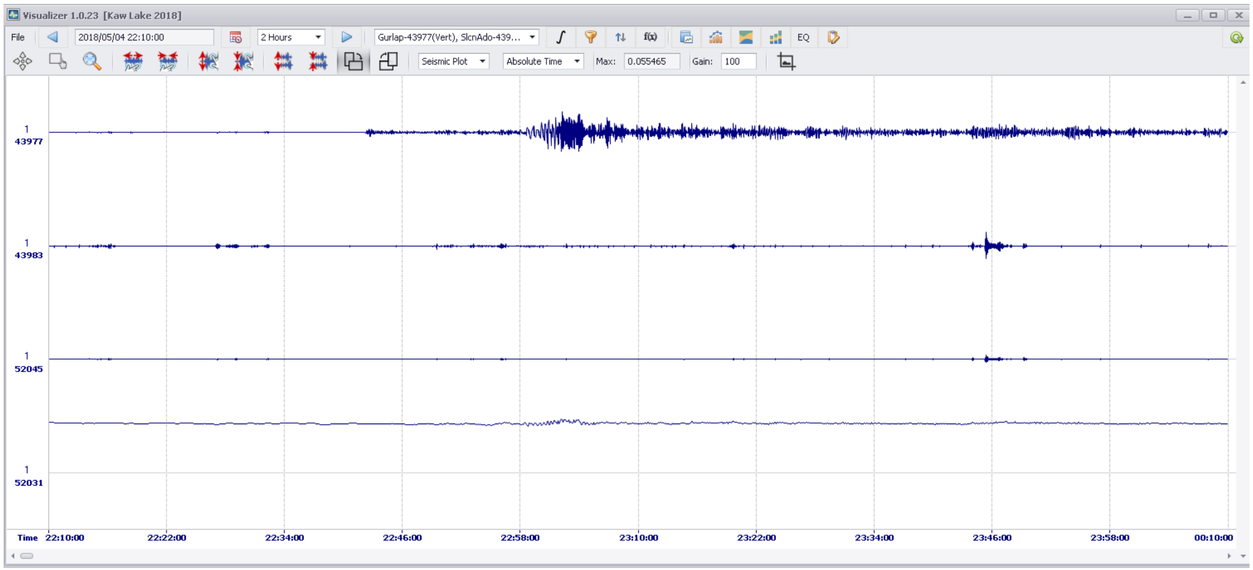
Hawaii M6.9


Hawaiian M6.9, 5/4/2018, recorded in NV & OK with geophones & Sigma 4 recorders
USGS ShakeMap
Ponca City
NSC-BC
5900 kms to Ponca City, OK
4300 Kms to Las Vegas, NV
© 2018 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
© 2018 INEGI
Google earth


USGS Shake Map showing seismic stations
MAUNA KEA
Kalaoa
Kailua-Kona
Holualoa
Hilo
Mountain View
M A U N A L O A
HAWAI'I VOLCANOES
Volcano
Pahala
Close Map

Raw Data from all 4 sensors

Z component Unfiltered



Channel 1 – Guralp 40T

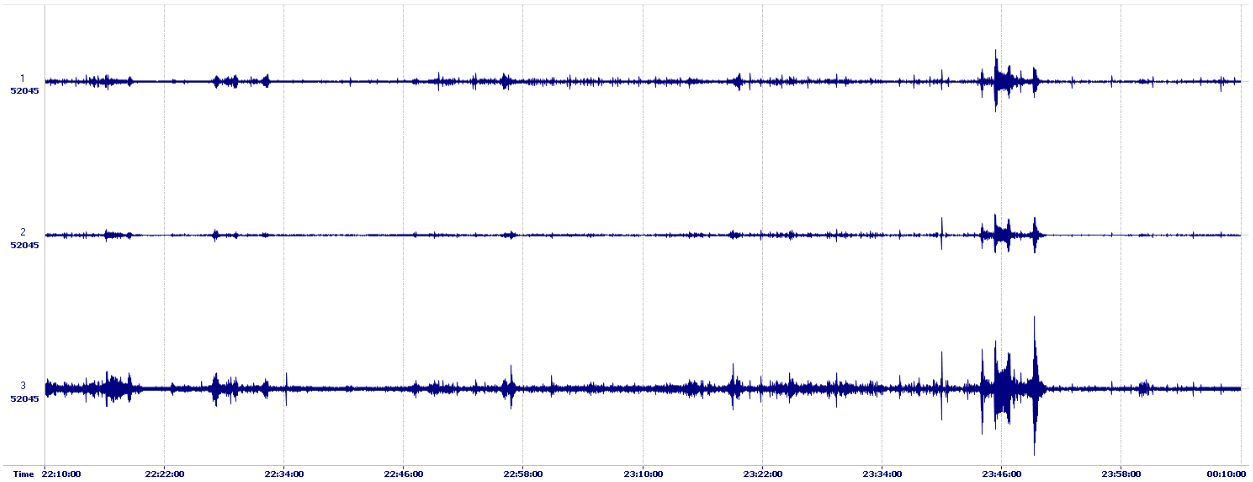
Channel 2 – PS2

Channel 3- Silicon Audio

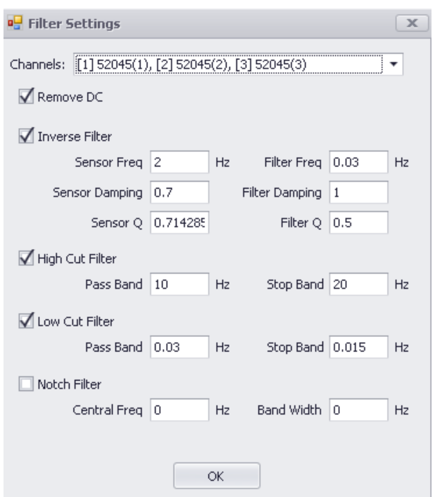
Channel 4 – Nanometric Compact

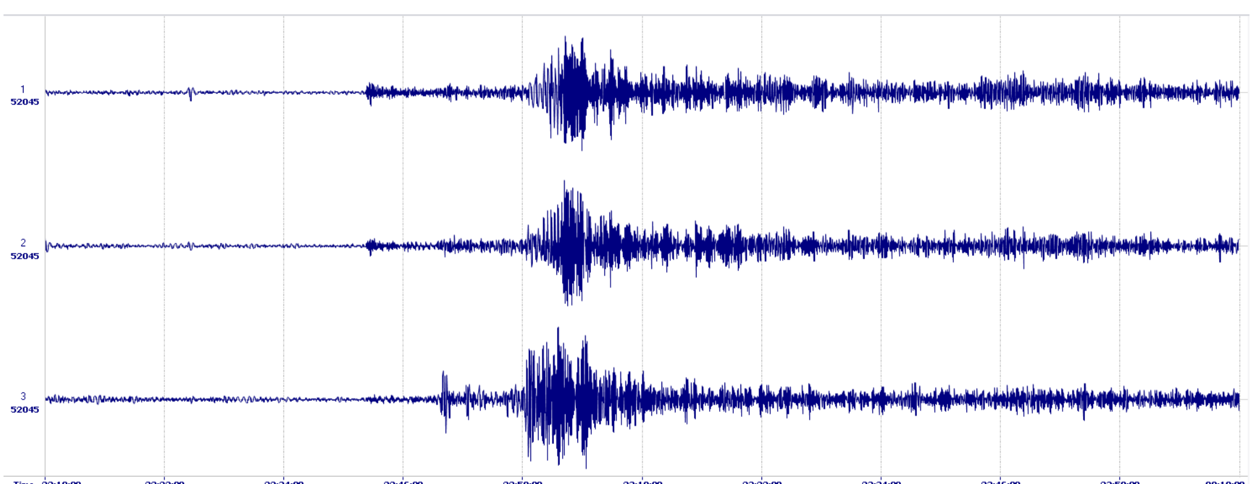
PS2 processing

Raw



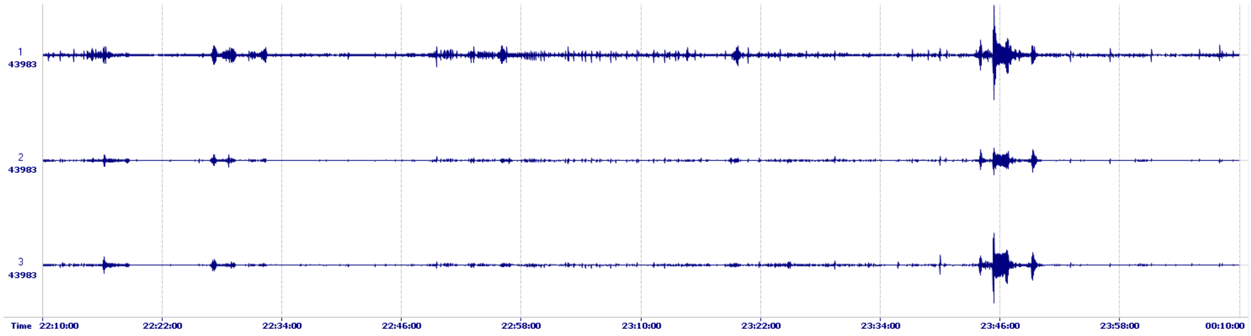
Inverse Filter PS2 to 30 second period



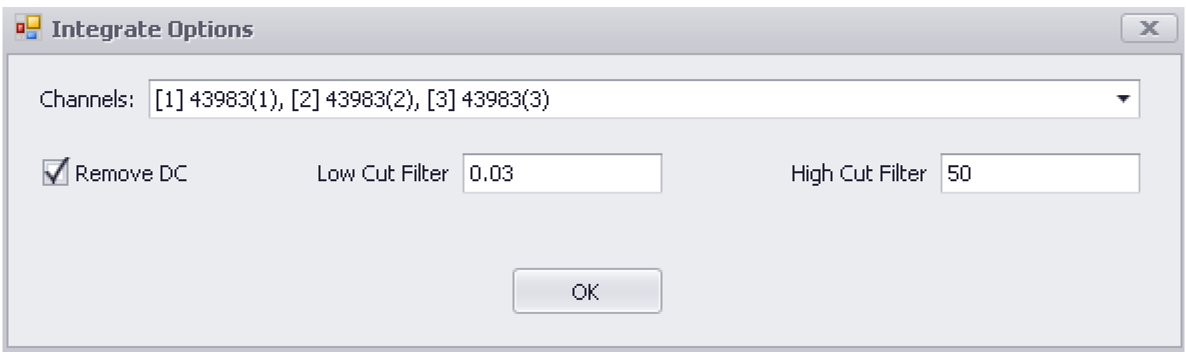


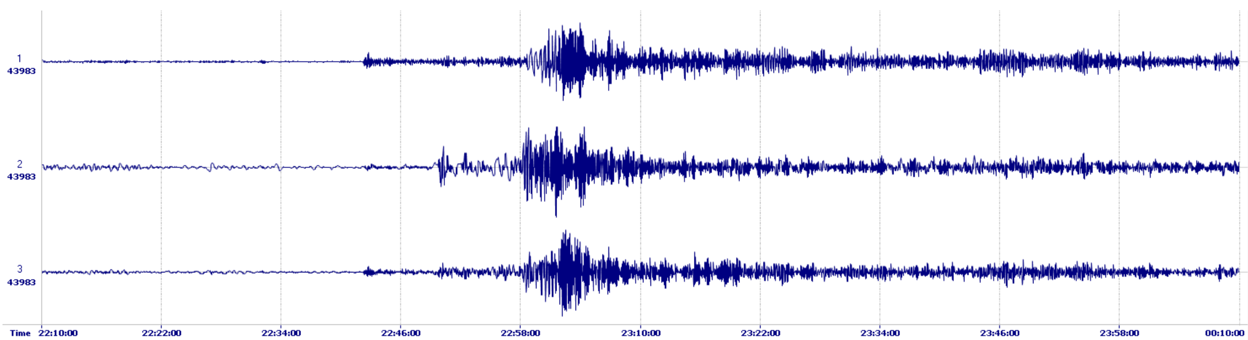
Silicon Audio

Raw Acceleration Data



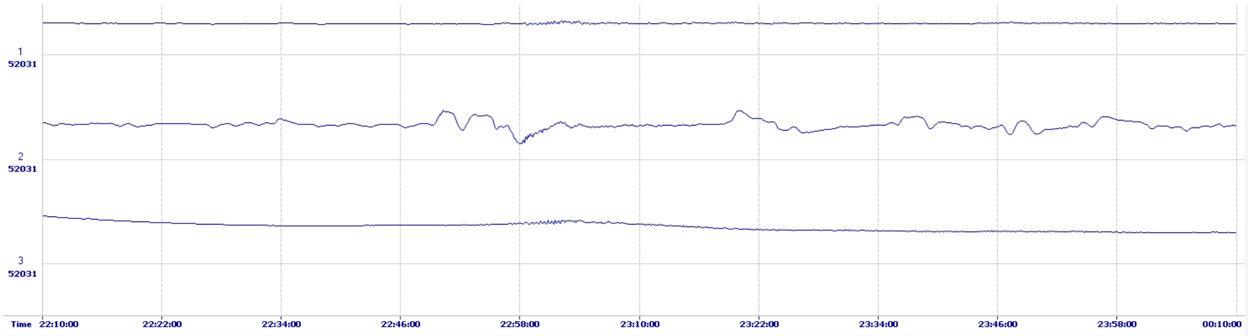
Integrate for Velocity



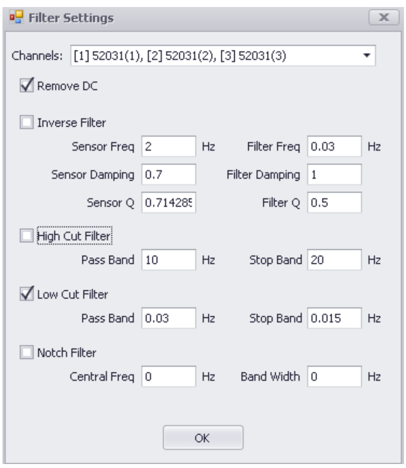


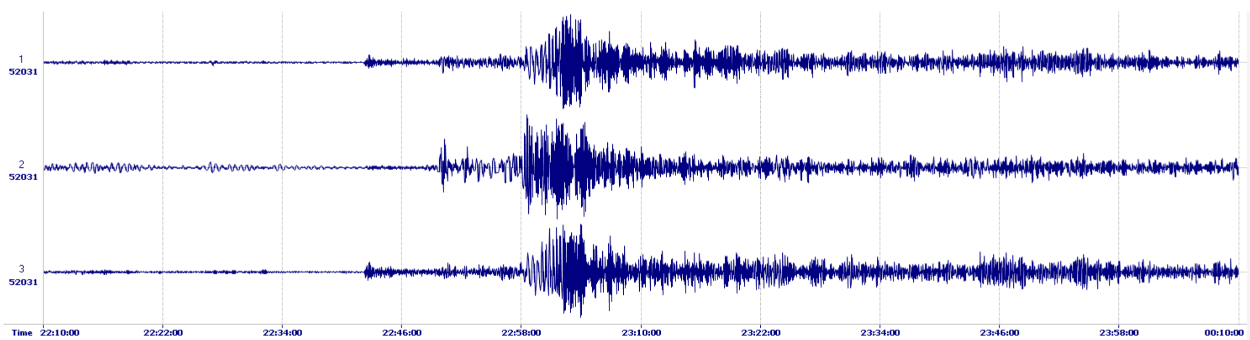
Nanometric Compact

Raw Data



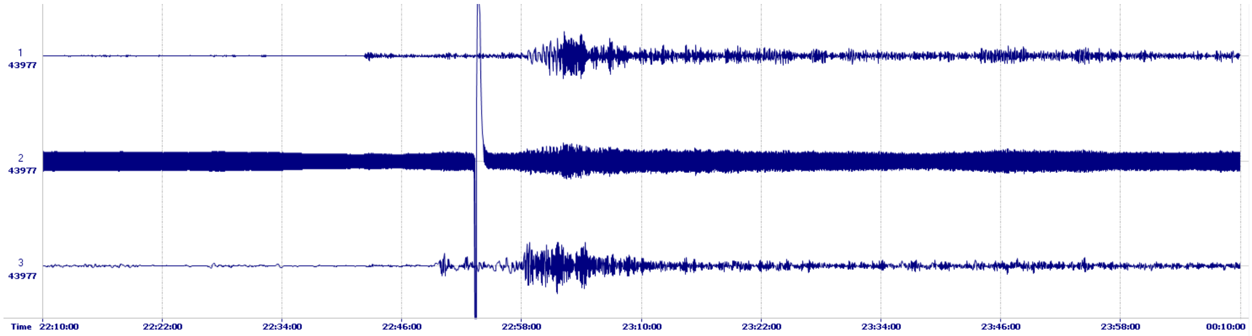
Filter low Frequency



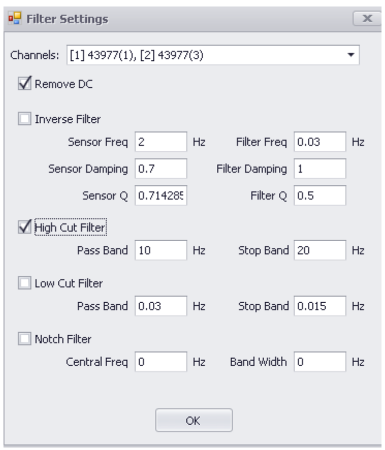


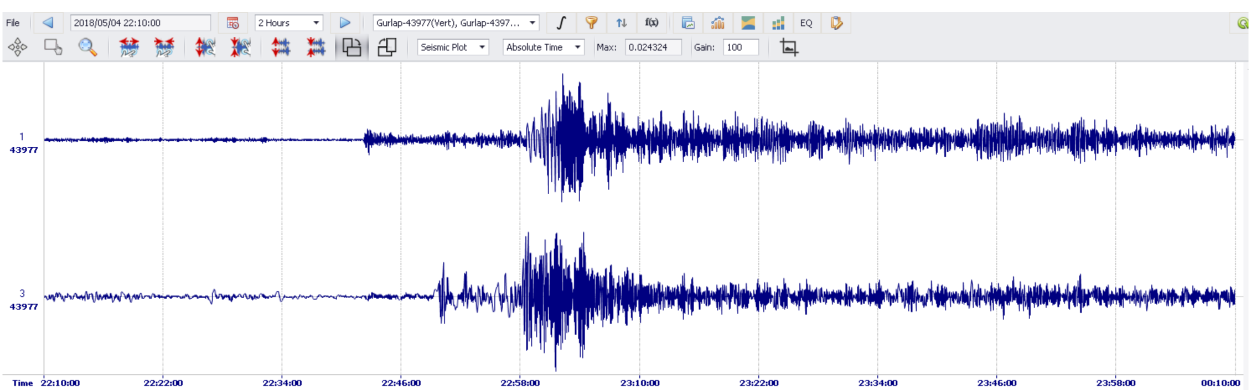
Guralp 40T

Raw Data – channel 2 (H1) is bad



Filter High Frequencies





Final Results

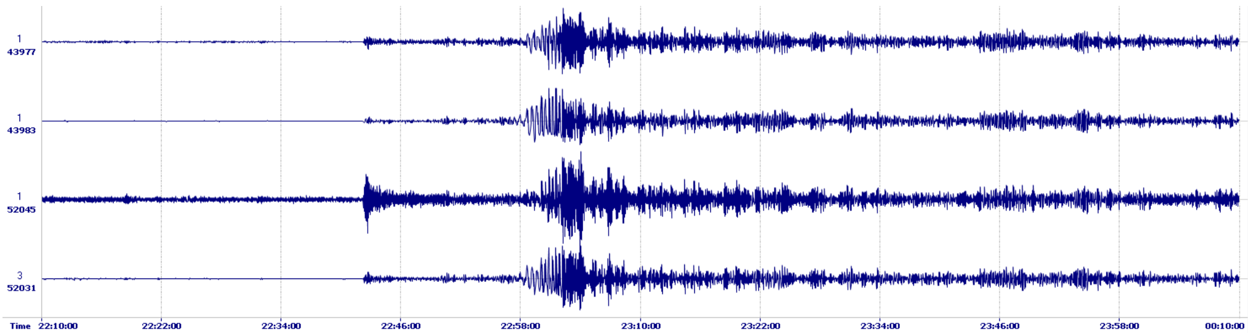
Z axis

Ch1 -Guralp

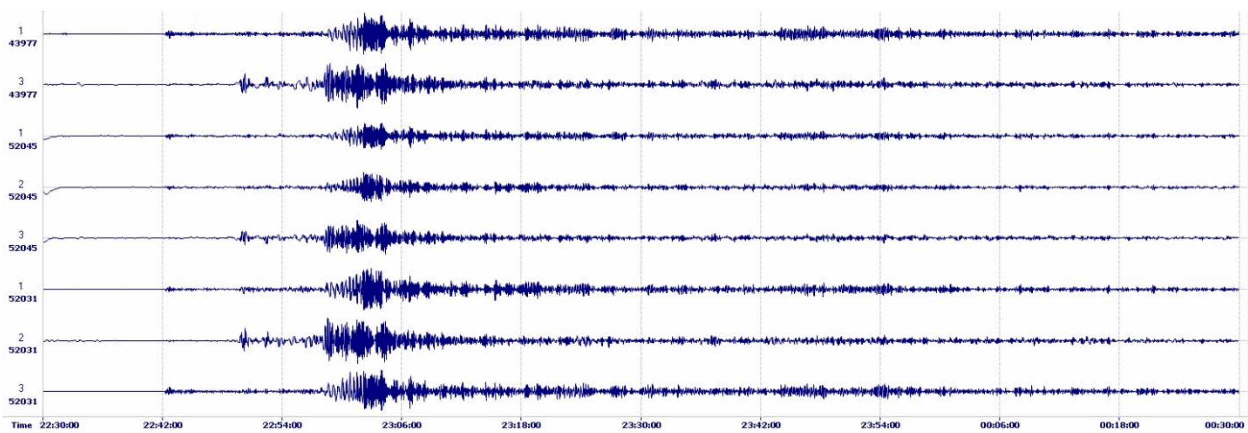
Ch2 – PS2

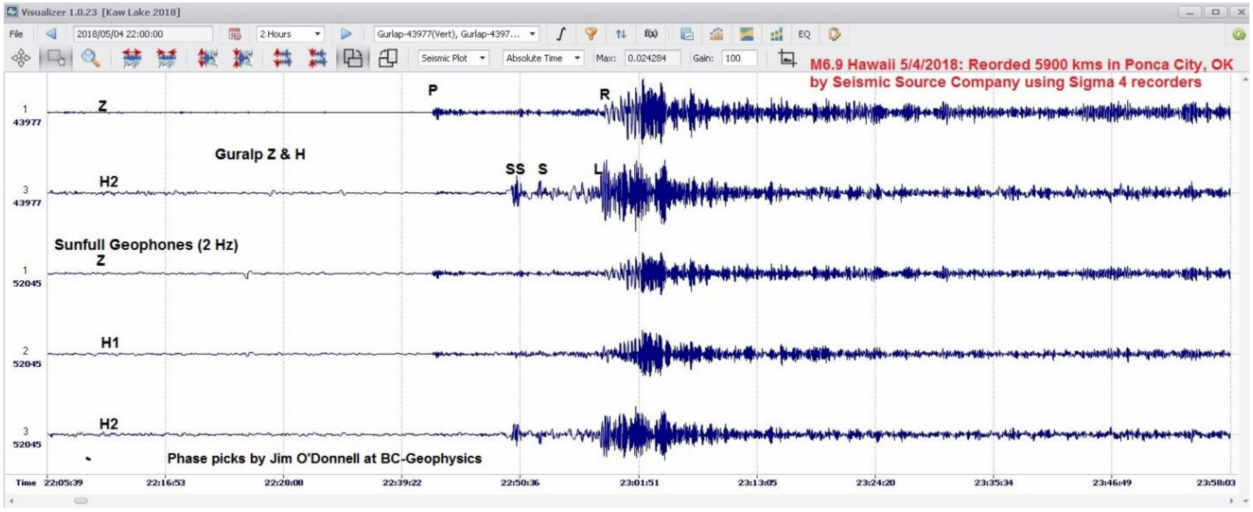
Ch3- Silicon Audio

Ch4 – Nanometric Compact

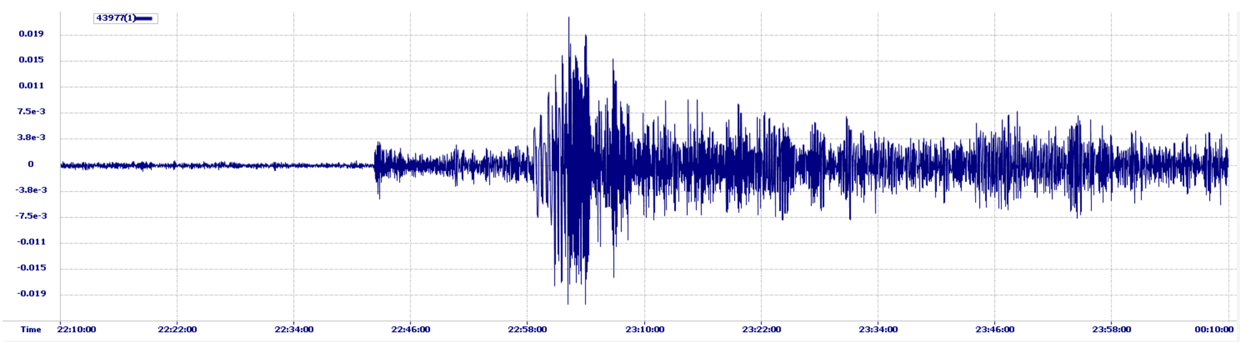


All three components

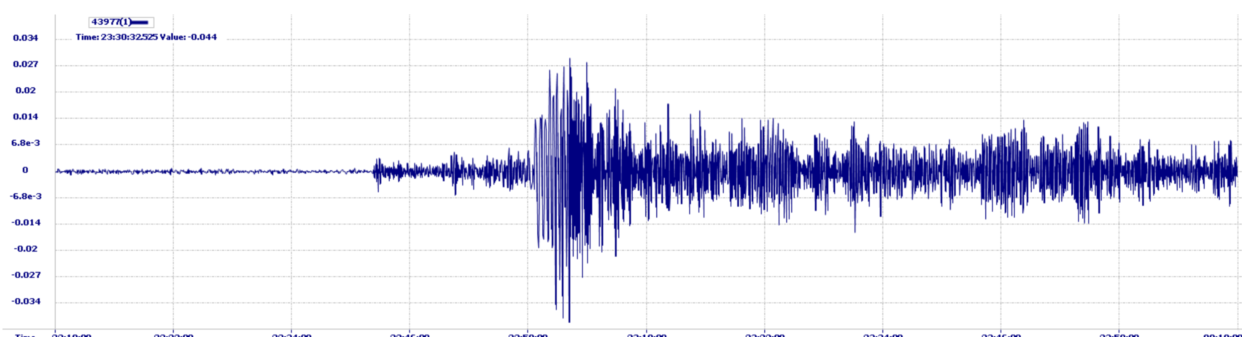




Guralp Z axis Velocity in mm/sec

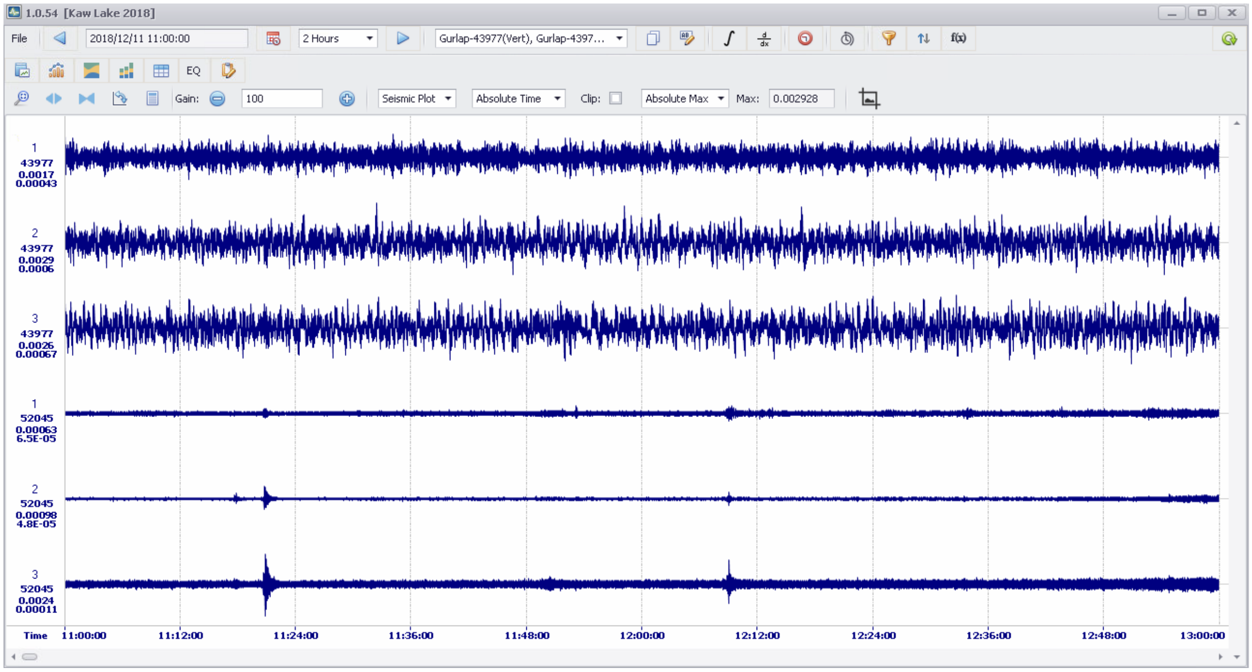


Guralp Z axis Displacement in mm

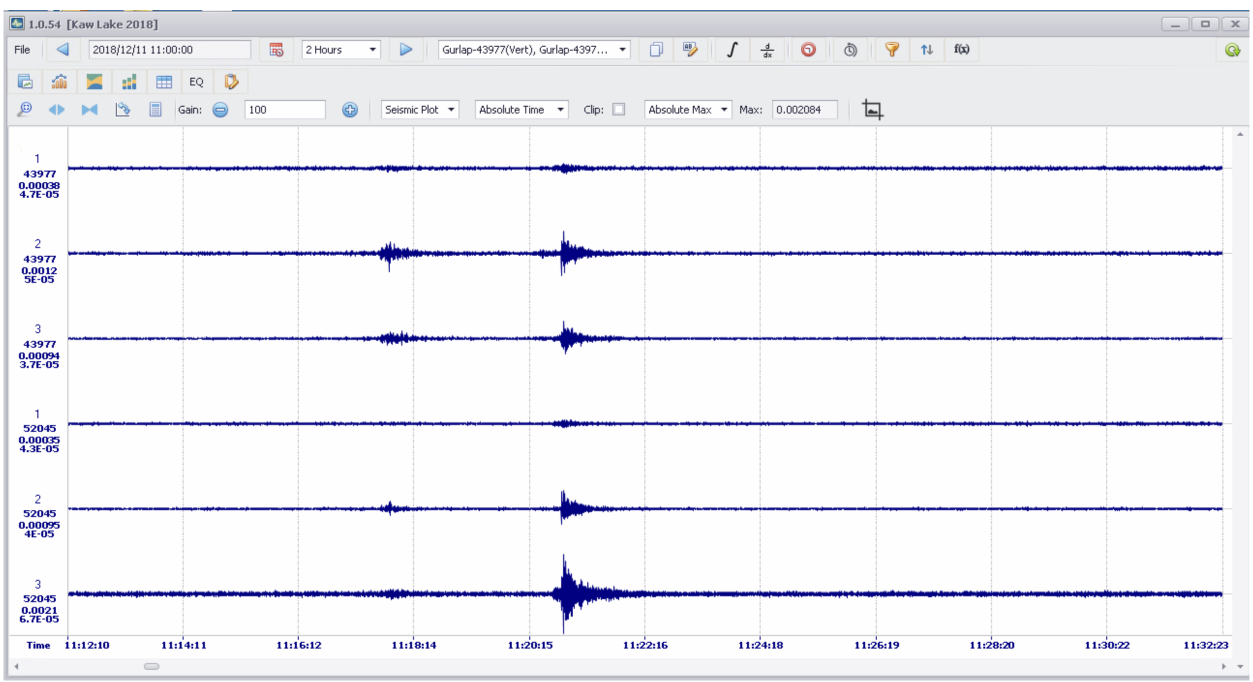


Mag 3.7 Gleenwood springs - 12/11/2018

Raw Guralp and PS2

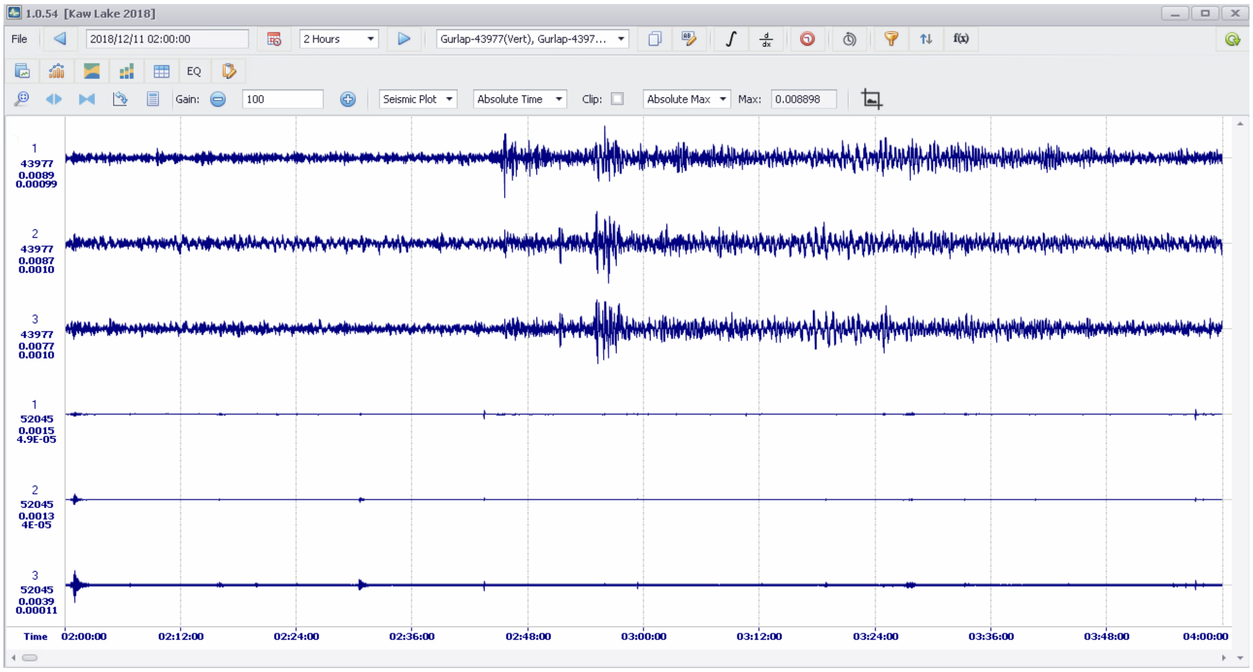


After Filtering and Cropping

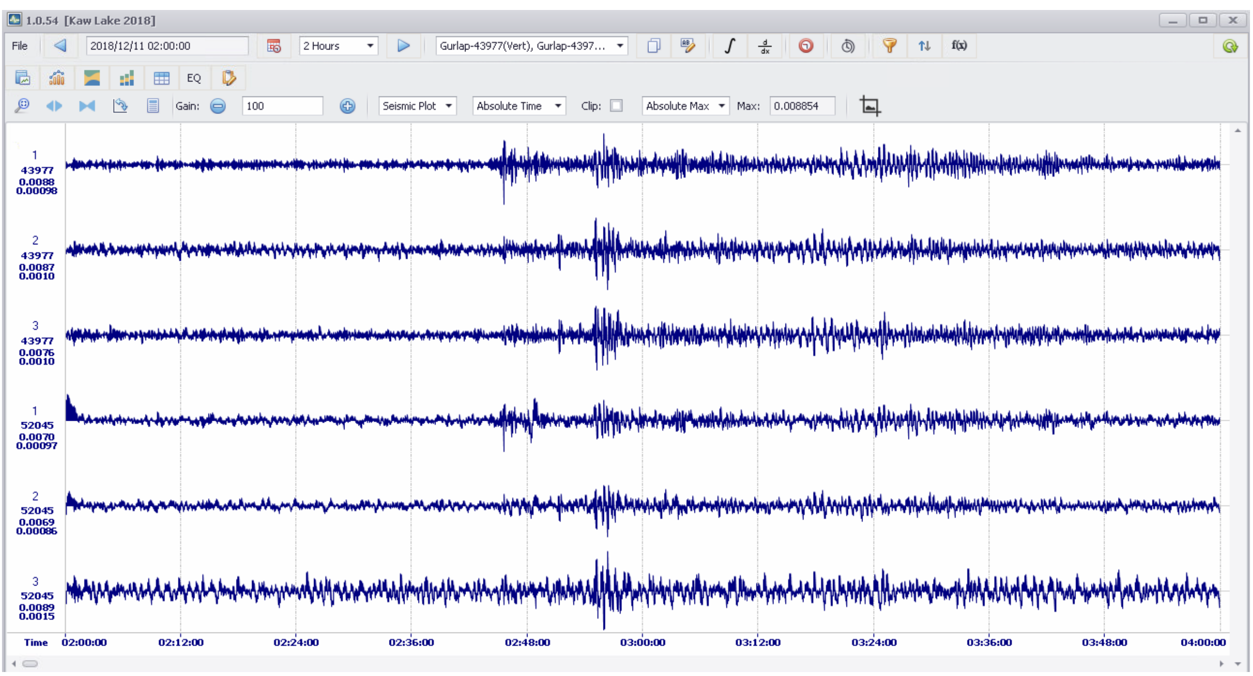


M 7.1 Sandwich Island 12/11/2018

Raw Guralp and PS2

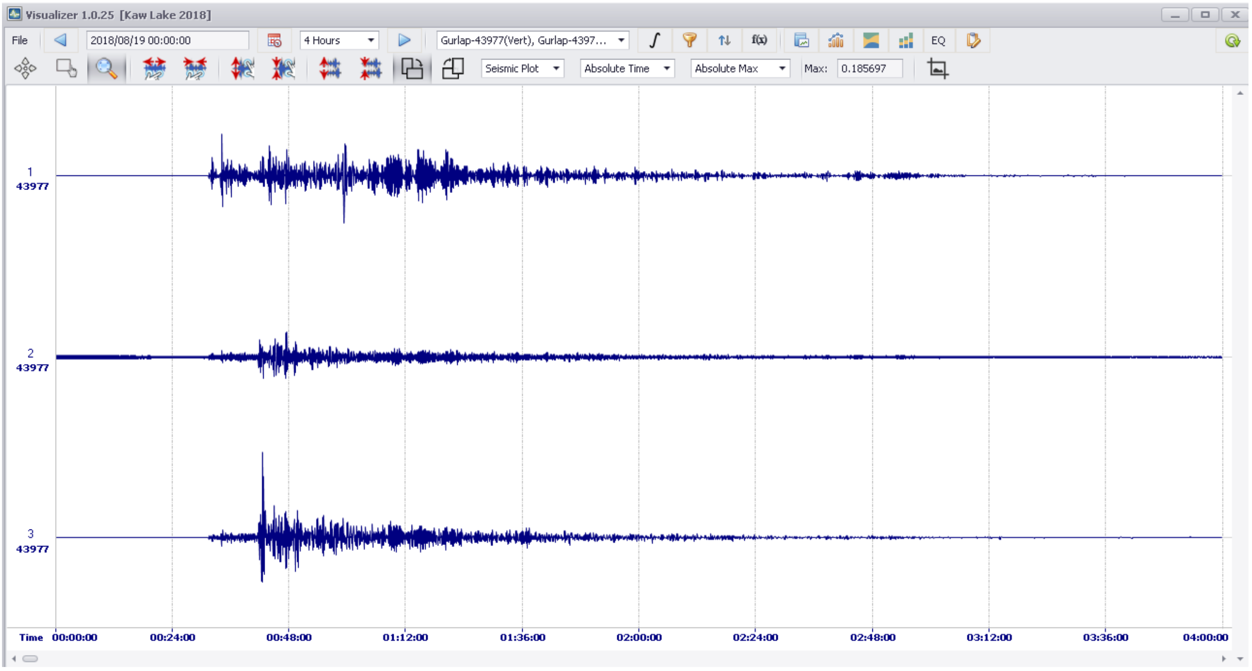


After Inverse Filtering PS2

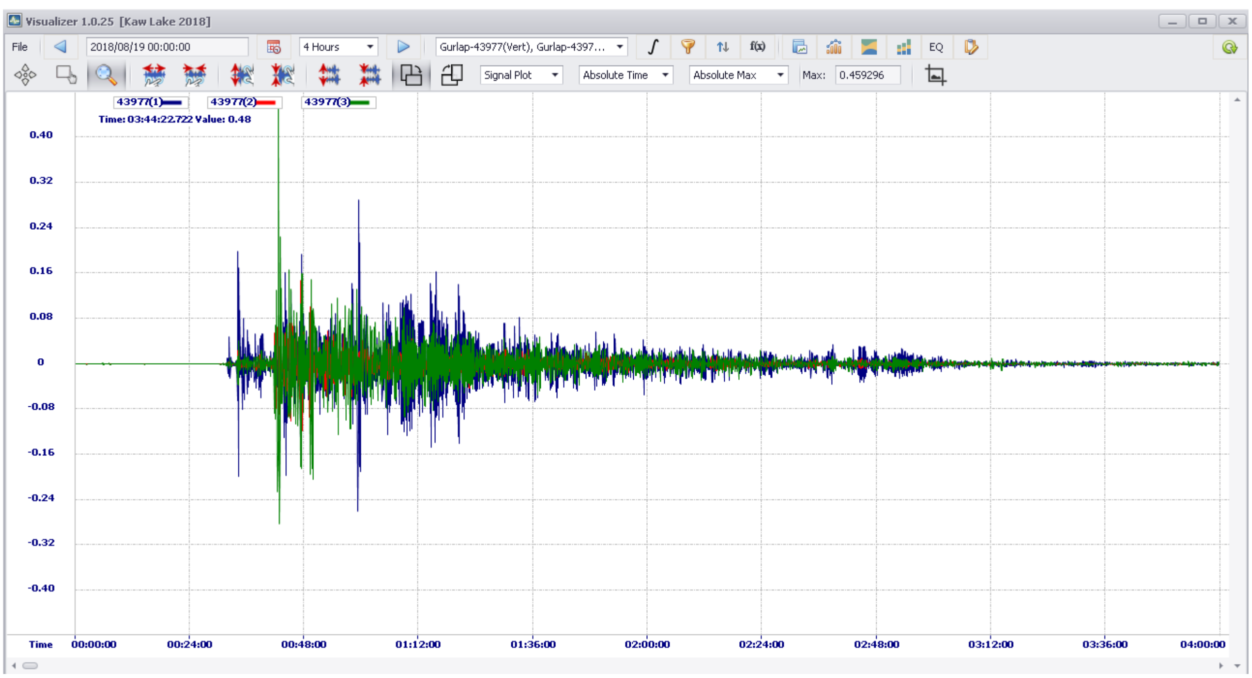


Fiji 8.2 8/19/2018

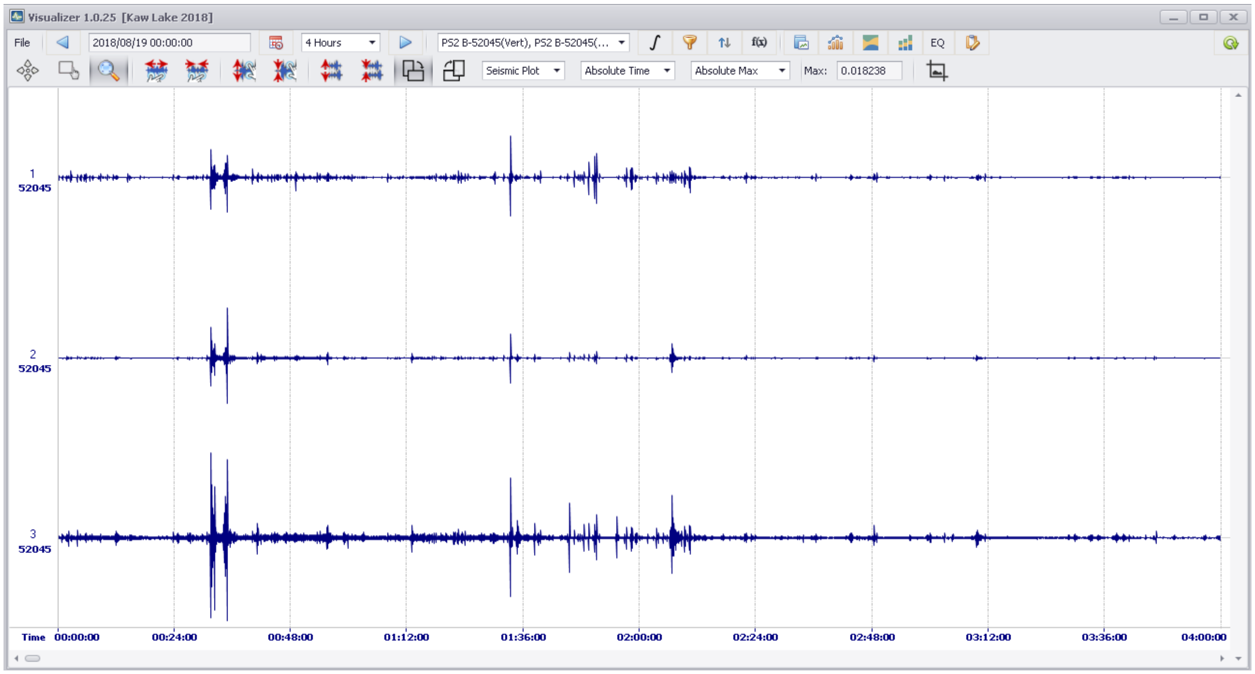
Guralp raw



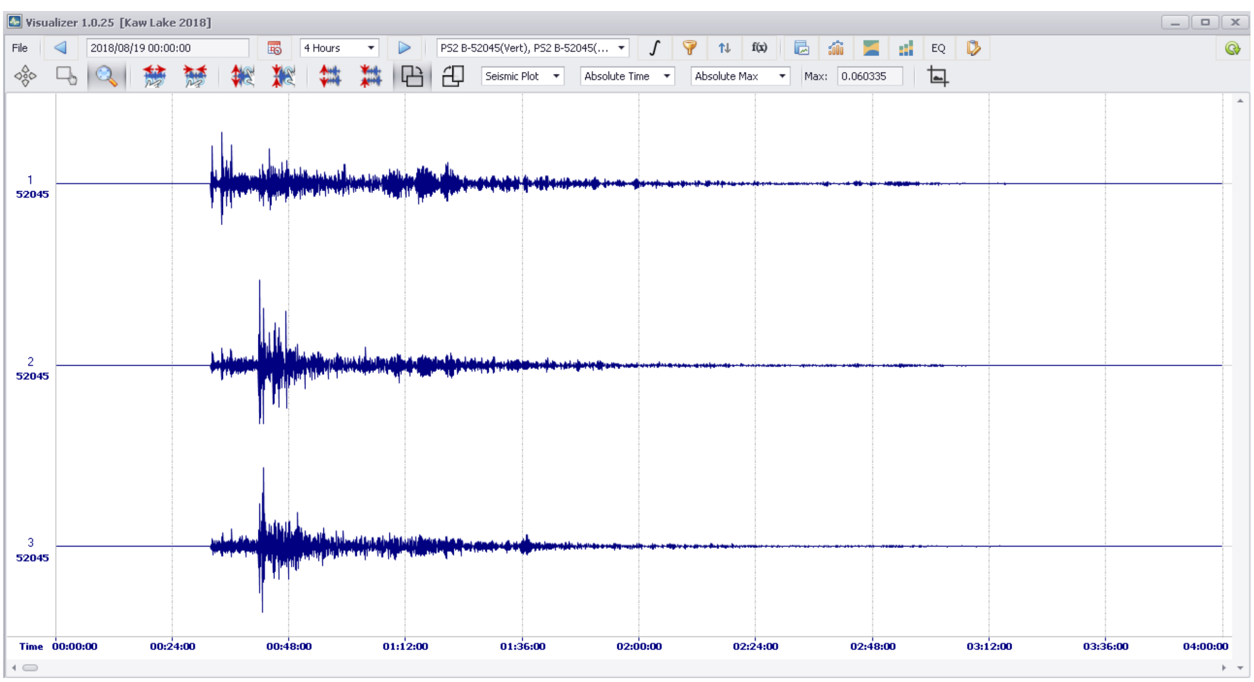
Guralp Displacement – 0.4 mm maximum displacement in Ponca City



PS2 raw



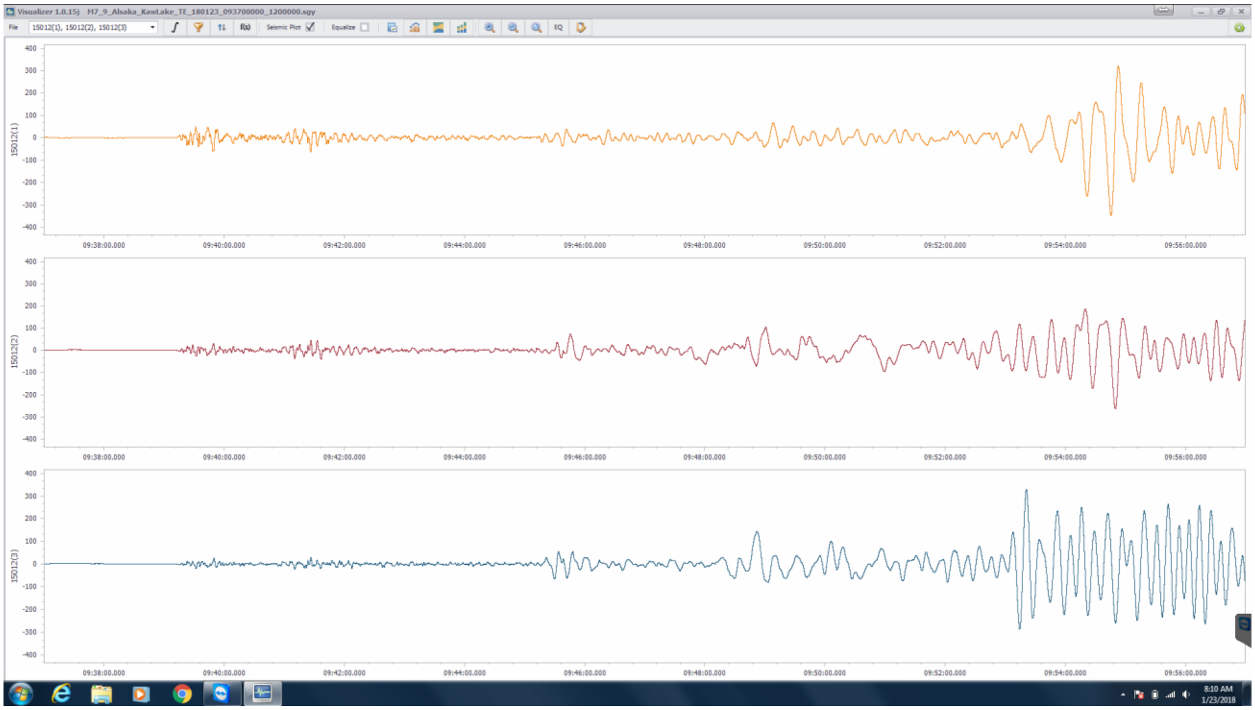
PS2 Inverse Filter to 30 seconds – Bandpass filter from 30 seconds to 2 hz



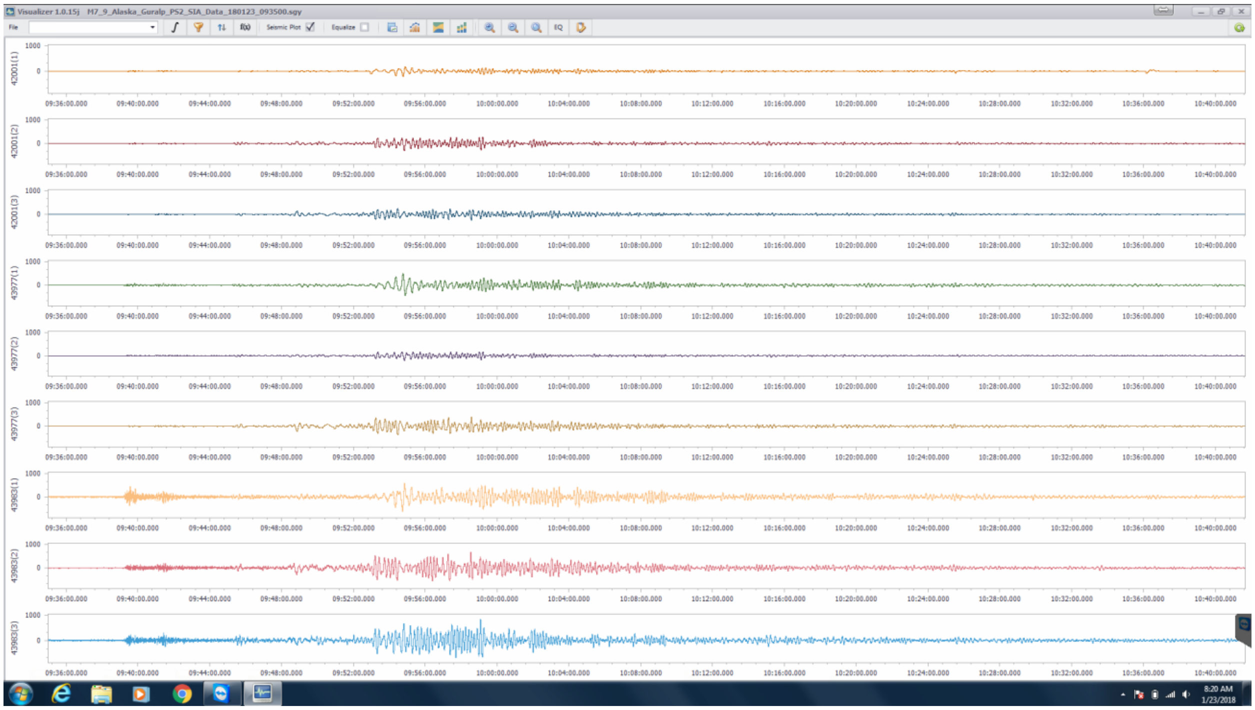
Alaska Earthquake Mag 7.9

Velocity in Um/sec

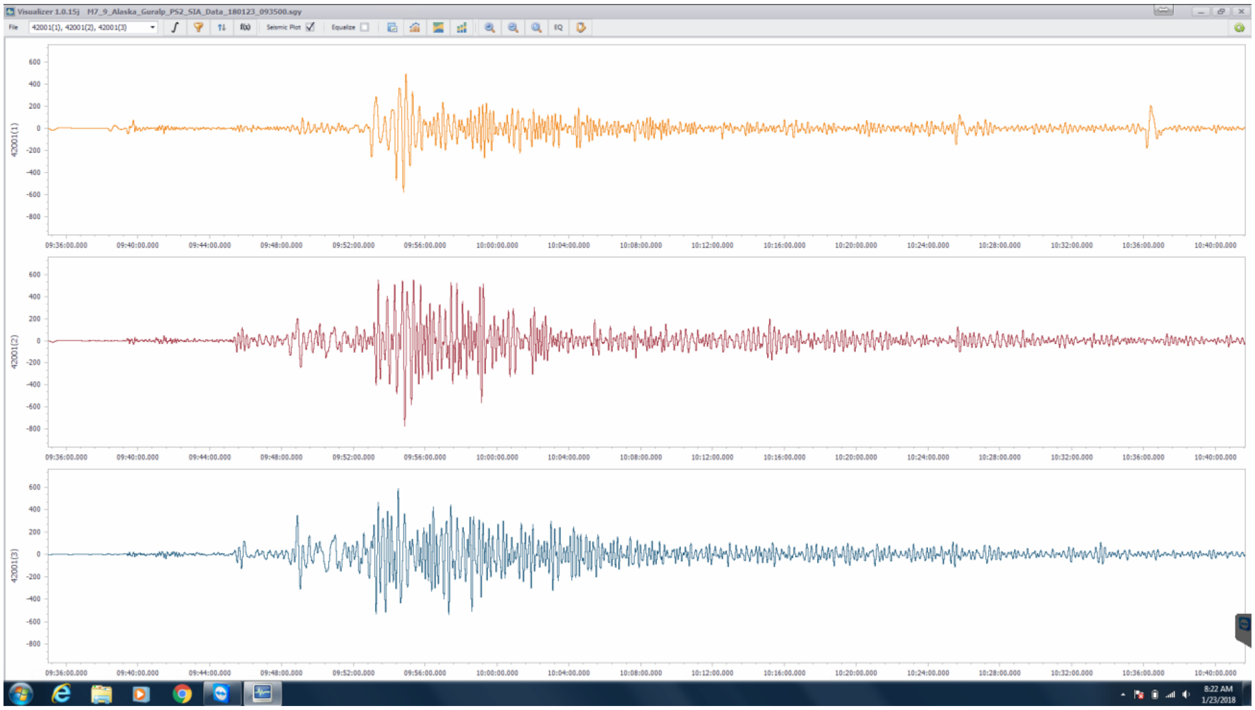
PS2 in Kaw lake Array



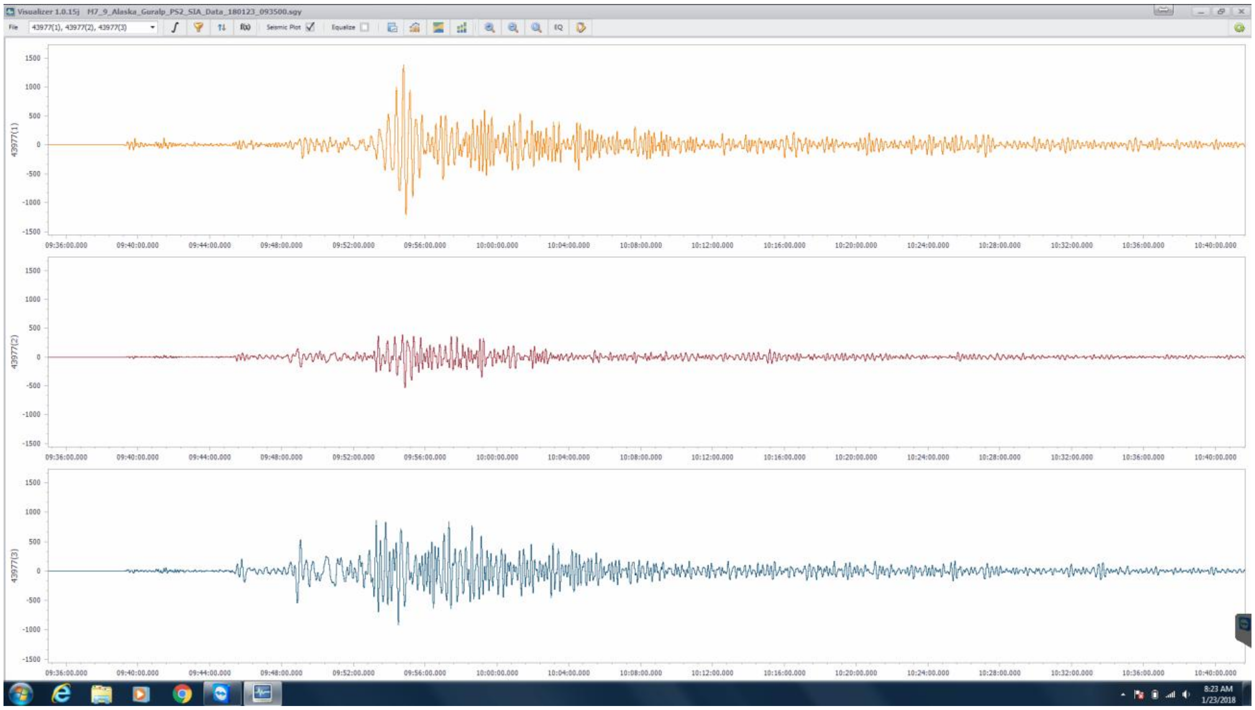
PS2_Guralp_SIA Huddle Test



PS2 displacement in um



Guralp displacement in um

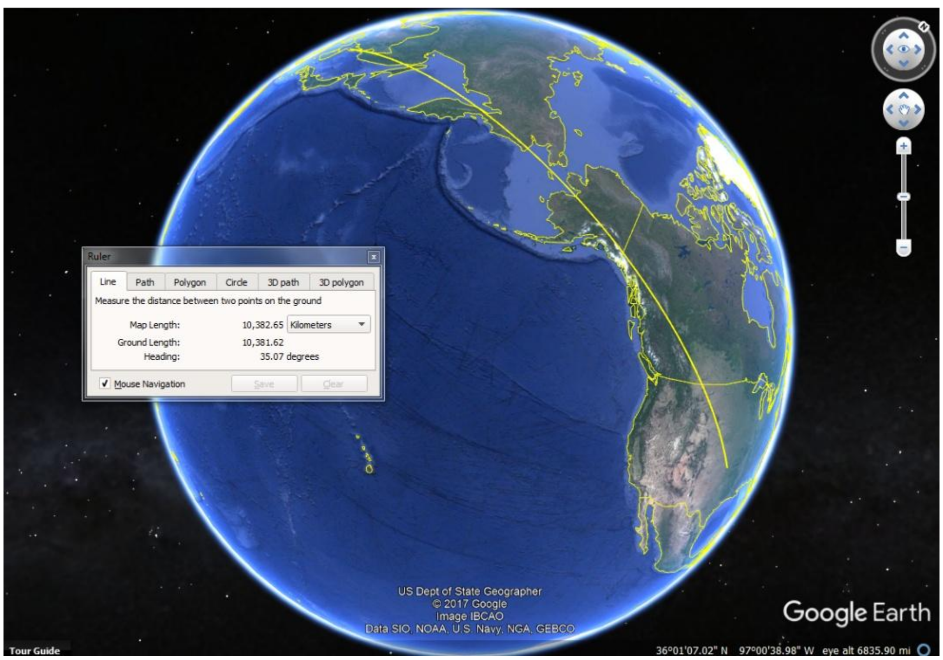


SIA displacement in um

North Korea Blast – PS2 Inverse Filter to 30 second period

North Korea conducted its sixth and largest nuclear test on September 3, 2017, at the Punggye-ri Nuclear Test Site, claiming it successfully detonated a thermonuclear weapon (hydrogen bomb). [1, 2, 3]

Test Details and Impact

- **Date and Location:** September 3, 2017, underground at the Punggye-ri test site in Kilju County, North Korea.
- **Seismic Activity:** Triggered a magnitude 6.3 earthquake, which was roughly 10 times more powerful than previous nuclear tests.
- **Explosive Yield:** Estimated by analysts and intelligence agencies to be between 140 and 250 kilotons of TNT.
- Distance = 10,000 Km
- 

  M 6.3 Explosion - 21km ENE of Sungjibaegam, North Korea

  x

V	VI	GREEN
DYFI?	ShakeMap	PAGER

Time	2017-09-03 03:30:01 (UTC)
Location	41.334°N 129.031°E
Depth	0.0 km
-

0.8 Hz velocity PS2 X, Y and Z

0.8 Hz displacement - max displacement =0.2 micro meters