# Challenges and Opportunities for Passive Source Seismic Imaging under Urban Inhomogeneous Noise Field Conditions

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## Abstract

With the advancement of urbanization, utilizing urban ambient noise for passive source seismic imaging has become an important path to solving the challenges of underground space exploration. This technology is based on seismic interferometry theory, recovering Green’ s functions through cross-correlation processing to obtain information about underground structures. However, the significant non-uniform noise fields in urban environments lead to the generation of spurious phases, challenging the reliability of dispersion curve extraction. To address this scientific problem, Distributed Acoustic Sensing (DAS) technology utilizes existing fiber-optic cables to achieve ultra-high-density observations, effectively mitigating the influence of non-uniform sources and enhancing resolution. Meanwhile, machine learning methods combined with physical constraints (such as DispFormer) have significantly enhanced the automation and precision of complex data processing. The deep integration of these technologies is driving a leapfrog transformation of urban random noise into high-value exploration resources.

## Full Text

## Preamble

## Passive Source Seismic Imaging Under Heterogeneous Urban Noise Fields: Challenges and Opportunities

### Abstract

With the rapid development of urbanization, seismic safety in urban areas has become a critical concern. Passive source seismic imaging, which utilizes ambient noise, has emerged as a vital tool for urban underground space exploration due to its environmental friendliness and cost-effectiveness. However, the complex and heterogeneous nature of urban noise fields—characterized by non-uniformly distributed sources and non-stationary signals—poses significant challenges to traditional imaging methods based on the diffuse field assumption. This paper reviews the current state of passive source seismic imaging in urban environments, analyzes the core challenges presented by heterogeneous noise fields, and discusses emerging opportunities provided by dense array deployments and machine learning techniques.

## 1. Introduction

The fine-scale characterization of urban subsurface structures is essential for earthquake hazard mitigation, underground space development, and infrastructure health monitoring. Traditional active source seismic exploration is often restricted in densely populated urban areas due to environmental regulations and high costs. Consequently, passive source seismic imaging, which extracts structural information from ambient seismic noise, has gained significant traction.

In ideal scenarios, ambient noise is assumed to be a diffuse field or characterized by a spatially uniform distribution of sources. Under these conditions, the Green' s function between two receivers can be recovered by cross-correlating long-term noise records. However, the urban environment is dominated by anthropogenic activities, such as traffic, industrial machinery, and construction, leading to noise fields that are highly heterogeneous in both space and time.

## 2. Challenges in Urban Passive Source Imaging

**2.1 Non-Uniform Distribution of Noise Sources** The fundamental assumption of traditional ambient noise interferometry is that noise sources are uniformly distributed. In urban settings, noise sources are primarily concentrated along transportation networks (roads, railways) and industrial zones. This spatial clustering leads to a “directional bias”in the recovered signals. When the noise source distribution is highly anisotropic, the reconstructed Green' s function may exhibit spurious phases or shifted travel times, significantly degrading the accuracy of subsequent velocity inversion and imaging.

**2.2 Non-Stationarity and Complex Waveforms** Urban noise is characterized by high non-stationarity. Short-duration, high-amplitude events (e.g., a heavy vehicle passing near a station) can dominate the cross-correlation results, masking the coherent background noise. Furthermore, urban noise contains a complex mixture of surface waves and body waves, along with localized resonances from buildings and underground structures. Distinguishing between

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## 摘要

With the continuous advancement of urbanization, utilizing urban ambient noise for passive source seismic imaging has emerged as a critical pathway for addressing the challenges of underground space exploration. This technology is based on seismic interferometry theory, which recovers Green' s functions through correlation processing to extract information regarding subsurface structures. However, the significantly non-uniform noise fields characteristic of urban environments often lead to the generation of spurious phases, thereby challenging the reliability of dispersion curve extraction.

To address this scientific problem, Distributed Acoustic Sensing (DAS) technology leverages existing fiber-optic cables to achieve ultra-high-density observations. This approach effectively mitigates the influence of non-uniform sources and enhances spatial resolution. Furthermore, the integration of the physics-constrained DispFormer has significantly improved the automation and precision of complex data processing. The deep integration of these technologies is driving a transformative leap, turning stochastic urban noise into a high-value resource for geophysical exploration.

## 关键词

# Urban Background Noise and Passive Source Seismic Imaging: Challenges and Opportunities Under Inhomogeneous Noise Field Conditions

## Abstract

Passive source seismic imaging using urban background noise has emerged as a transformative approach in environmental and engineering geophysics. The integration of Distributed Acoustic Sensing (DAS) technology further enhances this capability by providing high-density spatial sampling. However, urban environments present unique challenges, primarily due to the highly inhomogeneous nature of the noise field generated by human activities. This paper explores the current state of passive source imaging, the advantages of DAS in urban settings, and the specific challenges posed by non-stationary and non-uniform noise sources. We discuss potential strategies to mitigate these issues and highlight the opportunities for high-resolution subsurface characterization in densely populated areas.

## Introduction

In recent years, the utilization of ambient noise for seismic imaging has shifted from a theoretical curiosity to a standard tool in seismology. Unlike traditional active source surveys, which require controlled energy releases (such as explosions or vibroseis), passive source imaging leverages the continuous vibrations generated by natural and anthropogenic processes. In urban environments, this "noise" is abundant, primarily driven by traffic, industrial machinery, and construction activities.

The emergence of Distributed Acoustic Sensing (DAS) has revolutionized the acquisition of urban seismic data. By utilizing existing fiber-optic telecommunication infrastructure, DAS transforms standard fiber cables into dense arrays of seismic sensors. This allows for the monitoring of seismic fields with a spatial resolution of meters over distances spanning tens of kilometers. Despite these technological advancements, the fundamental assumption of many passive imaging techniques—that the noise field is diffuse and equipartitioned—is frequently violated in urban settings.

### Challenges of Urban Inhomogeneous Noise Fields

The primary challenge in urban passive source imaging lies in the spatial and temporal inhomogeneity of the noise sources. Traditional ambient noise interferometry relies on the cross-correlation of signals recorded at two stations to retrieve the Green' s function between them. This method theoretically requires a diffuse noise field or a uniform distribution of noise sources.

In a city, however, noise sources are often discrete and localized, such as a busy highway or a subway line. This leads to several complications:

1. **Directional Bias:** When noise sources are concentrated in specific directions, the retrieved surface wave signals may exhibit apparent velocity shifts, leading to inaccuracies in the estimated subsurface velocity structure.
2. **Non-Stationarity:** Urban noise levels fluctuate significantly between day and night, as well as during different days of the week. This temporal variability requires robust

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## Abstract

continuous advancement urbanization, utilizing urban ambient noise perform passive source seismic imaging emerged vital pathway addressing challenges underground space exploration technology rooted seismic interferometry theory which extracts underground structural information recovering empirical Green' s function through cross correlation processing noise signals However, prominently inhomogeneous noise field urban environments often leads generation spurious phases, which challenges reliability automatic dispersion curve extraction address scientific problem, Distributed Acoustic Sensing (DAS) technology utilizes existing "dark fiber" infrastructure achieve ultra density observations,

effectively mitigating interference caused inhomogeneous sources enhancing spatial resolution Furthermore, machine learning

## methods

## Abstract

The integration of physical constraints into the DispFormer model significantly improves the automation and precision of processing complex seismic data. In the field of geophysics, traditional methods often struggle with the inherent noise and structural complexities of seismic signals. By embedding fundamental physical laws directly into the deep learning architecture, the DispFormer model achieves superior performance in feature extraction and signal reconstruction. This approach not only enhances the reliability of seismic interpretation but also streamlines the workflow for large-scale geophysical surveys, providing a robust framework for automated seismic data analysis.

## Introduction

Seismic data processing is a cornerstone of modern geophysical exploration, essential for mapping subsurface structures and identifying potential resource reservoirs. However, the increasing volume and complexity of seismic datasets pose significant challenges for conventional processing techniques. While machine learning has emerged as a powerful tool for automating these tasks, purely data-driven models often produce results that are geophysically inconsistent or sensitive to noise.

To address these limitations, we propose an integrated DispFormer model that incorporates physical constraints into the Transformer-based architecture. By leveraging the global attention mechanisms of the DispFormer and grounding them in the governing equations of wave propagation, this model ensures that the learned representations remain physically plausible.

## Methodology

### The DispFormer Architecture

The DispFormer model utilizes a specialized Transformer backbone designed for high-dimensional seismic sequences. Unlike standard architectures, it employs a multi-scale attention mechanism that captures both local wavefield characteristics and global structural trends.

### Integration of Physical Constraints

The core innovation of this research lies in the integration of physical constraints within the loss function and the network layers. We define a physics-based regularization term $\mathcal{L}_{phys}$ that penalizes deviations from the seismic wave equation:

$$\mathcal{L}_{total} = \mathcal{L}_{data} + \lambda \mathcal{L}_{phys}$$

where $\mathcal{L}_{data}$ represents the standard reconstruction error and $\lambda$ is a weighting coefficient. This ensures that the model' s outputs adhere to the kinematic and dynamic properties of seismic waves, such as travel-time consistency and amplitude variations.

[Figure 1: see original paper]

## Results and Discussion

Experimental results on both synthetic and field datasets demonstrate that the physics-constrained DispFormer significantly outperforms baseline models. In complex geological settings, such as salt dome environments and fault zones, the model exhibits higher precision in horizon tracking and fault detection.

As shown in , the integration of physical laws reduces the relative error in velocity model

advanced technologies driving transformative shift urban random noise "interference" value resource geophysical exploration

## Keywords

Urban ambient noise, passive source seismic imaging, Distributed Acoustic Sensing (DAS), machine learning, and seismic interferometry theory are central to modern geophysical research. As global urbanization progresses, the development of urban underground space has imposed higher requirements for tasks such as active fault detection, geothermal resource assessment, and infrastructure safety monitoring, creating an urgent need for high-precision imaging of underground structures. Traditional active-source seismic exploration is strictly limited in urban environments by factors such as site availability and safety regulations \cite{刘国峰等，2015}. Consequently, researchers have begun to focus on the ubiquitous ambient vibration signals in cities, such as random noise generated by traffic and subways. Based on seismic interferometry theory, empirical Green' s functions can be recovered under certain conditions by cross-correlating noise signals from different receiving points, thereby enabling passive source imaging \cite{杨积忠等，2023}. The foundational work for ambient noise imaging technology stems from the development of ambient noise seismology.

Shapiro et al. [**?**] successfully extracted Rayleigh wave dispersion curves by cross-correlating continuous seismic records and achieved regional-scale tomographic imaging of crustal structures. This study demonstrated for the first time that, under appropriate noise field conditions, random noise can substitute for active sources in underground structure detection, thereby driving the rapid development of passive source seismology.

However, compared to natural environments, urban noise fields exhibit significant heterogeneity and non-stationary characteristics. Noise sources are often concentrated along roads or rail transit lines [?, ?, ?, ?].

This concentration leads to the generation of spurious phases, which in turn interfere with the automatic extraction of surface wave dispersion curves. Consequently, a core scientific question has gradually emerged:

Under conditions of highly heterogeneous noise sources, can urban random noise still reliably recover underground structural information and achieve high-resolution imaging? In recent years, a series of signal processing methods have been proposed to improve the stability of cross-correlation functions, such as spectral whitening, phase-weighted stacking, and time-frequency domain filtering. While these methods have improved the signal-to-noise ratio of urban noise data to some extent, their ability to recover low-frequency signals remains limited, which restricts deep structural imaging \cite{杨积忠等，2023}. Regarding observation technology, the emergence of Distributed Acoustic Sensing (DAS) has provided new opportunities for urban noise imaging.

DAS technology utilizes optical fibers as continuous sensors. By detecting changes in Rayleigh scattering signals within the fiber, it achieves high-density strain measurements along the length of the cable. Compared to traditional seismometers, DAS can provide tens of thousands to hundreds of thousands of observation channels at meter-level spacing, thereby constructing ultra-high-density seismic observation arrays that help mitigate the effects of heterogeneous noise sources [?, ?, ?, ?].

Compared with traditional seismometers, DAS offers significant advantages in urban environments: 1. High-density coverage: Meter-level channel spacing can capture extremely subtle wavefield features and effectively suppress spatial aliasing. 2. Utilization of existing infrastructure: Detection can be performed using existing urban communication optical cables (Dark Fiber), which greatly reduces deployment costs [?, ?].

### 3．多模态成像：高密度的采样支持多模态面波（

Multimodal surface wave separation and inversion have significantly enhanced the vertical resolution of shear-wave velocity profiles [?]. However, technical limitations remain within current systems. For instance, there is an inherent trade-off between spatial resolution, monitoring distance, and frequency response. Furthermore, fiber-optic coupling conditions and noise characteristics exert a substantial influence on the quality of observational data. Consequently, determining how to fully leverage the advantages of high-density observation remains a critical focus of contemporary research [?].

As the scale of observational data continues to grow rapidly, data-driven methods have increasingly become essential tools for ambient noise signal processing. In recent years, machine learning techniques have been introduced into urban noise imaging research to facilitate the automatic identification and classification of diverse noise sources.

Against this background, a multi-stage deep clustering framework (Deep Embedded Clustering, DEC) has been proposed to automatically learn and classify urban noise wavefield features in the frequency domain. This approach enables the effective differentiation of various noise types, including far-field coherent train sources, near-field interference sources, and intermittent monochromatic sources. Building upon this classification, the signal-to-noise ratio of cross-correlation functions is improved by selectively stacking noise segments with higher coherency. This optimization has successfully extended the usable signal range, lowering the minimum frequency from approximately···

## 4 Hz

Two distinct types of trains are identified within the wavefield: high-speed trains, characterized by shorter continuous time intervals, and freight trains, which exhibit longer continuous time intervals. The wavefield in this domain demonstrates discrete spectral characteristics.

Figure Characteristics of train sources. (a) Two different categories of trains identified from the x t domain wavefield: the shorter continuous time segment indicates a high speed train, while the longer continuous time segment indicates a freight train. Panels (b) and (c) show the corresponding f k domain wavefields, which display discrete spectral characteristics.

Zhao, K., et al. proposed the DispFormer model, a Transformer-based architecture designed to address the challenges traditional deep learning methods face when processing practical dispersion data. Unlike models that rely on fixed-length inputs, DispFormer can directly handle measured dispersion curves characterized by variable period ranges, noise, or missing data points. By employing pre-training and physics-constrained strategies, the model achieves high-precision end-to-end inversion. This framework not only enhances computational efficiency but also reduces the subjectivity inherent in manual feature extraction and modeling through automated feature learning.

Although machine learning methods have demonstrated significant potential in noise identification and data processing, their physical interpretability remains limited. Currently, most research utilizes machine learning primarily for data preprocessing or parameter inversion stages, rather than fundamentally altering the theoretical framework of ambient noise interferometry. A critical direction for future research lies in integrating machine learning with traditional seismic physical models, such as through the development of Physics-Informed Neural Networks (PINNs).

Overall, urban ambient noise imaging technology has made remarkable progress over the past two decades, yet several key challenges persist. First, the distribution of urban noise sources is highly non-uniform, making it difficult for cross-correlation functions to strictly satisfy the diffuse field assumption; this can lead to systematic biases in the recovery of empirical Green’ s functions. Second, the low-frequency energy in urban noise is typically weak, which limits the capability for deep structural imaging. Furthermore, the massive volume of data generated by large-scale arrays presents new challenges for data processing and storage.

Future research is likely to achieve breakthroughs in several areas: establishing theoretical models applicable to non-uniform noise source conditions to more accurately recover Green’ s functions; combining high-density observations with traditional seismic arrays to achieve multi-scale joint imaging; integrating machine learning methods with seismic physical constraints to improve the reliability of inversion results; and utilizing stable vibration sources, such as urban rail transit, to conduct controlled passive-source imaging experiments.

With the continuous development of observation technologies and data analysis methods, urban ambient noise is expected to transform from a traditional interference into a vital geophysical exploration resource. This shift will provide a new technical pathway for high-resolution imaging of urban subsurface structures.

## References

## Application of Passive Source Surface Wave and Body Wave Imaging in Shallow Covered Areas of Inner Mongolia

### Abstract

In response to the challenges of geological mapping and mineral exploration in the shallow covered areas of Inner Mongolia, this study utilizes passive source seismic technology to conduct high-resolution imaging of the subsurface structure. By integrating ambient noise surface wave tomography and body wave imaging techniques, we successfully delineated the thickness of the sedimentary cover and the velocity structure of the underlying bedrock. The results demonstrate that passive source seismic methods provide an effective, low-cost, and environmentally friendly solution for geological investigations in regions with complex surface conditions.

### 1. Introduction

The shallow covered areas of Inner Mongolia represent a significant frontier for mineral resource exploration in China. However, the presence of loose Cenozoic sediments poses a major challenge for traditional geological mapping and geophysical prospecting. Conventional active source seismic methods, while high in resolution, are often limited by high costs and environmental restrictions in sensitive pastoral regions. Consequently, there is an urgent need for non-destructive, efficient geophysical techniques to characterize the subsurface structure in these areas.

Passive source seismic imaging, which utilizes ambient noise generated by natural and anthropogenic activities, has emerged as a powerful tool in regional and local scale investigations. By extracting the Green' s function from the cross-correlation of continuous seismic records, researchers can reconstruct the velocity structure of the crust and upper mantle. In this study, we apply both surface wave and body wave imaging techniques to high-frequency passive source data to achieve high-resolution imaging of the shallow crustal structure in Inner Mongolia.

## 2. Data and Methodology

**2.1 Data Acquisition** The seismic data were collected using a dense array of short-period seismometers deployed across the study area. The array configuration was designed to capture a wide range of ambient noise frequencies, spanning from 0.1 Hz to 20 Hz. Continuous waveforms were recorded over a period of several weeks to ensure sufficient signal-to-noise ratios for the cross-correlation process.

[Figure 1: see original paper]

**2.2 Surface Wave Tomography** We employed the Ambient Noise Tomography (ANT) method to retrieve Rayleigh wave phase velocity maps. The processing workflow included: 1. Pre-processing of single-station continuous data (temporal normalization and spectral whitening). 2. Cross-correlation of station pairs to obtain the empirical Green' s functions (EGFs). 3. Dispersion analysis using the frequency-time analysis (FTAN) technique to extract phase velocity

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## Application of Active and Passive Source Seismic Exploration in Metallic Mineral Prospecting

### Abstract

Metallic mineral resources serve as the essential material foundation for social and economic development. As shallow mineral resources are increasingly depleted, mineral exploration is progressively shifting toward deeper targets. Seismic exploration, characterized by its significant detection depth and high resolution, has become one of the primary methods for deep metallic mineral exploration. This paper provides a systematic review of the research progress and application status of active and passive source seismic exploration technologies in the context of metallic mineral prospecting. It summarizes the fundamental principles, technical characteristics, and typical application cases of various methods, including reflection seismology, vertical seismic profiling (VSP), and ambient noise tomography. Furthermore, the paper discusses the challenges faced by seismic exploration in complex metallic mining areas, such as low signal-to-noise ratios and complex wavefield characteristics. Finally, the paper looks forward to the future development trends of seismic exploration in metallic mineral prospecting, emphasizing the integration of active and passive sources, multi-parameter imaging, and the application of machine learning in seismic data processing and interpretation.

## 1. Introduction

Metallic minerals are critical strategic resources for national economic development. With the continuous increase in global demand for resources, the exploration of "deep earth" has become a strategic frontier in the field of earth sciences. Compared to traditional oil and gas reservoirs, metallic ore bodies are often characterized by complex geometric shapes, strong heterogeneity, and high velocity/density contrasts with the surrounding host rocks. These characteristics pose significant challenges for traditional geophysical exploration methods.

Seismic exploration technology, which utilizes the propagation characteristics of elastic waves in the subsurface to image geological structures and identify ore bodies, offers advantages in depth and resolution that other geophysical methods (such as gravity, magnetic, and electromagnetic methods) struggle to match. In recent years, with the continuous advancement of hardware equipment and processing algorithms, seismic exploration has evolved from a single active source method to a diversified technical system incorporating both active and passive sources.

## 2. Active Source Seismic Exploration Methods

Active source seismic exploration primarily utilizes artificial sources (e.g., explosives, vibrators) to generate seismic waves. It remains the most widely used method in metallic mineral exploration due to its controllable source parameters and high data quality.

**2.1 Surface Seismic Reflection Method** The surface seismic reflection method is the most mature technology in active source exploration. By analyzing the reflected waves from geological interfaces, it can provide high-resolution images of the subsurface structure. In metallic mining areas, this method is

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# Advances in Seismic Interferometry Autocorrelation Imaging Methods and Applications

## Abstract

Seismic interferometry (SI) is a technique that extracts the Green' s function between two receivers by performing cross-correlation, convolution, or deconvolution of seismic records. As a specialized branch of SI, seismic autocorrelation imaging utilizes the zero-offset retrieval property of the autocorrelation (AC) function to extract reflection responses directly beneath a single station. This method effectively transforms ambient noise or earthquake data into virtual source reflection records, providing a powerful tool for imaging the Earth' s internal structure without the need for active sources. This paper reviews the theoretical foundations of seismic autocorrelation, including the transition from 1D layered models to 3D heterogeneous media. We summarize the key processing workflows, such as noise suppression, spectral whitening, and phase recovery, and discuss the application of this method across various scales—from global lithospheric imaging and Moho mapping to local resource exploration and shallow environmental monitoring. Finally, we analyze current challenges and future trends, highlighting the potential of integrating machine learning and dense array observations to improve the resolution and reliability of autocorrelation imaging.

## 1. Introduction

The fundamental principle of seismic interferometry is based on the concept that the correlation of signals recorded at two sensors can provide the impulse response (Green' s function) between them, as if one sensor were a source and the other a receiver. While cross-correlation typically requires a distribution of sources surrounding the receivers, autocorrelation (AC) simplifies this by considering the case where the source and receiver are co-located.

In the context of global and regional seismology, autocorrelation has gained significant traction because it allows for the imaging of deep discontinuities (such as the Moho or the Lithosphere-Asthenosphere Boundary, LAB) using continuous ambient noise or the coda of teleseismic events. Compared to traditional receiver functions, AC imaging is less sensitive to the complexity of the source mechanism and can be applied to a broader range of seismic data.

## 2. Theoretical Foundations of Autocorrelation Imaging

The theoretical basis for extracting reflection responses from autocorrelation was first proposed by Claerbout (1968), who demonstrated that for a 1D layered medium, the autocorrelation of the transmission response is equivalent to the reflection response.

**2.1 The 1D Layered Model** For a vertically incident wave in a 1D acoustic medium, the relationship between the transmission coefficient $T(\omega)$ and the reflection coefficient $R(\omega)$ can be

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*Note: Figure translations are in progress. See original paper for figures.*