UNIVERSITY *of*
TASMANIA

Part III Laboratory work

KYA312/322

Seismometry

Safety

12V AGM (Absorbent Glass Mat) lead-acid batteries are used as a power supply in this practical. Proper handling and awareness of associated hazards are essential for safety.

Potential Hazards

- **Short-Circuiting:** Connecting battery terminals directly (shortcutting) can generate intense heat and sparks. This is a serious fire hazard and can cause burns or explosions.
- **Manual Handling:** These batteries are heavy. Improper lifting can cause injury, and dropping the battery can result in damage and spills.
- **Chemical Exposure:** Although sealed, these batteries contain acid and lead. Damage to the battery casing may result in exposure to hazardous substances.

Safety Precautions

1. **Prevent Short Circuits:**
    - Never place tools or metal objects on top of the battery.
    - Always use insulated tools when working with batteries.
    - Ensure terminals are covered when not in use.
2. **Safe Lifting & Handling:**
    - Use proper lifting techniques (bend knees, keep back straight).
    - Wear safety footwear to protect against dropping.
3. **Chemical Safety:**
    - Inspect batteries regularly for cracks or leaks.
    - In case of leakage, avoid contact with the liquid and report immediately.
    - Wear gloves and eye protection when handling damaged batteries.

Emergency Procedures

- **In Case of Fire:** Use a CO_2 or dry powder extinguisher; do **NOT** use water.
- **In Case of Acid Contact:** Rinse affected area with plenty of water and seek medical attention.
- **In Case of Lead Exposure:** Wash hands thoroughly after handling batteries.

Personal Protective Equipment (PPE)

- Safety gloves
- Eye protection
- Safety footwear

Always follow manufacturer’s instructions and report any incidents or damaged batteries to your supervisor immediately.

Outline

Seismometry is concerned with recording vibrations of the Earth. These vibrations may come from earthquakes, oceanic disturbances, human activity, or a range of other sources, and contain useful information about their source and the medium they travel through. In this practical, you will gain practical experience in how seismometers are used to record seismic signals, and how these signals can be analysed to reveal insights into the properties of the Earth or the signal source. Time series analysis and signal recording is widely applicable across many applications beyond seismology – this is a broadly applicable skill set to develop.

Seismology explores the nature of vibrations within the Earth. These vibrations can come from a range of sources, and carry useful information about both the source and the propagation medium.

Experimental Objectives

- Understand the characteristics and origins of seismic signals.
- Understand how seismic signals are recorded.
- Apply common analysis techniques to investigate a range of seismic signals.

Background Theory

Seismology is the primary tool for studying the Earths interior, earthquakes, and tectonic activity. The basic data for a seismologist are seismograms - recordings of ground motion resulting from incoming seismic waves. Seismic waves come from a source, may be refracted, reflected and diffracted as they travel through layers of the Earth, and arrive at the seismometer. The resulting ground motion at the seismometer depends on the nature of the source, the material the wave travelled through, and the way that the seismometer itself responds to the ground motion. It is common to think of a seismogram as a signal resulting from these three effects: the source signal, $x(t)$, the effects of the Earth structure along the seismic wave path, $g(t)$, and the response of the seismometer to ground motion, $i(t)$,

$$u(t) = x(t) * g(t) * i(t) \tag{1}$$

Some studies may be more interested in inferring the origins of $x(t)$. Seismic vibrations can come from a range of passive (naturally occurring) and active (human made) sources, including:

- Tectonic activity, i.e. Earthquakes from fault activity and internal plate stresses
- An icequake caused by a moving or calving glacier
- Atmospheric or ocean disturbances - Storms, pressure changes, wind
- Human activity - vehicles, explosives
- Elephants

Other studies may be more interested in the properties of the earths interior through which the seismic waves are travelling, described by $g(t)$. This could be to find a mineral deposit for mining, to determine the subsurface structure for a major infrastructure project, or to determine deeper earth structures on a local or global scale. Understanding earth structure has implications in the tectonic history of the planet, landscape formation, earthquake prediction, and the evolution of the ice sheets in Antarctica.

Anatomy of a seismogram

Figure 1 shows a three component seismogram of an earthquake that occurred in the solomon islands in 2022, recorded at Casey station. The Earthquake had a moment magnitude of 7Mww. The top component shows ground motion in the Z (vertical) direction, while N and E show ground motion in the North and South directions respectively. This earthquake can be described as a **teleseismic** earthquake. An earthquake generally called teleseismic if it is a large, distant event that occured at a distance greater than 30 from the seismometer.

The first two pulses (marked by the orange and green lines) are the P-wave and S-wave arrivals. P and S waves are **body waves**, as they travel through the body of the Earth. P-waves involve compression of the medium in the direction of travel, while S-waves involve shearing perpendicular to the direction of motion.

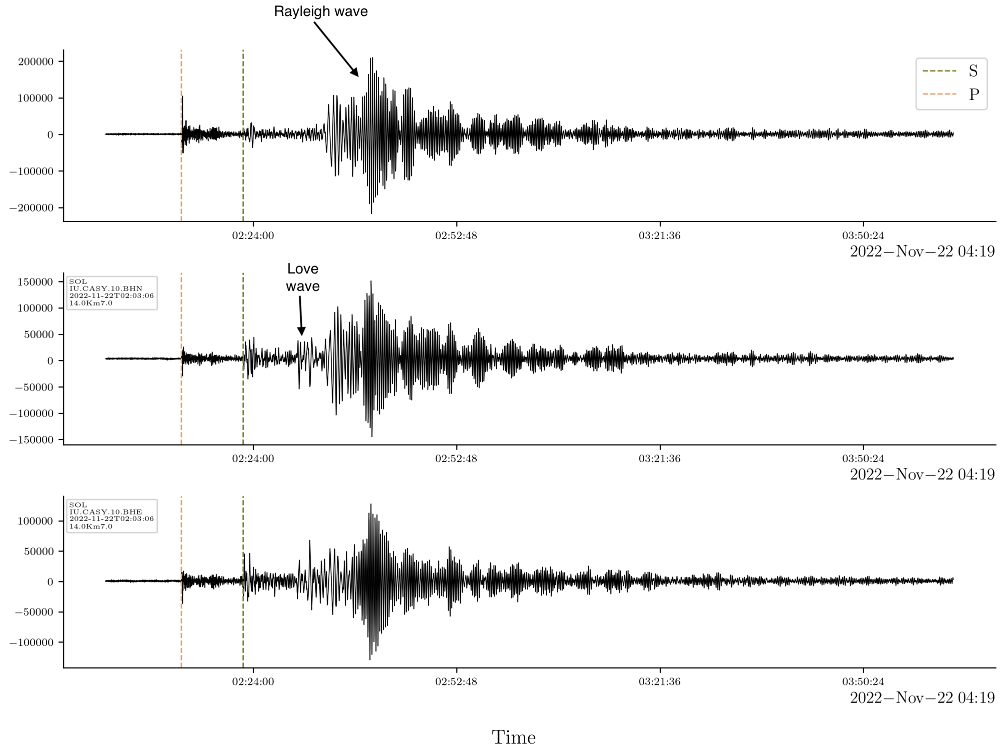


Figure 1: seismogram of an earthquake that occurred in the solomon islands in 2022, recorded at Casey station. The Earthquake had a moment magnitude of 7Mww.

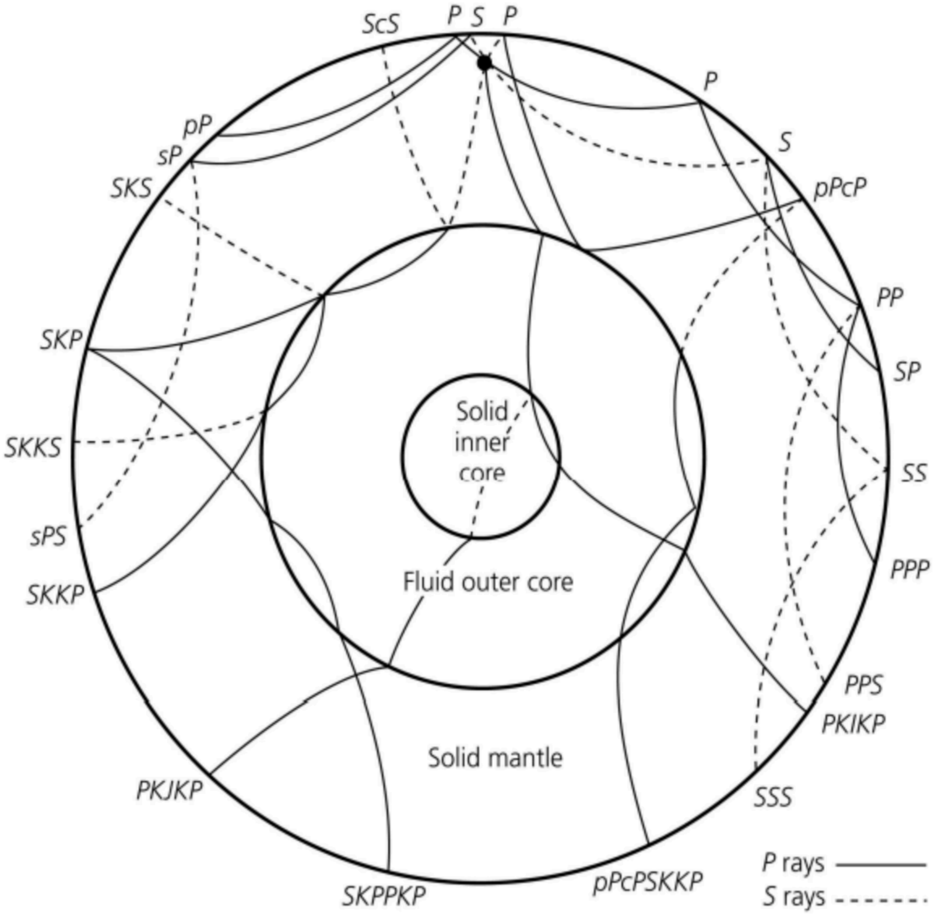


Figure 2: Naming conventions for body wave phases. Body waves can reflect and refract off interfaces inside the Earth. This produces a complex set of body wave phases.

Following the P and S wave arrivals there is a long wavetrain which show the **surface waves**. The energy of surface waves is confined to the Earth's surface. Surface waves are longer period than body waves, and they dominate most seismograms because the energy of a surface wave spreads over the surface of the Earth (i.e. a sphere), and hence decays with distance r from the source as r^{-1}. Rayleigh waves are the most prominant surface waves on a seismogram, and are a combination of P and vertical S wave oscillations. Love waves, sometimes visible on the horizontal component seismograms, contain horizontal S waves.

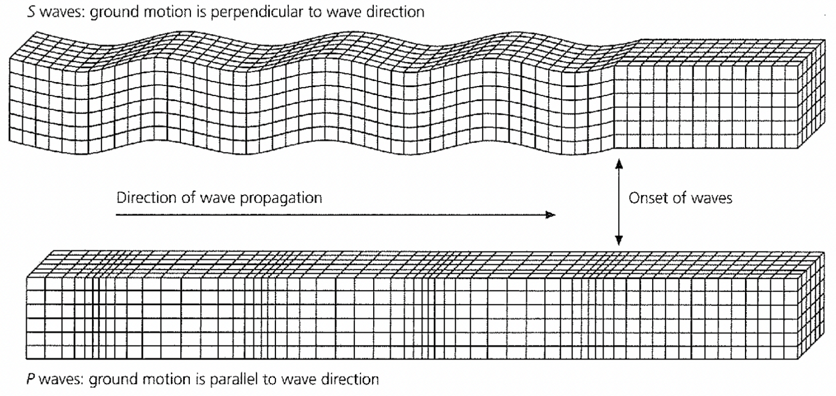


Figure 3: Caption

Seismic wave properties

The velocity of seismic waves within the Earth depend on the density and material properties of the medium, often represented in terms of the *shear modulus* and the *lamè constant*. Equations 5 and 6 give the P and S wave velocities in terms of these elastic moduli.

Equations

The 1D wave equation describes motion in an elastic, homogeneous string in 1 dimension.

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 u(x,t)}{\partial t^2} \tag{2}$$

When extended to 3 dimensions the situation becomes more complicated, as a 3D medium can support compressional, shear, and torsional forces in 3 dimensions. Deriving the seismic wave equations is beyond the scope of this practical, but the wave equations for P and S waves are shown below for interest.

The motion of P waves can be described by a *scalar potential* - note the $\frac{1}{\alpha^2}$ describing the velocity of P waves.

$$\nabla^2\phi(\mathbf{x},t) = \frac{1}{\alpha^2}\frac{\partial^2\phi(\mathbf{x},t)}{\partial t^2} \tag{3}$$

The motion of S waves can be described by a *vector potential*, since S waves involve shearing motion. Note again the $\frac{1}{\beta^2}$ describing the velocity of S waves.

$$\nabla^2\Psi(\mathbf{x},t) = \frac{1}{\beta^2}\frac{\partial^2\Psi(\mathbf{x},t)}{\partial t^2} \tag{4}$$

The velocities of P and S waves are determined by the *elastic properties* of the medium they travel through, and are commonly described in terms of the *shear modulus* μ and the *lamè constant*, λ. P waves are always faster than shear waves in a given medium.

$$\alpha = \left(\frac{\lambda + 2\mu}{\rho}\right)^{\frac{1}{2}} \tag{5}$$

$$\beta = \left(\frac{\mu}{\rho}\right)^{\frac{1}{2}} \tag{6}$$

Because seismic velocities depend on elastic properties, the *travel times* of body waves between source and receiver are commonly used to infer the elastic properties of the earth along a ray path. Despite seismic velocity being inversely proportional to density, it generally *increases* with depth - this is because the elastic moduli are also increase with density. Given enough recordings of enough ray paths, body waves can be used to perform **tomography** of the Eath. Body waves are often approximated as rays that reflect off interfaces and bend as they travel through materials of different properties. Because of this they can be used to investigate deep structures and interfaces in the Earth like the Core-mantle boundary (CMB), or the lithosphere-asthenosphere boundary (LAB).

Surface waves are *dispersive* by nature. Surface waves are concentrated near the Earth's surface, and their amplitude decays with depth. Longer period surface waves extend to greater depths and so are sensitive to the velocity of the earth at greater depth. As a result surface waves exhibit *geometric dispersion* and their velocity varies with period. This fact allows surface waves of different periods to be used to study how Earth structure varies with depth.

Instrument Response and Gain

Seismometers convert ground motion into measurable electrical signals through a combination of mechanical and electronic systems. The core mechanism involves a *mass-spring-damper* system where ground movement displaces a suspended mass relative to the frame, inducing motion in a coil attached to the mass. This coil moves within a magnetic field, generating a voltage via electromagnetic induction. The relationship between mechanical motion and electrical output is governed by the coil constant (G), a transducer sensitivity parameter expressed in volts per meter per second (Vs/m). For example, a coil constant of G=571.1 Vs/m means each meter-per-second velocity of the coil generates 571.1 volts. This proportionality ($V \propto G\frac{dx}{dt}$) shows the coil's control of how the vibration is turned into an electric signal that can be transmitted, recorded and processed.

The coil is made for a certain orientation: in a vertical seismometer, the coil (or magnet) is suspended so that gravity acts as the restoring force, and the system is most responsive to vertical accelerations. If the instrument is not properly levelled, the mass may not move correctly relative to the frame, reducing sensitivity and introducing distortion.

Before analog-to-digital conversion (ADC), the weak voltage signal from the coil (often nanovolts to millivolts) requires analog amplification to match the digitiser's (ADC) input range (e.g., 0–5 V). Amplification typically uses operational amplifiers (op-amps) with adjustable gain controlled by feedback resistors. Low-pass filters are integrated to reduce high-frequency noise and prevent aliasing; a distortion formed when a signal above the Nyquist frequency is sampled by the ADC.

The instrument response characterises how a seismometer modifies the true ground motion across frequencies. It combines:

1. Mechanical response: Governed by the mass-spring system's natural frequency (f_0) and damping (D)
2. Transducer sensitivity; defined by G
3. Digitiser gain: k_D

This response is a filter that distorts recorded signals by altering amplitude and phase. For example, a seismometer might attenuate low frequencies while amplifying mid-range frequencies. By integrating precise coil constants, optimised amplification, and rigorous response correction, modern seismometers are provided with instrument response information. Manufacturers of seismometers typically provide instrument response information in the form of standardised digital files, most commonly as dataless SEED files or separate RESP (response) files. Applying those corrections to the recorded signal allows for achieving high-fidelity recordings across a broad frequency range.

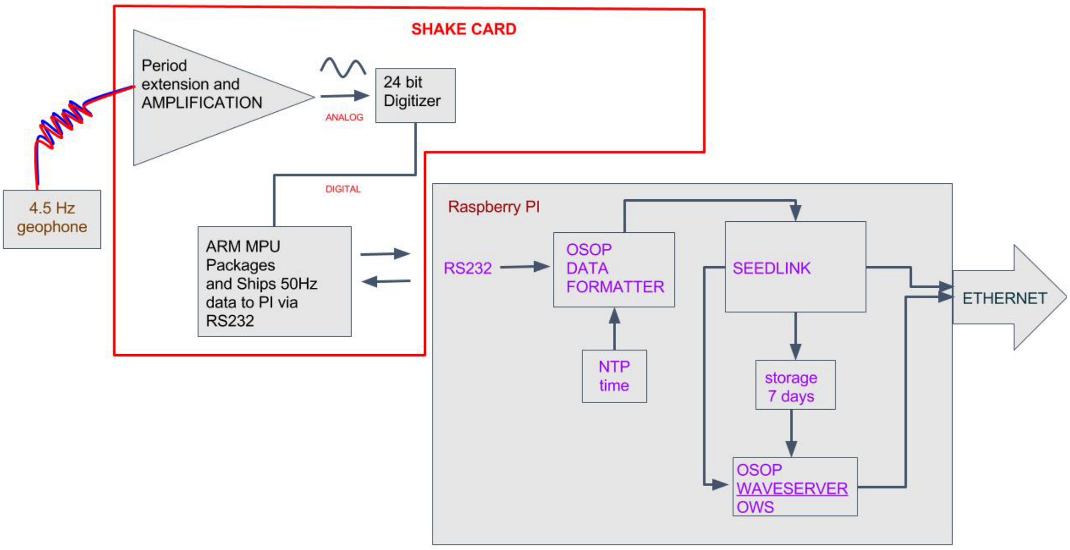


Figure 4: Raspberry Shake Flow Diagram indicating the analogue amplification, digitisation, and packaging for the RS232 protocol data transfer to the Raspberry Pi.

Apparatus

Instrumentation

The main components of the set up are the seismometer sensor, the data logger, and the 12V battery providing power. The sensor a Nanometrics compact, a small but very capable sensor. The seismometer records vibrations in 3 orthogonal directions and is able to detect frequencies as low as 120s.

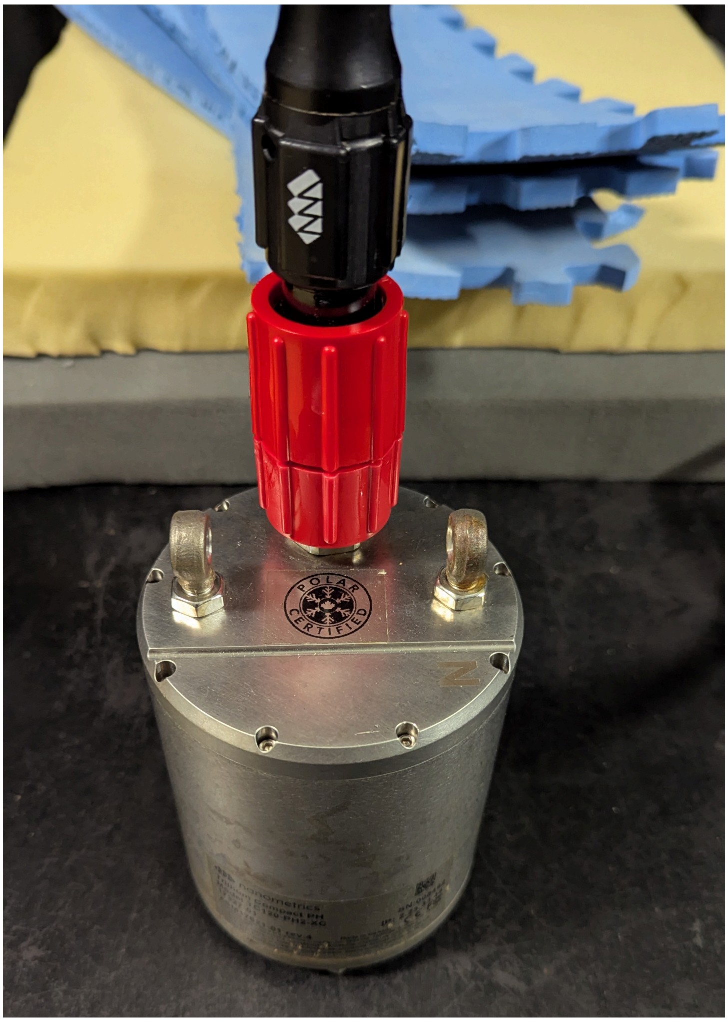


Figure 5: Nanometrics compact seismometer

Figure 6: Nanometrics Pegasus Data logger

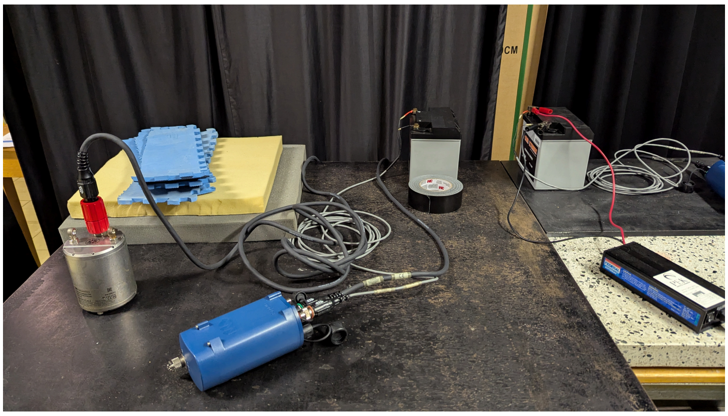


Figure 7: Full set up with 12V battery, data logger, and seismometer.

Seismometers also require a connected GPS in order to accurately provide timing to the recorded data. This is ommited in this set up, as the GPS needs a clear sky view to operate.

Software

The following software will be needed, or may be useful, for this experiment:

- Python will be used for data analysis. In particular, the python packages *obspy* [1] and *Cartopy* will be useful, as well as common packages such as matplotlib and numpy. A jupyter notebook will be provided as a guide. This notebook is a **tutorial** to guide your own exploration!
- Pegasus Harvester Application - used to harvest data from the pegasus recorder. A free account will be needed to access the download link.
- Nanometrics Pegasus Android/iPhone app - Used to interface with the nanometrics compact sensor. Needed to ensure the sensor is level and correctly configured.
- SWARM - Provides a live feed from the Raspberry Shake RS1D sensor. May be useful if using the raspberry shake but not essential.

Procedure

This experiment is an opportunity for exploration and experimentation. There are two main components to this experiment:

1. Working with seismometers and acquiring seismic data
2. Investigating, analysing and interpreting seismic data

The seismometer can be set up and left to run. During that time you can develop your computational and data handling skills with the Data Exploration tasks.

Setting up the seismometer

We will set the seismometer up in the lab and allow it to run for a week or two. Set up of the seismometer is simple, but when deploying instruments in the field care must be taken to ensure the sensor is placed correctly. The instrument being used is polar rated, and has previously been deployed in Antarctica and used to study the ice sheet, glaciers, and Earth structure in Antarctica.

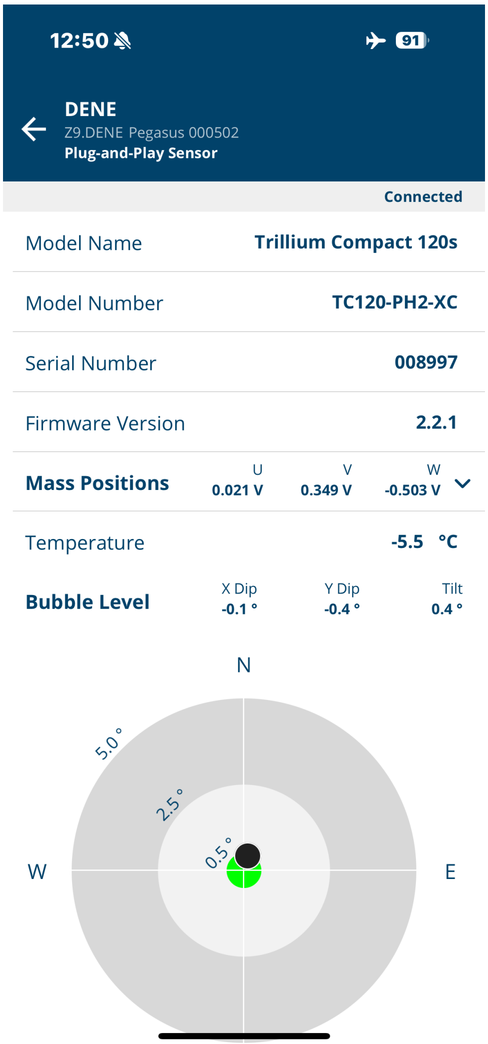
The seismometer set up requires power (from a 12V battery) to power the sensor and the data logger. A seismometer also requires accurate location and timing information with the recorded data, which is provided by a GPS antenna.

Care should be taken when connecting the power and data cables to the sensor and datalogger. These cables use mil-spec connectors with pins that can be bent, and only connect in a certain orientation (shown below)

Once the datalogger, sensor, and battery are connected, the seismometer can be set up.

Levelling and orienting the sensor

In order to ensure the components recording motion in all three directions behave properly the sensor needs to be levelled. This is done using a digital level in the Pegasus app.



12:50

DENE
Z9.DENE Pegasus 000502
Plug-and-Play Sensor

Connected

Model Name	**Trillium Compact 120s**
Model Number	**TC120-PH2-XC**
Serial Number	**008997**
Firmware Version	**2.2.1**

Mass Positions U 0.021 V, V 0.349 V, W -0.503 V

Temperature -5.5 °C

Bubble Level X Dip -0.1 °, Y Dip -0.4 °, Tilt 0.4 °

Figure 8: Pegasus app with the levelling menu

The sensor should also be oriented North as accurately as possible. This can be done using a compass or gps. Knowing the orientation of the seismometer is important for data processing in seismic analyses that use the horizontal components of motion.

Discuss

Why is it important for the instrument to be level and oriented accurately? How might incorrect orientation or levelling affect the recorded data?

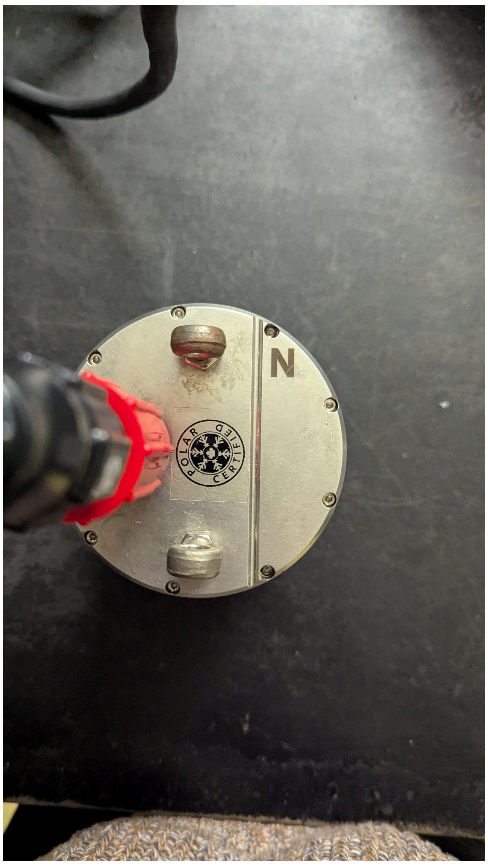


Figure 9: The seismometer should be oriented with the North arrow pointing north.

Data Exploration

The aim of this section is to develop your skills in exploring and analysing seismic data. Follow the tasks and discussions in this section while data is being recorded on the lab seismometer.

A jupyter notebook is provided as a guide on using obspy to download waveforms and station/event metadata. The workflows in this notebook are to demonstrate the basics of handling waveform data and should not be copied verbatim - you are encouraged to write your own workflows. Following the notebook will give you a basic toolbox that will allow you to explore the data you record in the lab. You are encouraged to make your own investigations, ask your own questions, and choose your own events to study.

Visualising Earthquakes

1. Select one or two large (magnitude > 6) earthquake events. IRIS provides a database of recent events, or you may choose to use obspy to find some interesting events.

2. Select 3 or 4 stations at different distances from your events to gather data from. Again, IRIS provides a useful map of stations, or you can use obspy to find what stations exist within a certain region.

Task

Create a map showing your chosen stations and events, including station names and earthquake magnitudes.

4. Download waveforms of your chosen events recorded at each station.

Task

Plot the waveforms from each station and identify the key features of an earthquake recording. What phase arrivals can you see on each of the three components?

Discuss

How does the recorded signal change across different stations? Why does the signal change and what can this tell us about the medium (i.e. the Earth) between the source and the station?

Frequency content

The frequency content of a seismic signal contains information about the source of the signal and what kind of material it moved through. Visualising the frequency spectrum of a signal can be very informative about what kind of signal you are measuring.

The provided jupyter notebook shows two different ways of visualising the frequency content of a seismogram - the power spectral density and the spectrogram. The spectrogram shows how the frequency content changes with time. Spectrograms perform a fast fourier transform (FFT) within a rolling window, hence there is a trade of between the size of the FFT window (i.e. time resolution) and frequency resolution.

Task

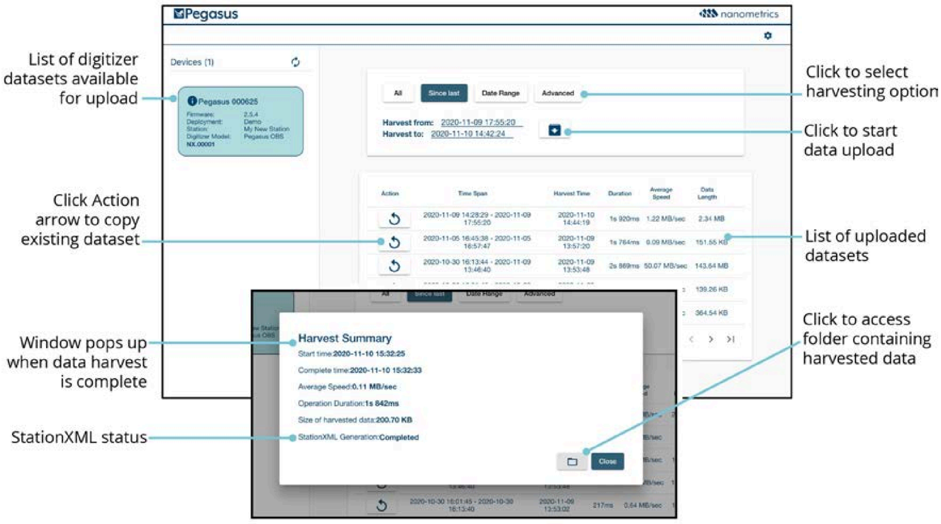
Plot spectrograms for some of your downloaded/recorded data using a few different values for the FFT window width (e.g. 256, 512, 1024, 2048).

Discuss

What features of the seismogram can you see in the spectrogram and what are their frequency characteristics? How does this change for different events/signal sources.

Data collection

Once the seismometer in the lab has been running for a couple of weeks, collect the data using the Pegasus Harvester application. The lab demonstrator can help you collect the data if necessary. Along with the raw data will be a StationXML file and some state of health (SoH) files. The SoH files can be ignored, but the StationXML file may be useful and can be read using obspy. Use the skills developed in the data exploration section above to investigate the data you have recorded.



Pegasus 000625
Firmware: 2.5.4
Deployment: Demo
Station: My New Station
Digitizer Model: Pegasus OBS
NX.00001

Harvest from: 2020-11-09 17:55:20
Harvest to: 2020-11-10 14:42:24

Action	Time Span	Harvest Time	Duration	Average Speed	Data Length
	2020-11-09 14:28:29 - 2020-11-09 17:55:20	2020-11-10 14:44:19	1s 920ms	1.22 MB/sec	2.34 MB
	2020-11-05 16:45:38 - 2020-11-05 16:57:47	2020-11-09 13:57:20	1s 764ms	0.09 MB/sec	151.55 KB
	2020-10-30 16:13:44 - 2020-11-09 13:46:40	2020-11-09 13:53:48	2s 869ms	50.07 MB/sec	143.64 MB

Harvest Summary
Start time:2020-11-10 15:32:25
Complete time:2020-11-10 15:32:33
Average Speed:0.11 MB/sec
Operation Duration:1s 842ms
Size of harvested data:200.70 KB
StationXML Generation:Completed

Figure 10: Pegasus Harvester program used to data from the pegasus data logger.

Task

Collect your data from the seismometer and visualise it (using techniques used in the data exploration section). Look for any recent events that might have been recorded on the seismometer. You might want to look for teleseismic (very distant) earthquakes, local earthquakes, or even signals from the building.

Task

See if any recent events you have downloaded from other stations appeared on the lab instrument. How do the recordings compare?

Discuss

What features can you see on the data recorded from the lab seismometer. Are there any earthquakes? What are other sources of signal (or noise) the sensor might be picking up, what are the characteristics of these other signals, and how can you visualise/identify their characteristics?

Bibliography

[1] Moritz Beyreuther et al. “ObsPy: A Python Toolbox for Seismology”. In: *Seismological Research Letters* 81.3 (2010), pp. 530–533.

[2] Seth Stein and M Wysession. *An Introduction to Seismology, Earthquakes*. Blackwell Publishing, 2003.