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8 SEPTEMBER ONLINE DAY
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Detection of Underground Nuclear Explosions Using Phase Picking Techniques in Seismic Analysis

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INTRODUCTION

CTBTO mission :

The Comprehensive Nuclear-Test-Ban Treaty Organization, or CTBTO, has the crucial mission of enforcing the global ban on nuclear testing.

These stations use four complementary technologies: seismic, hydroacoustic, infrasound, and radionuclide detection.

Importance of seismic monitoring: most effective for underground nuclear tests

Among these methods, seismic monitoring plays a particularly vital role, especially for detecting underground nuclear explosions

At the heart of this process is accurate phase picking. Identifying the precise arrival times of seismic waves, particularly P- and S-waves, allows analysts to reconstruct the source and determine whether it originates from a nuclear test or from a natural seismic event.

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Challenges in Nuclear Explosion Detection

- Overlapping seismic signals: earthquakes vs nuclear explosions

Underground nuclear explosions generate seismic waves that often resemble those produced by natural earthquakes. Both events create similar waveforms in the form of compressional P-waves and shear S-waves, making discrimination difficult

- High background noise levels reduce detection accuracy

Many of these stations are located in areas with varying levels of cultural, industrial, or natural noise. For instance, human activity, ocean microseisms, or local geological conditions can mask weak signals or distort their characteristics.

- Requires advanced techniques for reliable phase picking and classification

They also emphasize the importance of developing more robust and adaptive techniques. Accurate phase picking, combined with machine learning and advanced signal processing

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Research Objectives

- Develop & compare phase picking techniques (STA/LTA, PhaseNet)

Specifically, the traditional STA/LTA method and the deep learning-based PhaseNet. This comparison allows us to understand the strengths and weaknesses of each approach in detecting P-wave arrivals.

- Integrate amplitude & spectral analysis for event discrimination

While phase picking provides timing information, amplitude ratios and spectral features help us to better discriminate between natural earthquakes and underground nuclear explosions

- Apply methods to the CTBTO seismic station (SIJI, Indonesia) and Site West Java

Using this station as a case study provides a concrete demonstration of how these techniques perform in an operational monitoring context.

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Methodology

Data preprocessing

The raw seismic signals from SIJI station often contain noise and artifacts. So, we apply filtering, normalization, and windowing to make the data suitable for analysis.

Phase picking (STA/LTA & PhaseNet)

Here, we compare two approaches: the traditional STA/LTA method and the modern deep learning approach.

Amplitude & spectral analysis

We designed a workflow fully implemented in **Python**

he first was the classical **STA/LTA algorithm**, implemented directly in ObsPy. The second was a modern deep learning approach, **PhaseNet**, which we accessed through the **SeisBench framework**.

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Methodology

Traditional method: STA/LTA for P- and S-wave detection

- STA/LTA: Short-Term Average / Long-Term Average Widely used in seismic event detection: indicates the possible arrival of a seismic phase, such as a P-wave.
- Strengths: Simple, efficient, robust for high SNR.
- Limitations: Sensitive to noise, poor performance in low SNR or overlapping signals.
- STA/LTA remains a useful baseline method; there is a growing need for more advanced techniques that can improve detection accuracy in noisy or complex environments.

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Methodology

- Machine learning approach: PhaseNet

Deep learning architecture (Convolutional Neural Network)

- Trained on large global seismic datasets
- **Advantages**:
  - Automated detection
  - Robust to noise
  - Sensitive to weak signals
- Example: Waveform + picks (visualization)

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Methodology

P/S ratio

Explosions → stronger **P-waves**

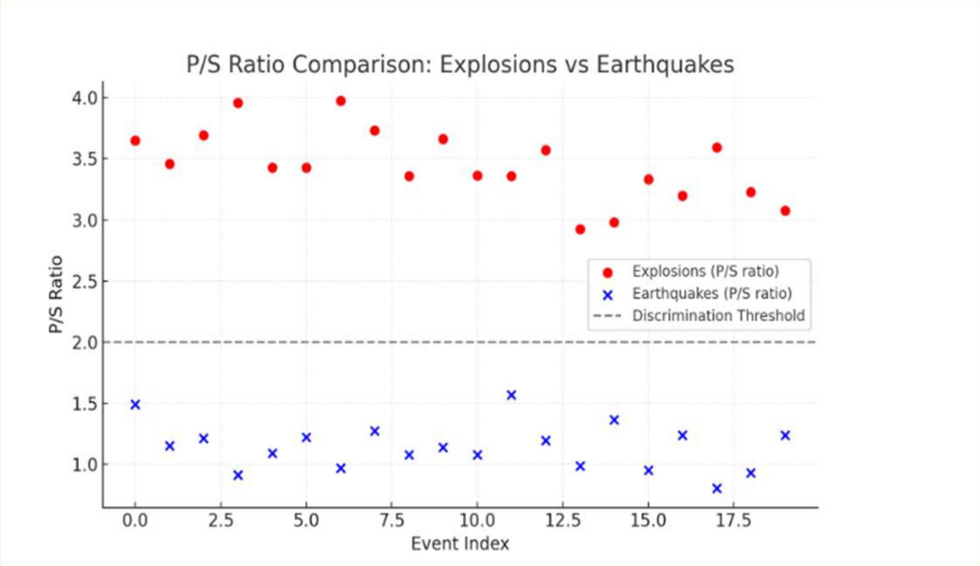
Earthquakes → stronger **S-waves**

Body vs Surface wave ratio

Explosions: high **body wave energy**

Earthquakes: significant **surface waves**

Useful for distinguishing natural earthquakes from nuclear explosions



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Dataset

- CTBTO monitoring site: For this study, we used seismic data from the CTBTO station SIJI,

CBJI JawaBarat Citeko, TSJM JawaBarat, Tanjungsiang, CMJI Cimerak located in Indonesia.

- This station is quite important because it sits in a tectonically active region, surrounded by both subduction zones and volcanic activity. That makes it a very useful site for monitoring, but also a very challenging one.
- One of the main challenges is the tropical noise environment. Unlike stations in quieter continental areas, SIJI often records additional disturbances from ocean waves, heavy rainfall, and even cultural noise from nearby human activity. These factors reduce the signal-to-noise ratio, especially for weak seismic phases.

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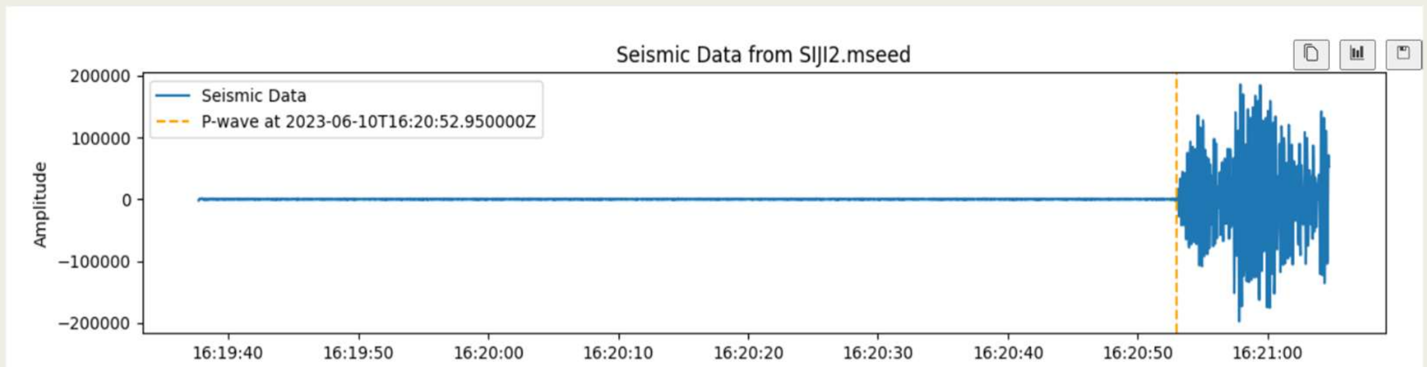
STA/LTA Results

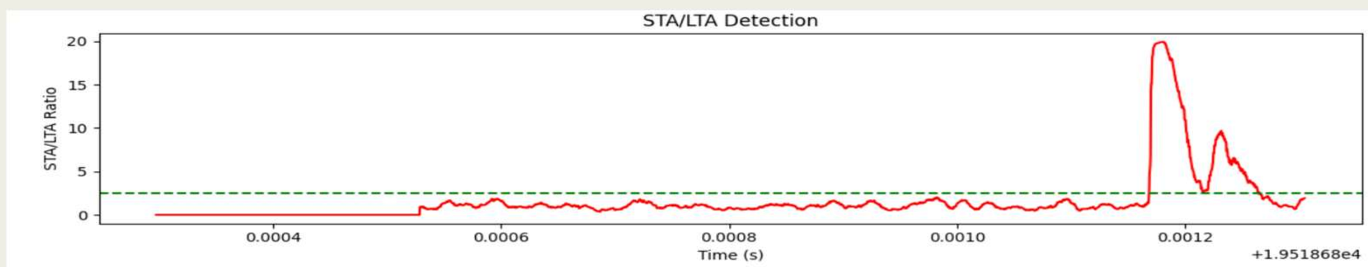
Seismogram (top) + STA/LTA ratio (bottom)

Top panel: Raw seismic waveform (amplitude vs time).

Bottom panel: STA/LTA ratio curve.

When a seismic event occurs (e.g., P-wave arrival), the STA/LTA ratio rises sharply and may cross a predefined threshold.





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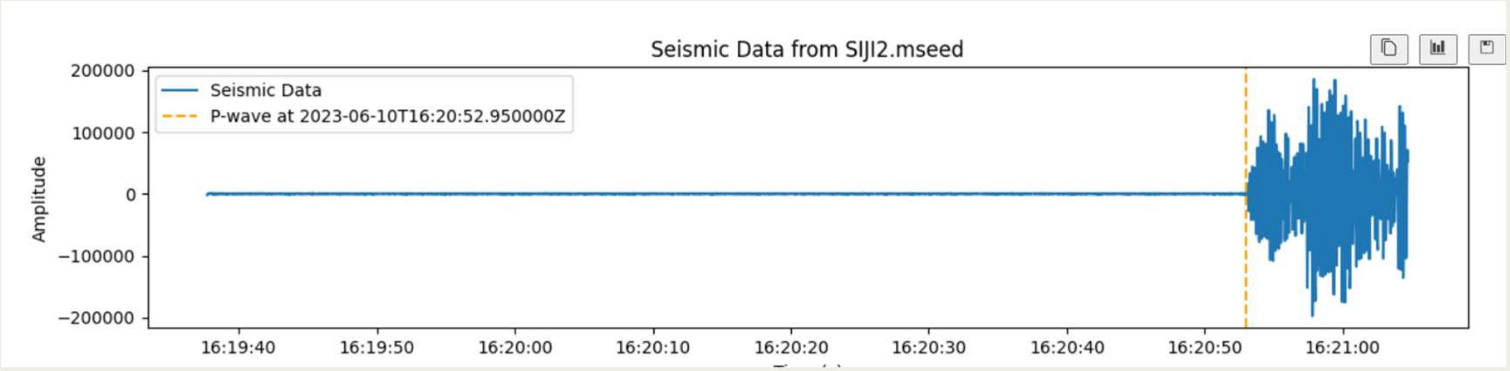
STA/LTA Results



File P-wave Arrival Time STA/LTA : 2023-06-10T16:20:52.950000Z

SNR (STA/LTA) : 8.216374 db

The signal-to-noise ratio that we obtained is around **8.2 decibels**. While STA/LTA has been widely used in seismology for decades, the results show that it often misses weak signals, especially when the noise level is high or when the seismic event is small in magnitude.

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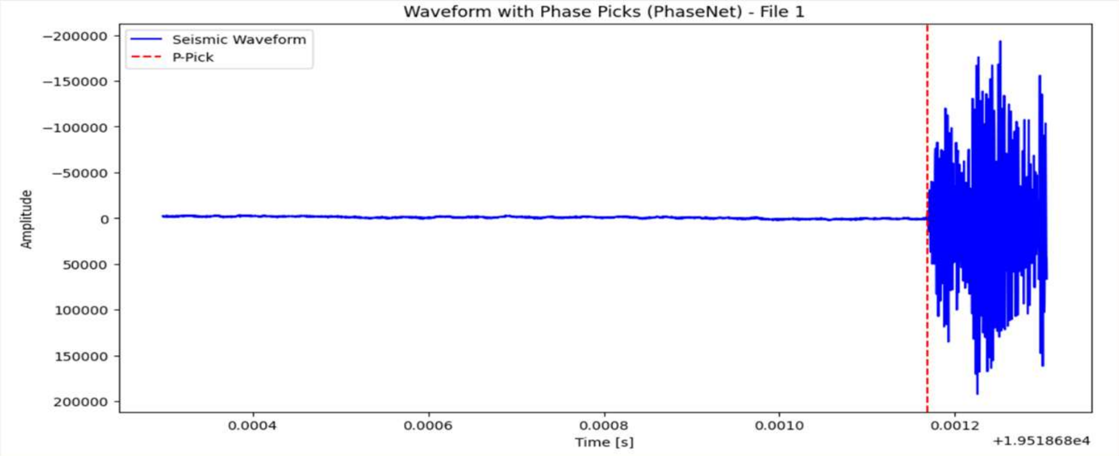
Phasenet Results



PhaseNet Results

SNR = 25.02 dB

More robust in noisy environments

Accurately detects weak P-wave arrivals

Provides consistent phase picks compared to STA/LTA

This means it can **detect P-wave onsets more clearly, even in a noisy tropical environment like at the SIJI station**.
Unlike STA/LTA, which often misses weak signals, PhaseNet provides **robust and consistent picks**, making it highly reliable for nuclear explosion monitoring

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Comparative Results

STA/LTA: SNR = 8.21 dB → often misses weak signals

PhaseNet: SNR = 25.02 dB → more accurate & robust picks

Key point: PhaseNet significantly improves detection in noisy conditions

This demonstrates that PhaseNet can reliably detect **P-wave arrivals**, even in noisy environments typical of Indonesia.
The comparison highlights why deep learning methods like PhaseNet are becoming essential for **nuclear explosion monitoring**." –

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Example Results

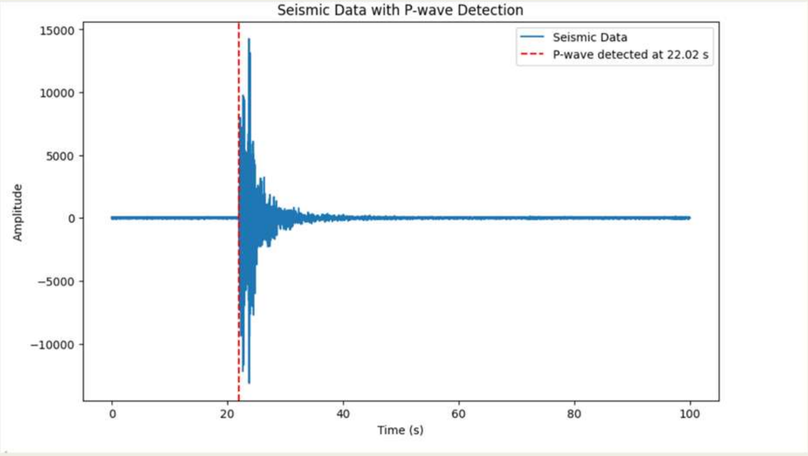
Interpretation of P/S Ratio

1.Theoretical Background

1. **P-waves (Primary waves)** are compressional waves that travel faster and are dominant in **underground explosions**, because explosions generate energy isotropically (outward push in all directions).
2. **S-waves (Secondary waves)** are shear waves that carry most of the energy in **tectonic earthquakes**, as fault slip produces significant shear motion.

2.Thus,

1. **P/S ratio >> 1 → Explosion (nuclear/chemical)**.
2. **P/S ratio ≈ 1 or < 1 → Tectonic earthquake**.



Stasiun POZA In Italy

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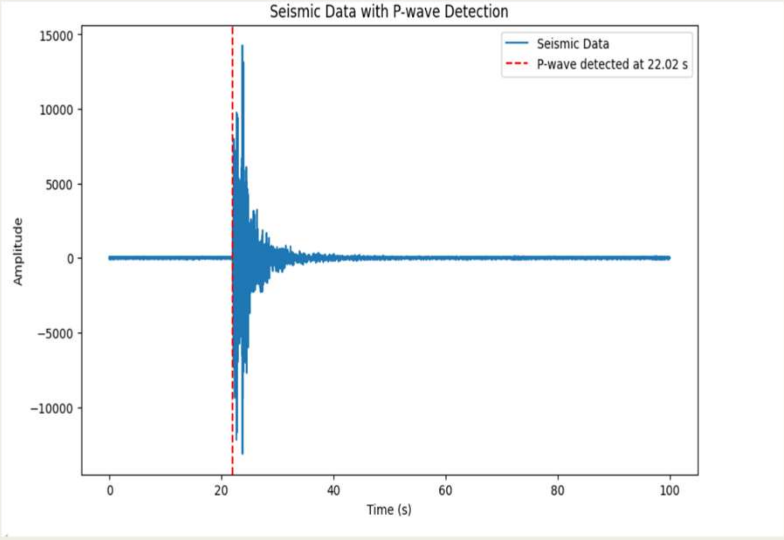
Example Results

STA/LTA Picks
P arrival: 2023-02-21T00:07:22.506024Z
S arrival: 2023-02-21T00:07:24.362024ZP/S **Ratio: 0.56**
PhaseNet Picks
P arrival: 2023-02-21T00:07:22.560000Z
S arrival: 2023-02-21T00:07:24.240000ZP/S **Ratio: 0.49**



Stasiun POZA In Italy

Both methods (STA/LTA and PhaseNet) give P/S ratios well below 1. This indicates that S-wave energy is comparable to or stronger than P-wave energy, which is a typical characteristic of tectonic earthquakes. If this event had been an underground explosion, we would expect the P-wave to be much stronger (P/S >> 1), but that is not the case here.

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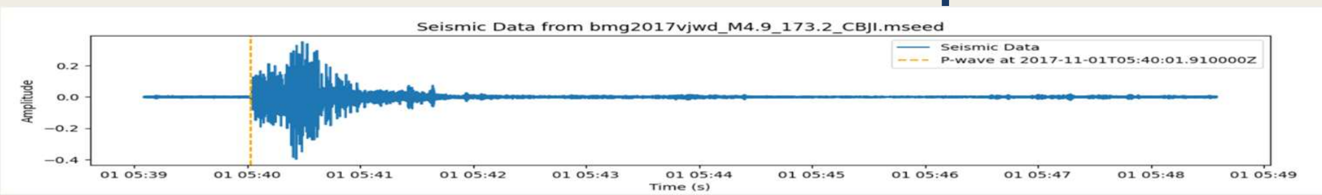
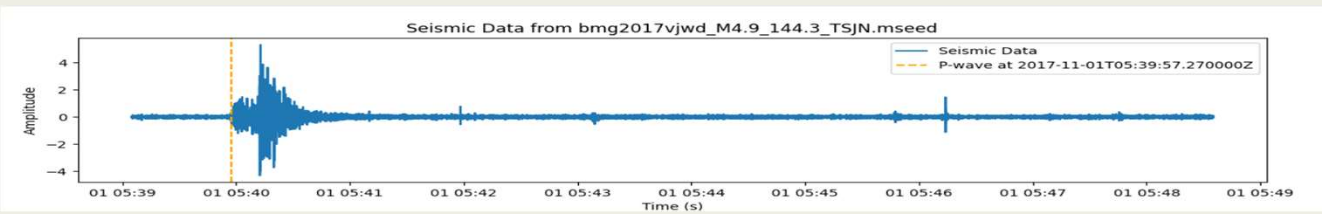
Example Results

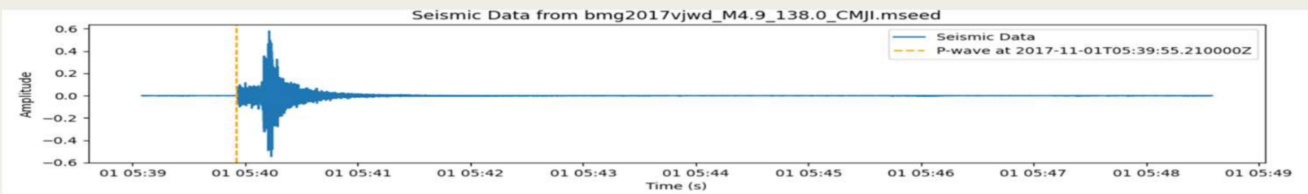
CBJI JawaBarat Citeko,Bogor



TSJM JawaBarat Tanjungsiang,Subang



CMJI JawaBarat Cimerak



P/S Ratio (STA/LTA): 0.7544165358133849

STA/LTA P pick: 2017-11-01T05:40:02.160000Z STA/LTA S pick: 2017-11-01T05:41:25.970000Z

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Key Findings

PhaseNet clearly outperforms STA/LTA in phase picking

It provides more accurate and consistent phase picks, especially under noisy tropical conditions.

Improved event classification between earthquakes and explosions

the P/S ratio and spectral patterns help us separate earthquakes from underground explosions more reliably.Overall, combining deep learning phase picking with amplitude and spectral analysis results in a more robust seismic monitoring framework

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Implications

Enhanced nuclear test monitoring capability

Contribution to the CTBT verification regime

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Conclusion

Automated deep learning picks significantly improve detection

SNR improvement: 8.2 → 25 dB

Phase picking + amplitude analysis = strong monitoring framework

Finally, by **combining accurate phase picking with amplitude and spectral analysis**, we establish a **strong and reliable framework** for seismic monitoring.
This framework not only enhances the detection of natural earthquakes but also strengthens our ability to identify potential underground nuclear explosions.

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THANK YOU

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