JOURNAL OF APPLIED PHYSICS VOLUME 95, NUMBER 12 15 JUNE 2004

Imaging from one-bit correlations of wideband diffuse wave fields

Eric Larose
LGIT, Université Joseph Fourier, CNRS UMR 5559, Grenoble, France

Arnaud Derode[a)]
LOA, Université Paris 7, CNRS UMR 7587, ESPCI, Paris, France

Michel Campillo
LGIT, Université Joseph Fourier, CNRS UMR 5559, Grenoble, France

Mathias Fink
LOA, Université Paris 7, CNRS UMR 7587, ESPCI, Paris, France

(Received 7 January 2004; accepted 23 March 2004)

We present an imaging technique based on correlations of a multiply scattered wave field. Usually the Green's function h_{AB} between two points (A,B) is determined by direct transmit/receive measurement. When this is impossible, one can exploit an other idea: if A and B are both passive sensors, h_{AB} can be retrieved from the cross correlation of the fields received in A and B, the wave field being generated either by deterministic sources or by random noise. The validity of the technique is supported by a physical argument based on time-reversal invariance. Though the principle is applicable to all kinds of waves, it is illustrated here by experiments performed with ultrasound in the MHz range. A short ultrasonic pulse, sent through a highly scattering slab, generates a randomly scattered field. Behind the slab is the medium to image: it consists of four liquid layers with different sound speeds. The cross correlation of the field received on passive sensors located within the medium is used to estimate the speed of sound. The experimental results show that the sound-speed profile of the layered medium can be precisely imaged. We emphasize the role of wideband multiple scattering and of source averaging in the efficiency of the method, as well as the benefit of performing one-bit correlations. Applications to seismology are discussed.
 [DOI: 10.1063/1.1739529]

I. INTRODUCTION

The physics of wave propagation in complex media covers various areas of research, ranging from quantum mechanics to classical waves like optics,[1–4] ultrasound,[5,6] seismology,[7,8] astrophysics, or ocean acoustics.[9,10] This diversity gave rise to fruitful transdisciplinary approaches. From the 1980's on, huge improvements have been achieved in understanding and modeling wave propagation in inhomogeneous, random, or reverberant media. Many domains of applications are concerned, e.g., imaging,[11] detection, or communication[12] in a complex environment. Usually, the first, essential step is to know the Green's function of the medium under investigation. When possible, the Green's function (or impulse response) h_{AB} between two points A and B is determined by a direct transmit/receive measurement.

When a wave propagates through a scattering medium, it progressively loses its coherence. The energy of the coherent part of the wave is converted to scattered waves that follow longer scattering paths. In seismology, these long-lasting waves constitute the *coda*[7] that can be observed in seismograms. Coda waves are not random noise: they are the deterministic signatures of the heterogeneities of the Earth's crust. Particularly, between 1 and 10 Hz, the coda waveforms show clear evidence of strong multiple scattering.[8] Mesoscopic physicists have introduced one parameter to characterize the importance of scattering: the transport mean free path ℓ^*. Very roughly, ℓ^* is the distance after which the wave forgets its initial direction. When the distance of propagation is significantly larger than ℓ^*, the attenuation due to scattering strongly reduces the direct coherent wave while the order of multiple scattering increases, which complicates the Green's function h_{AB} and makes conventional imaging very difficult. The cancellation of the direct waves due to multiple scattering has long been considered as a dramatic loss of information.

From a theoretical point of view, one way to analyze diffuse waves is to study ensemble-averaged quantities, e.g., try to fit the decay of energy in the coda by a diffusion or radiative transfer model. However, in seismology as well as in ultrasonics, what the sensors record is the actual wave field, both in amplitude and phase, on a given realization of disorder (there is only one Earth!). Even if the interpretation of the true wave field is much more complicated, the coda retains "deterministic information." In this article, we address the problem of imaging a heterogeneous medium by retrieving the Green's function h_{AB} from the correlation of coda waves.

Within the last 2 decades, strong attention was paid to correlation of scattered waves. In optics, short- and long-range intensity correlations of speckle patterns were thor-

[a)]Electronic mail: arnaud.derode@espci.fr

oughly investigated.[1] Time-varying correlation of scattered fields[6,13] (diffusive wave spectroscopy) have given new insight for monitoring changes in complex media.

Recently, another approach in the correlations of ultrasonic waves was proposed by Weaver and Lobkis[14,15] and applied to the case of a reverberant chaotic cavity. Their work stimulated researchers from various areas of wave physics.[16–18] Weaver and Lobkis showed that when A and B are both passive sensors, the Green's function h_{AB} can be recovered from the cross correlation of the fields received in A and B. Interestingly, the wave fields recorded in A and B could be generated either by deterministic sources or by random noise, like thermal fluctuations. If this idea could be generalized to complex environments other than reverberant chaotic cavities (for instance, open scattering media), it should be fruitfully applied to all areas of wave physics where it is difficult to place a source but easy to place a receiver that records the wave field, and not only its intensity. In seismology, for instance,[16] it is nearly impossible to control elastic sources, but there is a dense network of seismic stations all around the world (except in the oceans). Since earthquakes essentially occur in seismically active regions, many large aseismic areas around the world remain partially unstudied. In those regions, if the ''Weaver approach'' is applicable to seismic waves, studying the correlation of coda waves should provide a huge amount of impulse response measurements, thus allowing a more precise study of the internal structure of the Earth.

In their pioneering works, Weaver and Lobkis showed it was possible to reconstruct the Green's function using correlation of waves reverberated in an aluminum block. Mathematical arguments were given, based on a discrete modal expansion with random coefficients.[14,15] Later, Derode *et al.* proposed a physical interpretation of the emergence of the Green's function from the correlation, based on time-reversal invariance, and presented numerical simulations in open and closed multiple scattering media to support the argument.[17]

In this paper, we confirm the validity of this approach and show that it is possible to do ''passive imaging'' from the spatial correlations of the multiply scattered field received on passive sensors through a highly scattering (and open) medium. First, we recall the simple physical interpretation of the emergence of the Green's function in the correlations, based on reciprocity and time-reversal symmetry, which does not require a modal expansion of the field. Then, we present new experimental results with ultrasound as an example of ''small-scale seismology:'' we build an image of a layered medium through a highly scattering sample via the correlations of the ultrasonic coda waves. We emphasize the role of wideband multiple scattering and source averaging in the efficiency of the method, and we show the benefit of performing one-bit correlations. We also apply this imaging technique to the case of a slowly changing medium, similarly to diffuse wave spectroscopy (DWS).

II. PHYSICAL ARGUMENT

Why should the direct Green's function h_{AB} suddenly emerge from spatial correlations of fields received in A and B? In order to give a physical interpretation of that phenomenon, let us consider two receiving points A and B, and a source S. We will note $h_{IJ}(t)$ as the wave field sensed in I when a Dirac $\delta(t)$ is sent by J. If $e(t)$ is the excitation function in S, then the wave fields ϕ_A and ϕ_B received in A and B will be $e(t)\otimes h_{AS}(t)$ and $e(t)\otimes h_{BS}(t)$, $\otimes$ representing convolution. The cross correlation C_{AB} of the fields received in A and B is then

$$C_{AB}(t)=\int \phi_A(t+\theta)\phi_B(\theta)d\theta$$
$$=h_{AS}(-t)\otimes h_{BS}(t)\otimes f(t),$$

with $f(t)=e(t)\otimes e(-t)$. A simple physical argument based on time-reversal (TR) symmetry indicates that the direct Green's function h_{AB} may be entirely retrieved from C_{AB}.[17]

As long as the medium does not move (no flow), the propagation is reciprocal, i.e., $h_{IJ}(t)=h_{JI}(t)$. So, when we cross correlate the impulse responses received in A and B, the result $C_{AB}(t)$ is also equal to $h_{SA}(-t)\otimes h_{BS}(t)$. Now, imagine that we do a fictitious TR experiment: A sends a pulse, S records the impulse response $h_{SA}(t)$, time reverses it and sends it back; the resulting wave field observed in B would then be $h_{SA}(-t)\otimes h_{BS}(t)$ which, because of reciprocity, is exactly the cross correlation $C_{AB}(t)$ of the impulse responses received in A and B when S sends a pulse. So, the result C_{AB} of the ''real'' experiment (fire in S, cross correlate in A and B) is the same as the result of an imaginary experiment (fire in A, time reverse in S, and observe in B).

We would like the impulse response h_{AB} to appear in this cross correlation. But, in the most general case, C_{AB} has no reason at all to be equal to h_{AB}! Yet, we can go beyond: imagine now that we use several points S, and that we place them in such a way that they form a so-called ''TR cavity'':[19] such would be the case if the sources S were continuously distributed on a surface surrounding A, B, and the heterogeneities of the medium (which is assumed to be free of absorption). Then, no information would be lost during the TR operation. During the ''forward'' step, at time $t=0$, A sends a pulse that propagates everywhere in the medium [including in B where the field received is $h_{AB}(t)$], may be scattered many times, and is eventually recorded on every point S, with no loss of energy. After the TR, the wave should exactly go backwards: it should hit B, then refocus on A at time $t=0$,[20] which implies that the field received in B (at times $t<0$) is exactly $h_{AB}(-t)$, the time-reversed version of the Green's function. Once the pulse has refocused on A, it does not stop but diverges again from A and gives rise, at times $t>0$, to $h_{AB}(t)$ in B. Thus, the exact impulse response $h_{AB}(t)$ can be recovered from either the causal ($t>0$) or the anticausal part ($t<0$) of the sum of field–field correlations C_{AB} for all sources (the causality issue is discussed in more detail in Refs. 21 and 22).

Such a perfect distribution of sources surrounding sensors A and B has been tested in numerical simulations[17] where A and B were deep inside the scattering medium: the *exact* (not ensemble-averaged) Green's function was nearly perfectly retrieved. In real life, whatever the type of waves involved, expecting a perfect distribution of sources is unre-

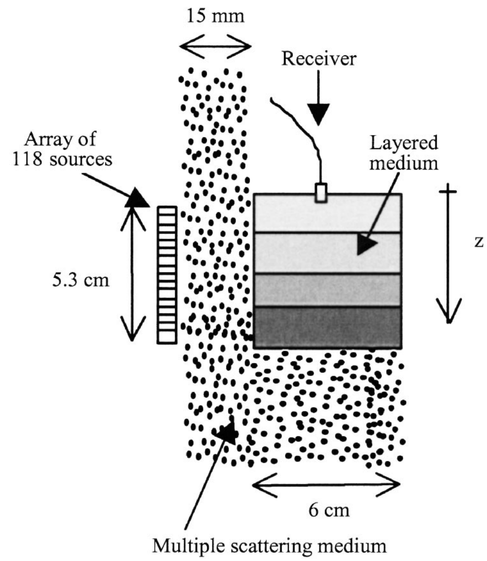

FIG. 1. Experimental setup.

alistic for at least two reasons: first the limited number of sources, second their uneven distribution. In seismology, for instance, seismic stations (A,B) record the displacement field at the Earth's surface but the sources (S, the earthquakes) are mostly aligned along faults.

Yet, in the seismic experiment described by Campillo and Paul,[16] it was shown that some features of the elastic Green's function could be retrieved using correlations of the late seismic coda in Mexico, with a limited number ($\sim$100) of distant earthquakes that were not surrounding the two seismic stations. The Green's function was preferentially reconstructed on one side of the time axis because of a preferential direction of diffuse transport in this source–station configuration.

In order to test and illustrate the possibility of imaging based on the correlation of coda waves with a limited number of sources, we have designed laboratory experiments (Fig. 1).

III. EXPERIMENTS

The experiments take place in a water tank. We use a 118-element ultrasonic array to simulate 118 ''earthquakes:'' each time, one of the elements sends a short pulse (3-MHz center frequency) that traverses a highly scattering medium. This medium consists of a random arrangement of vertical steel rods (average density 29.5 rods/cm^2, diameter 0.8 mm). The sample's mean free path is $\ell^*=3.5$ mm (this was estimated by the coherent backscattering effect[5]), whereas its smallest dimension is 15 mm; therefore, the waves undergo many scatterings before they can get out of the scattering slab and reach the receiver.

Behind the slab, we place the medium that we want to image: it consists of four liquid layers (alcohol, oil, water, sugar syrup) with different sound speeds. The receiver is a 0.39-mm piezoelectric transducer. It is translated downwards along the z axis, and records the scattered signals that are generated each time one of the elements on the array fires a pulse. Those records are equivalent to seismograms, except

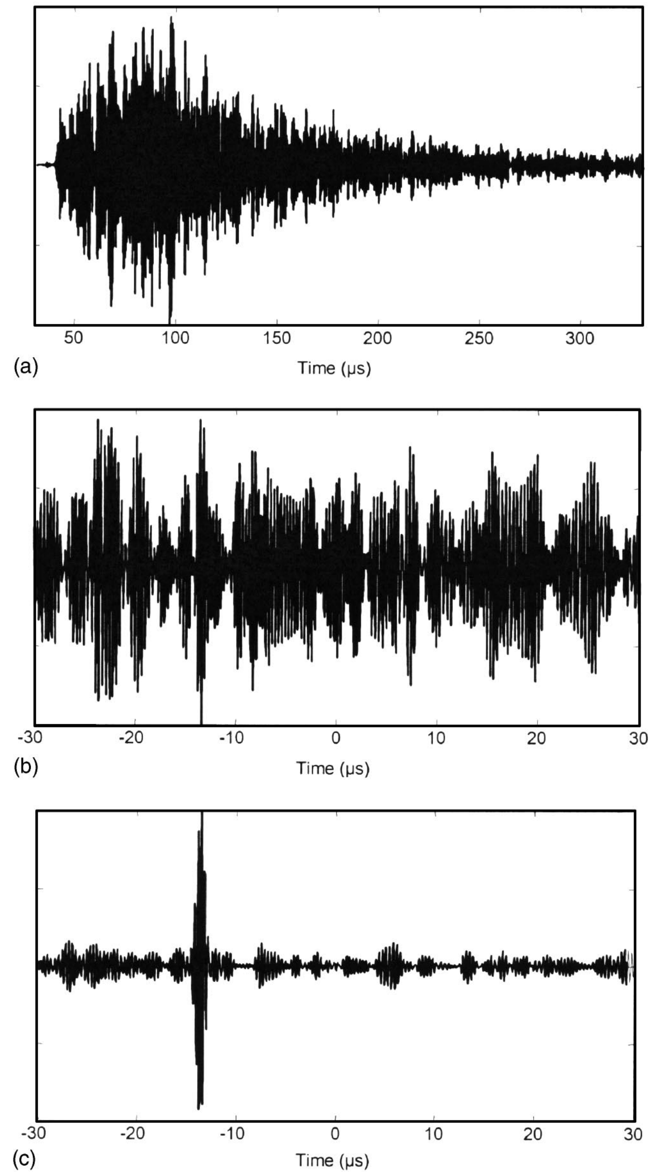

FIG. 2. Typical experimental results. (a) Waveform $h_{60}(z_1=36\text{ mm},t)$ received by the passive sensor at depth $z_1=36$ mm when source #60 fires a pulse. (b) Cross correlation $C_{S=60}(z_1=36\text{ mm},z_2=16\text{ mm},t)$. (c) Cross correlation $C(z_1=36\text{ mm},z_2=16\text{ mm},t)$ averaged over the 118 sources.

they are only made of compressional waves. A typical signal is plotted in Fig. 2(a). It lasts more than 300 μs, i.e., 300 times the initial pulse, and shows a high degree of multiple scattering. It should also be noted that the receiver is facing downwards; therefore, it cannot record direct waves coming from the sources, but purely multiply scattered contributions. Moreover, following the Van Cittert–Zernike theorem and given the typical distances involved here, the spatial coherence of the field measured by the receiver is $\sim\lambda$. No coherent wavefronts are propagating between the receiver's positions.

The 118 sources fire successively, and 118 ''seismograms'' are generated and recorded for each position z of the receiver. The scattered waveforms are $h_{SZ}(t)$, with S the index of the earthquake and Z the position of the receiver.

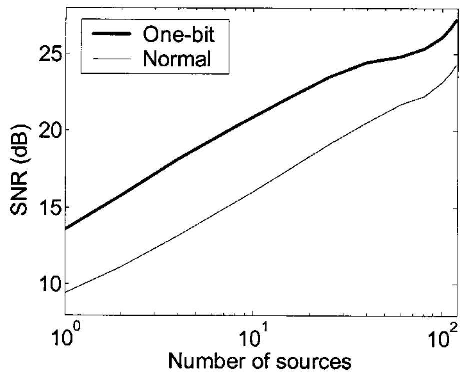

FIG. 3. Experimental results for the evolution of the signal-to-noise ratio (in dB) versus the number of sources. The thick line stands for the one-bit correlations, the thin one for "normal" correlations. The observation points were in $z_1 = 36$ mm and $z_2 = 16$ mm.

Next, we choose a pair of receiver positions (z_1, z_2) and we cross correlate the field due to the source S

$$C_S(z_1, z_2, t) = h_{SZ1}(t) \otimes h_{SZ2}(-t).$$

A typical result is shown in Fig. 2(b), for $S = 60$, $z_1 = 36$ mm, $z_2 = 16$ mm. Nothing seems to emerge from the correlation.

Then, we repeat this for the 118 sources and sum the correlations to get

$$C(z_1, z_2, t) = \sum_{S=1}^{118} C_S(z_1, z_2, t).$$

A typical result is plotted in Fig. 2(c). This time, a strong peak is emerging from the correlation at time $t = -13.6\ \mu$s, corresponding to the time of flight $|z_1 - z_2|/c$. This is the signature of the direct Green's function between z_1 and z_2. In this example, the distance between the receivers is 20 mm, so from the arrival time $t = -13.6\ \mu$s we get an estimation of the sound velocity between z_1 and z_2: 1.47 mm/μs. The peak appears only at negative times and not at positive times due to the location of the receiver, *viz.* the scatterers and its limited directivity:[21] the receiver only sees what is coming towards it front face.

Here, the sound velocity between z_1 and z_2 could only be estimated because the peak was sufficiently above the surrounding "noise" (actually, this term is improper since it is not noise *per se*, but fluctuations of the correlation between the waveforms outside the peak). In order to see the peak emerge from the signals presented in Fig. 2, we had to average the cross correlations on a large number of sources (up to 118). The evolution of the signal-to-noise (SNR) ratio in the averaged cross correlation versus the number of sources N is presented in Fig. 3. The SNR was calculated as follows. The "signal" level is the value of the envelope of the peak, and the "noise" level is the mean amplitude of the envelope of $C(z_1, z_2, t)$ outside the peak, in a 25-μs-long time window. As the number N of sources increased, the peak emerges more and more. The SNR seems to grow like $N^{0.4}$, whereas a classical $N^{0.5}$ dependence would have been expected. This indicates that the contributions from different sources are not fully decorrelated (indeed, the array pitch is slightly smaller than the wavelength) and/or do not contribute equally to the signal, but the range of N is too small to conclude that the exponent 0.4 is really meaningful.

Even though the sources were not arranged as a perfect time-reversal device, the experimental results show that the main feature of the direct Green's function can be retrieved from the correlations. This is achieved thanks to multiple scattering in the random sample. Once again we can refer to the TR analogy. As we have argued, in a time-reversal experiment, there is a forward step (propagation from A to B, record the field in S) and a backward step (time reverse and send back the field in S, observation of the resulting field at point B). If the time reversal could be perfect, then the backward step would be identical to the forward step. Similarly, the key question to the retrieval of the Green's function is: if this was a TR experiment, would the backward step be identical to the forward step? Of course, this is almost never the case, except in a thought experiment. But, past experiments have already shown that time-reversal focusing is more efficient (i.e., the backward step and the forward step are more alike) in the presence of strong multiple scattering or reverberation:[23–25] the focused peak is narrower in space, indicating that the angular spectrum of the wave field is precisely recovered. Strong multiple scattering or reverberation virtually enhance the size of a TR device, i.e., the number of sources involved.

Interestingly, this technique also works with *one-bit* correlations: instead of recording the entire waveforms $h_{SZ}(t)$, we only record and cross correlate their sign, i.e., a series of $+1/-1$ as shown in Fig. 4. And, one-bit correlations seem to give even better results than "normal" correlations [see Figs. 2(b) and 4(b) for a comparison]. Again, it was already shown[26,27] that one-bit time reversal in a multiple scattering or reverberating medium gives a higher SNR than a classical time reversal since it gives more importance to the longest scattering paths, thus artificially reinforcing multiple scattering. Of course, the benefit of one-bit correlation will only be effective if the recording time is significantly larger than the decay time of the multiply scattered signals. For a multiple scattering slab with thickness L, the typical decay time is the "Thouless time" L^2/D, with D the diffusion constant (here, $D \sim 2.6\ \mathrm{mm}^2/\mu\mathrm{s}$). As long as the recording time is larger than the Thouless time, the effect of one-bit digitization is to reinforce the weight of the longest and most diffracted scattering paths relatively to early arrivals. Experimental results show the interest of one-bit correlations: in Fig. 3, the SNR is systematically higher by $\sim$4 dB with one-bit correlation; therefore, a smaller number of sources can be employed which is interesting for any practical implementation of the method.

It should also be noted that the retrieval of the Green's function takes advantage of the large frequency bandwidth available in pulsed ultrasound (here, the spectrum spans from 2 to 4 MHz). Suppose we had only one source, working in a narrow frequency band: then, the retrieval of the Green's function would completely fail. Once again, the time-reversal analogy is enlightening. Indeed, in a one-channel time-reversal experiment performed in a multiple scattering medium on a single realization of disorder, focusing cannot

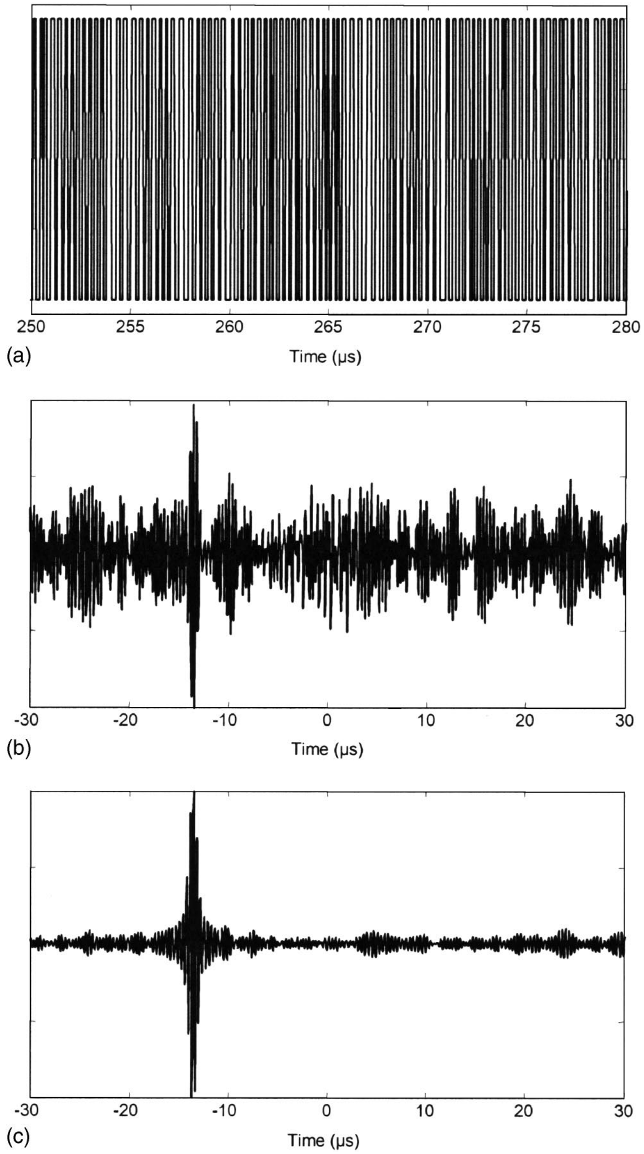

FIG. 4. Same as Fig. 2, except that only the sign (+1/−1) of the scattered wave forms has been recorded and cross correlated (“one-bit” correlations).

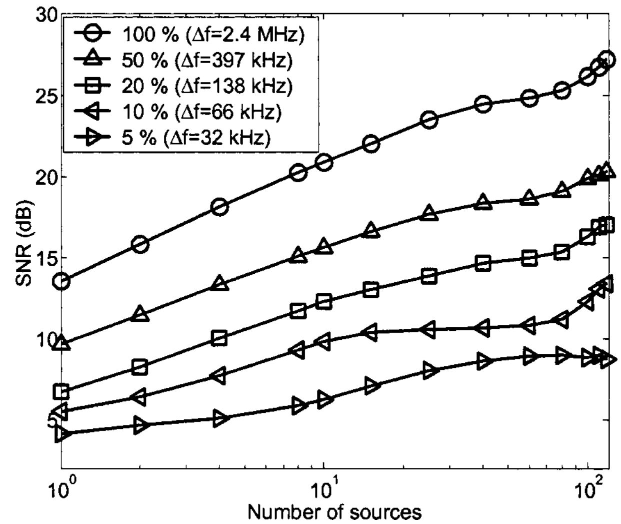

FIG. 5. Experimental results for the evolution of the signal-to-noise ratio (in dB) versus the number of sources for different frequency bandwidths. The observation points were in $z_1 = 36$ mm and $z_2 = 16$ mm. The scattered waveforms were one-bit digitized. The central frequency is 2.9 MHz. The frequency bandwidth Δf is indicated in the legend, as well as α the percentage of energy within each frequency band.

be achieved if the frequency band is too narrow:[23] the reemission of the phase-conjugated monochromatic wave just creates a speckle pattern that is not focused back at the source. However, as the frequency bandwidth $\Delta\omega$ is progressively enlarged, it has been shown that a TR device manages to refocus the wave through the multiple scattering slab, even with only one source.[23,24] The underlying idea is that we take advantage of frequency averaging as soon as the bandwidth $\Delta\omega$ is larger than the correlation frequency $\delta\omega$ of the scattering medium. In a homogeneous and lossless medium, $\delta\omega = \Delta\omega$. But, in a multiple scattering slab, the correlation frequency $\delta\omega$ is inversely proportional to the Thouless time ($\delta\omega$ is also often referred to as the Thouless frequency). Since there are roughly $\Delta\omega/\delta\omega$ “decorrelated frequencies” available in the spectrum, the SNR can be expected to rise as $\sqrt{\Delta\omega/\delta\omega}$, if the power spectral density is flat. Hence, using a large frequency bandwidth is another way of increasing the SNR. This is illustrated in Fig. 5, where the SNR has been plotted versus the number of elements and versus the bandwidth. The proportion α of energy within a frequency band (ω_1, ω_2) is denoted by

$$\alpha = \frac{\int_{\omega_1}^{\omega_2} S(\omega)\,d\omega}{\int_0^{\infty} S(\omega)\,d\omega},$$

with $S(\omega)$ the power spectral density of the scattered signals. In Fig. 5, the bandwidths are indicated by the values of α.

However, it should be noted that enlarging the frequency band cannot do miracles; in particular, it cannot really replace source averaging. If we want to retrieve all the details of the *exact* Green’s function, the only solution is to have sources surrounding the medium. But, if we are satisfied with a simple estimation of the first arrival of the Greens’ function, then enlarging the frequency band helps, because it increases the peak-to-noise ratio, at least as long as dispersion in the medium to be imaged between z_1 and z_2 can be neglected. A different approach consists of extending the bandwidth to infinity ($\Delta\omega \gg \delta\omega$) and invoking a self-averaging property to retrieve an *ensemble-averaged* Green’s function *with a single source*.[22] Naturally, this only holds if the ensemble-averaged Green’s function itself does not depend on frequency (i.e., the scattered wave field expressed as a function of frequency has to be a stationary, or even ergodic, random process) so that an ensemble average can be replaced by a frequency average.

As a preliminary conclusion, the time-reversal analogy indicates that in order to retrieve the *exact* Green’s function from the correlations, the sources of the “earthquakes” should be placed in such a way that they completely surround the medium and the sensors. But, the time-reversal analogy (based on previous works on time reversal) also indicate that when this condition cannot be fulfilled, one can still estimate the main features of the Green’s function (at least an arrival time) using several tricks: (1) take advantage

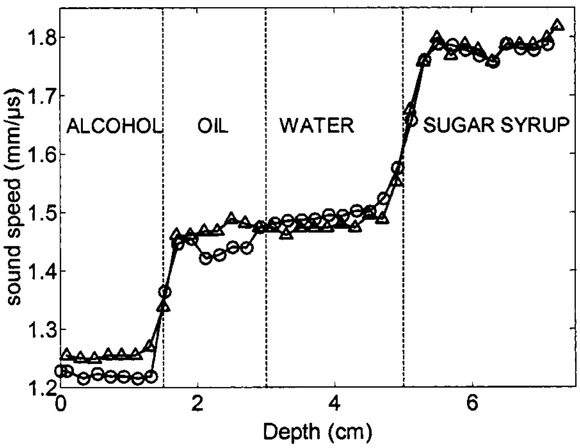

FIG. 6. Sound-speed profile deduced from the travel times measured by one-bit correlations of the scattered wave field. Two set of measurements were performed: before (thin triangles) and after (thick circles) heating up the sample by 8 °C. The four layers are clearly imaged.

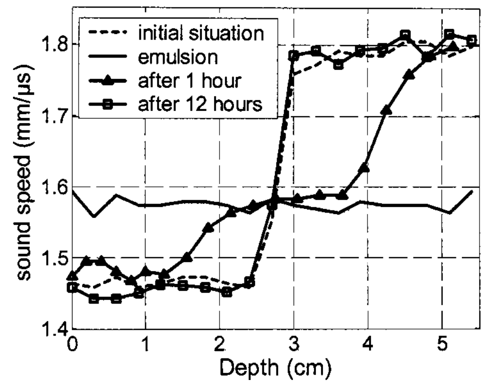

FIG. 7. Sound-speed profiles obtained as the medium under investigation changes. Initially, there are two well-separated layers (oil/syrup). Then, they are mixed together to form an apparently homogeneous emulsion. Progressively, the two phases of the emulsion separate again, and the process can be monitored by the sound-speed profiles. Twelve hours later, the separation is complete.

of a multiple scattering medium; (2) use a frequency bandwidth significantly larger than the correlation frequency of the scattering medium; (3) digitize the waveforms over a single bit; (4) average the results over all available sources. This is what was done in Fig. 4 to retrieve the arrival time of the direct Green's function between the two observing points located at $z_1 = 36$ mm and $z_2 = 16$ mm.

Now, we can repeat the same procedure for every pair of neighboring observation points (z_1, z_2), and estimate the velocity profile (i.e., build an image) of the layered medium (Fig. 6). We have done so all along the vertical axis, with a displacement step of 2 mm. Note that, at room temperature, it is difficult to distinguish between the water and the oil layers, since their estimated velocities are 1478 and 1472 m/s, respectively. Yet interestingly, if we repeat the experiment after heating the sample by 8 °C, we see that the measured velocity of the water layer increases to 1492 m/s, whereas that of the oil layer decreases to 1444 m/s, which is consistent with what is known from these two liquids, and the two layers are better separated on the profile (Fig. 6). The velocities estimated by ''passive imaging'' were found to coincide with those obtained by direct pulse–echo measurements in the four liquids within 2%.

The same experimental procedure was also applied to a two-layer medium (oil/sugar syrup). Initially the liquids are at rest, and the image of velocity profile clearly shows the two layers (Fig. 7). Then, the medium is scrambled to form an emulsion: the velocity profile we obtain shows an apparently homogeneous medium with a sound speed of 1.57 mm/μs. The experiment is repeated on the same sample while the two liquids progressively separate one from the other. After 12 h the separation is complete. Thus, the images obtained from correlation of the scattered fields were able to monitor the evolution of a medium undergoing a slow structural change. This amounts to ''passive diffusive wave spectroscopy,'' in analogy with DWS (diffusive wave spectroscopy) or coda wave interferometry.[28,29] However, in the situation depicted here, the change in the scattered wave fields is not due to a movement of the scatterers, but to a change in the medium we image through the scatterers.

IV. CONCLUSION

We presented a ''passive imaging'' technique based on correlations of highly scattered waves in an open medium. The first step of the imaging process is to retrieve the Green's function between two passive sensors from the correlation of the scattered wave fields generated by distant sources. We have proposed a physical interpretation of the emergence of the direct Green's function from the correlations of highly scattered wave fields. This interpretation is based on time-reversal symmetry. It does not require a modal decomposition of the wave field, nor the rigorous equipartition of energy between discrete random modes. Using this time-reversal analogy, we showed it was necessary to use several sources surrounding the passive sensors in order to retrieve perfectly the exact Green's function. This was called the TR criterion. Moreover, the analogy also tells us that when the TR criterion is only partially fulfilled, multiple scattering helps achieving a correct estimation of the arrival time of the Green's function. It was also shown that one-bit correlations (i.e., we only process the sign of the wave field) can give similar estimations with fewer sources, because one-bit processing tends to give more weight to the longest and most diffracted paths, which enhances the role of multiple scattering. The importance of the frequency bandwidth relatively to the correlation frequency of the medium was also emphasized. Two ultrasonic experiments were presented in the paper in order to illustrate the feasibility of passive imaging with wideband one-bit correlations. The first one consisted of imaging a layered medium: we measured the local sound velocities along the profile; the estimated error was less than 2%. The effect of an 8 °C heating was quantitatively observed. In the second experiment we monitored the progressive separation of a two-phase mixture (oil–syrup emulsion). In both experiments, ultrasonic wave fields were created by distant sources and underwent strong multiple scattering before they reached the medium to image.

Much attention is now paid to real seismic data,[16] where this passive imaging method should provide an efficient tool to improve classical seismic images. Using the passive ''coda correlation'' method, we would be able to retrieve the Green's function between seismic stations everywhere around the world.

More generally, whatever the types of waves involved, this technique should be applicable to any kind of wave and in every situation where it is hard to control the source but easy to place several synchronized sensors, as long as we can record the true wave field and not only the average energy. We are now looking forward to image localized reflectors or to quantify absorption effects, but also to use natural noise as it was done in closed media and in underwater acoustics.[9,15,30]

ACKNOWLEDGMENTS

This work originates from collaborations, mostly within two interdisciplinary ''Research Groups'' (Groupes de Recherches): PRIMA (GDR CNRS 1847) and IMCODE (GDR CNRS 2253). We would particularly like to thank Ludovic Margerin, Anne Paul, Bart Van Tiggelen, Arnaud Tourin, Julien de Rosny, and Mickael Tanter for many discussions and exchanges.

[1] R. Berkovits and S. Feng, Phys. Rep. **238**, 135 (1994); M. C. W. van Rossum and T. M. Nieuwenhuizen, Rev. Mod. Phys. **71**, 313 (1999). P. Sheng, *Introduction to Wave Scattering, Localization and Mesoscopic Phenomena* (Academic, San Diego, 1995).
[2] F. Scheffold and G. Maret, Phys. Rev. Lett. **81**, 26 (1998).
[3] M. Heckmeier, S. E. Skipetrov, G. Maret, and R. Maynard, J. Opt. Soc. Am. B **14**, 1 (1997).
[4] M. P. Van Albada, A. Lagendijk, P. E. Wolf, and G. Maret, Phys. Rev. Lett. **55**, 2692 (1985).
[5] A. Tourin, A. Derode, P. Roux, B. A. van Tiggelen, and M. Fink, Phys. Rev. Lett. **79**, 3637 (1997).
[6] M. L. Cowan, J. H. Page, and D. A. Weitz, Phys. Rev. Lett. **85**, 453 (2000).
[7] K. Aki and B. Chouet, J. Geophys. Res. **80**, 3322 (1975).
[8] R. Hennino, N. Trégourès, N. M. Shapiro, L. Margerin, B. A. van Tiggelen, and R. Weaver, Phys. Rev. Lett. **86**, 3447 (2001).
[9] T. L. Duvall *et al.*, Nature (London) **362**, (1993).
[10] P. Roux and M. Fink, J. Acoust. Soc. Am. **110**, 2631 (2001).
[11] M. Fink, W. A. Kuperman, J.-P. Montagner, and A. Tourin, *Imaging of Complex Media with Acoustic and Seismic Waves* (Springer, Berlin, 2002), Vol. 84.
[12] A. Derode, A. Tourin, J. de Rosny, M. Tanter, S. Yon, and M. Fink, Phys. Rev. Lett. **90**, 014301 (2003).
[13] G. Poupinet, W. L. Ellsworth, and J. Frechet, J. Geophys. Res. **89**, 5719 (1984).
[14] O. I. Lobkis and R. L. Weaver, J. Acoust. Soc. Am. **110**, 3011 (2001).
[15] R. L. Weaver, Phys. Rev. Lett. **87**, 134301 (2001).
[16] M. Campillo and A. Paul, Science **299**, (2003).
[17] A. Derode, E. Larose, M. Tanter, J. de Rosny, A. Tourin, M. Campillo, and M. Fink, J. Acoust. Soc. Am. **113**, 2973 (2003).
[18] R. Snieder, Phys. Rev. E **69**, 046610 (2004); P. Roux and M. Fink, J. Acoust. Soc. Am. **113**, 1406 (2003); A. E. Malcolm, J. A. Scales, and B. A. van Tiggelen, Phys. Rev. Lett. (submitted).
[19] D. Cassereau and M. Fink, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **39**, 579 (1992); J. de Rosny and M. Fink, Phys. Rev. Lett. **89**, 124301 (2002).
[20] We have made the change of variable $t \rightarrow t-T$, T being the time necessary for the pulse to propagate and be entirely recorded in every point C. Hence, the refocusing in A takes place at $t=0$.
[21] A. Derode, E. Larose, M. Campillo, and M. Fink, Appl. Phys. Lett. **83**, 3054 (2003).
[22] B. A. Van Tiggelen, Phys. Rev. Lett. **91**, 243904 (2003).
[23] A. Derode, A. Tourin, and M. Fink, Phys. Rev. E **64**, 036606 (2001).
[24] P. Blomgren, G. Papanicolaou, and H. Zhao, J. Acoust. Soc. Am. **111**, 230 (2002); C. Draeger, J.-C. Aime, and M. Fink, *ibid.* **105**, 618 (1999).
[25] M. Fink, D. Cassereau, A. Derode, C. Prada, P. Roux, M. Tanter, J. Thomas, and F. Wu, Rep. Prog. Phys. **63**, 1933 (2000).
[26] A. Derode, A. Tourin, and M. Fink, J. Appl. Phys. **85**, 6343 (1999).
[27] G. Montaldo, P. Roux, A. Derode, C. Negreira, and M. Fink, Appl. Phys. Lett. **80**, 897 (2002).
[28] R. Snieder, A. Grêt, H. Douma, and J. Scales, Science **295**, 2253 (2002).
[29] P. M. Roberts, W. S. Phillips, and M. Fehler, J. Acoust. Soc. Am. **91**, 3291 (1992).
[30] K. G. Sabra, P. Roux, W. A. Kuperman, W. S. Hodgkiss, H. C. Song, T. Akal, and M. Stevenson, J. Acoust. Soc. Am. **114**, 2462 (2003).