Seismologic Signal Processing

Earthquake detection and characterization

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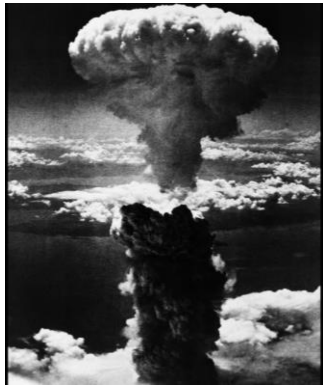
Overview

- Earthquake detection and characterization is a crucial application of seismological signal processing.
- Earthquakes can cause tsunamis, rockslides and avalanches.
- The goal is to detect and locate earthquakes in real-time, and to estimate their size and other characteristics, such as magnitude, focal mechanism, and source depth.
- The information can be used for earthquake early warning systems, seismic hazard assessment, and earthquake research.
- The same practice can be applied for finding oil and gas fields as well

What is a seismic signal?

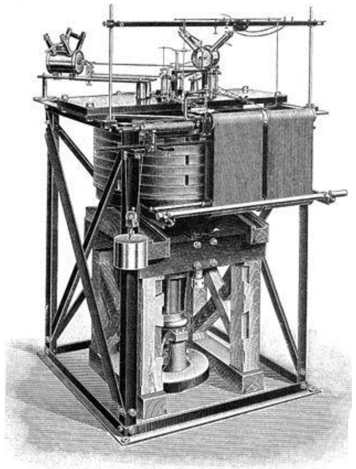
- Vibrations or waves that propagate through the Earth's subsurface due to natural or human-induced causes.

  - Earthquakes
  - volcanic activity
  - Explosions
  - mining or drilling.

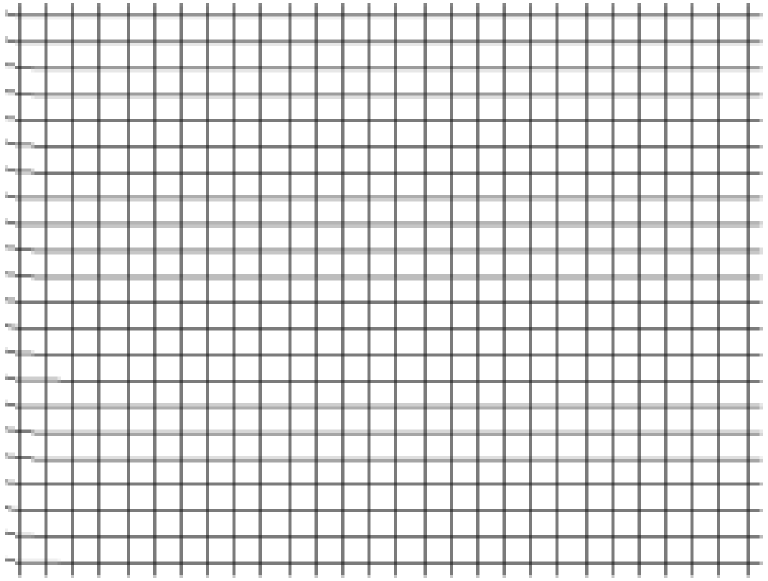


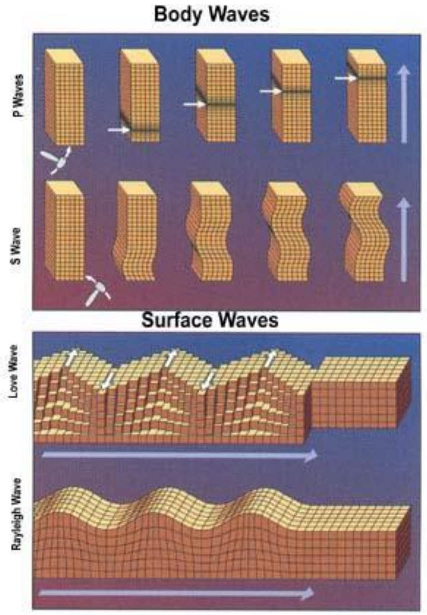
- The seismic signal represents the inelastic response of the ground structure

- Measured with a seismometer



Wiechert’s seismometer
1914





Two types of Seismic waves:

1. **Body waves** travel through the interior of the Earth.
   - P-waves
   - S-waves

2. **Surface waves** travel across the surface. Surface waves decay more slowly with distance than body waves which travel in three dimensions.
   - Love waves
   - Rayleigh waves

- Seismic signals are mainly characterized by a ground vibration of finite amplitude, high frequency and relatively short duration

Challenges

- **Signal-to-Noise Ratio (SNR):** Earthquake signals are often weak compared to background noise. The low SNR of earthquake signals can lead to false positives or false negatives in detection and characterization results.

- **Signal Variability:** Earthquake signals can vary greatly in their characteristics, such as amplitude, duration, and frequency content, depending on the source mechanism, location, and propagation path.

- **Computational Complexity:** Seismic data processing can involve large volumes of data and computationally intensive operations. Efficient and scalable algorithms and computational resources may be needed.

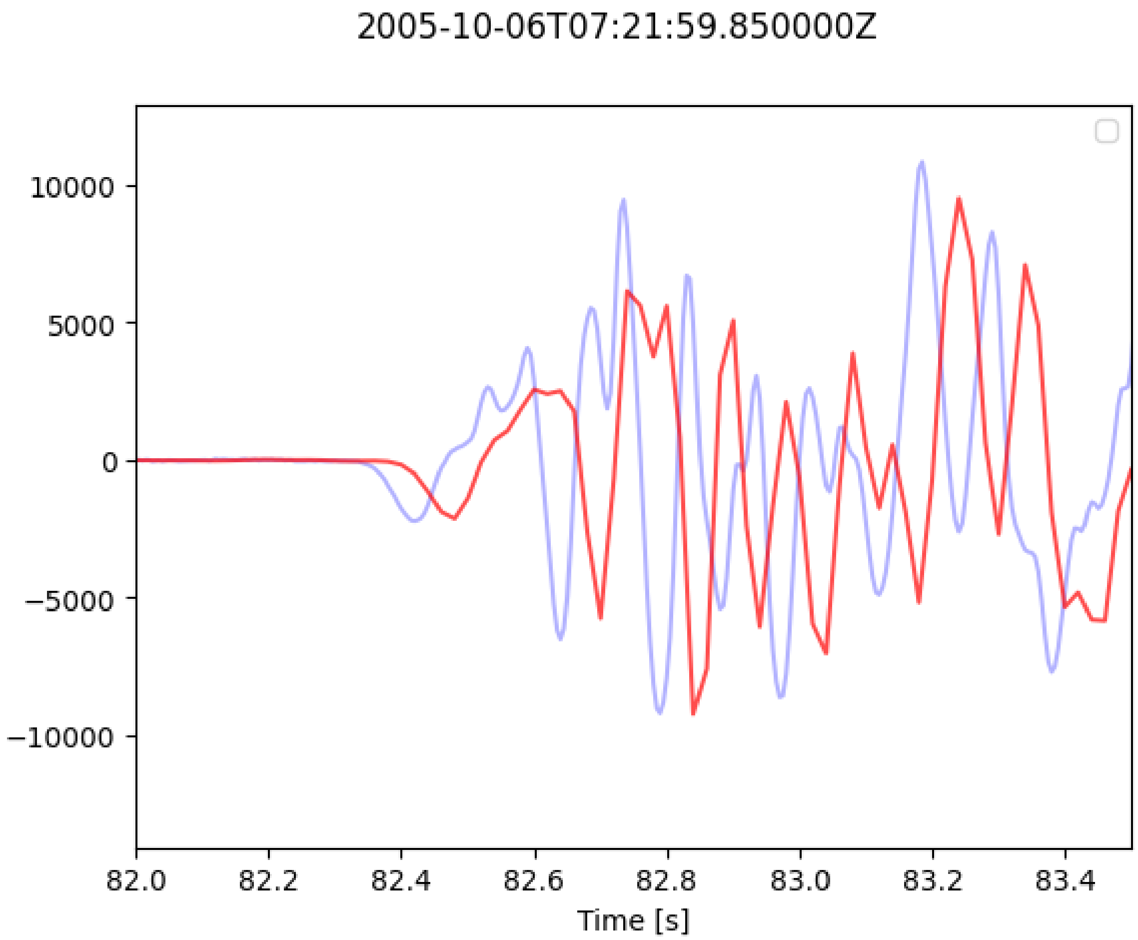
Approaches :

- Waveform correlation
- Template matching
- Statistical analysis
- Machine learning
- And more…

Waveform Correlation

The basic principle:

comparing seismic waveforms of recorded data with templates or reference waveforms to identify similar patterns.



Methodology

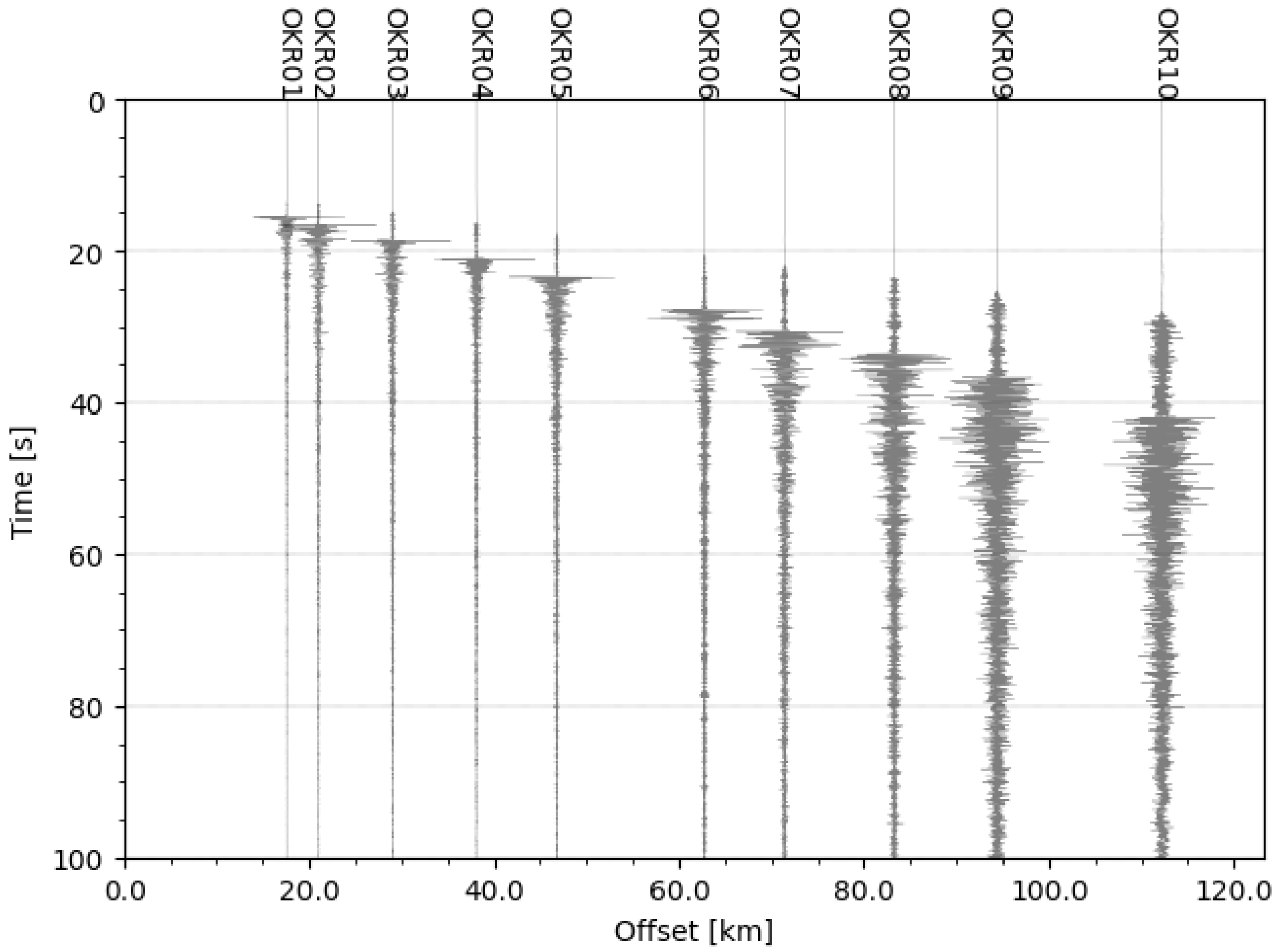
1. **Data Collection** - Load seismic waveforms from multiple stations, typically in the form of continuous waveforms in the time domain.
2. **Template Selection** - Select a template waveform from a known earthquake event.
3. **Pre-processing** - applying filters, normalization, decimation etc. to remove noise and other unwanted signals.
4. **Waveform comparison** - Perform cross-correlation between the template waveform and the waveforms from multiple stations. Determine the time lag and correlation coefficient with maximum cross-correlation.
5. **Detection** - Set a threshold to detect earthquake events based on the correlation coefficient.
6. **Localization –** Using the time delay between the template waveform and the correlated seismic waveforms at different stations to estimate the location of the earthquake. Typically done using triangulation or other methods that consider the travel time of seismic waves.
7. **Characterization** - Estimate earthquake parameters such as epicenter location, magnitude, and depth.

Template selection

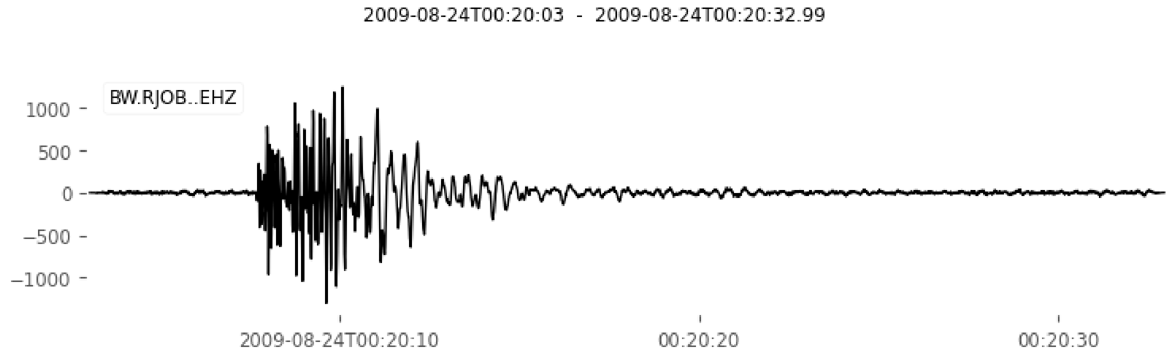
- Appropriate template selection is crucial for accurate earthquake detection and characterization.
- This can be challenging! earthquake signals can vary significantly.

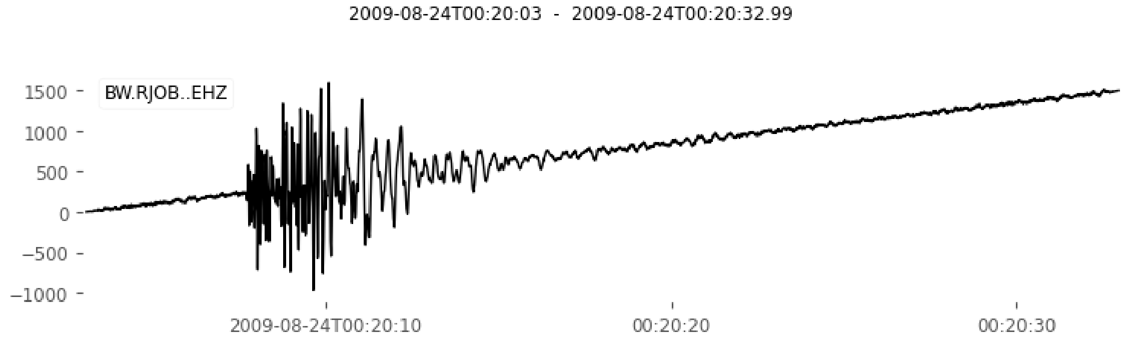
- Templates are typically designed/selected based on known or expected earthquake signals in the study area, and they can be generated from theoretical models, empirical data, or expert knowledge.

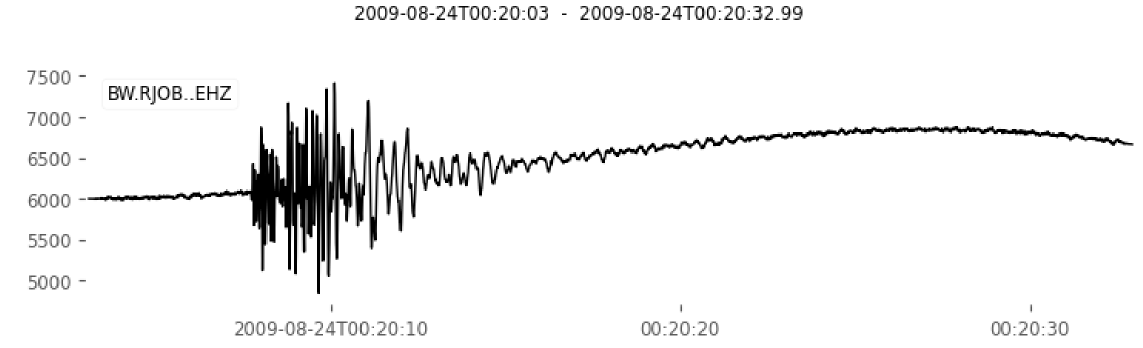
factors to consider:
- waveform characteristics
- frequency range
- amplitudes
- spatial distribution
- Etc.

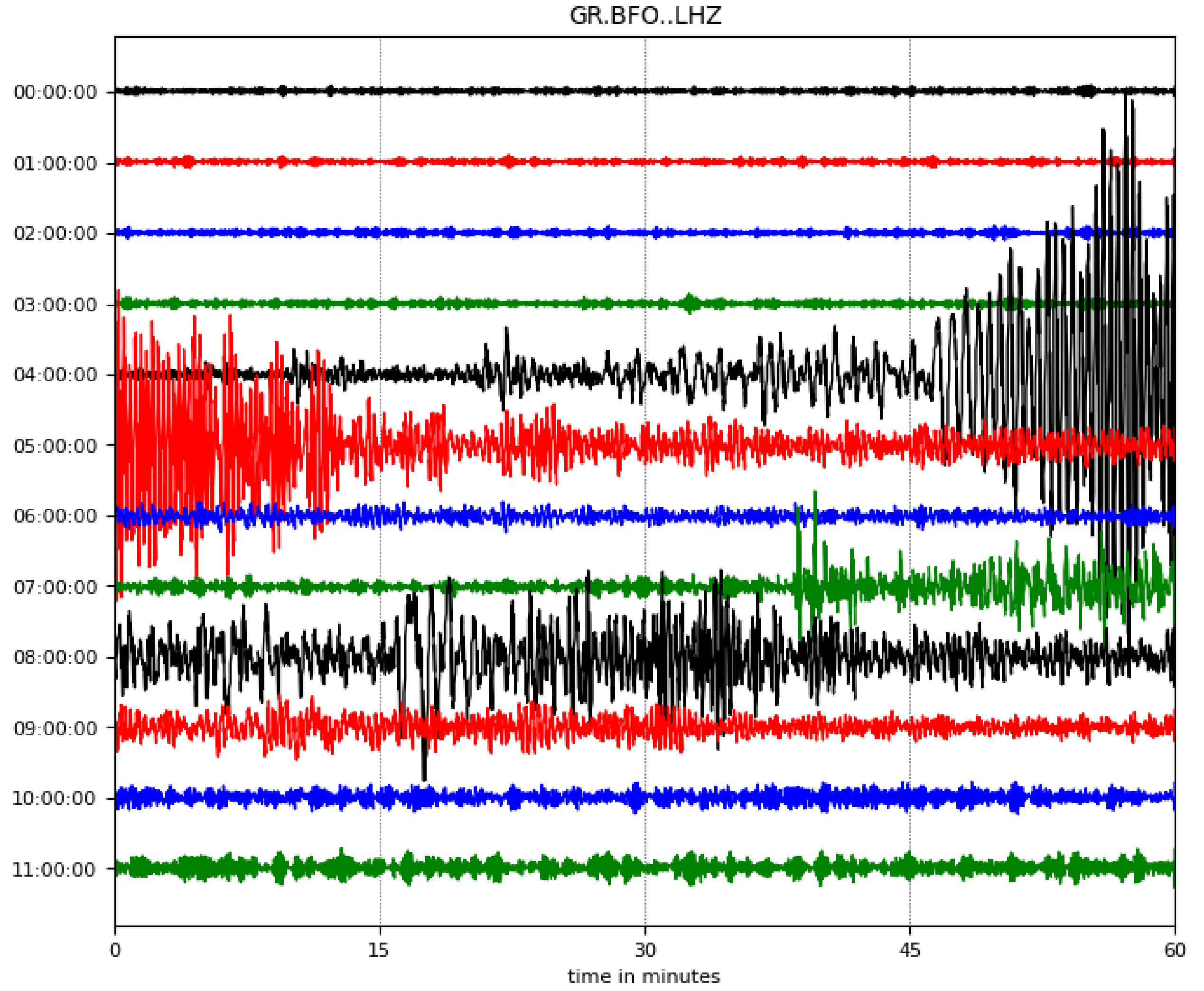


Pre- processing



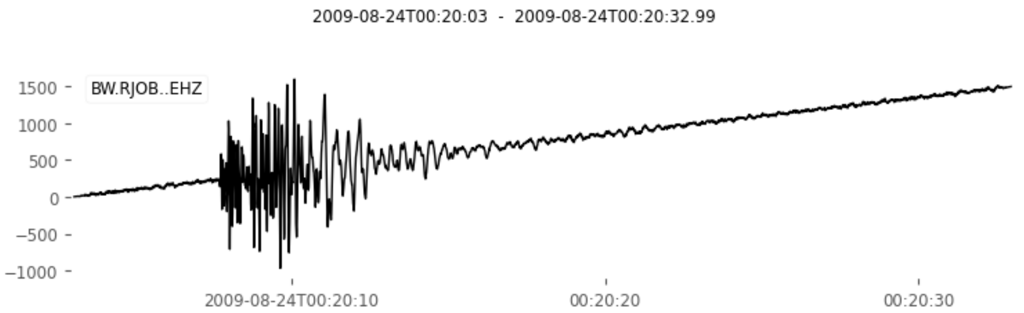






Normalization:

- Take care of differences in amplitude, scale and energy level between the template and recorded data waveforms.
- Common techniques are zero-mean normalization and amplitude scaling.

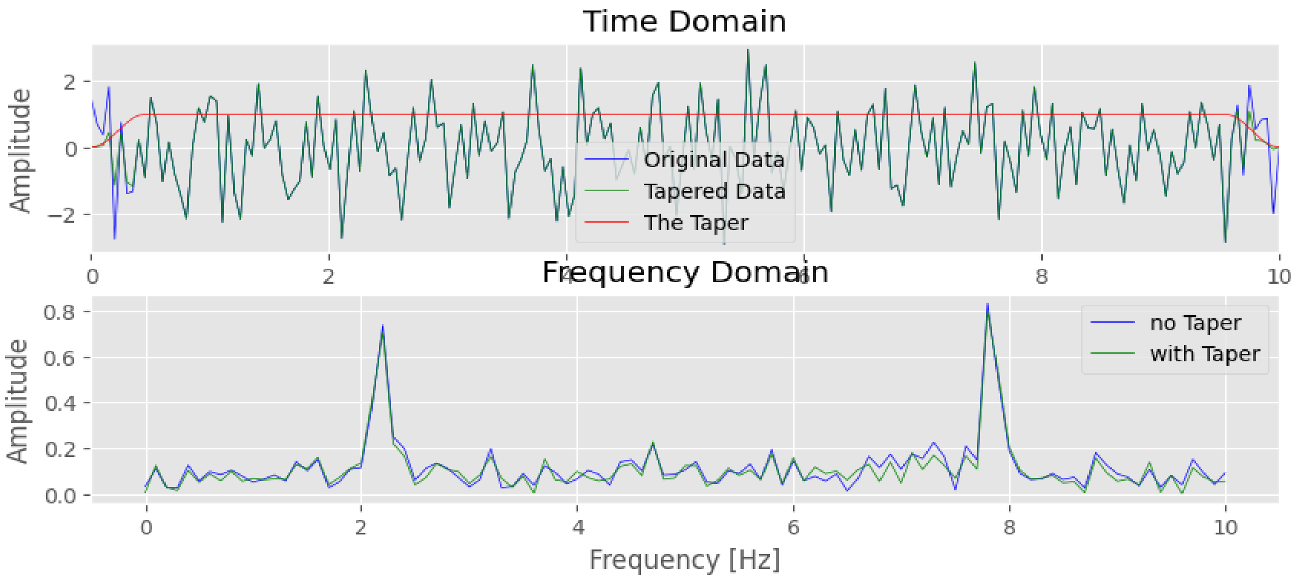


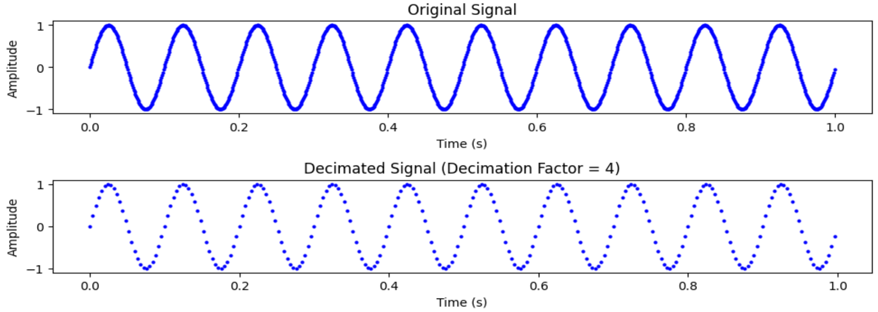
Decimation (down sampling):

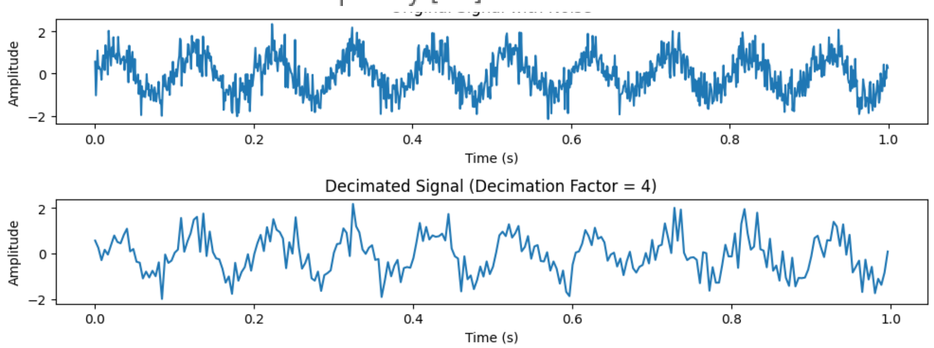
Process of reducing the sampling rate of a signal.

Helps for:

- Noise reduction
- Bandwidth reduction
- SNR improvement
- Computational efficiency





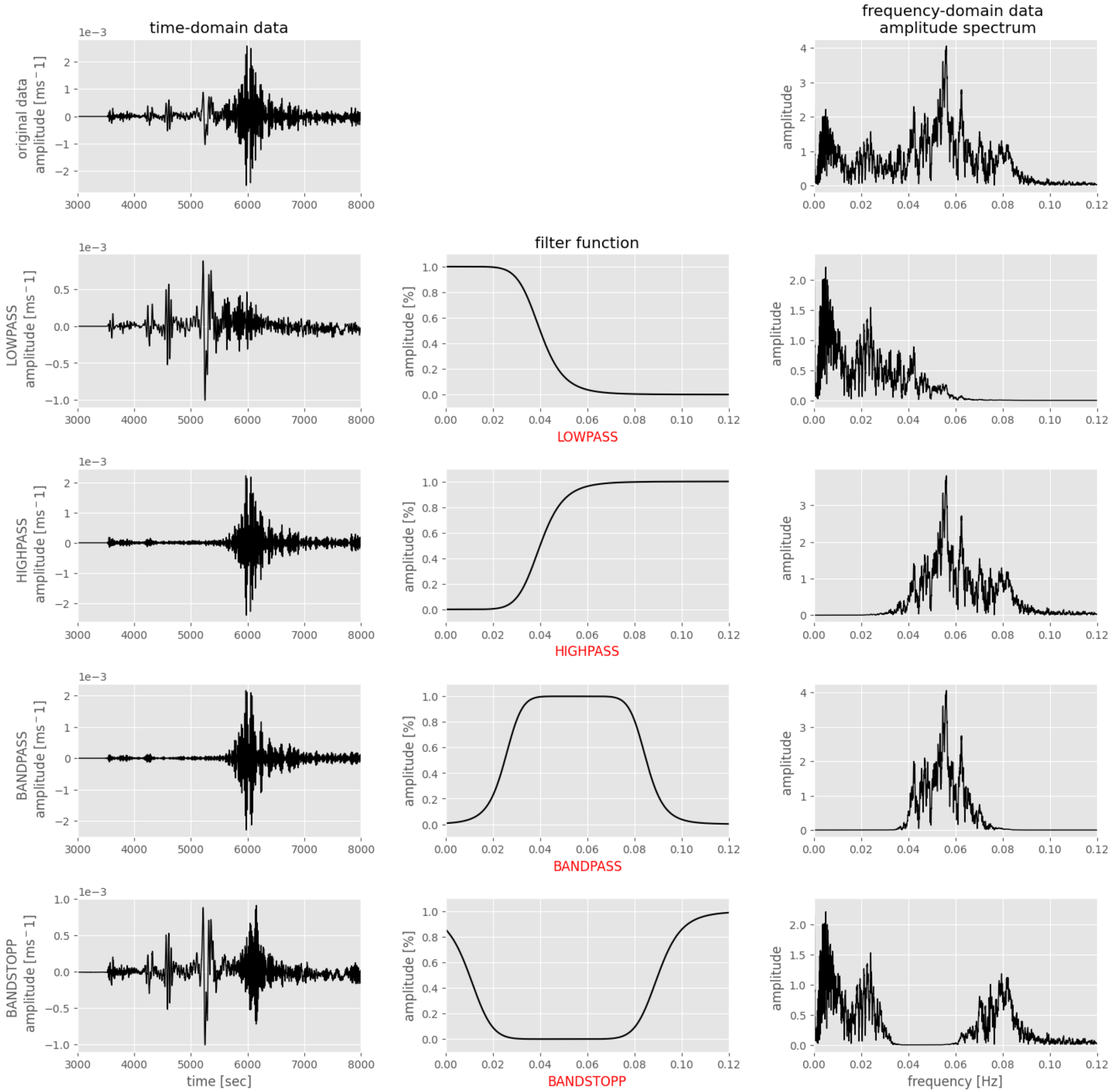


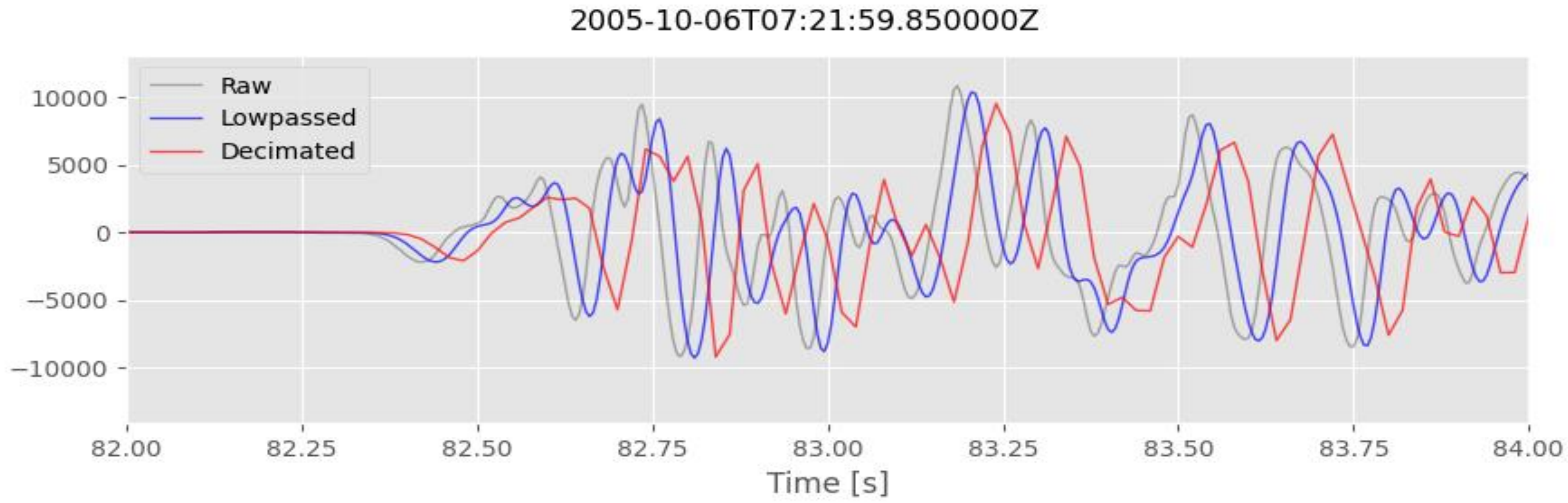
Trending

Tapering

Filtering:

- **Bandpass filter:** useful for isolating the frequency range associated with earthquake signals.
- **Low-pass filter:** useful in cases where the seismic signals of interest have lower frequencies, such as in the case of long-period earthquakes.
- **High-pass filter:** useful in cases where the seismic signals of interest have higher frequencies, such as in the case of short-period earthquakes.
- **Bandstop (Notch) filter:** useful in cases where there are known frequency interferences in the data that need to be removed.




2005-10-06T07:21:59.850000Z
Raw
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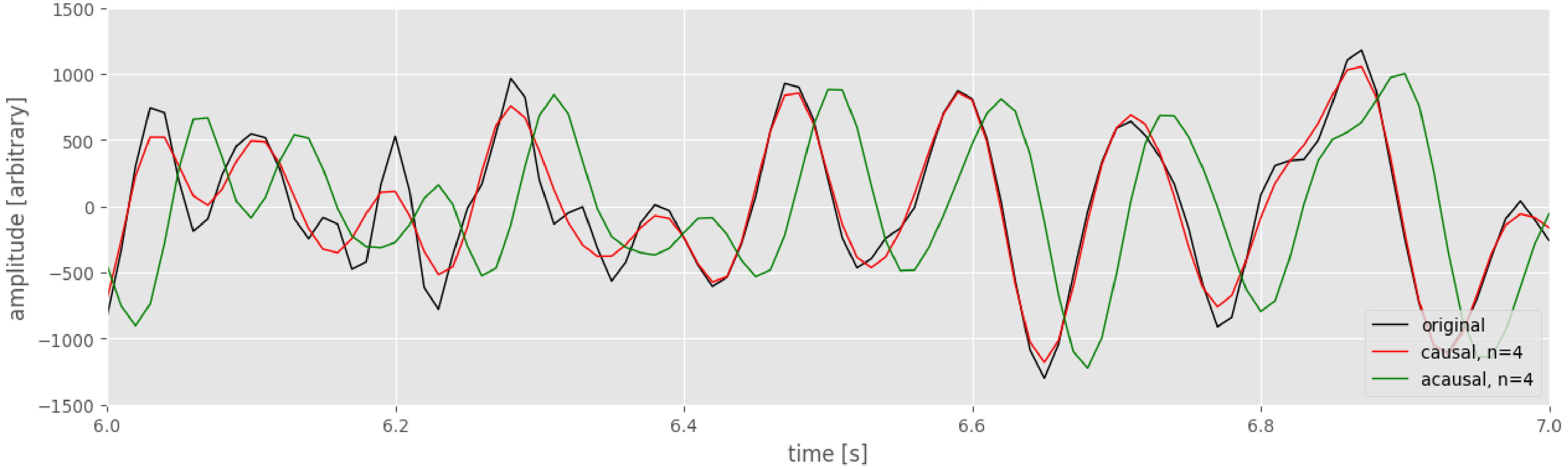
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causal, n=4
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Waveform comparison- Signal similarity

- We want to measure the similarity between two signals
- Similar signals can be signals that one is a scalar multiplication of the other, or a shift

we can compute the difference signal $\delta = x - y$ and define similarity as its energy E_δ being small.

But that doesn’t work if (with respect to x) :

- y has some gain
- y is shifted in time

For example, if $y = gx$ then the difference is $\delta = (1 - g)x$ which is only small if $g \approx 1$.

Cross correlation

We can derive something better from the energy E_δ :

$$E_\delta = \sum_n (x_n - y_n)^2 = \sum_n x_n{}^2 - 2\sum_n x_n y_n + \sum_n y_n{}^2 = E_x - 2C_{xy} + E_y$$

- C_{xy} is called the cross-correlation between x and y.
- When E_δ is minimal, C_{xy} is maximal. So, we can say the signals are correlated when C_{xy} is large.
- C_{xy} is still large even if y has arbitrary gain with respect to x since the gain is captured in the energy component.

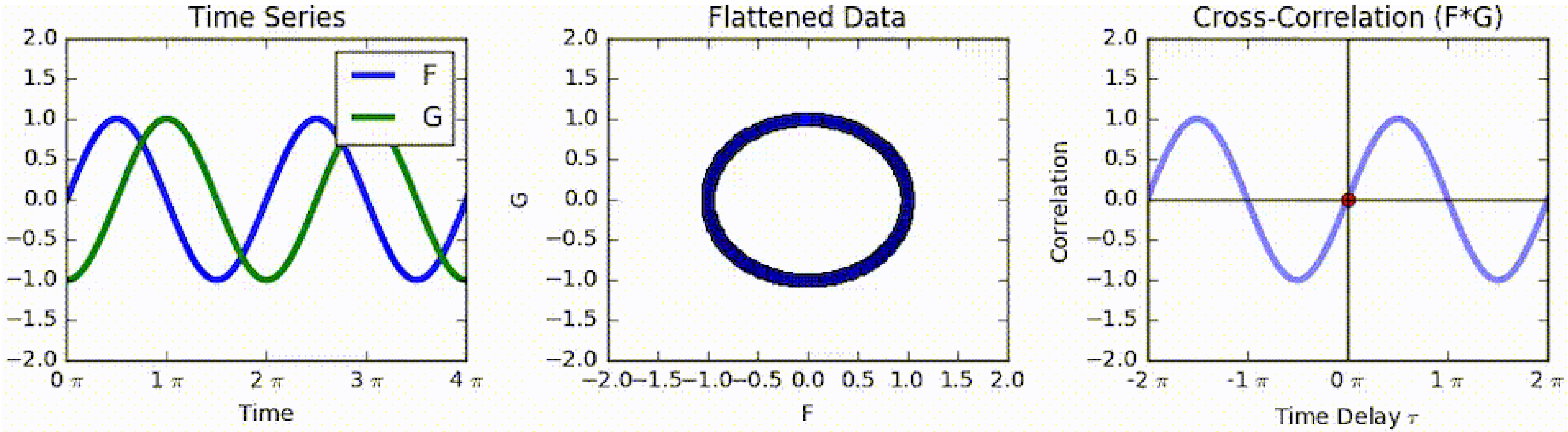
For example, if $y = gx$ (and thus $E_y = \sum_n gx_n gx_n = g^2 E_x$)
then $C_{xy} = \sum_n x_n y_n = g\sum_n x_n x_n = gE_x = \sqrt{E_x E_y}$

Correlation with lags

- However, C_{xy} will not indicate similarity if y is shifted in time.

- To take care of time shifts we define $C_{xy}(m) = \sum_n x_n y_{n-m}$ (m is called the correlation *lag).*

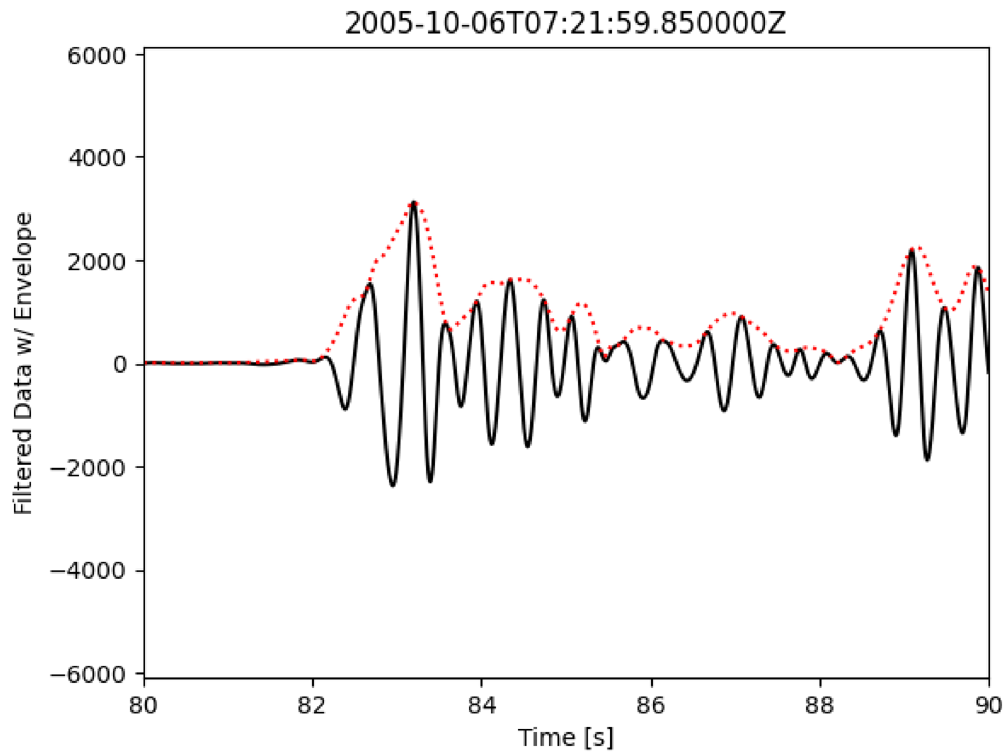
- We now look for its maximum value (its peak). This peak corresponds to the optimal time shift. If there the correlation is significant (using the same criterion as before) - then we have found our similar signal



Envelope correlation

- **The envelope of a signal** is a smoothed version of the signal that represents the overall amplitude modulation of the signal over time
- It can provide valuable information about the energy content or shape of the signal

- **Envelope correlation technique** - we compute the envelopes of two seismic signals and then cross-correlation applied to these envelopes
- It can be useful in identifying seismic signals that have similar energy patterns or shapes, even if their amplitudes or frequencies may be different



Computational Complexity

Waveform correlation is computationally intensive in terms of processing time and memory requirements.

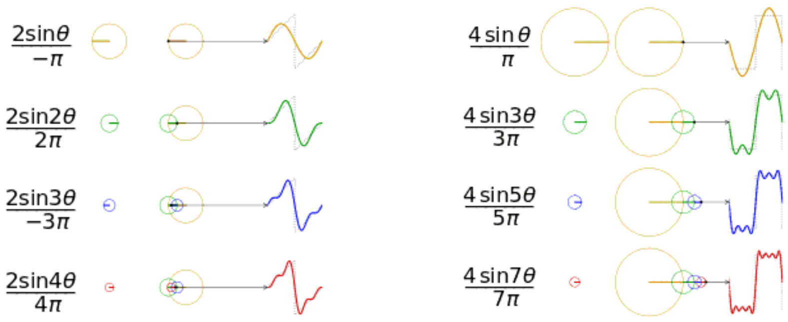
Cross-correlation computation involves computing the dot product of two waveforms at different time lags.

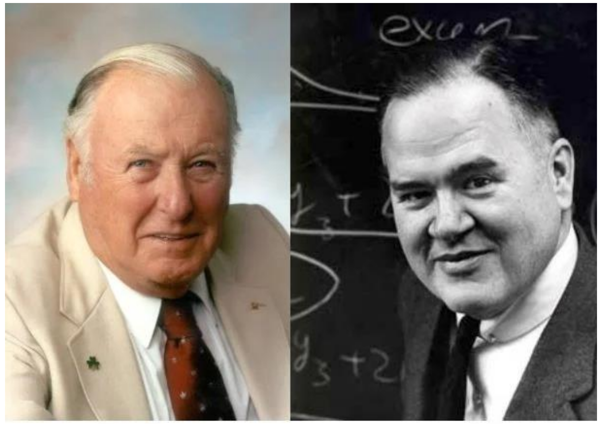
- Large amount of data - multiple templates against a large dataset
- Seismic data is often high-frequency and is continuously streaming - dealing with high sampling rates and long-time durations
- Dealing with real-time or near-real-time
- Pre-processing might involve convolution, which can be computationally expensive

What can we do?

- **Efficient and Scalable Algorithms**:
  - Fast Fourier Transform (FFT)
  - Fast Multipole Method (FMM)

- **Optimization Techniques**:
  - Parallel processing (multiple processors or cores)
  - Data reduction:
    - Singular Value Decomposition (SVD)
    - Principal Component Analysis (PCA)
  - Distributed computing:
    - cloud computing
    - distributed computing clusters
  - Hardware acceleration:
    - Graphics Processing Units (GPUs)
    - Field-Programmable Gate Arrays (FPGAs)
  - Machine Learning





James William Cooley　　John Wilder Tukey

An Algorithm for the Machine Calculation of Complex Fourier Series

By James W. Cooley and John W. Tukey

(1965)