TS114 : signal processing project

François Le Neindre, Gia-Thuy Pham, Romain Tajan
francoisleneindre@gmail.com, phamgiathuy@gmail.com, romain.tajan@ims-bordeaux.fr

May 5, 2020

Contents

1 Organization and project evaluation

This project is divided in 7 sessions of 2h40. The assessment relies on a personal grade depending on the **student's behaviour** (assiduity and reliability during the sessions), as well as a **report of the project**. The instructions for the report are given below:

- The report should be typed using LaTeXor Word, in plain page format with a font size of 11 points. The target number of pages is 10 with **15 pages the absolute maximum**.

  If you are using Word, all equations should be typed with the specific editor, and should be numbered if they are cited. All figures should have a number, a title and labeled axes (with units).

2 Introduction

2.1 Earthquake and tsunami phenomena

An earthquake is a geological event which is the result of a sudden displacement (i.e. a rupture) between two rock systems. This rupture starts at a given point -the hypocenter- and spreads along a plane which separates the rock systems: the fault. The orthogonal projection of the hypocenter at the surface of the Earth is called the epicenter.

Given the solid and elastic properties of rock at a macroscopic scale, this sudden displacement releases energy under the form of heat (about 66%), the remaining being several type of mechanical waves (around 33%) known as seismic waves, radiated in all directions. These seismic waves split into two categories :

- The P-Waves which travel the fastest, around 6km/s near the surface. They are compression waves, like sound, and deform the rock in the direction of propagation at a rather high frequency (10Hz). Also responsible of the thunder noise happening during an earthquake, they moderately shake the ground mainly vertically.
- The S-Waves are slower (4km/s near the surface) but carry more energy than the P-Waves. They can be destructive as they hit the ground, because the motions induced are mainly horizontal, something against which buildings are vulnerable. Lower frequencies (around the hertz or lower) are met and can emphasize with resonance frequency of buildings which explains why they can be very damaging.

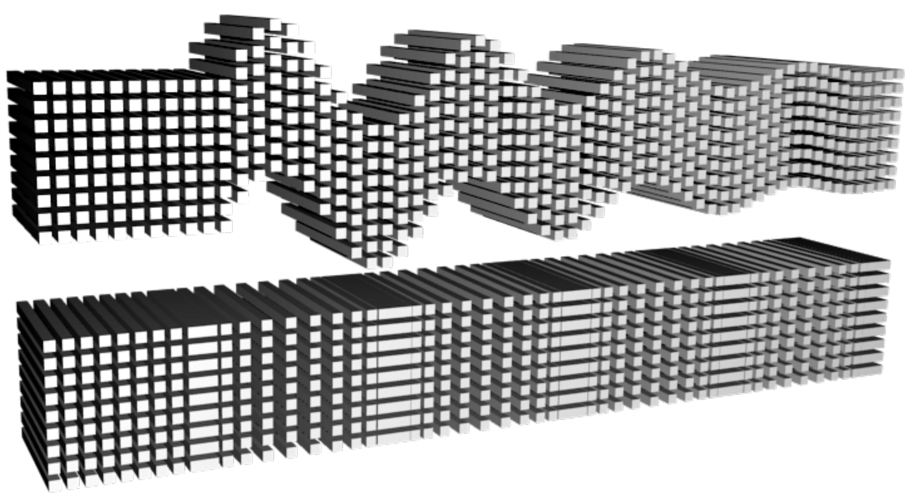

Figure 1: P-wave and S-wave

You can find a short introductory video at this link `https://www.iris.edu/hq/inclass/animation/3component_seismogram_records_seismicwave_motion`.

2.2 Goal of this project

The main purpose of this project is to implement signal processing algorithms using MATLAB to detect seismic activity and analyze this activity in order to warn the population of a Tsunami risk or of a large magnitude seismic activity. During this project you are going to

- detect automatically the occurence of an earthquake,
- locate automatically the hypocenter of an earthquake in space and time,
- evaluate automatically the magnitude of an earthquake.

A tool for warning people in case of a tsunami hazard is the conceived from these points.

2.3 Signal acquisition

Seismic activity is monitored thanks to seismographs that records ground motion in different Japanese cities. Each station records a three dimensional acceleration signal $\mathbf{a}(t) = [a_x(t)\ a_y(t)\ a_z(t)]$ at a sampling frequency of $F_s = 100Hz$ where

- a_x is the acceleration in the North-South direction,
- a_y is the acceleration in the East-West direction,
- a_z is the acceleration in the Up-Down direction.

In the MATLAB data, $\mathbf{a}(t)$ is given as a $3 \times N$ matrix where the first column represents $a_x(t)$ the second represents $a_y(t)$ and the third $a_y(t)$.

2.4 Signal Database

A database containing different earthquake recordings from various stations in Japan is provided. It can be downloaded at `https://rtajan.github.io/ts114/`. Each .mat file can be loaded into the MATLAB workspace using the command `load`, and is composed of a vector of structure called *list*. More specifically, the s^{th} element of this vector (`list(s)`) is itself a structure containing the following fields:

- `list(s).sismo` contains a three dimensional acceleration signal in cm/s^2. The three components of this field represent acceleration in the North-South direction, the East-West direction and the Up-Down direction.
- `list(s).id` contains the id of the station (as well as its name in Japanese).
- `list(s).lon` is the longitude of the station.
- `list(s).lat` is the latitude of the station.
- `list(s).offset` is the time offset of the first sample of the signal (this offset is given compared to a common reference for all signals).

2.5 Organization of your report

Your **final report** should contain the following five sections:

1. An introduction section: in this section you have to present the project, using your **own words** (do not rewrite the subject!). The reader should understand the goal and the environment of the project.
2. A seismic signal visualization section: in this section you will answer Section 3. In this section, a reader with signal processing background should understand some key aspects of seismic signals.
3. A section about automatic P-waves detection and hypocenter localization: in this section you will answer Section 4.1. In this section, the reader should understand the process done to detect P-waves and locate the hypocenter.
4. A section about measuring the intensity of the earthquake: in this section you will answer Section 5. In this section, the reader should understand the process done automatically measure the magnitude of the earthquake.
5. A conclusion

3 Signal Visualization

The aim of this section is to display and analyze the seismograph signals under Matlab.

3.1 Time display

Matlab. *Under* Matlab*, load the signals given in the file entitled recording_1.mat and display the time evolution of the* 5^{th} *recording. On the same figure, highlight regions of this signal containing seismic noise (when there is no earthquake), the P-wave, and the S-wave.*

Report task. *In the section dedicated to the seismic signaling, use the previous* Matlab *task to illustrate the following key points presented in introduction about seismic waves*

- *S-waves are more powerful than P-waves,*
- *P-waves are mainly vertical,*
- *S-waves are mainly horizontal.*

To do so, add the following figures to your report and comment those figures:

- *A figure of the complete signal that you can annotate.*
- *A figure at focusing on the very beginning of the earthquake.*
- *A figure at focusing on a part of the signal containing the S-wave.*

3.2 Time/Frequency display

As the seismic signals are non-stationnary signals, we will use a spectrogram to display their frequency content. Seismic activity varies slowly (compared to the sampling frequency of $100Hz$), indeed as we have seen, the P-wave comes first then the S-Wave. The Fourier transform (or Discrete Forurier Transform) provide the frequency content of the signal; however it does not capture well the localization in time. Consequently, we analyze $x(t)$ signal using a sliding window. In particular, computing the Discrete Fourier Transform (DFT) of each window captures the frequency content of the windowed signal and how it changes with time. This operation is called **Short Term Fourier Transform** (STFT). Mathematically, the STFT is expressed as follows

$$X(m,\nu) = \sum_{n=0}^{L-1} x_n w_{n-m} e^{-j2\pi\nu n}. \tag{1}$$

The modulus squared of this STFT is called the spectrogram

$$S_x(m,\nu) = \frac{1}{N} \left|X(m,\nu)\right|^2. \tag{2}$$

To compute spectrograms, you may use the MATLAB function `spectrogram`, before doing so **read carefully the documentation** !

MATLAB. *Under* MATLAB*, load the signals given in the file entitled recording_ 1.mat and display the spectrogram of the* 5^{th} *recording. On the same figure, highlight regions of this signal containing seismic noise (when there is no earthquake), the P-wave, and the S-wave.*

Report task. *Comment this spectrogram in your report.*

MATLAB. *After computing the spectrogram this task is divided into three sub-tasks :*

1. *Compute the power contained in each window of the spectrogram (you may use the Perseval's identity). Plot this power as function of time.*
2. *Compare the spectrum of a window of signal containing the P-wave only with another window containing the S-wave.*

Report task. *From the previous tasks, illustrate the fact that S-waves are much more powerful than P-waves and observe the frequency content of both type of waves.*

4 P-Wave detection and epicenter localization

4.1 P-Wave detection

For station s, the P-wave can be automatically detected using the algorithm described hereafter. For each sample n in the signal of station s, compute the following two signals

$$STA^{(s)}(n) = \frac{1}{N_l} \sum_{i=n-N_l+1}^{n} \left|a_z^{(s)}(n)\right|^2 \tag{3}$$

$$LTA^{(s)}(n) = \frac{1}{N_L} \sum_{i=n-N_l-N_L}^{n-N_l} \left|a_z^{(s)}(n)\right|^2 \tag{4}$$

where N_l and N_L are integers respectively equivalent to duration $T_l = 1$ and $T_L = 5$ seconds. The start of the P-Wave is then located by finding the **smallest** n such that the ratio of STA and LTA is above a threshold T, that is

$$n_P^{(s)} = \inf\left\{ n : \frac{STA^{(s)}(n)}{LTA^{(s)}(n)} > \Gamma \right\} \tag{5}$$

A good value for T can be $T = 2.5$ but feel free to try other values. The time in seconds at which the station s can detect a P-wave is then obtained by converting the result of equation into seconds (5) :

$$t_P^{(s)} = \frac{n_P^{(s)}}{Fe} \tag{6}$$

Matlab. *Implement a function* `sta_lta` *that takes as input* $a_z^{(s)}(t)$, F_e, T_l, T_L, Γ *and returns* $t_P^{(s)}$.

Report task. *Explain the STA/LTA algorithm with your own words. In particular, you should lay emphasis on*

- *why this algorithm works, what is the rationale behind this method*
- *what signal processing steps did you use to implement this algorithm (filters, FFT, ...)*
- *what will happen if T is changed*

(Hint) Here if we deliberately remove illustrations about this method; don't hesitate to add some (draw the algorithm as signal processing chain, plot some signals...).

4.2 Estimation of the hypocenter localization

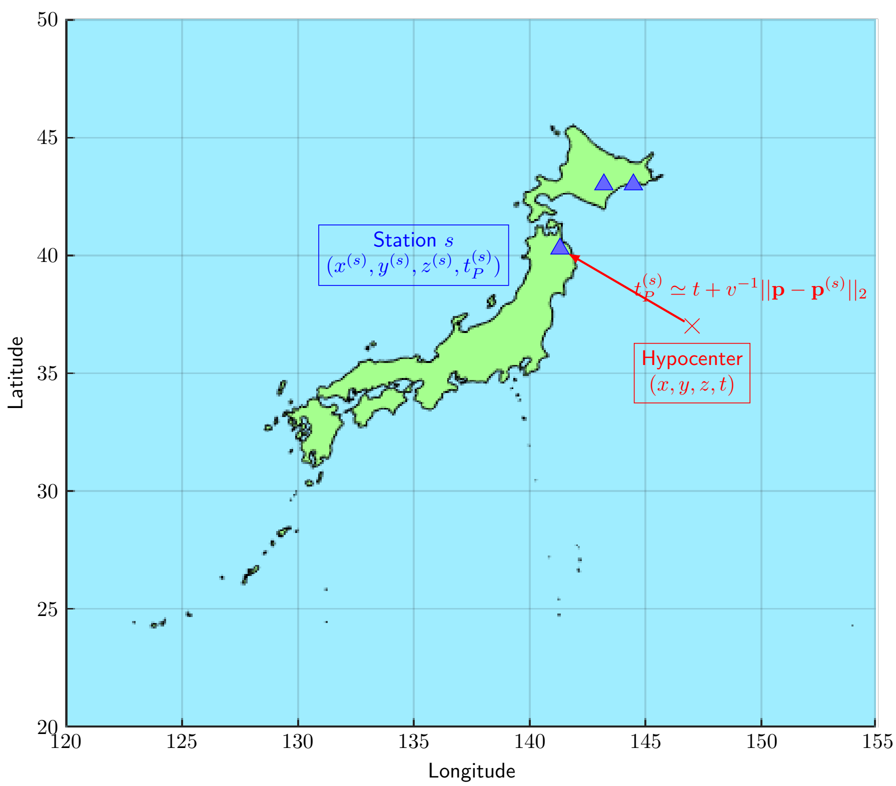

Figure 2: P-wave and S-wave

The algorithm for locating the hypocenter is the following :

1. For every station s in the database, compute the time of arrival of the P-wave, let t_P^s be this time of arrival.

2. For every station s in the database, compute its position for its longitude and latitude. Let the vector $\mathbf{p}^{(s)} = (x^{(s)}, y^{(s)}, z^{(s)})$ be this position. (We will assume $z^{(s)} = 0$ altitude for the stations.)

   Let $\mathbf{p}$ be the position of the hypocenter and let t be the start of the earthquake. To locate the hypocenter, we will use a simple model for P-waves: we will assume that they travel through the earth at a speed of $v = 7300m/s$. Under this assumption, the time at which the P-wave reaches station s, t_P^s can be expressed as

   $$t_P^s \simeq t + v^{-1}||\mathbf{p} - \mathbf{p}^{(s)}||_2 \tag{7}$$

3. The hypocenter is then located by finding t, and $\mathbf{p}$ that minimizes the following cost function

   $$J(t, \mathbf{p}) = \sum_{s=1}^{S} \left(t - t_P^s + v^{-1}||\mathbf{p} - \mathbf{p}^{(s)}||_2\right)^2 \tag{8}$$

5 Estimation of the seismic magnitude

5.1 Earthquake Magnitude

The magnitude of an earthquake is an indicator which evolves logarithmically with the total amount of seismic energy released by the fault rupture. Several estimators of this magnitude exist among which we can find the two followings.

5.1.1 The Local Magnitude M_L

Introduced by Charles Francis Richter in 1935 as the Richter Scale and updated thereafter, it has the advantage of providing a quick estimation of the earthquake magnitude. It is usually used for Early Warning. It relies on making the assumption that the earthquake is a point and the rupture happens instantaneously, therefore linking the energy released with the maximum displacement amplitude and an attenuation formula. The result is obtained by the empirical mean of the magnitude estimations at each seismic stations inside a 200km radius from the hypocenter. At a given station i, the magnitude estimation is described as :

$$m_s = 1.1235 \times \left[\log_{10}(\Delta_{max}) + \log_{10}(D_s) + 1.9 \times 10^{-3} D_s - 5 \times 10^{-3} d_H - 0.02\right] \tag{9}$$

Where:

- Δ_{max} is the maximum modulus of high-pass filtered displacement, at the $0.5Hz$ cut-off frequency, in μm. You can design this filter using the `butterworth` in MATLAB.
- D_s is the distance between the station and the hypocenter in km.
- d_H is the hypocenter depth in km.

5.2 JMA seismic intensity

5.3 Tsunami alert

References