Physics

VIEWPOINT

Acoustic Experiments without Borders

A new approach to laboratory acoustic experiments could remove unwanted effects caused by the reflections of acoustic waves from the boundaries of the experimental setup.

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To image Earth's subsurface at depths of up to 50 km, geophysicists often use imaging techniques based on the principles of seismology. These seismic experiments—much like medical ultrasounds—involve measuring how acoustic waves are scattered from the subsurface. For instance, in a marine seismic experiment, an array of air guns creates an acoustic signal that propagates through the water and into the subsurface. A vessel towing kilometer-long receiver cables then records the waves scattered from the subsurface, from which the subsurface geometry can be reconstructed (Fig 1).

Seismic methods have steadily improved over the past decades [1], mostly driven by applications in hydrocarbon exploration but also by scientific purposes such as the study of Earth's crust. But reconstructing the subsurface geometry from acoustic measurements remains an inherently complex process. To test seismic-wave-propagation models and image reconstruction techniques, researchers would like to carry out controlled, smaller-scale laboratory experiments. In contrast to experiments performed in open environments, however, laboratory schemes are inevitably restricted by the walls of the experimental setup. Now, Theodor Becker at the Swiss Federal Institute of Technology (ETH) in Zürich and colleagues have experimentally demonstrated an approach to laboratory seismic experiments known as immersive wave propagation. This approach can effectively make the boundaries transparent, eliminating unwanted reflections and making the experimental enclosure function as if it were bigger than it is [2]. While demonstrated for a 1D channel, the authors' approach could soon be extended to 2D and 3D configurations.

Among the many challenges facing seismic experiments, two are particularly daunting. First, for seismic modeling and imaging purposes, one often assumes that Earth's crust

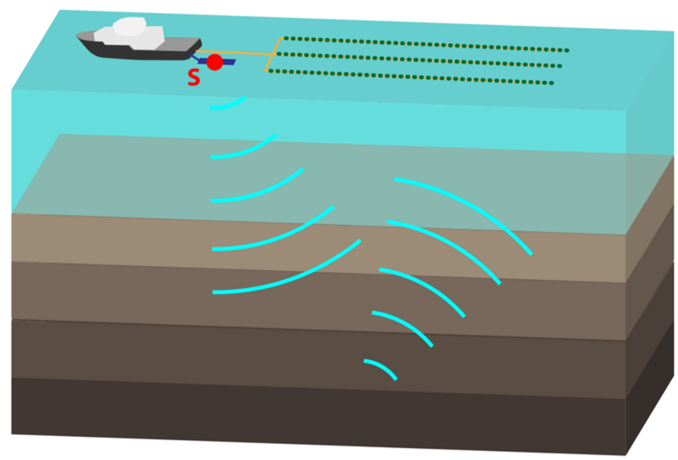

Figure 1: Scheme of a marine seismic survey. A source (S) on a vessel generates an acoustic signal that propagates through the water and into the subsurface. The vessel tows kilometer-long cables with sensors that record the waves reflected from the subsurface. The timing, amplitude, and frequency of the reflected waves yield information about Earth and its subsurface structures. (APS/Alan Stonebraker)

can be described as an elastic medium in which attenuation can be neglected. This assumption is invalid in many practical cases. The second challenge stems from the fact that image reconstruction is an inverse problem: from a set of acoustic-wave measurements, one reconstructs the topography that has produced such waveforms. For the problem to be well posed, one has to carry out a sufficient number of measurements to constrain the many unknown parameters characterizing the complex subsurface structure. Even though a typical 3D seismic survey of a 200×200 km^2 area collects several terabytes of data, the surface parameters are often not fully constrained.

Laboratory experiments could help researchers tackle these challenges by offering a controlled platform for studying the effects of attenuation and for optimizing data collection strategies. Lab setups, however, have important limitations. Their scales are by necessity thousands of times

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smaller than the kilometer-scale Earth structures they aim to represent. What's more, experiments have to be carried out in an enclosure, typically a tank, of finite size. The multiple and complex acoustic reflections from the walls in the tank make it hard to compare field data with laboratory data. A setup in which the boundaries could be made "transparent" would eliminate the reflection problem and effectively expand the tank size. An intuitive solution would be to use absorbing layers that attenuate the waves that are backscattered at the boundaries. However, such methods cannot completely solve the problem, mostly because there are no perfect absorbers that work for a broad range of acoustic frequencies.

To overcome the limitations of passive absorbers, researchers have theoretically explored methods involving active sources that cancel reflection through destructive interference. A seminal proposal was put forward by Rune Mittet in 1994 [3]. Using numerical modeling, Mittet demonstrated that if one records the wave field at a surface surrounding the volume of a seismic experiment, a proper combination of monopole and dipole sources placed at the surface can exactly reproduce an arbitrary elastic wave field within the volume (Fig. 2). Building on this conclusion, other researchers showed that this reconstruction process can be used to generate a field that exactly cancels out the effect of reflections at the boundaries [4–6], leading to the proposal of the method of immersive wave propagation.

Becker *et al.* have now turned these theoretical ideas into a physical experiment. The team uses active, computer-controlled monopole sources at the boundaries. In principle, both monopole and dipole sources would be needed for a perfect cancellation of boundary scattering, but acoustic dipole sources are challenging to engineer. Becker *et al.* replace the dipole-source contributions by inserting a boundary layer that has an effective reflection coefficient that depends on frequency. This approach is similar to recently developed active anechoic chambers [7], which use noise-canceling sources to eliminate echoes from wall reflections. Active chambers can have better performance than passive ones (which are based on absorbing coatings on the walls), in particular, in the low-frequency range below 70 Hz.

The team provides the first proof-of-principle demonstration of immersive wave propagation by carrying out experiments in a $\sim$ 145-cm-long, 1D sound-wave tube filled with air. They generate acoustic waves with a loudspeaker at one end of the tube and place immersive sources at the other end of the tube. The immersive wave propagation method requires characterizing, at one point along the tube, the in- and out-going wave fields in real time. The authors do this by measuring both the pressure field and its gradient with two microphones located 51 cm away from the source. The results show that the immersive wave propagation scheme leads to a more than 95% reduction in reflected energy from the boundary, over a frequency range of three octaves (0.6–5.6 kHz).

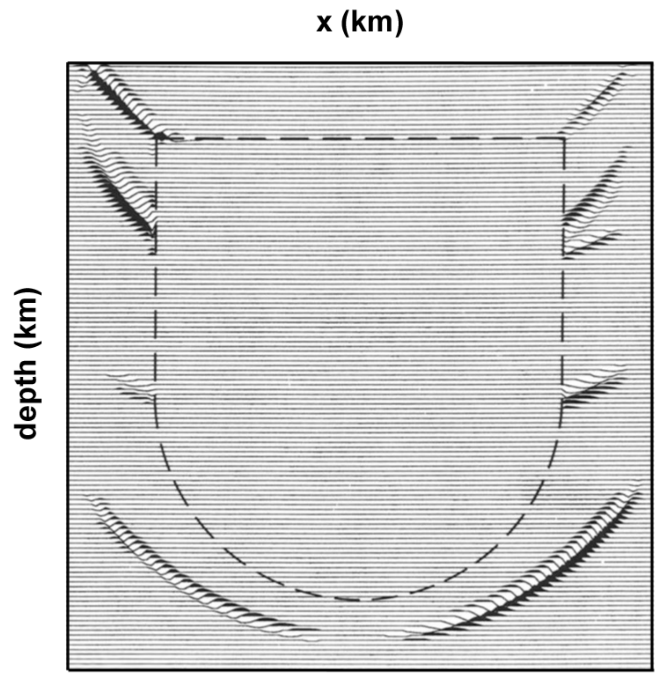

Figure 2: Plot showing the difference between an input wave field that propagates through the experimental region and its reconstruction, as calculated by Mittet [3]. The reconstructed wave field is generated by acoustic sources based on measurements of the original wave field at the boundaries of the experiment (shown by the dashed line). The difference between the reconstructed and input field vanishes within the experimental region. (R. Mittet [3])

The authors have demonstrated immersive wave propagation in a 1D configuration and for a narrow range of frequencies around 2 kHz. To extend it to a broader frequency range and to 3D, the researchers will need to answer several questions: What is the optimal number of sensors for a scheme in 3D? How closely spaced do they have to be, and will they interfere with each other? How will the structure supporting the sensors impact the wave field? Can monopole sources generate sufficient energy at low frequencies for the scheme to work? Despite these challenges, we believe that this new acoustic technique will open new possibilities for experiments and significantly reduce the gap between experiments in the field and those in the lab.

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Correction (23 July 2018): The article was revised to correct several details about the experimental setup. Specifically, the sound-wave tube is filled with air, not water; the acoustic waves are generated with a loudspeaker, not a microphone; and the distance of the microphones from the acoustic-wave source is 51 cm, not 95 cm

REFERENCES

[1] M. Landrø and L. Amundsen, Introduction to Exploration Geophysics with Recent Advances (Bivrost, Trondheim, 2018); https://bivrostgeo.no/wp-content/uploads/2018/04/IEGRA-92-preview-red.pdf.

[2] T. S. Becker *et al.*, "Immersive Wave Propagation Experimentation: Physical Implementation and One-Dimensional Acoustic Results," Phys. Rev. X **8**, 031011 (2018).

[3] R. Mittet, "Implementation of the Kirchhoff Integral for Elastic Waves in Staggered[U+2010]Grid Modeling Schemes," Geophys. **59**, 1894 (1994).

[4] D.-J. van Manen, J. O. A. Robertsson, and A. Curtis, "Exact Wave Field Simulation for Finite-Volume Scattering Problems," J. Acoust. Soc. Am. **122**, EL115 (2007).

[5] M. Vasmel, J. O. A. Robertsson, D.-J. van Manen, and A. Curtis, "Immersive Experimentation in a Wave Propagation Laboratory," J. Acoust. Soc. Am. **134**, EL492 (2013).

[6] F. Broggini, M. Vasmel, J. O. A. Robertsson, and D.-J. van Manen, "Immersive Boundary Conditions: Theory, Implementation, and Examples," Geophys. **82**, T97 (2017).

[7] D. Habault, E. Friot, Ph. Herzog, and C. Pinhede, "Active Control in an Anechoic Room: Theory and First Simulations," Acta Acust. united Ac. **103**, 369 (2017).

10.1103/Physics.11.71