A though examination of extraterrestrial seismic detection in reference to detection and analysis using the program ngc_4e5e

Abstract

The purpose of this paper is to provide deep insight into the workings of the program ngc_4e5e in reference its seismic detection and analysis capabilities which include: reading and graphing of any MSEED data, extrapolation of parameters for categorization of seismic events into LF(Low Frequency), HF(High Frequency), VHF(Very High Frequency and Rs(Resonance Events)and the calculation of information relating to the specifics of the event, namely - Peak Velocity, Seismic Energy(est.), Seismic Moment and Magnitude, SNR(Signal to Noise Ratio), Coda Wave Analysis and the Spectral Ratio.

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Introduction

Extraterrestrial Seismic Event Analysis:

Since 1969, seismology has extended beyond the Earth, and seismic sensors have been placed on the surface of other bodies of the solar system. A Lunar seismic network thus operated for the 8 years after 1969, with up to 4 stations, and detected some 1000 Moonquakes per year. A single seismic station was also operated on the Martian surface for 19 months since 1977. The inner structure of the Moon was determined by inversion of seismic data obtained by the Apollo network. The oldest station of this network operated for nearly 8 years, while the youngest has operated for 5.5 years. The seismic experiment, called **P**assive **S**eismic **E**xperiment (PSE), consisted thus of a tri axis **L**ong **P**eriod (LP) seismometer, with a resonance period of 15 s, and one vertical **S**hort-**P**eriod (SP) seismometer, with a resonance period of 1 s. propagation conditions in the Moon are very different from those on Earth (Figure 2).

In particular, the scattering is much stronger, and the attenuation much lower on the Moon. The huge amount of data collected during the 26.18 active station years (6.3 108 kbits) thus provided one of the most exciting seismic experiments of this century

The deployment of InSight's SEIS (**S**eismic **E**xperiment for **I**nterior **S**tructure) was a monumental step in Martian Seismology. Unlike terrestrial seismometers, that are networked so that together they can be used to pinpoint an earthquake, for at least two years SEIS will remain alone on its landing site, an equatorial plain in an area of Mars called Elysium Planitia. The SEIS is also capable of detecting meteorite impacts from Mars' moons Phobos and Deimos. **S**eismic **E**xperiment for **I**nternal **S**tructure) instrument; a six-axes seismometer equipped with both a long-period three-axes **V**ery **B**road **B**and (VBB) instrument and a three-axes short-period (SP) instrument. These six sensors will cover a broad range of the seismic bandwidth, from 0.01 Hz to 50 Hz, with possible extension to longer periods. Data will be transmitted in the form of three continuous VBB components at 2 **s**amples **p**er **s**econd (SPS), an estimation of the short period energy content from the SP at 1 SPS and a continuous compound VBB/SP vertical axis at 10 SPS. The continuous streams will be augmented by requested event data with sample rates from 20 to 100 SPS .From seismograms, the most reliable seismological secondary data that could be extracted should be: ravel times of body waves (in the short period range, 0.1–5 Hz)group and phase velocities of Rayleigh surface waves (in the long period range, 0.01– 0.1 Hz)eigenfrequencies of spheroidal fundamental normal modes in the frequency range of 0.01–0.02 Hz

In light of the innumerable advances in planetary seismology it is an obvious assumption that analytical tools are to also take a leap forward.

Objective

The primary goal of the project is to provide an analysis tool that provides a maximally optimized interpretation of seismic data from extraterrestrial bodies and present a generalized categorization of any and all seismic events recorded.

Data and Methods

Th primary format of data used for the analysis is the MSEED (**M**ini - **S**tandard for the **E**xchange of **E**arthquake **D**ata) format. This format was adopted was adopted in December 1992. It is now the standard defined by the FDSN (**F**ederation of **D**igital **S**eismogram **N**etworks) Working Group on Data Exchange.
The data that was used for testing and verification was provided by NASA (**N**ational **A**eronautics and **S**pace **A**dministration), ESA (**E**uropean **S**pace **A**gency) and IRIS (**I**ncorporated **R**esearch **I**nstitutions for **S**eismology).

The ALSEP (**A**pollo **L**unar **S**eismic **E**xperiment **P**ackage) and the Mars Insight Data Archive - specifically the SEIS (**S**eismic **E**xperiment for **I**nternal **S**tructure of Mars) were used for training and testing. After completion of the program the following is the list of datasets and archives that the program was used to analyze:

- ESA PSA
- ESA Mars Science Archives
- ASEP

The primary analysis of the MSEED file is done by the rdmseed function (stored as a separate script within the same path) which is called by the (main) ngc_4e5e script.

Seismic Data Processing:

The rdmseed function is an adaption of the MSEED reader provided by IRIS which follows the following process to do so:

1. **File Reading:** The miniSEED file is read block by block. Each block contains a header and time series data (amplitude values).

2. **Header Extraction:** The reader extracts metadata from the header, such as the station ID, start time, sample rate, and the number of samples.

3. **Data Decoding:** The time series data is decoded based on its encoding format, which could be raw integers, floating points, or compressed formats like Steim compression. The reader decompresses or converts these into a usable time series.

4. **Time Reconstruction:** Using the start time and sample rate, the reader generates a time vector for the seismic data.

5. **Output:** The reader provides the time series (amplitude over time) and metadata like station information and sampling rate.

Data Preprocessing:

- **Normalization:** It involves scaling the seismic amplitude data to a range that simplifies further analysis. The amplitude is normalized by dividing each data point by the maximum absolute value of the amplitude, ensuring that the values are scaled between -1 and 1.

```
% Preprocess amplitude data
amplitudeNorm = amplitude / max(abs(amplitude));
```

•*amplitude*: Raw amplitude data extracted from the miniSEED file.

•*max(abs(amplitude))*: The maximum absolute value of the amplitude is calculated, and each data point is divided by this value to normalize the data.

- **Noise Filtering and Removal:** A bandpass filter is applied for the noise removal. Given noise can exist at extreme frequencies, the filter keeps only a certain frequency range relevant to the seismic data.

```
% Bandpass filter to remove noise
filterLowCutoff = 0.1;  % Lower cutoff frequency for bandpass filter (Hz)
filterHighCutoff = dynamic_upper_cutoff(fs);  % Adjusted upper cutoff based on the data
filteredAmplitude = bandpass(amplitudeScaled, [filterLowCutoff filterHighCutoff], fs);
```

- *Bandpass filter*: Filters out frequencies outside the defined range (filterLowCutoff to filterHighCutoff).

- The low cutoff frequency (*filterLowCutoff* = lcf(c) Hz) and *high cutoff frequency set* at hcf(c) Hz or the Nyquist frequency (half of the sampling frequency fs), whichever is smaller eliminates extreme frequencies.

- **Noise:** It is calculated as the difference between the original amplitude and filtered amplitude.

Frequency - Domain Analysis:

- **Fast Fourier Transform:** It is used to convert data from the time domain into frequency domain.

```
[Pxx, F] = periodogram(amplitudeNorm, [], [], fs);
```

- *amplitudeNorm*: The normalized amplitude of seismic data (after preprocessing).
- *Pxx*: This represents the Power Spectral Density (PSD), which measures how the power (or variance) of the signal is distributed across different frequencies.
- *F*: These are the corresponding frequency values in Hz (Hertz).
- *fs*: The sampling frequency (in Hz) of the seismic data.

- **Power Spectral Density:** Quantifies the power of each frequency component in the signal. It essentially shows how the energy of the seismic signal is distributed across different frequencies helping identify the dominant frequency.

  *Done using the periodogram function

3.**Extracting the Dominant Frequency**: It is the frequency where the signal has the most energy. It is crucial in identifying and classifying the seismic event.

```
[~, maxIdx] = max(Pxx);
dominantFreq = F(maxIdx);
```

- *max(Pxx)*: Finds the maximum power in the PSD.
- *F(maxIdx)*: Finds the frequency corresponding to the maximum power, which is the dominant frequency of the seismic event.

Time-Domain Analysis:

Measuring Event Duration: It is the duration of the seismic event calculated as the difference between the first and last timestamp in the time vector.

```
eventDuration = eventTime(end) - eventTime(1);
```

Event Classification:

1. **Defining Frequency Thresholds**:

- **L**ow **F**requency (LF) Event: Dominant frequency is less than lowFreqThreshold (e.g., 1.5 Hz).
- **H**igh **F**requency (HF) Event: Dominant frequency is between lowFreqThreshold and highFreqThreshold (e.g., 1.5 Hz to 5 Hz).
- **V**ery **H**igh **F**requency (VF) Event: Dominant frequency is between highFreqThreshold and veryHighFreqThreshold (e.g., 5 Hz to 10 Hz).
- **S**uper **H**igh **F**requency (SF) Event: Dominant frequency is higher than veryHighFreqThreshold (e.g., 10 Hz)

  The input is then compared against these values and assigned a type.

P and S wave detection:

1. **Initial P wave detection (CWT)**: the program uses the CWT function to break down the signal into its frequency components over time using the 'amor' wavelet.

```
[wt, f] = cwt(amplitude, 'amor', fs);
```

- *amplitude*: This is the normalized seismic amplitude signal (i.e., the seismic data scaled to ensure it falls within a consistent range)
- '*amor*': The Morlet wavelet used for analyzing the signal.
- *fs*: The sampling rate of the seismic data.

  This produces two outputs:

- *wt*: The wavelet transform coefficients matrix. Each row represents a particular frequency component of the signal over time.
- *f*: The frequency vector corresponding to the rows of wt. Each value in f represents a frequency in the signal that corresponds to a row in wt.

2. **Isolating P Wave frequency range:** the program uses a predefined frequency range, which is extracted from the full wavelet coefficients matrix.

```
pWaveFreqRange = [1, 5];
sWaveFreqRange = [0.5, 3];
```

```
pWaveEnergy = sum(abs(wt(f >= pWaveFreqRange(1) & f <= pWaveFreqRange(2), :)), 1);
sWaveEnergy = sum(abs(wt(f >= sWaveFreqRange(1) & f <= sWaveFreqRange(2), :)), 1);
```

- coefficients corresponding to the frequencies between 1 and 5 Hz. These are the coefficients associated with the P-wave.
- *abs(wt)*: Taking the absolute value of the wavelet coefficients gives the magnitude of the signal at each time point for the P-wave frequency range.
- *sum(..., 1)*: Summing the coefficients across the P-wave frequency range gives the total energy of the signal in this range for each time point. This results in a time series of P-wave energy.

3. **Detecting the P wave:** The program detects the time point where the p wave reaches its peak, assuming, that the p wave arrival corresponds to the maximum energy in the p wave frequency range.

```
[~, pWaveIdx] = max(pWaveEnergy);
```

- *max(pWaveEnergy)*: This function finds the maximum value of the P-wave energy time series.

- *pWaveIdx*: The index of the time point where this maximum occurs is stored in pWaveIdx. This index represents the point in time where the P-wave arrives at the seismic station.

4.**Detrmining P wave arrival Time:** the program uses the corresponding value on the time vector.

* The s wave is detected similarly varying the values of the Frequency Range to be less than the P wave.

Distance Estimation:

1.**deltaT:** It is the difference between the p and s wave arrival times.

```
deltaT = sWaveArrival - pWaveArrival;
```

2.**Distance Estimation using Wave velocities:** the program uses the known velocities of the P and S waves to estimate the distance to the seismic event.

```
estimatedDistance = deltaT_seconds * pWaveVelocity * sWaveVelocity / (pWaveVelocity - sWaveVelocity);
```

This formula is based on the fact that the difference in arrival times of the two waves depends on their velocities and the distance from the source of the seismic event. The basic concept is that P-waves travel faster than S-waves, so the greater the time difference between their arrivals, the farther away the seismic event is.

Energy and Magnitude:

Seismic Energy: It is the total energy released by the seismic event. It is calculated based on the filtered amplitude data.

1.**Filtered Amplitude:** Filtered seismic signal using a bandpass filter for noise removal.

```
filteredAmplitude = bandpass(amplitudeScaled, [filterLowCutoff filterHighCutoff], fs);
```

2.**Energy Estimation:** It is measured as the sum of squares of the filtered amplitude, which provides a measure of the wave's power. The summation is scaled by the inverse of the sample rate (1/fs) to account for the intervals between time samples. The formula used is

```
eventEnergy = sum(filteredAmplitude .^ 2) * (1/fs);
```

filteredAmplitude .^ 2: This squares each value in the filtered amplitude, representing the power of the seismic wave at each time point.
sum(): The total energy is the sum of the power values over the entire event duration.
(1/fs): This scaling factor accounts for the sampling rate, which is the number of samples per second. By multiplying by 1/fs, the energy calculation considers the actual time duration over which the event occurs.

Seismic Moment: It is a measure of a seismic event, directly related to the degree of slip on the fault and area of the fault that slipped.

Moment Magnitude: It is a logarithmic measure of the event's size.

1.**Peak Velocity**: It is the highest observed velocity during the seismic event.

```
peakVelocity = max(abs(amplitudeScaled));
```

2.**Seismic Moment**: It is calculated according to the following formula

```
seismicMoment = calc_seismic_moment(peakVelocity, distanceEstimate, density, pWaveVelocity)
```

- *peakVelocity*: The peak velocity observed during the event.
- *distance*: An estimated distance to the seismic event (default value of 100 km in the code).
- *velocity*: The P-wave velocity in the medium
- *density*: The density of the medium

The formula is based on the wave propagation through the medium and crust properties along with the peak velocity. Measured in **N**ewton-**M**eters (Nm) reflects the force exerted by the seismic event.

3.**Moment Magnitude Calculation:** It is calculated using the following empirical relation:

```
momentMagnitude = (2/3) * log10(seismicMoment) - 6;
```

The formula presents the seismic moment as a logarithmic magnitude scale, following the moment magnitude (Mw) scale.
*This metric is used to compare the relative strength of seismic activities.

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Implementation

Algorithm Overview:

1.**Bandpass Filtering:** It is a signal processing technique allowing frequencies within a certain range (passband) attenuating frequencies outside this range, isolating sequences of interest which often reside in a specific frequency range.

1.a **Components of a Bandpass Filter:**

Low Cutoff Frequency:
Defines the lower boundary of the passband. Any frequency component below this threshold is attenuated.
Example:

High Cutoff Frequency:
Defines the upper boundary of the passband. Frequencies above this threshold are also removed.
Example:

Nyquist Frequency:
Maximum frequency that can be represented correctly in the data and is equal to half the sampling rate. The filter is constrained to avoid exceeding this limit.
Example:

1.b **Mathematical Representation**:
It is represented as a product of two transfer functions:

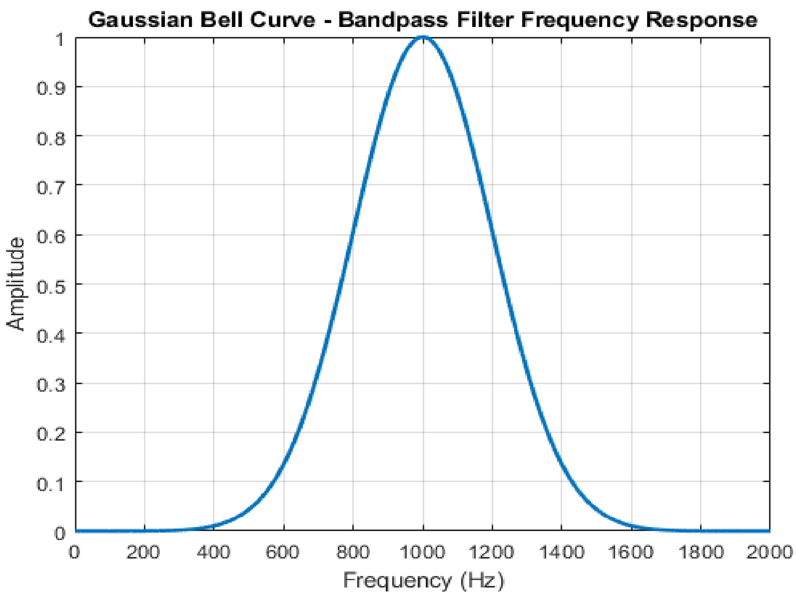
$$H(f) = H_{\text{lowpass}}(f) \times H_{\text{highpass}}(f)$$

Where:

- $H_{lowpass}(f)$ attenuates frequencies above the high cutoff
- $H_{highpass}(f)$ attenuates frequencies below the high cut-off

Frequency Response:
It is typically shown as a bell curve.

$$H(f) = A \cdot e^{-\frac{(f-f_c)^2}{2\sigma^2}}$$



Where:

- $H(f)$ is the frequency response at f
- A is the peak amplitude of the filters response

- F_c is the frequency of the bandpass
- σ is related to the bandwidth of the filter, defining the width of the bell

Digital Implementation:

The bandpass filter used in MATLAB internally creates a **f**inite **i**mpulse **r**esponse (FIR) or an **i**nfinite **i**mpulse **r**esponse (IIR) filter, depending on the implementation. These filters are designed using standard techniques like the Butterworth filter, which is common in seismic analysis for its flat passband.

2.**P wave:**

P-waves (primary or pressure waves) are longitudinal waves, meaning they cause particles in a medium to move in the direction of wave propagation. These waves travel faster than S-waves and are the first to be detected in a seismic event.

2.a **Mathematical representation:**

It is represented as a sinusoidal wave moving with velocity v_p through the solid

$$u_P(x,t) = A_P \cdot e^{i(k_P x - \omega t)}$$

Where:

- $U_p(x,t)$ is the displacement at position x and time t
- A_p is the amplitude
- K_p is the wave number
- x is the spatial position along direction of propagation
- t is time
- ω is the angular frequency

3.**S Wave:**

S-waves (secondary or shear waves) are transverse waves, meaning they cause particles to move perpendicularly to the direction of wave propagation. They travel slower than P-waves and arrive later during a seismic event.

3.a **Mathematical Representation**
It is also represented as sinusoidal wave with the direction of propagation perpendicular to displacement.

$$u_S(x,t) = A_S \cdot e^{i(k_S x - \omega t)}$$

Where:

- $U_s(x,t)$ is the displacement at position x and time t
- A_s is the amplitude
- K_s is the wave number
- x is the spatial position along direction of propagation
- t is time
- ω is the angular frequency

4.**Detection using CWT** (**Continuous Wavelet Transform**):
Wavelet transformation is used to analyze the signal at different time-frequency scales, allowing for the detection of features like P-wave and S-wave arrivals.

4.a **Mathematical Representation**:
For a signal *x(t)* The wavelet transformation is mathematically expressed as:

$$W(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\psi^* \left(\frac{t-b}{a}\right) dt$$

Where:

- *W(a,b)* is the wavelet coefficient at scale a and position b

- *x(t)* is the signal in the time domain

- *$\Psi(t)$* is the mother wavelet (a time localized oscillating function)
- *a* is the scaling parameter (related to frequency)
- *b* is the translation parameter (related to time)
- *$\Psi*$* denotes the complex conjugate of the wavelet function
- .$\frac{1}{\sqrt{|a|}}$ is a normalization factor ensuring energy conservation across scales

4.1 **P Wave and S wave detection using Energy in Frequency Bands:**
Once the wavelet transform has been computed, the energy in specific frequency bands corresponding to the P-wave and S-wave frequencies is computed.

4.1a **Mathematical Representation:**

$$E_P(b) = \int_{a_{P1}}^{a_{P2}} |W(a,b)|^2 \, da$$

Where:
Ep(*b*) is the P wave in the time window centered at b
[*ap1*, *ap2*] is the range of scales corresponding to the P wave frequency band

4.2 **Peak Detection:**
Mathematically, a peak occurs when E(b) satisfies the following condition:

$$E(b) > E(b - \delta) \; and \; E\ (b) > E(b + \delta)$$

Where:
For a small time-shift of δ indicates that E(b) is larger than its neighboring values. The position b_{peak} where the condition is satisfied represents the point in time of the detected peak.

Brief mention of Related Work

1. Seismic Data Processing Techniques:

1.a Time-Domain Analysis:

Seismic data processing traditionally begins in the time domain, where raw data is filtered to remove noise and baseline drift. Amplitude normalization, as implemented in your project, is one of the first steps to scale the seismic data for subsequent analysis. The Hilbert Transform is often used to compute the amplitude envelope of seismic signals, which helps in the detection of distinct seismic phases like P-waves and S-waves.
In planetary seismology, one challenge is the lack of prior knowledge of the planetary subsurface, which complicates preprocessing, and normalization compared to terrestrial data. Time-domain filtering approaches, such as bandpass filtering, are commonly employed to remove noise from raw signals, as seen in many terrestrial seismic studies (e.g., Aki and Richards, 2002).

1.b Frequency-Domain Analysis:

Frequency-domain analysis has become essential for understanding the dominant frequencies of seismic events and characterizing different seismic phases. The Fast Fourier Transform (FFT) and Power Spectral Density (PSD) are used to assess the frequency content of the seismic signal. This method is applied both in terrestrial and planetary contexts.

For example, the lunar seismic data from the Apollo missions was processed using similar frequency-domain techniques, and Fourier Transforms were used to derive spectral content (Nakamura, 1983). The InSight mission for Mars has followed a similar approach, using the FFT and PSD for event classification and distinguishing between low-frequency events (interpreted as possible tectonic activity) and high-frequency events (often interpreted as meteorite impacts).
2.3 Wavelet Transforms
The Continuous Wavelet Transform (CWT) is another powerful tool used to analyze non-stationary signals such

as seismic waves. CWT is particularly useful for distinguishing between overlapping seismic events, such as when S-waves follow P-waves. In planetary seismology, CWT is increasingly being used for detecting the onset of these seismic phases. The InSight mission utilized CWT to study small, transient seismic events on Mars, leading to the detection of over 450 seismic events by 2021 (Giardini et al., 2020).
Wavelet-based denoising techniques have also been applied to planetary seismic data, helping to improve the signal-to-noise ratio (SNR), which is a critical issue for Martian seismology due to wind-induced noise.

2. Event Detection Techniques:

2.a Short-Term Averaging / Long-Term Averaging (STA/LTA): In terrestrial seismology, one of the most commonly used methods for event detection is the STA/LTA algorithm, where short-term amplitude increases are compared to the long-term average to identify seismic events. STA/LTA has been adapted for planetary seismology, with adjustments to account for noise characteristics on the Moon and Mars.

The SEIS instrument aboard InSight has employed this approach to detect both large tectonic events and smaller impacts on Mars. An example is the detection of mars quakes with STA/LTA algorithms using data from InSight's broadband seismometer (Banerdt et al., 2020).

2.b Machine Learning Approaches:

Recently, machine learning has gained attention in seismic event detection. For example, the use of convolutional neural networks (CNNs) has been explored to classify seismic signals and distinguish between different types of seismic events (e.g., tectonic, volcanic, and impact events). These approaches can be particularly useful in planetary seismology, where the limited data makes traditional statistical methods less effective. Machine learning models can be trained on Earth-based seismic data and adapted for planetary environments.

3. P-Wave and S-Wave Detection:

Detecting P-waves and S-waves is critical for determining the distance and magnitude of seismic events. P-waves are typically detected as the first arriving waves, while S-waves follow, allowing the estimation of the event's epicenter through the difference in arrival times.
3.a Continuous Wavelet Transform (CWT)
As noted earlier, CWT has been successfully applied in both terrestrial and planetary seismic data for the detection of P-wave and S-wave arrivals. For Mars, this technique has been essential, given the lower signal-to-noise ratio of seismic data (due to environmental noise, such as wind) compared to Earth. In Giardini et al. (2020), CWT was used to detect low-amplitude seismic signals on Mars and differentiate between different seismic phases.

3.b Discrete Wavelet Transform (DWT):

The discrete wavelet transform (DWT) has also been explored for detecting seismic phases. DWT, as implemented in your code, has the advantage of better time resolution in low-frequency signals, making it suitable for planetary seismology, where the signal is often low-amplitude and high-frequency.

4. Seismic Moment and Magnitude Calculations:

4.a Seismic Moment:

Seismic moment is a measure of the size of an earthquake, which is based on the physical properties of the fault that slipped to cause the quake. Seismic moment is related to both the amplitude of the seismic waves and the distance between the seismic source and the sensor. For Mars and the Moon, seismic moment is calculated similarly to Earth, though the physical parameters (e.g., P-wave and S-wave velocities, crustal densities) differ between planets.
Seismic moment has been calculated for both Martian and lunar seismic events. On the Moon, seismic moment

calculations were used to estimate the size of moonquakes detected by the Apollo missions (Nakamura et al., 1982).

4.b Moment Magnitude:

Moment magnitude is a logarithmic scale of the seismic moment and is the most commonly used scale for measuring earthquake sizes. On Earth, moment magnitude is widely used, and on Mars, it has been employed to estimate the size of the largest detected mars quakes. Calculating moment magnitude on Mars is more challenging due to the thin atmosphere and noise from environmental factors, but it remains one of the core calculations in planetary seismology.

Results

The code outputs the following parameters in the terminal window:

- Event duration
- Dominant frequency
- Event classification (type)
- Peak velocity
- Event energy
- Seismic moment
- Moment magnitude
- Signal-to-noise ratio (SNR)
- Coda Q-factor
- Spectral ratio (S-wave/P-wave)
- P-wave and S-wave arrival times
- Estimated distance to the seismic event source

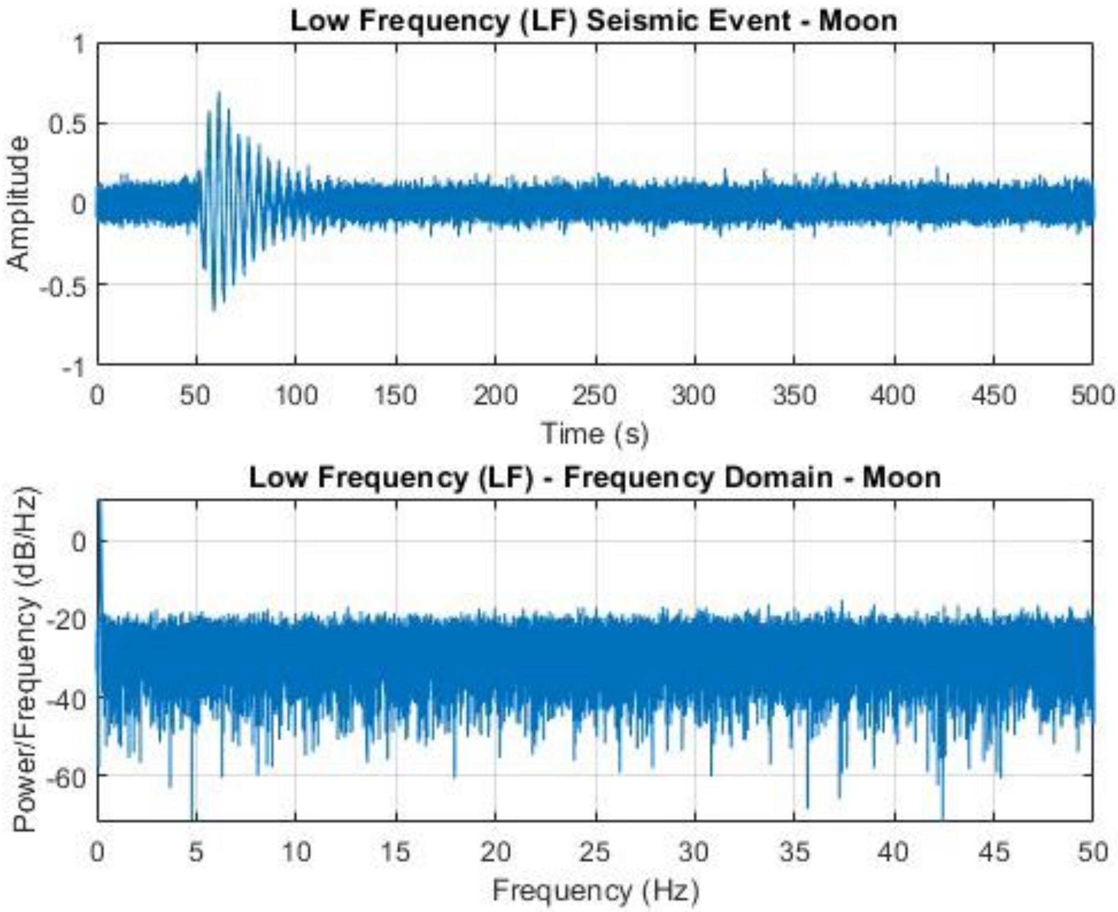
Units:

1. Event Duration - HH:MM:SS (hours:minutes:seconds)
2.Dominant Frequency - Hz (Hertz) with accuracy to 2 decimal places
3.Peak Velocity - Ms^{-1} (Metres per Second)in the range of micro to nano 10^-6 - 10^-9 . Expressed in the exponential format (%.Ne)

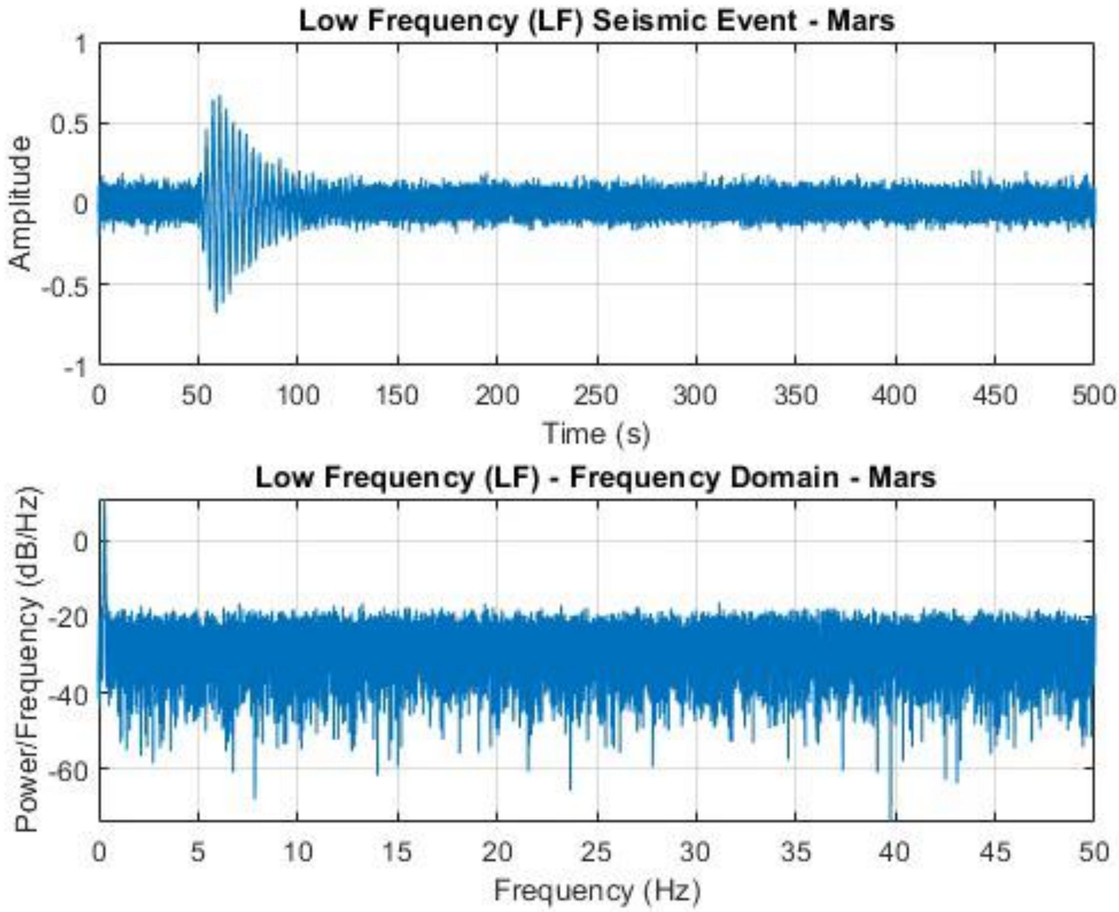
4.Event Energy - J (Joules). Expressed in exponential format(%.Ne)
5.Seismic Moment - Nm (Newton-Metres). Expressed in exponential format (%.Ne)
6.Moment Magnitude - *dimensionless (logarithmic scale). Accuracy up yo 2 decimal places (%.2f)
7.SNR - dB (Decibels)
8.Coda Q-factor - *dimensionless. Accuracy up to 2 decimal places (%.2f)
9.Spectral Ratio - *dimensionless. Expressed in exponential (%.Ne) as well as up to 2 decimal places (%.2f)

The events are finally classified as LF, HF or VF and Rs events. The exemplary plots for which are given below.

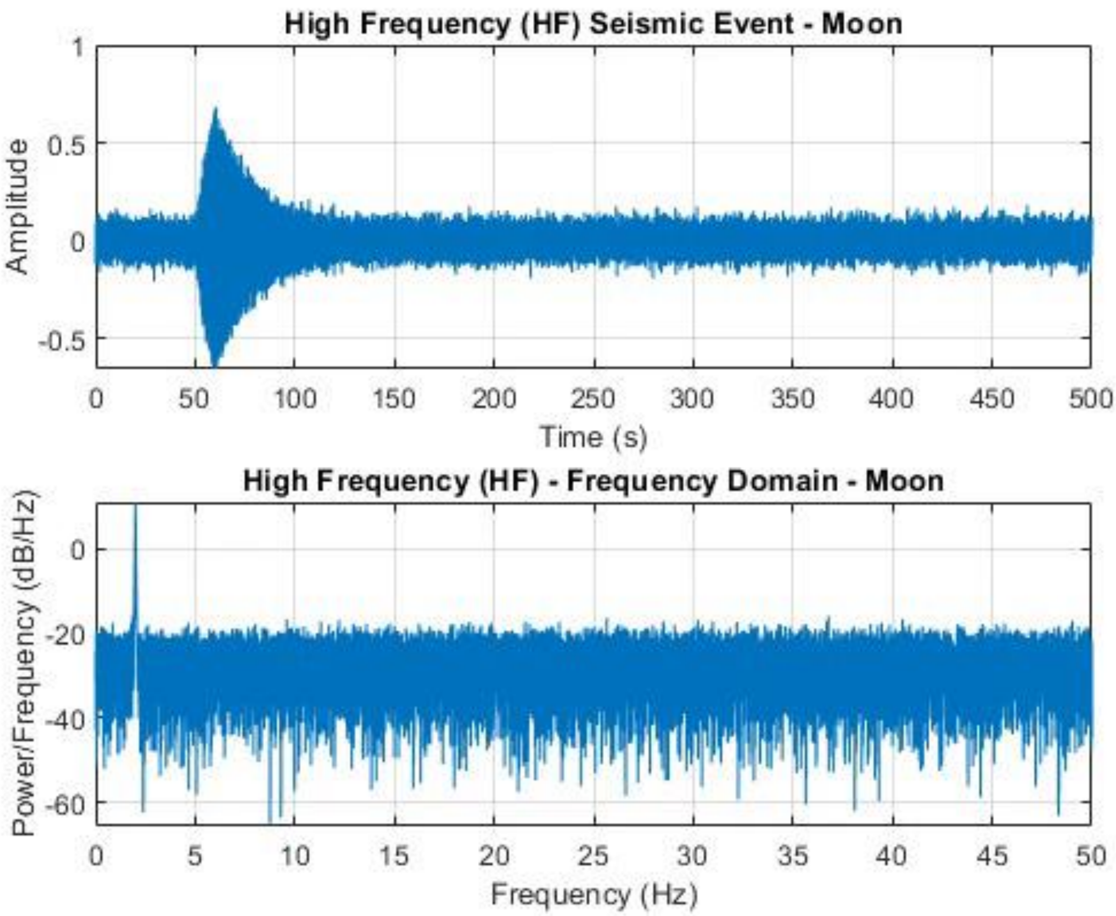
Low Frequency Event (Lunar):



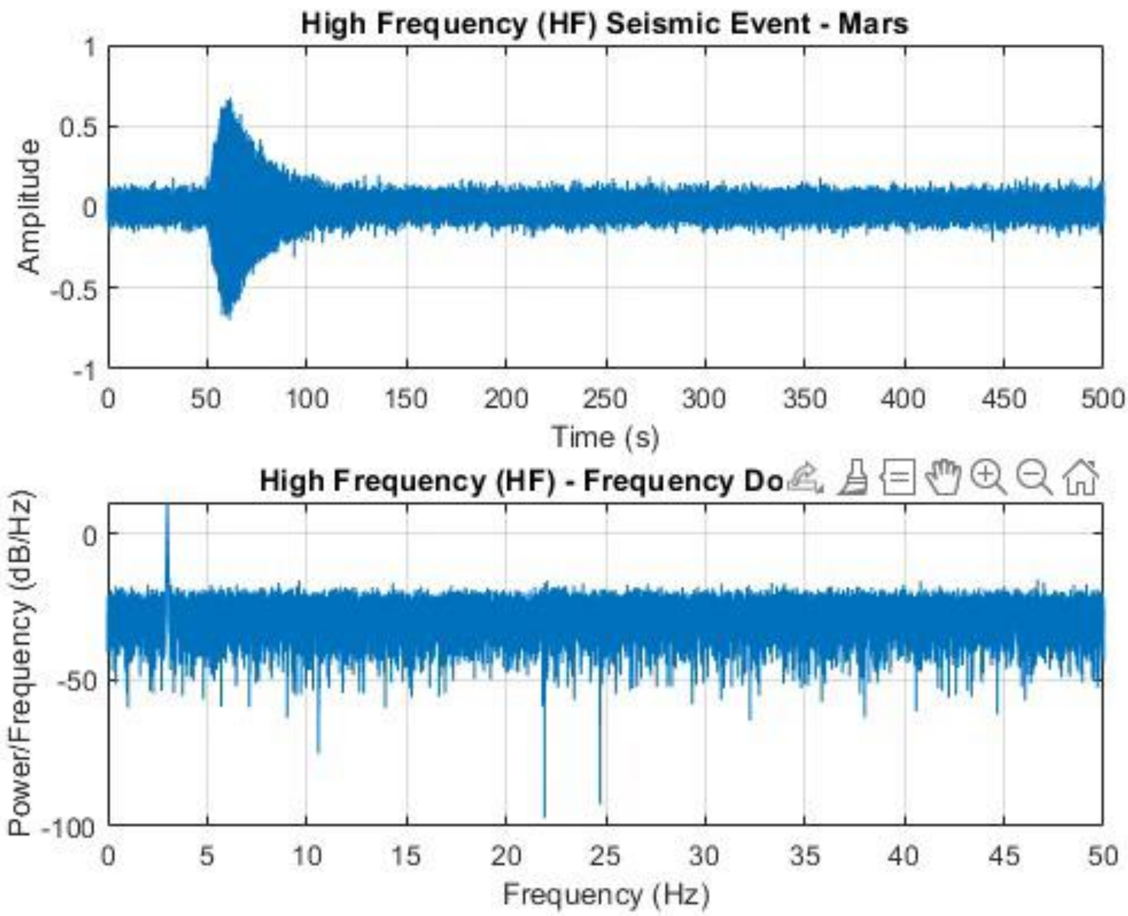
Low Frequency Event (Martian)



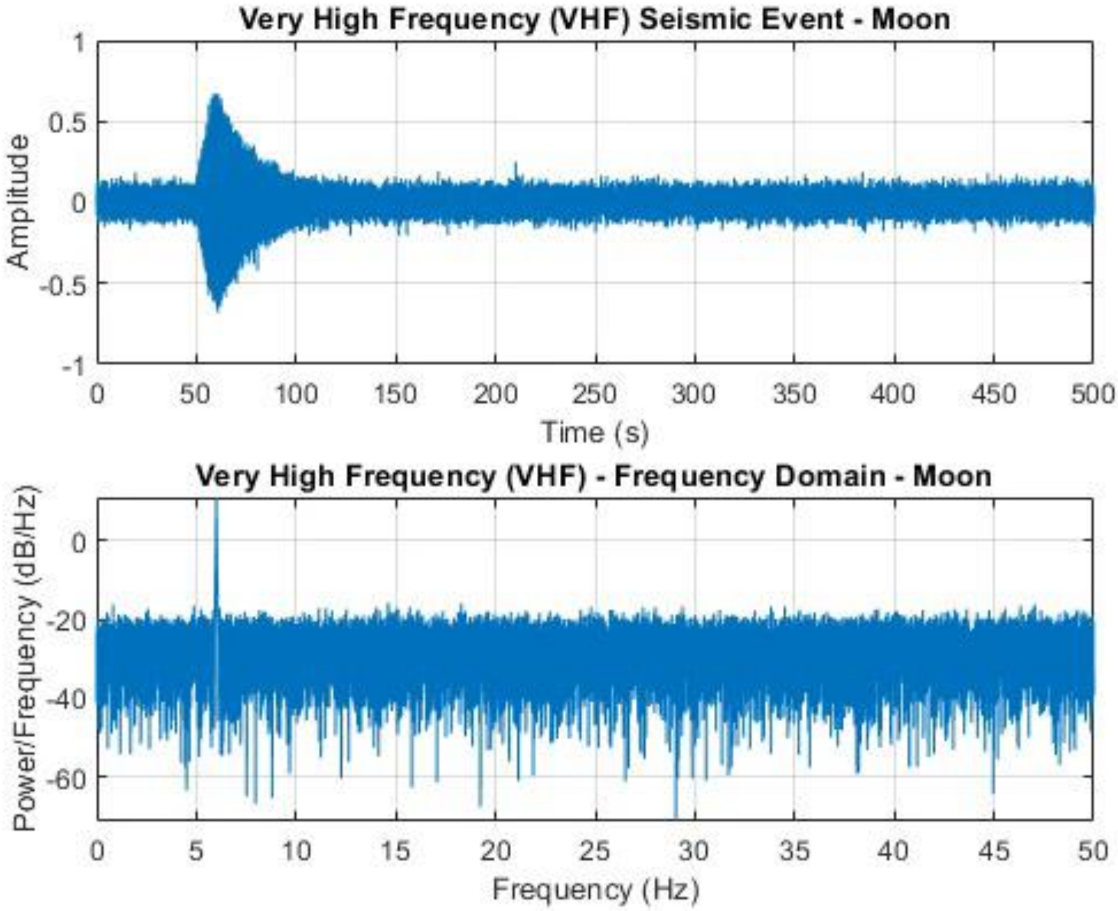
High Frequency Event (Lunar)



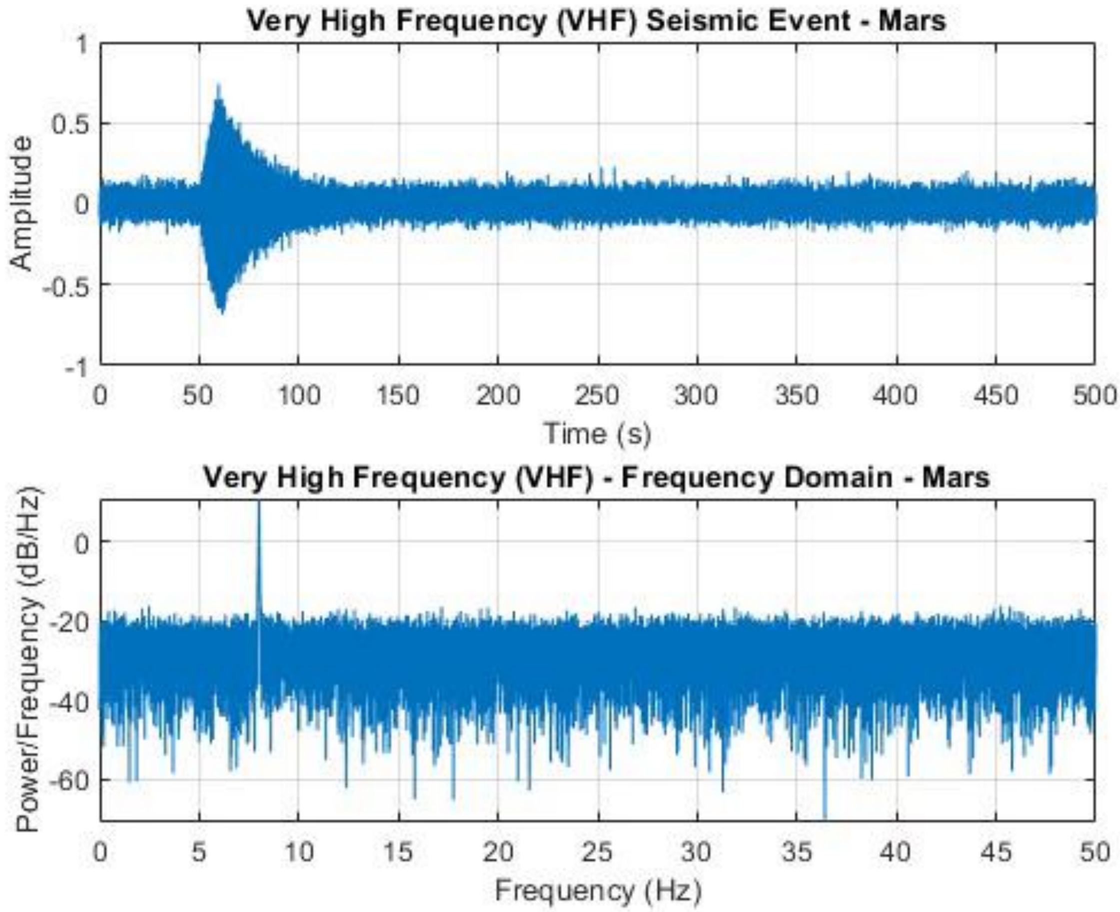
High Frequency Event (Martian)



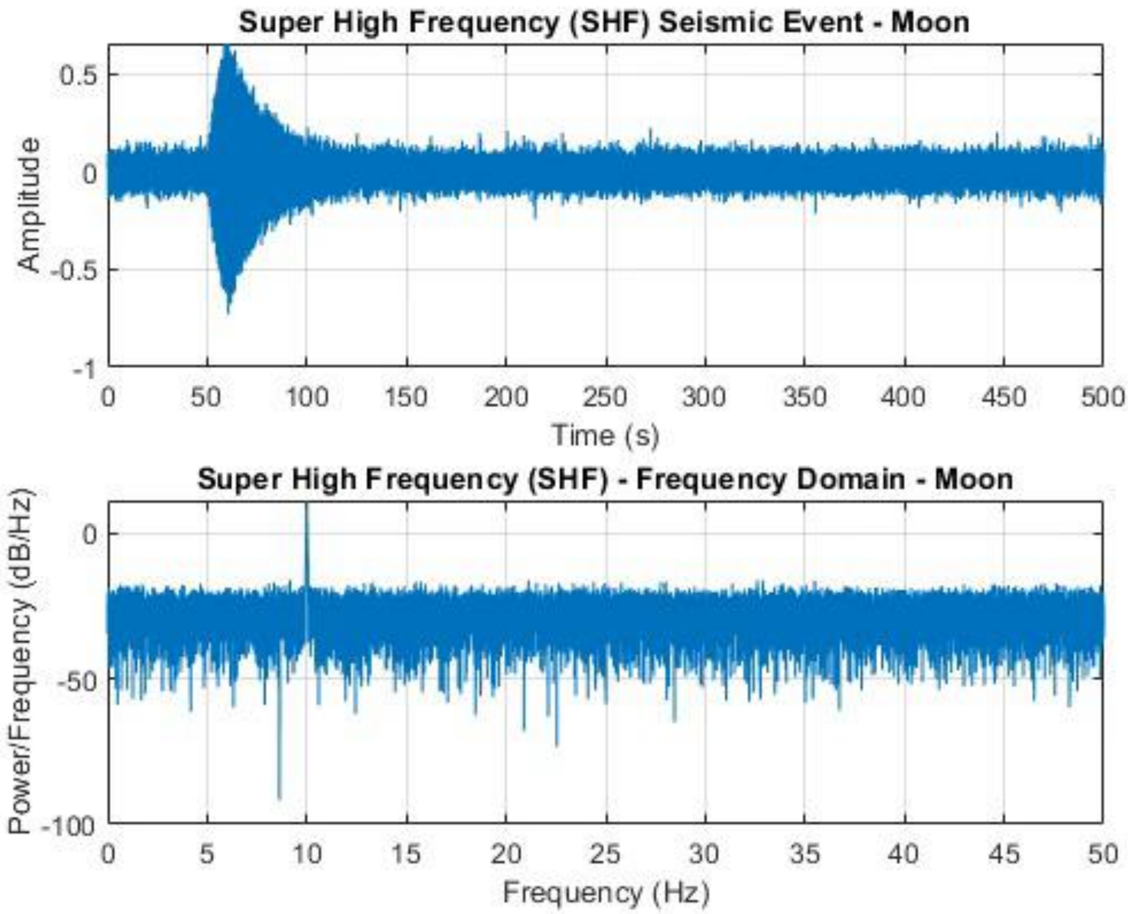
Very High Frequency Event (Lunar)



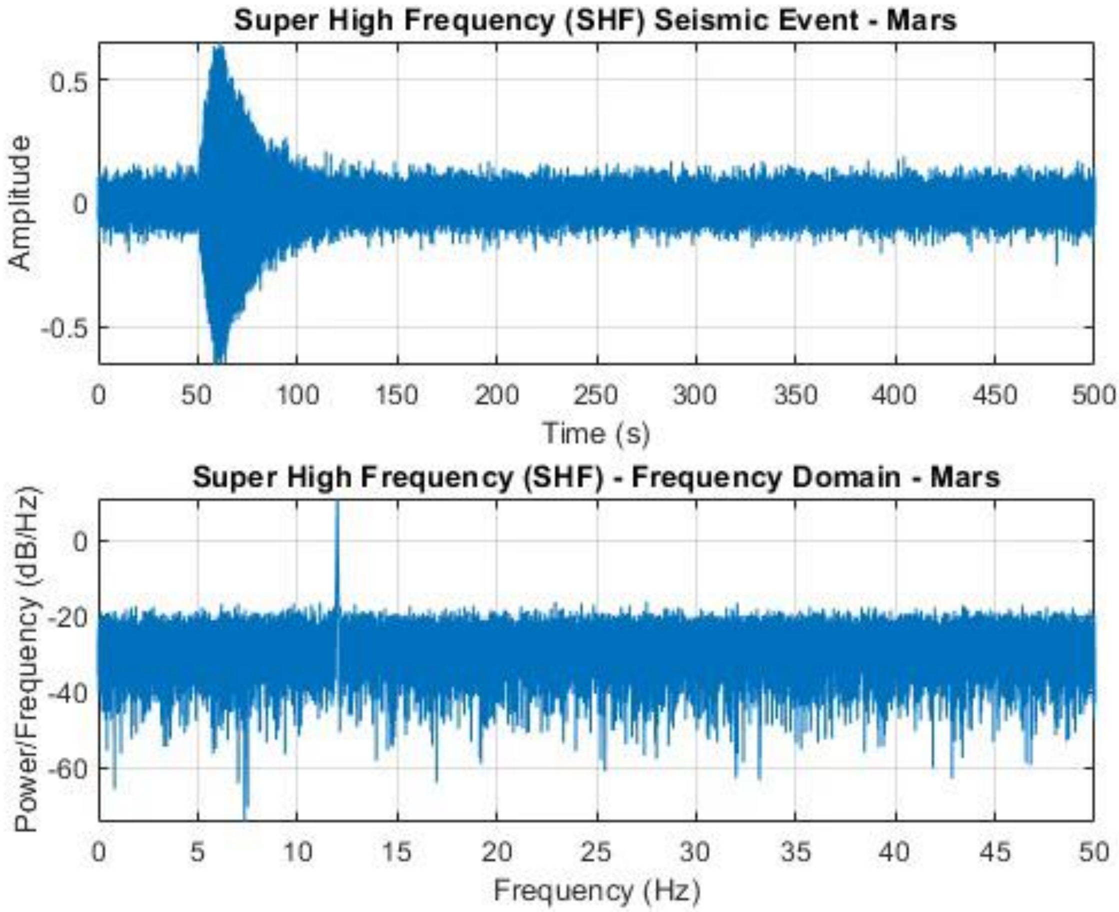
Very High Frequency Event (Martian)



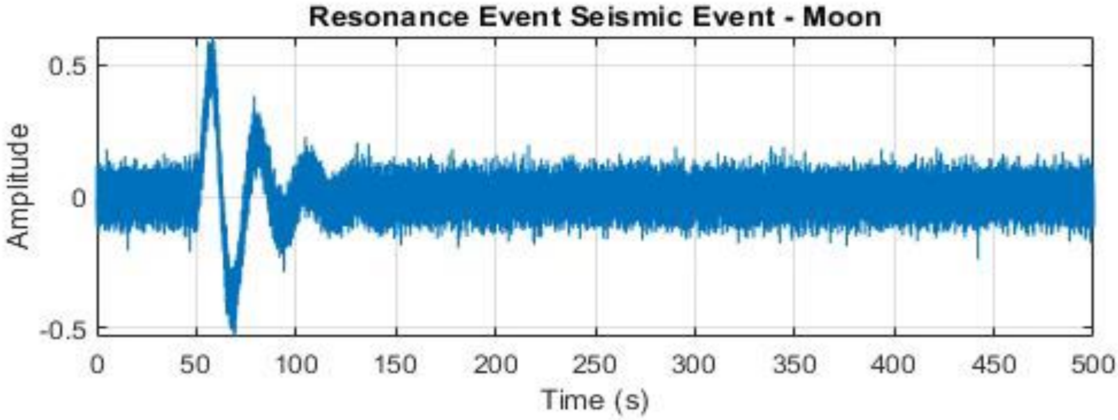
Super High Frequency Event (Lunar)

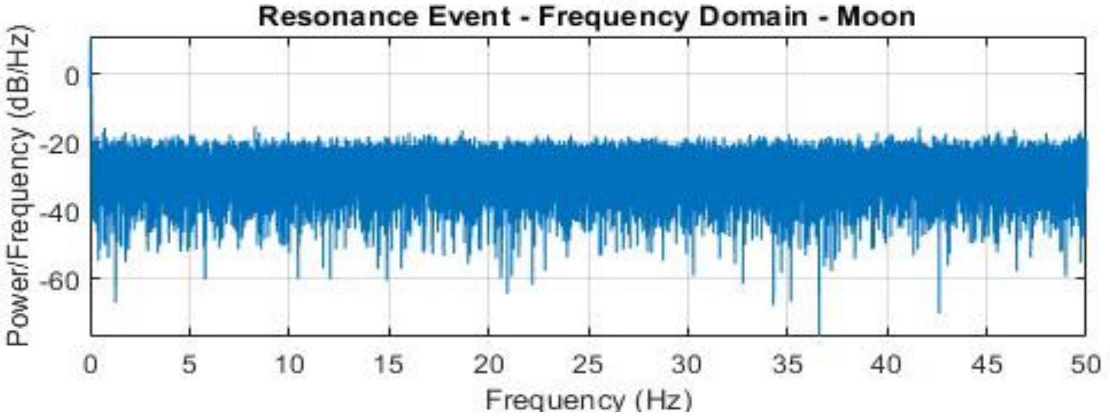


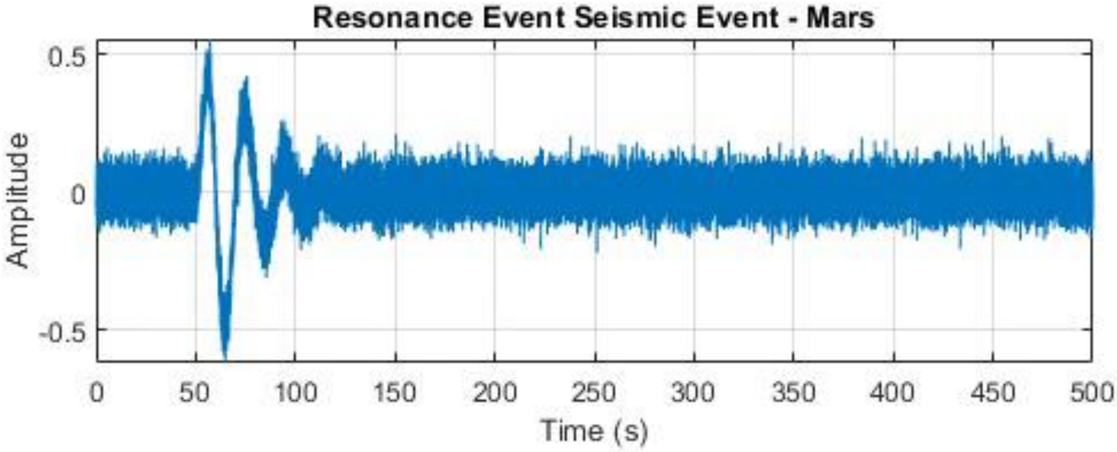
Super High Frequency Event (Martian)

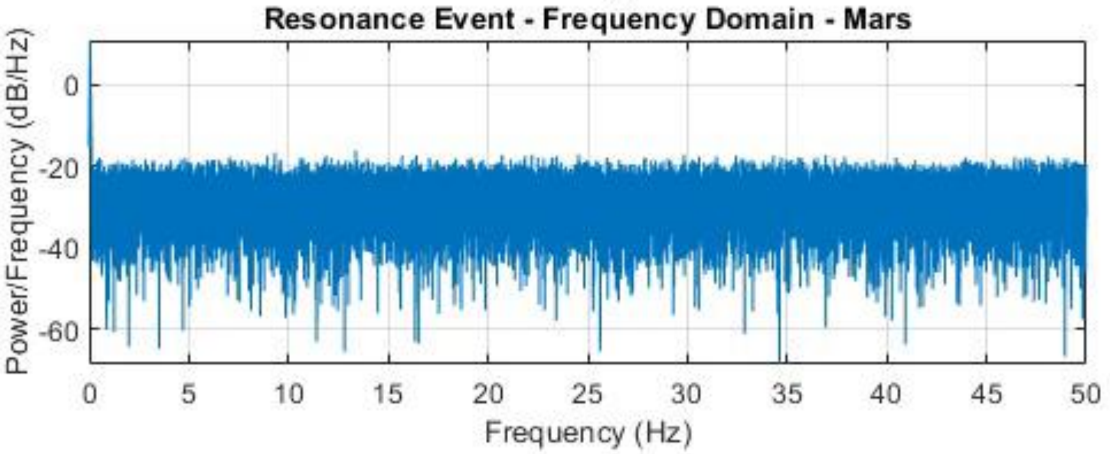


*Resonance Event(s):









Discussion

Challenges faced and counter:

The lunar data proved to be quite inconsistent in terms of the completeness of the data and the missing sections with random spikes due to instrumentation glitches proved to be quite a hurdle in terms of the detection, especially when coinciding with seismic data.

Given the generality of the tool, the output accuracy is barely accurate enough for any further scientific analysis and provides a relatively fundamental starting point for interplanetary geographical analysis.

The counter for the lunar data to the best of our abilities is elimination of data gaps with simulated data, which can be implemented quite effectively if the simulated data is accurate enough but will always produce an infinitesimal amount of deviation from what the actual data could have produced. In some cases, maybe even leading to omission of seismic amidst an event.

There were none if any discrepancies in the Martian dataset which was to be expected given that the instrumentation and data logic methods are quite a bit modern compared to data from the Apollo missions.
This proved to be quite beneficial in the detection and classification

Implications for Future Research

Enhanced Planetary Exploration:

In-situ Seismic Analysis on New Planetary Bodies:

The tool can be adapted for seismic missions to unexplored planets and moons. For example, future missions to icy moons like Europa or Enceladus could leverage the tool to detect and analyze seismic activity beneath their icy crusts. Understanding seismic waves in such environments will provide clues about subsurface oceans and explanations for formations of other exotic terrestrial features

Integration with Multi-Sensor Systems:

Combining Seismic Data with Other Geological Data:
Future versions of the tool can be designed to integrate data from other sensors, such as heat flow probes, gravimeters, or magnetometers, to create a more comprehensive geophysical model of planetary bodies. This would improve our understanding of planetary structures and geological processes.

Cross-Referencing Across Multiple Sites:

In future missions, the tool could be applied to a network of seismometers placed at multiple locations on a planet or moon, enabling researchers to triangulate seismic event sources more accurately and map planetary interiors in more detail.

Automated classification and prediction:

Long-term Monitoring for Predictive Models: By analyzing long-term seismic data, the tool could be used to model the probability of seismic events occurring in the future. This is especially important for understanding seismic hazards on Earth as well as potential risks on other planets that could impact human exploration or colonization.

Customization for extreme environments:

Adapting for Harsh Planetary Conditions:

The tool could be refined to work in extreme conditions, such as high-radiation environments on Jupiter's moons or the extreme pressure and temperature conditions on Venus. This could involve developing robust detection algorithms that compensate for noisy or corrupted data due to harsh environments.

Seismic Detection in Ice-Covered Oceans:

For missions targeting ice-covered moons (e.g., Europa), the tool could be customized to detect seismic waves propagating through ice and water. This would provide insights into subsurface oceans and the potential for geothermal or hydrothermal activity, which is key for assessing habitability.

Network Optimization:

Optimizing Seismic Networks:

Future research could focus on optimizing the placement of seismic stations based on the tool's performance. By analyzing data from different planetary locations, researchers could develop algorithms that suggest the most effective locations for seismometers to maximize coverage and sensitivity in detecting seismic events.

High-Resolution Seismic Imaging:

Through continued refinement, the tool could contribute to the creation of high-resolution seismic images of planetary interiors. This could reveal previously undetectable features, such as magma chambers, subsurface lakes, or tectonic fault lines, providing a more detailed understanding of planetary geodynamics.

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International **F**ederation of **D**igital **S**eismograph **N**etworks

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References

NASA InSight Mission

IRIS miniSEED Documentation

USGS Seismic Monitoring

ESA Planetary Science

IRIS Wilber Data Access

IRIS MiniSEED Format

Seismological Society of America

Abbreviations

PSE – Passive Seismic Experiment

InSight - Interior Exploration using Seismic Investigations, Geodesy and Heat Transport

SEIS – Seismic Experiment for Interior Structure

MSEED – Mini Standard for Exchange of Earthquake Data

NASA – National Aeronautics and Space Administration

ESA – European Space Agency

IRIS – Incorporated Research Institutions for Seismology

ALSEP – Apollo Lunar Seismic Experiment Package

FDSN – International Federation of Digital Seismograph Networks