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Introduction to the supplement on seismic interferometry

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In 1968, J. F. Claerbout derived a remarkable relation between the transmission and reflection responses of a horizontally layered medium, bounded by a free surface (Claerbout, 1968). He showed that autocorrelation of the transmission response is equal to the reflection response plus its time-reversed version (plus an impulse at time zero).

This implies that when one measures the response of a plane-wave source in the subsurface by a geophone at the free surface, the reflection response is obtained simply by taking the causal part of the autocorrelation of the observed response. Primary as well as multiple reflections are recovered correctly by that procedure. The source wavelet in the recovered reflection response is equal to autocorrelation of the source signal in the subsurface.

Hence, if one would measure the response of a band-limited white-noise source in the subsurface, the autocorrelation would give the impulsive reflection response, convolved with a band-limited delta function. This shows that noise observed at the surface can be turned into a signal with information about the subsurface. The principle of using passive-noise measurements to derive the reflection response and subsequently form an image of the earth's interior was called *acoustic daylight imaging*.

Later, Claerbout conjectured that his relation could be generalized for offset measurements in 3D inhomogeneous media, i.e., that by crosscorrelating noise traces recorded at two locations on the surface, one can construct the wavefield that would be recorded at one of the locations as if there were a source at the other. Since its conception, several attempts have been made to make this idea work on real data, some more successful than others (Scherbaum, 1987a, 1987b; Cole, 1995; Daneshvar et al., 1995; Rickett and Claerbout, 1999). The first convincing results have been obtained by solar seismologists (Duvall et al., 1993).

In the exploration-geophysics community, the research on retrieving information from crosscorrelations received new momentum after a sabbatical stay of Gerard T. Schuster at the Stanford Exploration Project in 2000. He applied the correlation method not only to passive data but also to exploration seismic data with man-made sources. Schuster introduced the concept of interferometric imaging, which involves an integration of crosscorrelation and migration. He supported his interferometric-imaging method by an elegant theory based on stationary phase analysis (Schuster, 2001; Schuster et al., 2004).

Schuster's coworkers at the University of Utah, notably Jianhua Yu and Jiaming Sheng, successfully applied his method to various types of data, including shot records, VSP data, and drill-bit data.

In the meantime, the Delft Applied Geophysics group developed a theory based on seismic reciprocity, which formally generalizes Claerbout's relation between transmission and reflection responses to 3D inhomogeneous acoustic and elastic media (Wapenaar et al., 2002). Draganov et al. (2003) confirmed this theory with numerically modeled data in laterally varying media.

Mathias Fink at University of Paris VII pioneered an initial independent field of research in the early 1990s, making use of the invariance of the wave equation to time reversal. Through various physical-modeling tests using ultrasonic transducers, Fink's group showed that strongly scattered wavefields could be time-reversed and back-propagated through the complex medium to result in a focused wavefield (Fink, 1997). Researchers around the world in different disciplines were amazed at the robustness of the time-reversal process in cases governed by severe multiple scattering, and this led to a renewed interest in the use of the multiply scattered coda (Snieder and Scales, 1998; Snieder et al., 2002).

Since the beginning of the new millennium, various research groups in other fields of science have discovered independently that crosscorrelation of signals at two different receivers in an acoustic diffuse field yields the response at one of the receiver positions as if there were a source at the other. This work was pioneered by Weaver and Lobkis (2001, 2002) in ultrasonics and by Campillo and Paul (2003) in seismology. These and other researchers speak of Green's function reconstruction. The assumed diffusivity in their theory can be caused by multiple scattering among heterogeneities in a disordered medium, reverberations in an enclosure with an irregular bounding surface, a random distribution of uncorrelated noise sources, or any combination of those causes. Roux and Fink (2003) obtained similar results for underwater acoustics, assuming a wavefield consisting of orthogonal modes in a waveguide.

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Since 2003, researchers in different fields have become aware of one another's results and started to make links among the different approaches. In time-reversed acoustics, Derode et al. (2003) showed that recording a time-reversed wavefield at a second point other than the original source point yields the Green's function between the two points.

Equivalently, the central idea in all cases of interferometry is that the crosscorrelation of signals at two observation points tends to yield the impulse response between those points, which explorationists call the reflection response and physicists and seismologists call the Green's function.

The main differences between the various approaches are found in the underlying assumptions: Whereas explorationists consider deterministic media, the main underlying assumption in the theory of Weaver and Lobkis (2001) and others is that the wavefield is diffuse because of any of the causes mentioned above. The approaches converge for the situation of uncorrelated sources in a deterministic medium, where *uncorrelated sources* should be interpreted in a broad sense, including transient sources sufficiently separated in time.

Since 2003, the research on retrieving new responses from crosscorrelations has taken an enormous flight, in exploration geophysics and in ultrasonics, seismology, and underwater acoustics. During the SEG annual meeting in 2004, Gerard Schuster, who was then the editor of SEG, asked us to compile a supplement for GEOPHYSICS, dedicated to this emerging branch of science. The result is the 21 papers published in this supplement.

We decided to name the supplement *Seismic Interferometry*. The term *interferometry* is borrowed from radio astronomy, in which it refers to crosscorrelation methods applied to radio signals from distant objects.

To stimulate cross-fertilization among seismic exploration, ultrasonics, and seismology, we invited researchers from outside seismic exploration as well and asked them to explain their methods and indicate possible applications for applied geophysics.

Many of the papers in this supplement have been presented at the workshop titled "Seismic Interferometry, Daylight Imaging and Time-Reversal," organized in connection with the SEG annual meeting in 2005.[4]

We have grouped the papers into three main categories (the same as in the workshop). These are (1) Green's function reconstruction, (2) redatuming, and (3) imaging. Any ordering of papers is to some extent subjective and arbitrary. Within those categories, where appropriate, we have subdivided into methods employing diffuse wavefields versus those for which the medium and wavefield are assumed to be deterministic.

We hope you enjoy reading this supplement just as much as we enjoyed preparing it.

Green's function reconstruction: Diffuse wavefields

Weaver and Lobkis show that practical passive imaging using correlations of diffuse fields is good, but laboratory and field measurements sometimes fail to fully or faithfully converge to the precise Green's function. The authors review recent measurements and recent developments in theory and ascribe the differences to incomplete convergence in some cases and to nonfully diffuse fields in other cases.

Larose et al. give an overview of the theoretical foundations for passive imaging techniques based on correlation of random wavefields. The authors present applications of the method to ultrasonic nondestructive testing and seismic tomography.

Gerstoft et al. use crosscorrelations of seismic-noise data from 151 stations in southern California to extract group velocities of surface waves between station pairs for determining surface-wave velocity structure.

Green's function reconstruction: Deterministic wavefields

Wapenaar and Fokkema derive exact representations of Green's functions between any two points in an arbitrary inhomogeneous medium in terms of crosscorrelations of wavefield observations at those points. These representations form a theoretical basis for seismic interferometry.

Van Manen et al. propose an efficient and flexible interferometric modeling scheme for wave propagation in arbitrary inhomogeneous elastic media. After systematic illumination of the medium from a surrounding surface, Green's functions between arbitrary points in the volume can be computed using only crosscorrelation and summation.

Draganov et al. use numerical experiments to show how to reconstruct the reflection response from crosscorrelation of the transmission response from deterministic media. The authors show this for acoustic and elastic media for the case of separate measurements from transient subsurface sources as well as for the situation of simultaneously acting white-noise sources in the subsurface.

Fan et al. develop an algorithm to remove free-surface multiples for teleseismic transmission and to construct reflection responses. This approach integrates the one-way reciprocity and the inverse-scattering series in the teleseismic framework.

Van Wijk demonstrates a controlled ultrasonic laboratory experiment that provides detailed analysis of retrieving a band-limited estimate of the Green's function between receivers in an elastic medium. Instead of producing a formal derivation, this article refers to a series of intuitive operations, common to geophysical data processing, to understand the practicality of seismic interferometry.

Poletto and Petronio discuss the use of transmitted waves using autocorrelogram interferometry techniques with a tunnel-boring machine (TBM) as a seismic source. The approach, which offers the advantage of obtaining reflections from the transmitted (front) wavefield, is used to improve prediction of fractures ahead of the TBM.

Mercier et al. present a novel deconvolution technique to improve retrieval of the Green's functions from passive-source data, particularly teleseismic data. They successfully demonstrate application of this method to data from three stations of the Canadian National Seismic Network.

[4]The presentations of the above-mentioned workshop can be found at http://www.geos.ed.ac.uk/homes/acurtis/SEG2005Interferometry.html.

Redatuming: Deterministic wavefields

Schuster and Zhou review the theory underlying redatuming methods which effectively time-shift traces using natural or model-based traveltimes. The model-based traveltimes are computed from an a priori velocity model. The correlation-based redatuming methods use natural phase information in the data to time-shift weighted traces so that they appear to have been generated by sources (or recorded by geophones) shifted in location. The correlation-based redatuming methods differ in their choice of trace weights and are superior to model-based methods because they do not require a velocity model and they eliminate statics at the source and/or receiver locations.

Snieder et al. show that correlation of single-reflected waves can be used to recover primary reflections. In addition, artifacts that behave as spurious multiples may be introduced.

Weglein et al. present several distinct approaches that derive from inverse-scattering series concepts that input measured reflection data and predict the wavefield at depth and the transmitted wavefield. These maps are realizable without the traditional need for subsurface information or phase assumptions about the reflection data.

Bakulin and Calvert propose a new way of imaging in complex geologic media by placing downhole geophones below the most complicated part of the overburden. By measuring transmission responses and applying time-reversal logic, the surface shots are redatumed to downhole locations without the overburden velocity model, thus explaining the term *virtual source method*.

Imaging: Diffuse wavefields

Fink shows that a time-reversal mirror acts as an antenna that uses complex environments to appear wider than it is. The author investigates this property for various media.

Borcea et al. describe a coherent interferometric approach for imaging in clutter, in which they migrate crosscorrelations of the traces over appropriately chosen space-time windows rather than the traces themselves. The space-time windowing leads to a statistical smoothing of the data and therefore to reliable results in clutter, at the cost of some blurring, and the optimal trade-off between stability and resolution can be achieved adaptively during image formation.

Artman shows that direct migration of passive seismic-field data can produce appropriate images of the subsurface even while simultaneously processing wavefields from multiple sources without demanding that they be random (uncorrelable) time series. The author uses synthetic data and a meter-scale experiment to show the efficacy of the approach.

Imaging: Deterministic wavefields

Zhou et al. present a reduced-time migration method and an interferometric migration method with seminatural Green's functions for seeing beneath salt when the migration velocity in the salt and above is not well known. Synthetic and field CDP data tests show that by picking reflection traveltimes from a reference layer beneath salt, both methods can significantly mitigate kinematic defocusing effects caused by errors in the overburden velocity model.

Xiao et al. describe how VSP interferometric imaging of transmitted PP and PS waves can delineate the flanks of salt bodies. This method does not require the migration-velocity model of the salt or upper sediments to image the salt flank.

Berkhout and Verschuur show that multiples traditionally have been considered as noise and are discarded after removal. The authors argue that multiple reflections contain a wealth of information that can be used in seismic processing to improve resolution of reservoir images beyond current capability.

Shragge et al. detail how shot-profile migration can be tailored to image teleseismic wavefield-coda data based on interferometric principles. The authors (1) develop a 2.5D imaging procedure that enables kinematic and structural imaging using recorded transmission and free-surface reflected passive wavefields and (2) demonstrate its effectiveness by migration of the IRIS_PASSCAL CASC-1993 data set.

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