EARTHSCIENCES

Blind source separation in seismology: exploiting small-amplitude shaking to track ocean waves or subsurface structure

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Research theme(s):	• Geophysics and Geodynamics • Geodesy, Tectonics, Volcanology and related hazards
Eligible courses for this project:	• DPhil in Earth Sciences • Environmental Research (NERC DTP) • Intelligent Earth (UKRI CDT)

Overview

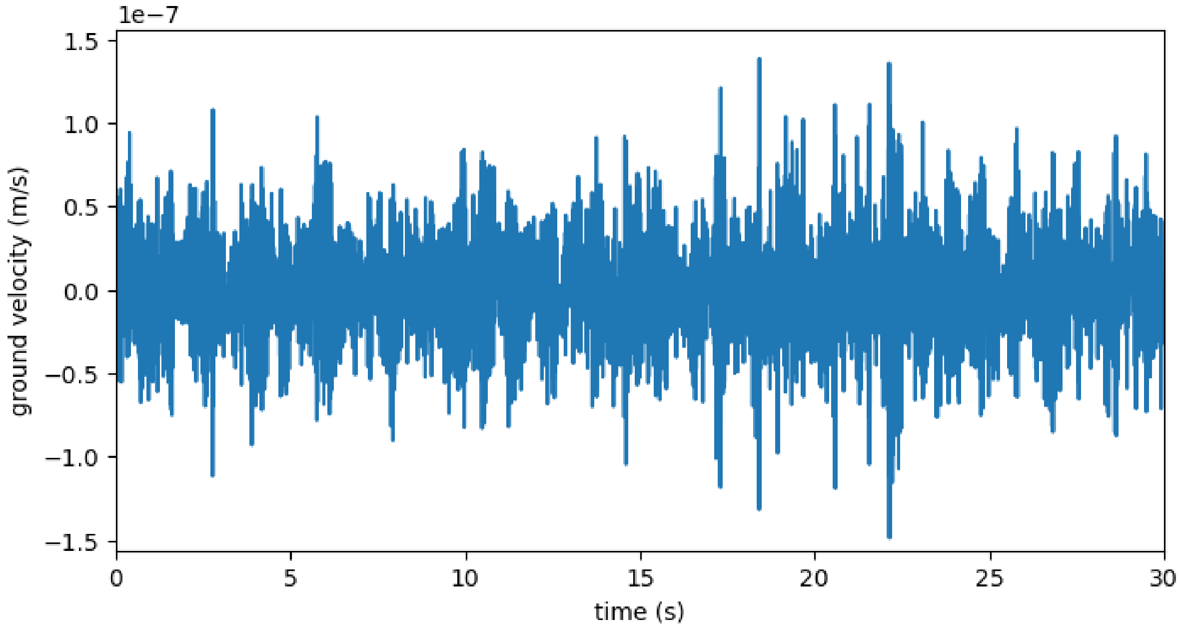
The surface of the Earth moves nearly continuously. It is shaken by wind, ocean waves, meteor impacts, earthquakes, cars, and trains, among other sources. Much of this shaking can be observed with modern, high-precision seismic stations. And much of the shaking is high-frequency (1 to >100 Hz); it thus has the potential to provide spatially detailed information about the sources—about wind, waves, earthquakes, and trains—and about the structure of the Earth or other planets.

To date, however, continuous seismic signals like wave noise have been dramatically underused. They have been hard to use because (1) long-duration seismic signals are complex and (2) there are often multiple sources active at a given time, creating overlapping signals. In this PhD, the student will use and develop cutting-edge tools to address these challenges: to disentangle complex seismic sources and thus probe the details of the Earth. They will build on source separation techniques common in speech processing to fully exploit the range of small-amplitude signals, be they ocean waves, traffic noise, or people chatting at a cocktail party.

A tool to separate complex sources will have a wide range of uses, and the student may choose what they wish to focus on and whether they wish to deploy their own seismic stations. Two example projects are described below, but other targets are possible: perhaps volcanic tremor, draining glacial lakes, or mountain streams.

In the first potential project described here, the student will identify coupling between ocean waves and the seafloor along a complex coastline. They may use their understanding to track localised regions of high seafloor pressure that could cause scouring or to probe connections between surface wave height, seafloor pressure, and bathymetry.

In the second potential project, the student will again identify a number of seismic sources---perhaps wind, waves, or anthropogenic signals. But instead of focusing on these sources, they will use the sources to image the Earth. The range of high-frequency seismic sources could illuminate the shallow (<1 km deep) subsurface in detail.



Ground shaking observed during storm Eunice in Pembrokeshire, Wales. Could you disentangle these observations to identify where wind pushes on trees and where ocean waves break on the seafloor?

Technique development: blind source separation in seismology

A recorded seismic signal is a function of two things: the source that generates the seismic waves and the path that the seismic waves travel from source to receiver.

recorded signal = source * path from source to receiver

Continuous signals like wave-induced shaking are hard to analyse because both of these components are complex; the source could consist of seafloor pressure variations at hundreds of locations, and the path reflects Earth structure at 100-m length scales.

In order to disentangle these complex sources, we need to do two things: (1) isolate the path component for each of the hundreds of locations and (2) use the estimated path components to separate the complex sources themselves.

To date, path isolation in seismology has been approached primarily with brute force, visual inspection, and synthetics. But these approaches are not good enough in taking advantage of the ever-increasing mountain of continuous seismic data. It is likely more useful to frame the path isolation problem as a blind source separation problem, as is common in underwater acoustics and speech processing. Our group has been working to develop source separation tools appropriate for complex, long-duration, and low-amplitude seismic sources. Major progress is possible here. The student may wish to use the newest tools from speech processing or go back to older tools and reconsider how we combine data from multiple stations. With these techniques, the student should be able to isolate the components of the seismic signals determined by the path with high precision.

Once the student has isolated the path components, they will be able to do two things. First, they may locate the sources and use the isolated paths to image the Earth.

Second, they may use the observations to track the temporal variations in the sources.   This, however, is still not an easy problem, as some of the paths could be similar, and some of the sources may vary similarly in time. To disentangle the various sources, the student will likely need neural network-based tools to identify and disentangle the paths' connections.

Potential Project 1: Exploring nearshore ocean wave dynamics

Any ability to localise sources from complex shaking has a variety of uses, and applicants are encouraged to propose applications they are particularly interested in. As one example, however, a student might explore seismic waves created by nearshore ocean waves, in order to probe wave and current dynamics.

They may begin by deploying an array of nodal seismic stations around a harbour or complex coastline. Nodal stations are quick to deploy, and the student could maintain an array of tens of stations for one to a few months.

They may use their source separation techniques to identify locations on the seafloor where ocean waves couple strongly to the solid earth—where large variations in seafloor pressure create strong seismic waves.

The student may examine how seismic sources vary with wave period, bathymetry, and time. They may ask if waves with certain periods couple strongly to a particular pattern of bathymetry. They may probe how wave frequency content changes with time as the ocean height varies in storms. And they may begin to model the kinematics of currents and scattering using the seismic wave observations.

Potential Project 2: Exploring the shallow subsurface

Alternatively, a student may choose not to focus on the particular sources of shaking. They may simply use their identified sources as probes of the shallow (<1 km deep) subsurface—to understand soil, regolith, and sediment structure, in addition to spatial-temporal variations in groundwater level. Such depths are often difficult to image because the short-wavelength features require nearby sources, and those nearby sources are often complex and difficult to separate.

Depending on interest, a student may choose to deploy an array of nodal seismic stations or to use individual stations that have already existed for years—on the Earth, Moon, or Mars.

They will use their source separation techniques to identify numerous seismic sources coming from within 10 km of the stations and will isolate the component of the shaking determined by the paths from the sources to the stations. Then they will invert for the shallow Earth structure by modelling speeds of surface and body waves.

Depending on interest, a student may invert for wave speed at a range of times to probe changes in groundwater level and consolidation, linking to themes around water resource stabililty and soil health. They may probe sediment structure to understand recent deposition or erosion. Or they may probe porosity near the lunar surface to understand impact-induced fracturing.

Sample Timeline

Year 1: training and literature review, consideration of approach, begin developing source separation techniques

Year 2: finalise source separation approach, identify range of seafloor sources, write technique and observation paper(s)

Year 3: probe behaviour of seafloor sources or groundwater through time

Year 4: further probe sources, develop physical models of currents or groundwater flow, write physical analysis paper and finalise thesis

Training & Skills

Over the course of the PhD, the student will develop strong skillsets in signal processing, seismic data analysis, and physical modelling. They will pursue formal and informal coursework in seismology, mathematics, machine learning, and water flow.

Attendance at a summer school is likely. Guidance and training will be available from supervisors as well as formal coursework. The student will benefit from a strong seismology group in the department and will develop connections with other students and colleagues in the UK and internationally.

The student will also be trained in written and in-person communication and present their work at various conferences.

This project would suit incoming students with a range of backgrounds, including geophysics, maths, computer science, engineering, ocean or environmental science, or physics. Undergrad-level knowledge of time series analysis and linear algebra would be helpful. Prior knowledge of seismology is useful but by no means required.

References & Further Reading

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Further Information

Contact: If you're interested, please do get in touch with Prof. Jessica Hawthorne (jessica.hawthorne@earth.ox.ac.uk) to have a chat about which aspects of the project you think you'd like to focus on.