John Edwards

Signal Processing Enhances Environmental Sensing

Sensors and other data sources, combined with sophisticated signal processing techniques, promise to help scientists better observe and analyze various types of environmental data.

Biologist Nathan Merchant, for example, has created a method for tracking ships and monitoring underwater noise levels in protected marine mammal habitats. Merchant, senior scientist for underwater noise at the U.K. Centre for Environment, Fisheries, and Aquaculture Science (CEFAS), developed the system with coresearchers Enrico Pirotta, Tim Barton, and Paul Thompson, of The Institute of Biological and Environmental Sciences at Scotland's University of Aberdeen.

"Underwater noise levels have risen significantly over time in step with human activity," Merchant says. These changes in the acoustic environment affect marine mammals, which rely on sound as their primary sensory mode. "The disturbance caused by man-made noise can disrupt crucial activities, such as hunting for food, affecting the animals' health."

To help understand the impact noise might exert on dolphins and their population levels, the researchers conducted a study on Moray Firth, Scotland's largest inlet (Figure 1). Moray Firth is home to a population of bottlenose dolphins as well as numerous types of seals, porpoises, and whales. The protected habitat also hosts construction yards that supply Scotland's rapidly expanding offshore wind farm industry. Projected increases in wind farm construction are expected to drive more shipping through the habitat—something many scientists believe could eventually negatively impact resident marine mammals.

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"Various types of ships emit noise at different levels and frequencies, therefore it is vital to know which kinds of vessels are crossing the habitats and migration routes of marine mammals," Merchant says. Merchant and his fellow researchers recently monitored underwater noise levels using hydrophone sensors (underwater microphones), ship-tracking data, and shore-based time-lapse photography. The techniques created a ship-noise assessment toolkit.

"In this project, we used signal processing techniques to integrate several different data sources into one package: time-lapse video, underwater sound recordings, and ship-tracking data," Merchant says. Using signal processing techniques in combination with video editing software, the researchers combined video, audio, and spatial data to produce a synchronized audiovisual representation of the soundscape, including shipping activity and weather conditions across the marine mammal habitat.

The main challenge the researchers faced was processing each data source in a way that would supply a common time resolution for the audiovisual output. "We used geolocation tools to map the ship tracking data through time, which involved temporal and spatial interpolation of the raw data, which has a fairly coarse, ~10 minute time resolution," Merchant explains. "The sound recordings were averaged at intervals that corresponded to the time resolution of the video and spatial data, and an adaptive thresholding algorithm was also developed which detected when a ship was passing."

The approach, Merchant says, allowed the researchers to link diverse data sources and gain insights into the habitat's sonic environment in a way that would not have been possible by interpreting each data source individually. "The integrative approach produced a ship noise assessment analysis that was much more than the sum of its parts," Merchant adds.

One of the main difficulties in studying underwater sound is that long-term recordings generate vast amounts of acoustic data—several terabytes in the case of this project. "Consequently, we have had to develop high-performance computing techniques for processing big data, which involved using parallel processing across many cores of a large server or cluster," Merchant says. "Now that we have these in place, we can process large datasets rapidly, but getting there was quite a challenge."

Merchant notes that the biggest challenge he currently faces is developing models to predict how sound will spread through an underwater area, which would enable the researchers to produce maps of sound levels in a particular habitat. "This [capability] can be used in environmental impact assessment of noisy activities, like offshore wind farm construction, because it shows us over how big an area marine mammals could potentially be disturbed," Merchant says. "We are currently refining and testing scripts using data from several field studies."

According to Merchant, there is an almost endless number of coastal areas where shipping interacts with nearby habitats. "Not only... marine mammals but also fishes and invertebrates, which we are aware are also sensitive to noise," he says. "The techniques that have been developed in this project can very much be applied to assess what kind of ships are making noise, what kind of noise level is generated, and how they are concentrated spatially, as well as how all of this interacts with the habitats."

Merchant also believes that the new techniques will spin off applications extending far beyond marine habitat

[FIG1] Researchers deploy a hydrophone sound sensor in Scotland's Moray Firth as a dolphin surfaces nearby. (Photo courtesy of U.K. CEFAS.)

protection. "There will potentially be a lot of people interested in being able to, for example, detect when ships are passing along a corridor that's on a tracking system," he adds. "We are aware that there might be some interest in doing that kind of thing [from] Coast Guard and military types."

FOLLOWING URBAN VIBRATIONS

Urban traffic—including cars, trucks, trains, and planes—generates both acoustic and seismic noise. While most people can easily detect vehicle noise, seismic vibrations are usually not perceptible to humans. Nevertheless, a pair of researchers at the Scripps Institution of Oceanography at the University of California at San Diego believe that seismic "noise" could soon become a useful data source for next-generation traffic information systems.

While the detection of naturally occurring seismic vibrations has long been useful to scientists searching for subsurface features like earthquake faults and petroleum resources, the various types of vibrations generated by traffic flows have never been explored in any real depth, says Nima Riahi, a Scripps postdoctoral fellow working alongside Peter Gerstoft, a Scripps geophysicist. The pair believes that a future urban seismic network could tap into vehicle-generated vibrations to monitor the flow of human transport across a specific area.

Last year, energy company Signal Hill Petroleum of Signal Hill, California, gave the researchers access to a large vibration data set covering the area under the city of Long Beach, California. "We seized the opportunity," explains Riahi. The data set—mapped by a 5,300-geophone network—was as part of a hydrocarbon industry survey covering an area of more than 7×10 km (Figure 2). Geophones are devices commonly used by private, government and academic researchers to record energy waves reflected by subsurface geology, typically as a way of mapping out geologic structures or tracking earthquakes.

"By analyzing vibrations from geophones spaced approximately 100 m (300 ft) apart, we were able to examine activity in Long Beach with a resolution below a typical city block," Riahi adds. He notes that the spatiotemporal structure of the man-made seismic noise intensity revealed individual train activity along the area's Blue Line Metro railway line, allowed the counting of departing and landing aircraft at Long Beach Airport (as well as estimating their motion) and gave clues about traffic movement along Interstate 405, a major southern California freeway. More advanced analysis techniques and algorithms promise to reveal many other types of manmade signals within the ground, Riahi says, potentially leading to the monitoring of activities beyond traffic flow.

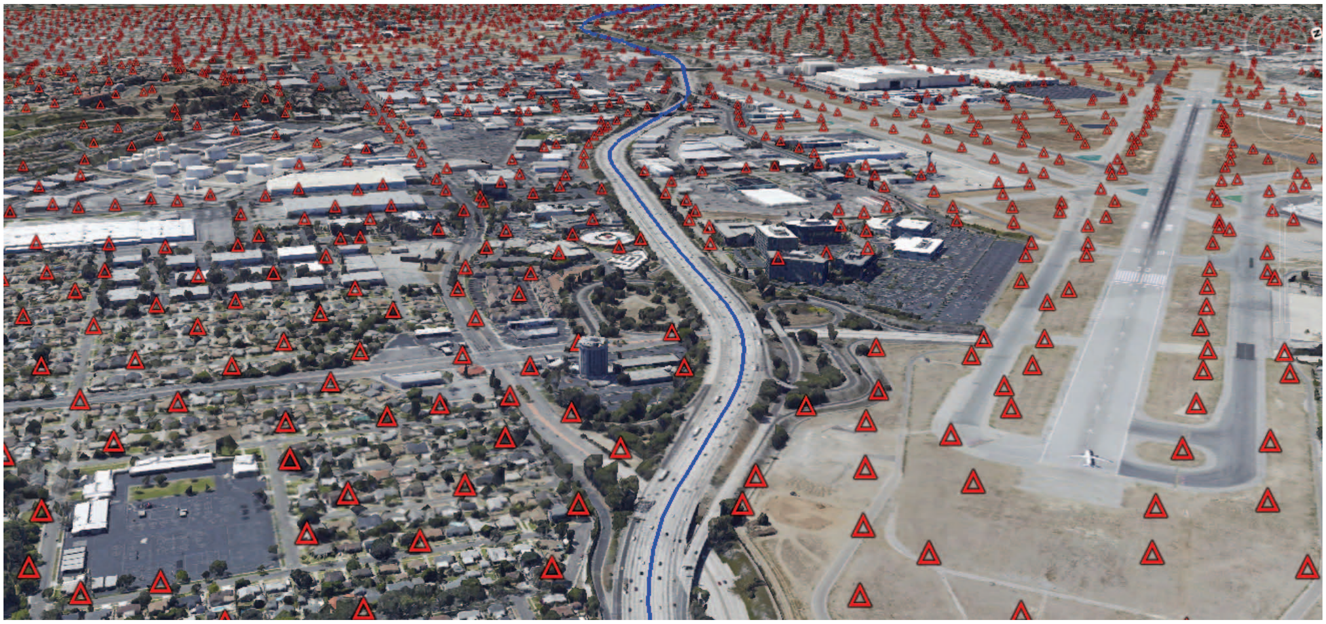
"The findings indicate that human seismic noise might serve as a rich data source for the observation of cities," Riahi says. "The approach could also be used for urban area characterization, allowing various types and schedules of activities to be visualized, making it possible to vibrationally identify specific industrial, residential or office zones."

Riahi describes the research accomplished so far as "simple and straightforward" signal processing. "We tried to keep it simple at first. It is essentially calculating the power of the vibration as a function of time." A custom-design spatiotemporal filter was also used to remove vibrations that failed to match a pattern indicating a type of ongoing movement, such as a train traveling down a track.

The researchers are only interested in examining various types of continuous vibrations, which exist in many different variations. "There are a lot of things happening: day/night variations, trucks passing, which might be different than when a car passes," Riahi says. "We want to see if there are similarities between different things; can we group things together, like in cluster analysis?"

Freeway traffic proved to be more difficult to discern and analyze than train or airport movements. "The 405 is challenging because it is a ten-lane highway, two directions," Riahi says. "We had about 13 sensors per kilometer of highway—that is really a low spatial sampling." Yet, although they were restricted to only a limited number of sensors, the researchers were still able to detect individual trucks moving along the roadbed at night. "We know that, because there is a continuous motion detected from one sensor to the next at about 55 miles per hour going through the entire stretch of the 405 section we were looking at," Riahi explains.

Finding seismic needles in a geological haystack required Riahi and Gerstoft to



[FIG2] An aerial view of Long Beach, California, showing a portion of the 5,300-geophone network. Interstate 405 runs through the photo's center; a Long Beach Airport runway is on the right. (Photo courtesy of Scripps Institution of Oceanography at the University of California at San Diego.)

consider a wide range of approaches. "Clustering techniques are an interesting path to pursue when you are just trying to look for structure in the data," Riahi remarks. The team investigated the potential of various clustering algorithms. "One of them, obviously, is *K*-means, which is a popular but nonoptimal clustering algorithm," Riahi says. "There are also algorithms based on sparse coding and sparse reconstruction, where you are saying, 'I have some signal, I think it is composed of a few elemental components and I am trying to find out which one it is.'"

According to Riahi, the spatiotemporal filter required significant creativity. "I had to custom-write that filter because I was not aware of anything that would work for our data," Riahi says. "There were other options; I tried image processing filters, for instance, but the ones that I came across and tried out did not work so well."

Riahi says the study showed that anthropogenic seismic power—a relatively simple attribute—when analyzed with a dense grid of urban seismic sensors, can measure a wide range of human activities. "The human imprint on the seismic wave field provides a rich, but so far underappreciated, data source to observe cities," Riahi remarks.

MEASURING SEA LEVELS FROM SPACE

A new way of measuring sea levels, developed by researchers at Sweden's Chalmers University of Technology, promises to generate faster and more accurate readings. Measuring sea level is an important part of climate research, since a rising mean sea level is a key indicator of climate change.

Johan Löfgren and Rüdiger Haas, research scientists at Chalmers' Department of Earth and Space Sciences, have created a Global Navigation Satellite System (GNSS) tide gauge, an instrument that measures sea level by using radio signals from satellite navigation systems. "We want to be able to make detailed measurements of sea level so that we can understand how coastal societies will be affected in the future," Löfgren says.

The GNSS tide gauge uses radio signals from Earth-orbiting satellites within satellite navigation systems like global positioning system (GPS) and Glonass (Russia's equivalent of GPS). Two antennas measure signals directly from the satellites and signals reflected off the sea surface (Figure 3). By analyzing these signals together, the sea level and its variation can be measured up to 20 times per second.

[FIG3] When a satellite passes overhead, the GNSS tide gauge uses signals from the satellite and signals reflected off the sea surface to measure the current sea level. (Photo courtesy of Onsala Space Observatory/J. Löfgren.)

The GNSS tide gauge has an advantage over previous technologies in that it can measure changes in both land and sea simultaneously in the same location. Therefore, both long-term and short-term land movements can be taken into

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consideration. The separation of sea level and land motion change is a matter of great importance for global change research, Löfgren says. "How much does the sea level change in different parts of the world and what are the causes of this change?"

The researchers note that existing coastal GNSS stations, installed primarily for the purpose of measuring land movements, can be easily adapted to make sea level measurements. "We have successfully tested a method where only one of the antennas is used to receive the radio signals," Löfgren says. "That means that existing coastal GNSS stations—there are hundreds of them all over the world—can also be used to measure the sea level."

Löfgren regards signal processing as essential to his research. "What I want to do is to convert my GNSS measurements into measurements of sea level in the most accurate way possible," he remarks. "Most of the signal processing is more or less standard in the GNSS world, but I have applied it on a new and different data set."

For the two-antenna technique, Löfgren determines the vertical distance between the upward-looking and the downward-looking antenna (the downward-looking antenna will appear to be a virtual antenna below the sea level, since the reflected signal will travel an additional path compared to the direct signal). "The signal processing is done by analysis of the phase of the recorded signals," he says. "An observational model is set up for the difference in recorded phase between the two antennas (incorporating clock differences in the receivers, differences in geometry and differences in the phase ambiguity parameter), and it is then fitted in a least squares sense to the phase observations."

For the one-antenna technique, a different type of signal processing is applied. "The interference between the direct and the reflected signals can be seen as oscillations in the signal-to-noise ratio (SNR) observable," Löfgren says. "With the assumption of a horizontal non-moving sea level, the frequency of these oscillations is constant with respect to the sine of the satellite elevation angle." This means that the oscillations first need to be found and extracted from the data. Next, the oscillations' frequency content (with respect to the sine of the satellite elevation angle instead of the usual time) should be found either by Fourier transform or a Lomb-Scargle periodogram (LSP), Löfgren says. Finally, the main oscillation frequency must be converted to the distance between the antenna and the reflection point, which is directly proportional to the sea level.

"In both the one- and two-antenna methods, the actual installations that measures reflected signals are already set up," Löfgren says. This means that the geodetic GNSS receivers are first applying some kind of signal processing when they record the satellite signals. "What I am using as techniques are least squares analysis [for the] two-antenna technique, and LSP [for the] one-antenna technique."

For the project's next step, the researchers are looking toward developing multi-GNSS solutions, possibly even combining GPS and GLONASS signals together to increase the number of observations in a combined phase delay analysis, providing more accurate sea level estimates. The combination of GPS and GLONASS for SNR analysis is expected to increase the temporal resolution of the corresponding sea level results.

After that step is accomplished, the goal will be to use multi-GNSS, multi-frequency, phase delay, and SNR analysis in a filter approach. "Doing so, we expect that it will be possible to derive continuous and accurate absolute GNSS sea level time series in a wide range of wind speeds," Löfgren says.

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