Comparing and Combining Strong and Weak Motion to Optimize Data Quality

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Abstract

Co-locating weak-motion seismometers with strong-motion accelerometers enables monitoring of seismicity at all scales, from the largest earthquakes to background-level microtremors. However, a combined analysis depends on having comparable data from both instruments, installed at the same depth, accurately aligned in the same package, and precisely calibrated so they can produce equivalent data, i.e. the same ground motion velocity or acceleration signals after response correction.

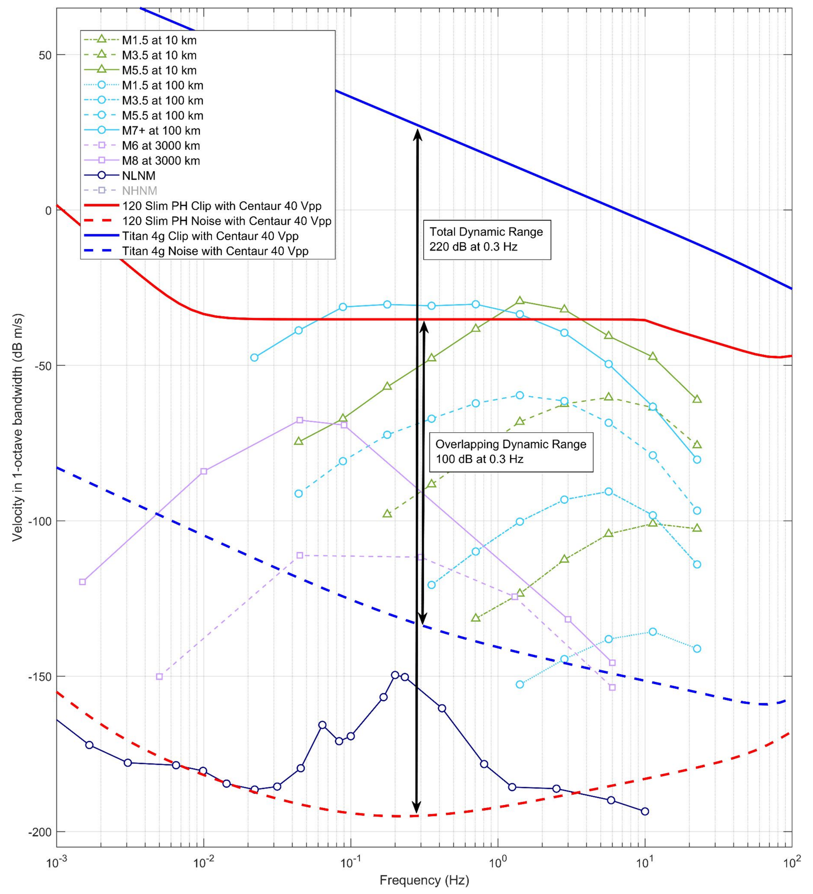
We present data from recent earthquake sequences in the Hualien region of Taiwan, captured by dual downhole sensors (Cascadia Slim Posthole) in the Downhole Seismic Observation Network of Taiwan CWB. In this example the seismometer and accelerometer signals match within 0.5% on average after response correction, allowing for the synthesis of a combined data stream with an unprecedented dynamic range of 220 dB. Algorithms for optimal combination of the data are discussed and demonstrated.

This processing also enables a new quality assurance metric for calibration accuracy. Previously, it has only been possible to verify this by running a calibration test procedure, typically no more often than once a year, since the test process is laborious and interrupts normal data collection. However, in analyzing data from a dual instrument, coherence between the strong and weak-motion data streams can be continuously measured and reported as a state-of-health metric, to verify that the two instruments are operating correctly and measuring ground motion with the same accuracy in terms of sensitivity and frequency response.

Cascadia 120 Dual Downhole Instrument Network in Taiwan

Earthquake magnitudes span a larger range than can be captured by any single instrument. Ideally strong and weak motion data should be combined into a single dataset, but often are not because

- Networks may be funded and built separately
- Stations may be separate
- Instruments may be separate, e.g. seismometer in borehole, accelerometer at surface
- Uncertainty in location, orientation, response, and sample timing makes it difficult to combine data from separate instruments

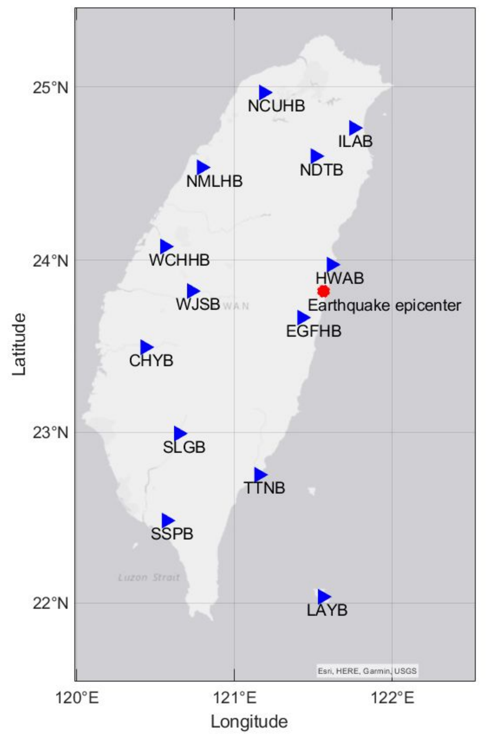


Nanometrics Cascadia 120 Slim Posthole (shown below right) combines a strong-motion sensor (Titan accelerometer) and a weak-motion broadband sensor (Trillium 120 seismometer), aligned together in a single 104 mm diameter package for downhole installation.

Its dynamic range covers the full range of seismic ground motion as shown in the chart at right. There is a large overlap in the ranges of the two instruments to ensure events that clip the seismometer still have good signal-to-noise ratio on the accelerometer.

The Taiwan Central Weather Administration has deployed 13 Cascadia 120 Slim PH instruments in their Downhole Seismic Observation Network, for earthquake early warning and better understanding of blind fault systems.

Station locations are shown at right. They are distributed across the island, at different distances from any particular earthquake, such as the 2024 Mw 7.4 Hualien earthquake (epicenter shown by red dot). Signals from this event at the closest station HWAB and farthest station LAYB are analyzed here.



Algorithm to combine data

The accelerometer and seismometer data from the Cascadia 120 Slim PH instrument are aligned and calibrated so as to provide matching data, typically within 1% after response correction. Therefore they can be used interchangeably, depending on the magnitude of the signal. However we wish to avoid a discontinuity of even 1% when switching between data streams. Therefore a smooth blending algorithm is required.

We recommend time-tapered windowing rather than a purely amplitude-based algorithm, to avoid frequent switching between data streams which would add distortion. Note the specific parameter values in the algorithm below are only example values and can potentially be further optimized.

Response Correction

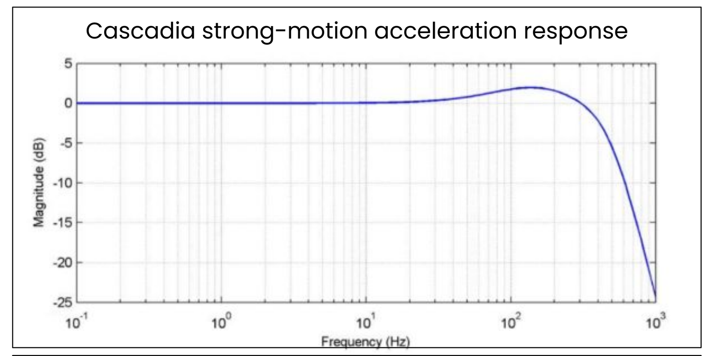
To combine the data, first both data streams must be converted to have the same units and frequency response.

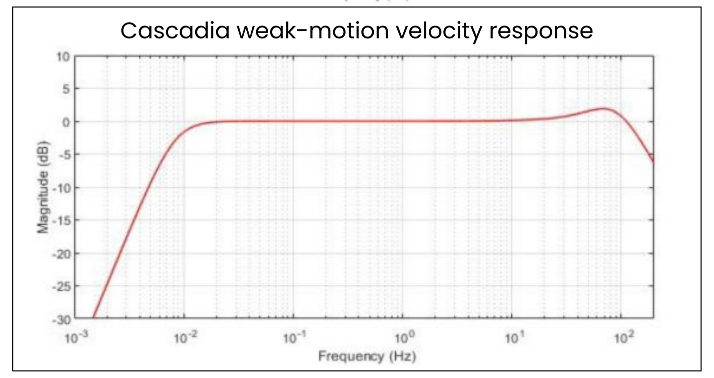
Converting between velocity and acceleration is straightforward based on **a = dv/dt = iωv** in frequency domain.

Matching frequency response is more complicated. High frequency poles and zeroes can be inverted for each sensor to flatten the response. However at low frequencies, an accelerometer normally has flat response, whereas seismometer response rolls off to zero at zero frequency and this cannot be inverted (see plots at right).

To make the low-frequency response match,

- low-frequency response of the seismometer can be left as it is
- accelerometer response can be rolled off in the same way as the seismometer, e.g. a double pole at 120 s to match Trillium 120 in the Cascadia system



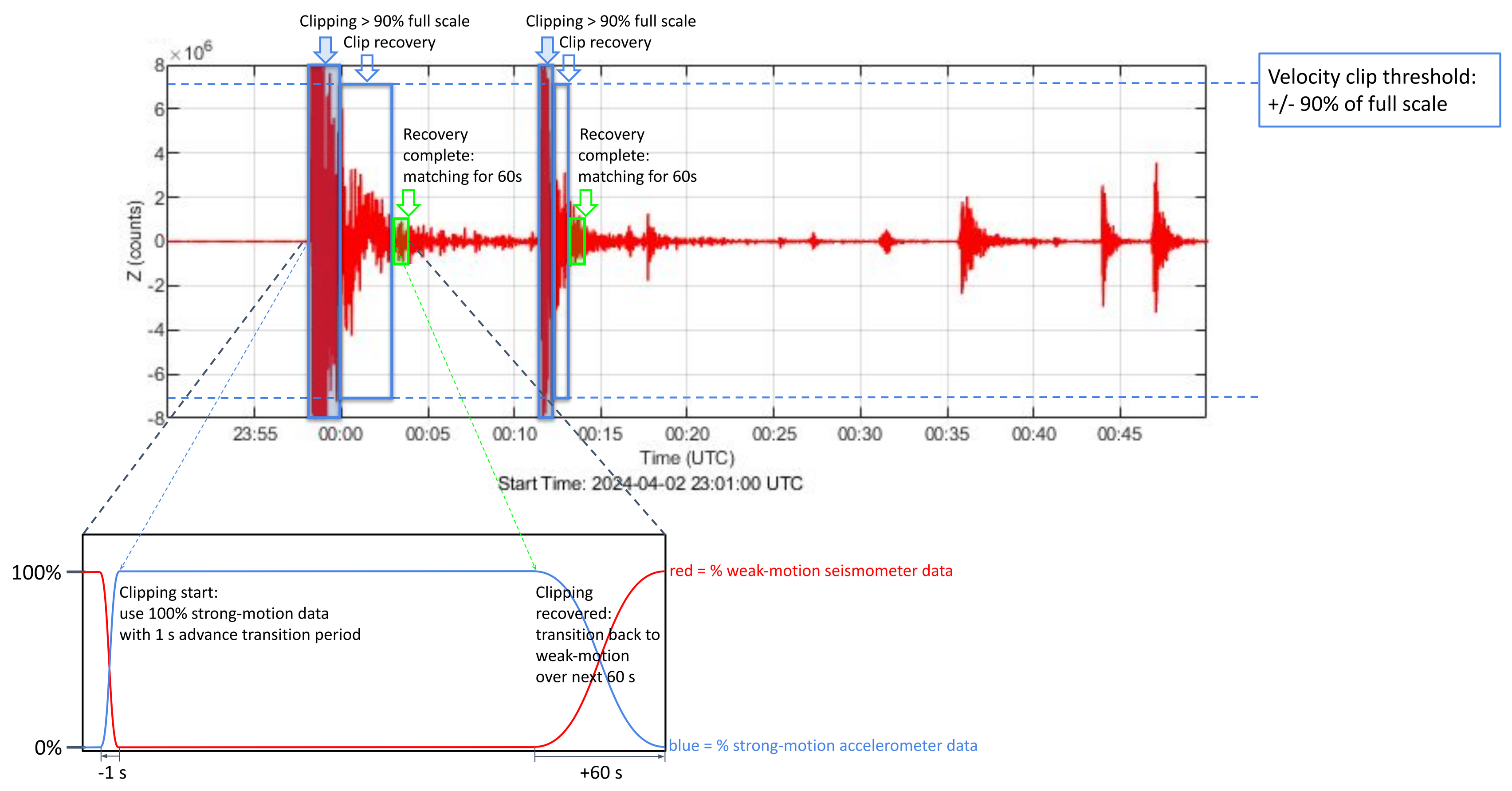


Details of Algorithm to Combine Data

With reference to the diagram below (seismometer data from nearest station HWAB during the 2024 Mw 7.4 Hualien earthquake),

1. Use weak-motion seismometer data by default when its signal is not clipping
2. Clipping is detected when either
   a. **velocity > 90%** of velocity clip level of the seismometer (15 m/s = 90% of 16.7 m/s clip velocity for Trillium 120)
   b. **acceleration > 90%** of acceleration clip level of the seismometer (1.08 m/s^2 = 90% of 1.2 m/s^2 clip acceleration for Trillium 120)
3. For 1 second of data prior to clipping, transition from weak-motion to strong-motion data by blending using a cosine squared taper (transition period is short to preserve weak-motion data immediately preceding the earthquake)
4. After clipping, use strong-motion data until clip recovery is complete (since a weak-motion seismometer takes time to recover from clipping distortion, proportional to its low-corner period **$T = 1/f_0$**)
   a. Criteria to detect clip recovery: response-corrected strong and weak-motion signals **match within 5% for T/2** = 60s for T120

   See the right column of this poster for further discussion of the signal-matching metric
5. In the T/2 time window as described above, transition from strong-motion to weak-motion data by blending using a cosine squared taper



Data Matching as a State-of-Health Metric

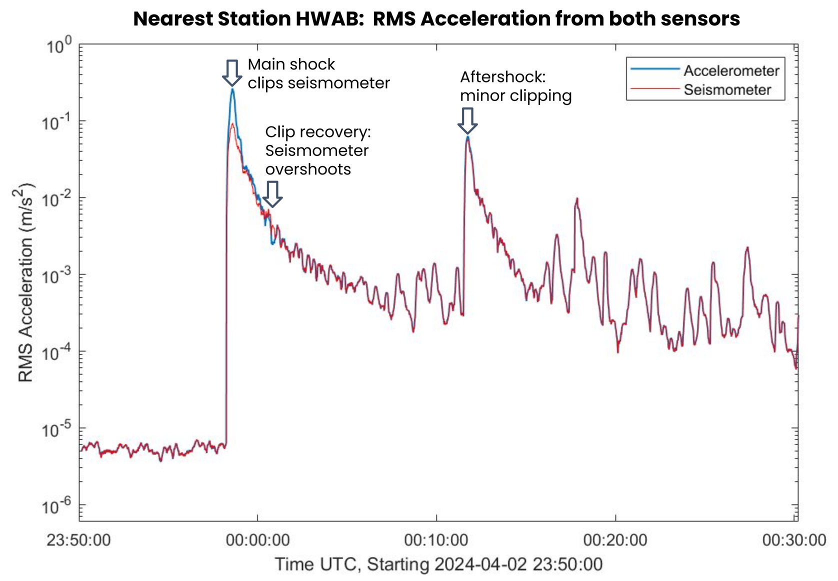
The two Cascadia data streams provide equivalent measurements of ground motion, for moderate-amplitude signals where the dynamic ranges of the strong-motion and weak-motion signals overlap. Their ratio should be close to 1, so this ratio can be monitored to provide a new state-of-health metric. Here we follow a similar methodology to **Li et al. (2019)**. However in this case because the strong and weak-motion instruments are integrated we can see more accurate matching of the data.

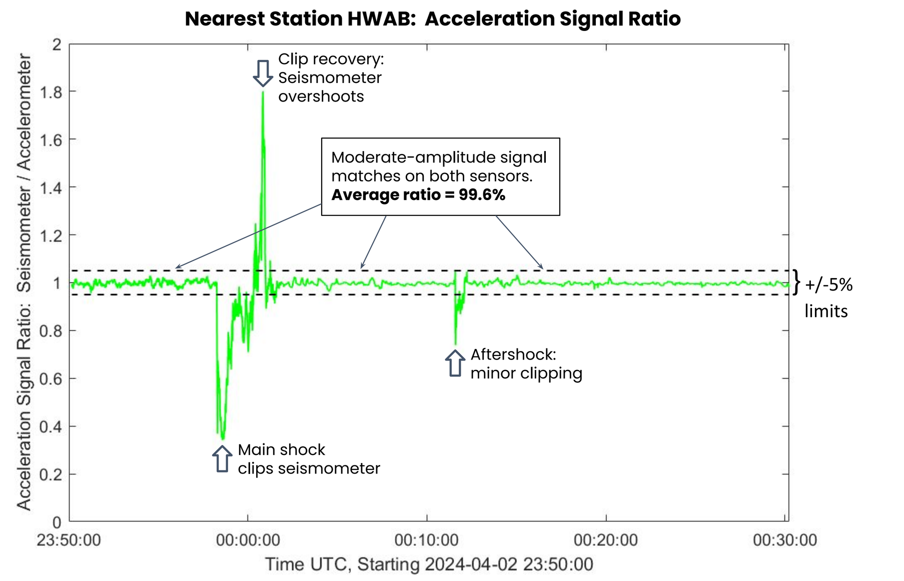
If the signal ratio is within defined limits such 95-105%, both instruments can be considered to be working and well calibrated. If they do not match, the absolute amplitude of the signals should also be checked, as described below.

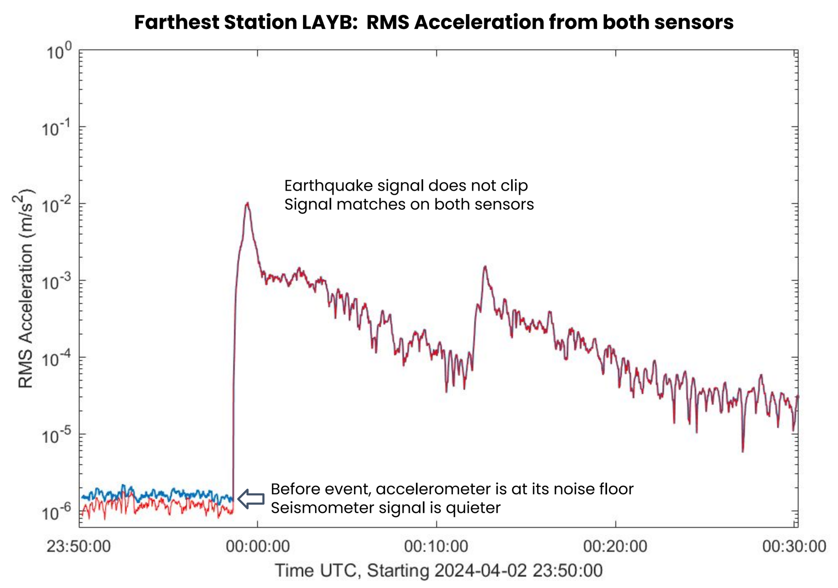
Below are two examples of signal ratio before, during, and after the M7.4 earthquake, taken from the closest station HWAB in Hualien, and the most distant station LAYB (see map in the lower right section of this poster). The RMS acceleration (in a rolling 10 s window) is also shown to indicate how the signals can become mismatched at high and low amplitude extremes. The signal ratio metric is valid and close to 1 as long as:

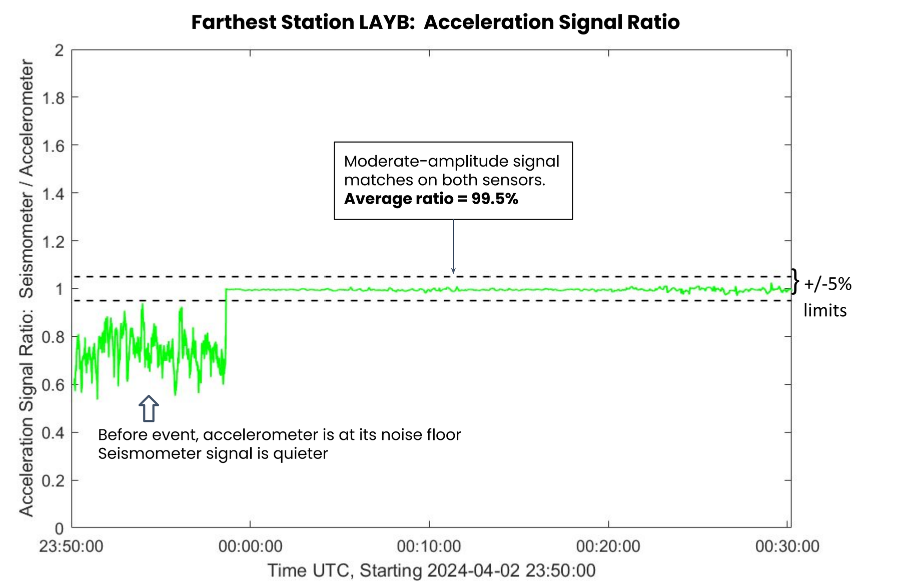
1. The signal is not too large, over the clip level of the seismometer (see clipping events at HWAB)
2. The signal is not too small, below the noise floor of the accelerometer (see quiet time before EQ at LAYB)

Temporary mismatch of signals indicates the signal has gone outside the range of one of the instruments. Permanent mismatch would indicate one of the instruments is malfunctioning.









Conclusion: The new state-of-health metrics shown above (absolute and relative magnitudes of the two data streams) can be used to:

1. Verify that both instruments are working and well calibrated
2. Indicate if the signal is outside the dynamic range of either the seismometer (clipping) or the accelerometer (below its noise floor)

References

- Chou, C C; Wu, L; Chai, J F; Yao, G C; (2024) Summary Report on Hualien Earthquake in Taiwan on April 3, 2024 (first edition, v1.0), NARLabs National Center for Research on Earthquake Engineering.
- Li, Z; Hauksson, E; Heaton, T; Rivera, L; Andrews, J (2019) Monitoring Data Quality by Comparing Co-located Broadband and Strong-Motion Waveforms in Southern California Seismic Network, Seismological Research Letters (2019) 90 (2A): 699–707.
- Peterson, J. (1993). Observations and Modeling of Seismic Background Noise, USGS Open-File Report 93-322, 94 pps.
- Sleeman, R., van Wettum, A. and Trampert, J. (2006) Three-Channel Correlation Analysis: A New Technique to Measure Instrumental Noise of Digitizers and Seismic Sensors, Bulletin of the Seismological Society of America, Vol. 96, No. 1, pp. 258–271.