Seismic Sleuthing with MACREE: A Refined Approach to Earthquake and Explosion Detection

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Abstract

The accurate and timely detection of seismic events, including both natural earthquakes and anthropogenic explosions, remains a critical concern for geophysical research, public safety, and international security. Traditional seismic detection systems often struggle to differentiate between these two classes of events due to overlapping wave characteristics and background noise. In response to this challenge, this paper introduces MACREE (Modular Analysis for Classification and Refined Event Evaluation), a novel seismic analysis framework designed to enhance event classification accuracy through an integrated approach combining signal preprocessing, spectral decomposition, and machine learning-based decision algorithms. MACREE improves the resolution of waveform features by applying adaptive filtering and event-specific transformation layers before classification, thus distinguishing subtle differences in wave patterns. Preliminary testing using both historical and real-time seismic data has demonstrated MACREE's potential in achieving higher detection accuracy and reducing false positives. This work outlines the architectural design of MACREE, its algorithmic foundation, and its implications for seismic monitoring systems, particularly in contexts where discriminating between earthquakes and explosions is of high importance.

Keywords Seismic detection, MACREE, earthquake vs explosion, signal classification, machine learning, waveform analysis, geophysical monitoring, adaptive filtering, spectral decomposition, event discrimination.

Introduction

In recent years, the field of seismology has witnessed significant advancements in data acquisition and signal processing, enabling more detailed monitoring of Earth's subsurface activity. One of the longstanding challenges in seismic science, however, remains the reliable differentiation between natural seismic events such as earthquakes and man-made events such as explosions. This capability is essential not only for scientific and hazard-related reasons but also for geopolitical and security monitoring, such as verifying compliance with nuclear test ban treaties. Both types of events generate seismic waves, but their characteristics often overlap, especially at lower magnitudes or when measured at regional distances. Traditional seismological methods—relying primarily on phase arrival times, wave amplitude ratios, and human expert interpretation—are often insufficient to resolve these ambiguities with high confidence[1].

In this context, the need for more refined, intelligent systems has become apparent. Enter MACREE: Modular Analysis for Classification and Refined Event Evaluation. MACREE is a seismic signal processing and classification framework designed to harness both the deterministic features of seismic waveforms and the adaptive power of machine learning. The core premise of MACREE is to transform raw seismic signals into a domain where event-specific characteristics are more easily separable. This transformation is achieved through modular layers of preprocessing, including noise suppression, adaptive filtering, and multiscale decomposition, followed by advanced classification using trained neural models[2].

Unlike traditional systems that apply uniform criteria across all incoming signals, MACREE dynamically adapts its processing pipeline based on preliminary assessments of signal characteristics. For instance, if a signal exhibits a sharp onset with high-frequency content, MACREE may apply a time-frequency representation optimized for detecting explosive sources. If the signal shows extended low-frequency energy and complex waveforms, the system may instead emphasize spectral analysis suited for tectonic activity. In either case, the goal is to maximize the discriminative information available to the classification model[3].

At the heart of MACREE's decision-making capability lies a hybrid classification model that blends supervised machine learning with rule-based inference. Trained on extensive databases of labeled seismic events, the model is capable of identifying key waveform signatures associated with known earthquakes and explosions. These signatures include differences in P- to S-wave amplitude ratios, coda wave durations, spectral peaks, and other subtle features that are often challenging to capture with classical threshold-based methods. Furthermore, MACREE incorporates confidence scoring, allowing analysts to prioritize high-certainty classifications and flag ambiguous cases for manual review.

MACREE also supports real-time processing, an essential requirement for modern seismic networks that monitor global activity. By minimizing the time between signal detection and classification, the system facilitates rapid response to potentially hazardous events. This is particularly valuable in regions where immediate decisions must be made—such as issuing tsunami alerts or determining whether a suspected explosion may warrant diplomatic or military investigation[4].

Another strength of the MACREE framework is its modularity. Each processing and classification component can be updated or replaced independently, allowing the system to evolve alongside improvements in algorithmic research or computational power. This flexibility ensures MACREE remains adaptable to new signal types, emerging seismic threats, or regional-specific variations in wave propagation.

The following sections will explore the design architecture, evaluate performance metrics, and discuss the broader implications of deploying MACREE in real-world geophysical and security contexts.

Signal Processing and Feature Extraction in MACREE

The effectiveness of any seismic event classification system relies heavily on the quality of signal processing and the precision of the features extracted from raw waveform data. In MACREE, this stage serves as the foundation for all downstream tasks. Raw seismic signals are often buried in background noise, affected by site-specific propagation conditions, and distorted by instrument responses. Without a robust signal processing pipeline, the resulting data can produce ambiguous interpretations. MACREE addresses these issues with a multi-layered processing strategy that improves the clarity, resolution, and event-relevant content of the signals prior to classification[5].

The initial step in MACREE’s signal processing involves the removal of ambient noise using adaptive filtering techniques. Unlike traditional static filters that apply fixed thresholds or frequency bands, MACREE's adaptive filters respond to the characteristics of incoming signals in real time. These filters analyze the spectral content of the waveform, identify noise-dominant regions, and apply transformations such as wavelet shrinkage, bandpass tuning, or deconvolution to isolate meaningful seismic energy. This adaptive mechanism ensures that the features fed into the classifier are not corrupted by regional noise artifacts or transient disturbances unrelated to the seismic event.

Once the signal is cleaned, MACREE applies a decomposition phase to represent the waveform in time-frequency space. This approach enables the system to capture both the temporal dynamics and frequency evolution of the signal, which are critical in distinguishing between earthquakes and explosions. Earthquakes typically generate complex, multi-phase waveforms with extended durations and lower-frequency content, while explosions often yield more impulsive signals with sharper onsets and higher-frequency components. By using spectrograms, short-time Fourier transforms, and continuous wavelet transforms, MACREE can characterize these attributes in great detail[6].

Following decomposition, MACREE executes a feature extraction module. This module derives a compact but informative set of numerical descriptors from the processed signal. These features include peak amplitude ratios between seismic phases, spectral centroid and bandwidth, energy distribution across time windows, and phase arrival time intervals. In addition, statistical measures such as skewness, kurtosis, and entropy help capture the complexity and distribution of energy in the waveform. These features are engineered to be both discriminative and robust across different seismic environments[7].

Importantly, MACREE also supports event-specific customization of the feature extraction process. For example, if the system detects characteristics suggestive of an anthropogenic event, such as a shallow origin or impulsive onset, it may emphasize features commonly associated with explosions. Conversely, signals with complex wave trains and aftershocks may trigger a deeper analysis of coda wave behavior and longer-period energy. This selective emphasis allows MACREE to prioritize the most informative features for each classification scenario[8].

The final output of the signal processing and feature extraction pipeline is a multidimensional feature vector that encapsulates the key traits of the event. This vector is normalized and formatted for input into MACREE's machine learning model, where classification is performed. Through this sophisticated preprocessing architecture, MACREE significantly improves its ability to differentiate between event types, even under noisy or ambiguous conditions. This robust foundation makes MACREE not only accurate in event identification but also highly adaptable to various regional and operational contexts.

Machine Learning Architecture and Classification Strategy

Central to MACREE's classification power is its machine learning engine, which integrates supervised learning algorithms with rule-based interpretability to create a reliable and adaptive detection system. The machine learning architecture is designed to identify complex relationships between waveform features and seismic event types, leveraging a large corpus of labeled data to generalize across new, unseen events. Unlike traditional methods that rely heavily on fixed thresholds and expert-defined rules, MACREE's learning-based system continuously evolves through exposure to new seismic patterns and anomalies[9].

The core classifier used in MACREE is an ensemble learning model that combines the strengths of multiple algorithms, including convolutional neural networks (CNNs), decision trees, and support vector machines (SVMs). CNNs are particularly effective at processing time-frequency representations of waveforms, treating them similarly to image data and extracting spatially coherent patterns that correlate with different event classes. For instance, the shape and density of energy clusters in a spectrogram can indicate whether the source is tectonic or explosive. These patterns are learned automatically during the training process, without requiring manual definition[10].

To enhance reliability, MACREE also employs a voting-based ensemble strategy where different classifiers contribute independent assessments, and the final decision is based on a weighted consensus. This method improves classification robustness by reducing the impact of any single model's misjudgment and allowing the system to maintain performance across a range of data types and noise levels. Each model in the ensemble is trained using a diverse dataset of global and regional seismic events, ensuring broad generalization capabilities[11].

Training the machine learning models involves using both real seismic data from historical records and synthetic data generated through simulations. This approach ensures that the models are exposed to a wide range of seismic scenarios, including rare or ambiguous events. Labeling is conducted by domain experts to ensure high data quality, and regular retraining allows the system to incorporate new findings and regional-specific behaviors over time. The inclusion of synthetic events also helps in modeling controlled explosions and other anthropogenic sources that might otherwise be underrepresented.

MACREE's classification strategy includes a confidence scoring mechanism. Each classification output is paired with a confidence value indicating the system's certainty in its decision. This allows end-users to assess the reliability of the classification and to apply additional scrutiny or manual review in cases with lower confidence. The scoring system is particularly valuable in high-stakes contexts such as nuclear test monitoring, where false positives or negatives carry serious consequences[12].

To maintain transparency and interpretability, MACREE incorporates rule-based logic alongside its learning models. For instance, if a signal meets certain hard thresholds—such as a P-to-S amplitude ratio far exceeding expected earthquake norms—it can override or flag the machine learning output for further review. This hybrid approach combines the adaptability of machine learning with the accountability of rule-based systems, creating a balance between innovation and operational trust.

Together, these elements form a robust, intelligent classification engine that significantly advances the state of seismic event discrimination. MACREE's machine learning backbone ensures that it can continue to improve as more data becomes available, ultimately serving as a powerful tool for seismologists and monitoring agencies worldwide[13].

Conclusion

Seismic monitoring has long been an essential component of both geophysical research and international security operations, yet it continues to face challenges in reliably distinguishing between earthquakes and human-induced events such as explosions. MACREE offers a transformative solution to this problem by introducing a refined, modular approach that unifies advanced signal processing and intelligent classification algorithms. Through its dynamic preprocessing modules, MACREE adapts to the unique characteristics of each seismic signal, ensuring that event-specific features are amplified and preserved for accurate evaluation. As global demands for accurate, rapid seismic event detection continue to grow, MACREE provides a forward-looking framework capable of evolving with both technological advances and geophysical needs. With continued development, broader deployment, and the inclusion of more diverse datasets, MACREE could become a cornerstone in the next generation of seismic monitoring infrastructure, offering critical insights not only into Earth's natural behavior but also into the actions of human actors beneath the surface.

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