Sensitivity Specifications in Broadband Seismometers

Broadband Seismometers

- Modern force-feedback broadband seismometers are capable of measuring a wide range of ground motion signals
- Best instruments can measure extraordinarily small ground motions (i.e. distant teleseismic events) but also moderate-to-large regional & small local events
- Does sensitivity specification serve as a fair measure for sensor performance comparison?
- Sensitivity specification is about how to interpret the signal, not whether a particular sensor performs better or worse than another
- Focusing on sensor interface & signal interpretation determines if the instrument is used properly and deployed in an environment where it can reach its full potential

Seismometer Performance Specifications

- Performance specification questions…..
  - How well will the seismometer measure ground motions?...
  - Over what amplitudes & frequencies?
- Interface specification questions….
  - How should the seismometer be interfaced to the entire system?
  - How should the signal be interpreted?
- Are instruments with higher sensitivity better?
  - "Sensitivity" has more than one definition
    - "the minimum input signal required to produce a discernable output signal"
      (i.e. higher sensitivity = ability to detect weaker signals)
    - "input-output gain"
      (i.e. the ratio of the output (V) to the input (ground motion velocity in m/s))

Input-output gain & Nominal Sensitivity

- "input-output gain"
  - Scaling factor used to translate the output signal voltage into meaningful units of ground motion
  - Trillium 120P/PA has a nominal sensitivity of 1201 V/m/s
  - 1.2 V for every mm/s of ground motion
    (for frequencies that lie within the flat section of the frequency response)
  - Trillium 120P/PA output signal voltage is guaranteed usable to at least +/- 18 V → ground velocities exceeding 15 mm/sec may be clipped
  - What if we had higher nominal sensitivity of 1500 V/m/s?
  - The maximum velocity that can be measured drops to 12 mm/sec

Input – Output - Gain

- Car Analogy
  - Performance specifications (acceleration, fuel consumption, etc.)
  - Interface specifications (speedometer calibration km – or – miles)
  - Changing the speedometer of the car from miles/hr to km/hr
    - 60 miles = 100 km (speedometer is not better because it is more sensitive)
    - If the speedometer can only read 150…
      - 100 miles / hour is measurable
      - 160 km / hour will clip

Input – Output - Gain

- What if we only want to measure weak signals?
- Increasing the gain of the output amplifiers increases noise as well
- Prior to 24-bit digitizers with high dynamic range faint seismometer signals would be lost in the noise floor of low-resolution 16-bit digitizers
- Pre-amplifiers were used to increase the input-output sensitivity & push weak signals into the usable frequency range
- This came at the expense of reduced dynamic range & clipping of strong signals
- Broadband seismometers with 20,000 V/m/s sensitivities would clip even moderate events (M6) within 875 kms
- Modern, 24-bit, adjustable digitizers (such as Nanometrics Taurus & Trident) are able to measure the strongest & weakest signal levels from seismometers with a very wide range of sensitivities (no reason to require a spec. sensitivity Sensor)

Increasing System Sensitivity

- System sensitivity can be optimized to properly suit the study environment
- Achieved by changing the digitizer input range
- Decreasing the digitizer input range increases system's sensitivity, however, at the expense of minimizing the system's velocity coverage range
- There is a high potential for clipping if the digitizer input is reduced to 2 V_{pp} and connected to the Trillium 120P/PA with velocity output of 40 V_{pp}

Digitizer Input Range	Digitizer Software Gain	Digitizer Sensitivity	Trillium 120P/PA Sensitivity	System Sensitivity (Counts/(m/s))
40 Vpp	1	0.4 count /µV	1201 V/(m/s)	4.804e+8
16 Vpp	1	1 count /µV	1201 V/(m/s)	1.201e+9
8 Vpp	1	2 count /µV	1201 V/(m/s)	2.402e+9
4 Vpp	1	4 count /µV	1201 V/(m/s)	4.804e+9
2 Vpp	1	8 count /µV	1201 V/(m/s)	9.608e+9

System Sensitivity

- Why is the seismometer sensitivity specified at all?
- It is an important "interface parameter"
- Required for proper signal interpretation
- Signal processing software must be aware of both seismometer sensitivity (V/m/s) & digitizer sensitivity (counts / µV) to determine the true scale of the seismic data set
- $S_{Sys} = S_{Sen} \times S_{Dig}$
- Sensitivity and system poles & zeroes determine the full frequency response (a.k.a the transfer function), which specifies the input-output gain & phase for a given frequency of ground motion
- Knowing the full transfer function allows the output signal to be interpreted as accurate ground motion across a wide frequency range well outside the passband of the sensor

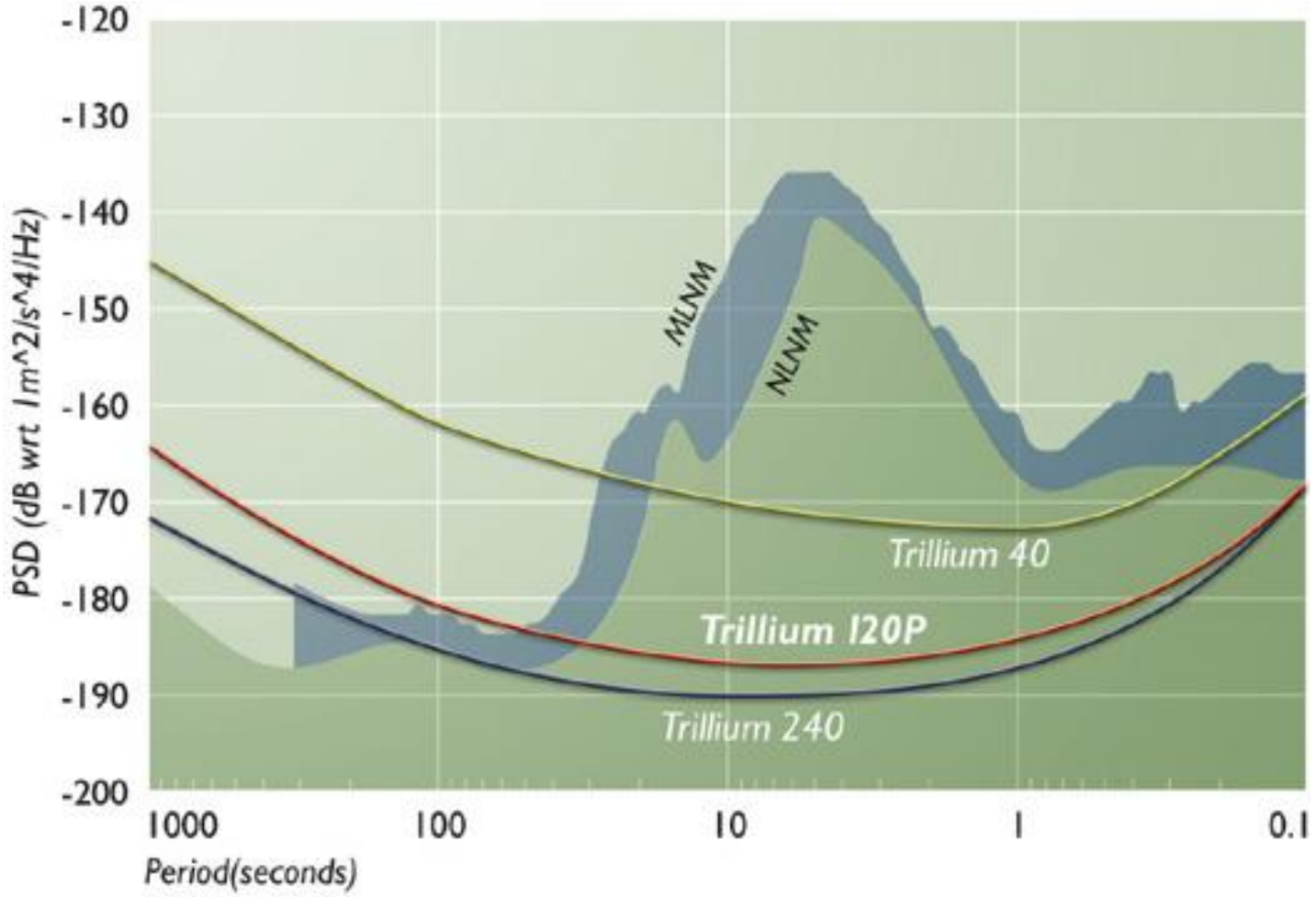
Sensitivity Conclusions

- With adjustable gain 24-bit digitizers, the choice of a specific input-output sensitivity value is unimportant
- Knowing the accurate sensitivity value is very important!
- Some manufacturers measure & document sensitivity of each indiv. instrument
- Nanometrics sensors are factory calibrated to same channel-to-channel & unit-to-unit sensitivity
- The sensitivity is guaranteed to be within +/- 0.5% of the published specification
- More convenient to manage a network of instruments that all have the same sensitivity
- If sensitivity isn't a useful indicator of a seismometer's ability to measure ground motion, what are the important performance parameters?

Self-Noise & Clip Level

- Key performance specifications that indicate the range of signals a seismometer is capable of measuring are self-noise & clip level
- Self-Noise
  - What is the weakest ground motion the seismometer can measure?
  - Self-noise = expected level of signal produced within the seismometer even if there is no ground motion
  - Self-noise is inevitable; knowing how much & at what frequencies is crucial
  - Specified in “Power Spectral Density” (PSD) plot [typical level of noise as a function of frequency]
  - Any signal that exceeds the self-noise PSD is true ground motion
  - Seismic activity with a power spectrum below the self-noise curve cannot be distinguished from the instrument’s self-noise

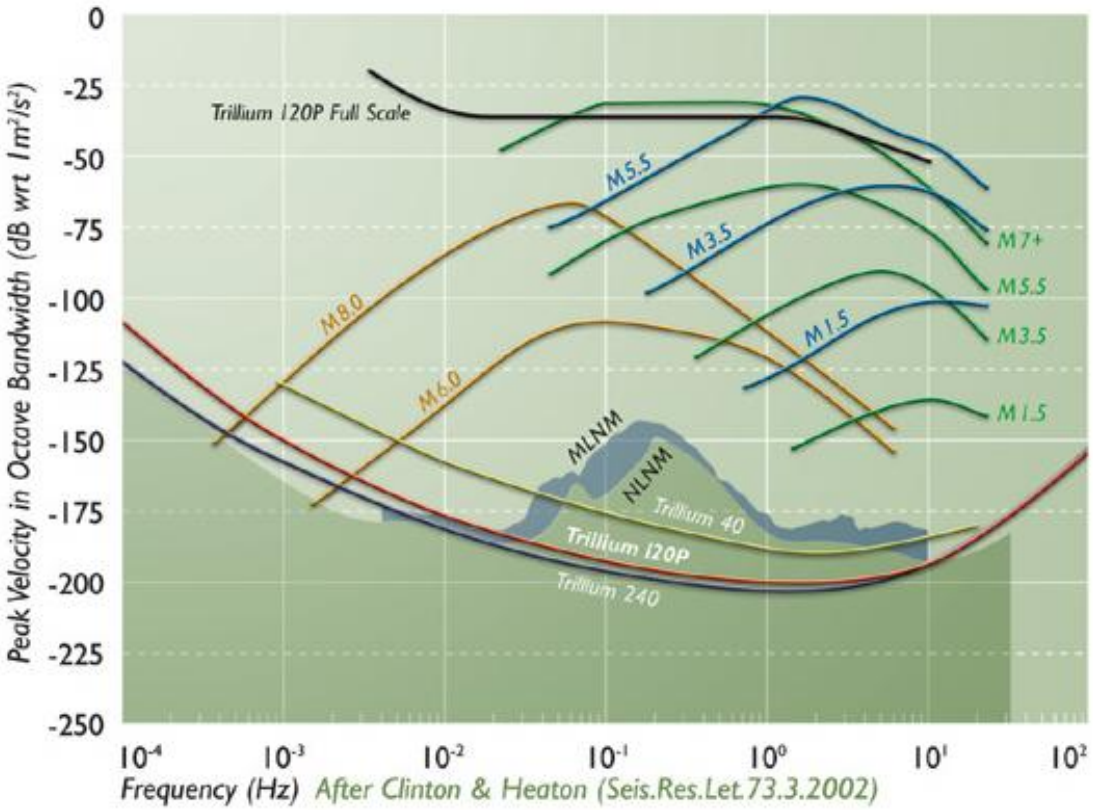
Trillium Self-noise Comparisons



Self-Noise & Clip Level

- Clip Level
  - What is the strongest ground motion the sensor can measure?
  - Common unit to represent the maximum velocity = mm/sec
  - Trillium120P/PA has a clip level of 15 mm/sec
- Clip level & self-noise enforce upper & lower limits on the range of signals a seismometer can measure
- The space between the clip & noise curves is the usable range of the sensor
- Proper installation is crucial to reliably measure true ground motion on both vertical & horizontal channels down to the level of an instrument's self-noise

Trillium 120P/PA Self-noise & Clip Level



Earthquake Categories

Local events	<~10km	Several seconds to 30Hz
Regional	>~10km	30 seconds to 10Hz
Teleseismic	>~3000km	3600 seconds to 2 seconds

Back to Performance Specifications Slide

Nanometrics SEISMOLOGICAL INSTRUMENTS

Establishing Seismometer Sensitivity

- The input-output sensitivity of a particular seismometer is established by the manufacturer during design
- A good value must be consistent with vendor's clipping & seismic signal output specifications
- As clipping should occur near the peak output voltage, the sensitivity should be close to the peak output voltage divided by the clip level
- 20 Vpp / 15 mm/s = 1.333 V/mm/s = 1333 V/m/s → close to actual 1201 V/m/s
- The sensitivity specification of all Nanometrics sensors is accurate to 0.5%
- The published value for the Trillium 120P/PA sensitivity is 1201 V/m/s +/- 0.5%
  S_{MIN} = 1195 V/m/s; S_{MAX} = 1207 V/m/s

In Summary

- Clip level & self-noise are the important performance parameters that respectively specify sensor's maximum & minimum detectable signals
- Input-output sensitivity is an interface specification that has little bearing on performance
- The quality of the signal is also determined by other factors such as sensor's immunity to atmospheric pressure variations, environmental factors, as well as installation techniques
- The emphasis on seismometer input-output sensitivity is a largely historical issue (passive sensors coupled to low-resolutions digitizers or analog devices with limited dynamic range)
- Active broadband seismometers with higher output voltage ranges & 24-bit digitizers with built-in adjustable gain have made the sensitivity of a seismometer relatively unimportant
- Its exact value is unimportant as long as it is accurately known