Single-channel time reversal in elastic solids

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Reverberant volume time reversal in 3D elastic solids (doped glass and Berea sandstone) using a single channel are presented. In spite of large numbers of mode conversions (compressional to shear wave conversions at the walls), time reversal works extremely well, providing very good spatial and time focusing of elastic waves. Ceramics were bonded to the surface as sources (100–700 kHz); a broadband laser vibrometer (dc—1.5 MHz) was used as detector. Temporal and spatial time-reversal focusing are frequency dependent and depend on the dissipation characteristics of the medium. Doped glass (inverse dissipation Q between 2000 to 3000) shows time-reversed spatial focal resolution at about half of the shear wavelength. The Berea sandstone ($Q=50$) yields a wider focusing width (a bit more than the shear wavelength) due to its lower Q. Focusing in the doped glass is better because the time-reversal (virtual) array created by wave reflections is larger than in the highly attenuating sandstone. These are the first results reported in granular media, and are a first step toward geophysical and field applications.
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I. INTRODUCTION

Time-reversed acoustics (TRA) is unquestionably one of the most interesting topics to have emerged in modern acoustics. Most of the recent innovative research in this area has been carried out by the group at the Laboratoire Ondes et Acoustique at the Université Paris 7,[1] who have demonstrated the ability and robustness of TRA (using time-reversal mirrors) to provide spatial control and focusing of an ultrasonic beam. However, the topic of time reversal had its beginnings in ocean acoustics more than 40 years ago. In fact, Parvulescu[2] filed a patent application in 1962 for a time-reversal method (which he called a matched-signal technique) for underwater communication and underwater object detection. Some of the first experiments were conducted by Parvulescu and Clay,[3] who used their matched-signal technique to study the reproducibility of signal transmission in deep ocean water over a distance of 36 km. The results of current research to apply TRA for underwater communication in the field can be found in Refs. 4 and 5 and in highly reverberant conditions in the laboratory in Refs. 6 and 7. The ability to obtain highly focused signals with TRA has numerous other applications as well, including lithotripsy,[8] ultrasonic brain surgery,[9] and nondestructive evaluation.[10,11]

Notably, the study of time reversal in solids and in the earth is still relatively new and presents questions and challenges not seen in fluids. The work reported here on laboratory-scale solids was intended, in part, to be a prelude to trying time-reversal methods in the earth. For example, seismic imaging could benefit from using time-reversal techniques—concurrent with conventional imaging techniques—to focus energy only on the strongest scatterers (e.g., fault zones) to better classify interesting underground features. We have reported on similar ideas to develop time-reversal techniques for nondestructive testing (e.g., flaw detection in solids).[12] The problem of time reversal in the earth (and in all solids) is fundamentally different from the purely acoustic one due to the excitation and propagation of both compressional (bulk) and shear waves, conversions between the two types of waves, and the scattering and potentially high losses in the medium. In the preliminary laboratory experiments reported here, solids were chosen where internal scattering from the medium is not an issue. The results shown in this paper demonstrate that time reversal works both in solids and granular media where unwanted wave conversions and high losses could easily ruin the time-reversal process.

Draeger *et al.*[13] developed a simple theory describing a time-reversal (TR) process with elastic waves. Their paper nicely illustrates the potential problems of time reversal in solids. Draeger examined the case of a compressional (P) and vertically polarized shear (SV) wave—both generated simultaneously by a point source in a solid—propagating to a time-reversal mirror somewhere in a fluid surrounding the solid. When the time-reversal mirror sends the signals from the two waves back into the solid, there are now four waves generated in the solid, a shear and a compressional wave from each of the compressional and shear waves. The "unwanted" waves (i.e., those which will not properly time reverse) are simply thrown away in the analysis since they

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"yield a low-level noise, they are not focused, and arrive at different times."[13] In the reverberant volume experiments described here, the initial wave may undergo hundreds of reflections (and corresponding wave conversions), yielding potentially hundreds of unwanted waves from all these reflections. Being able to see a reconstructed source signal in spite of significant mode conversion was not an obvious outcome. We chose to examine these ideas using a simplified numerical simulation of the experiment—these results have already been published and are reported elsewhere.[14] In that simulation, we made a first attempt to model and simulate the process numerically using the local interaction method known as LISA.[15] The initial results from that work (simulating just a few reflections) were encouraging. Now that the experiments reported here have demonstrated that time reversal in granular solids works very well, research continues on extending the simulation to multiple reflections and simulating more realistic situations.

A few experiments in solids have been reported already. In one experiment, an aluminum cylinder was a basic element in a TR system developed for lithotripsy.[8] Another experiment describes TR focusing in a 2D silicon wafer where only shear (Lamb) waves can propagate. Strong temporal and spatial focusing were demonstrated. The aperture of focus for their experiment had a radius of about half a wavelength and was highly focused in time. In another work, Prada *et al.*[11] studied TR scattering techniques for nondestructive testing applications in a sample composed of titanium billets and, unlike experiments described here, carefully avoided all reflections from the surfaces of the billet.

In this work we describe results from single-channel, 3D experiments in two solids, a doped glass and a fine-grained Berea sandstone. Both are essentially experiments in solid reverberant volumes with numerous wave conversions. These wave conversions were absent in the 2D silicon wafer experiments discussed above.[16,17] The doped-glass sample was used as a low dissipation standard and was chosen because it has a similar wave speed to compare with the sandstone (which has high dissipation). Unlike earlier experiments conducted with solids, submersion in a fluid to conduct TR studies is neither possible nor desirable in many solids. Thus, in these experiments, we also report on the first use of direct-coupled transducers on solids in tandem with a large-bandwidth laser detector. We show that despite the fact that the transducer radiates primarily compressional waves, the TRA spatial focusing has a width comparable with a half wavelength of the shear wavelength. We surmise that shear waves dominate the reverberant wave field due to numerous wave conversions for each reflection at each free surface. This paper begins with a description of the experimental procedure, followed by a description of experimental results, discussion, and conclusions.

II. EXPERIMENTAL PROCEDURE

In experiments conducted in fluids, the same device is frequently used for both source and receiver, either by itself or as part of an array.[13,16,17] In the experiments in solids described here, a single piezoelectric ceramic disk directly bonded to the sample surface was used as a source for both

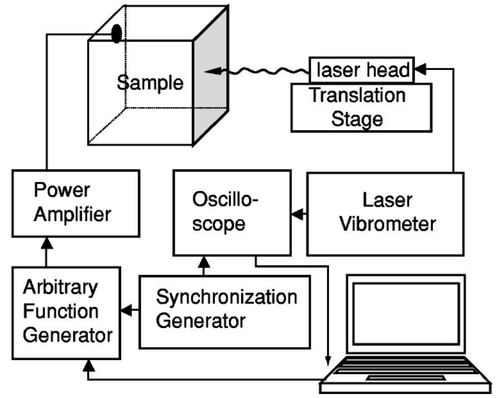

FIG. 1. Experimental setup for measurements of single channel, time reversal in solids.

the initial waves and also for the time-reversed waves (Fig. 1). The ceramic operated in thickness mode and thus generated primarily compressional waves. The received signal—specifically the motion normal to the surface—was detected at various places on the solid by a laser vibrometer which measured surface velocity (a Polytec 301 with 303 laser head). The laser vibrometer is a noncontact measurement device and thus experiences no coupling effects, and has a flat, broadband response from near-dc to 1.5 MHz. The sample was placed on an optical table and the laser vibrometer was placed on a translation stage.

A typical time-reversal experiment in these solids was carried out in the following way. A short, triangular pulse (see Fig. 2) was generated by an arbitrary waveform signal generator (HP 33120A), amplified by a power amplifier (Krohn-Hite 7500), and applied to the transducer. The transducer generated a fairly broad, multifrequency tone burst into the sample. The laser vibrometer was then aimed at one of several arbitrary points on the opposite wall of the block being tested. The recorded signal—a fairly long wave train consisting of the initial arrival and its reverberation or *coda*[18]—was time reversed and then fed into the arbitrary waveform generator and radiated *from the original source* as done by Draeger *et al.*[17] The time-reversed signal then propagates through the sample and is detected by the laser vibrometer. The focusing aperture was obtained by conducting repeated measurements across the sample face with the laser mounted on a translation stage. We note that these time-reversal experiments were conducted for several different receiver locations—although not near an edge or corner—in each block and, somewhat surprisingly, *qualitatively the time-reversal focus does not depend on the where the receiver is placed*. A quantitative study of the influence of receiver location is beyond the scope of this paper, but should be conducted.

III. OBSERVATIONS AND RESULTS

A. Doped-glass block

The first experiment was carried out in a $101\times89\times89$-mm doped glass parallelepiped. The bulk wave speed in the sample was approximately 3000 m/s with a quality factor Q (inverse dissipation) between 2000 and 3000 in the

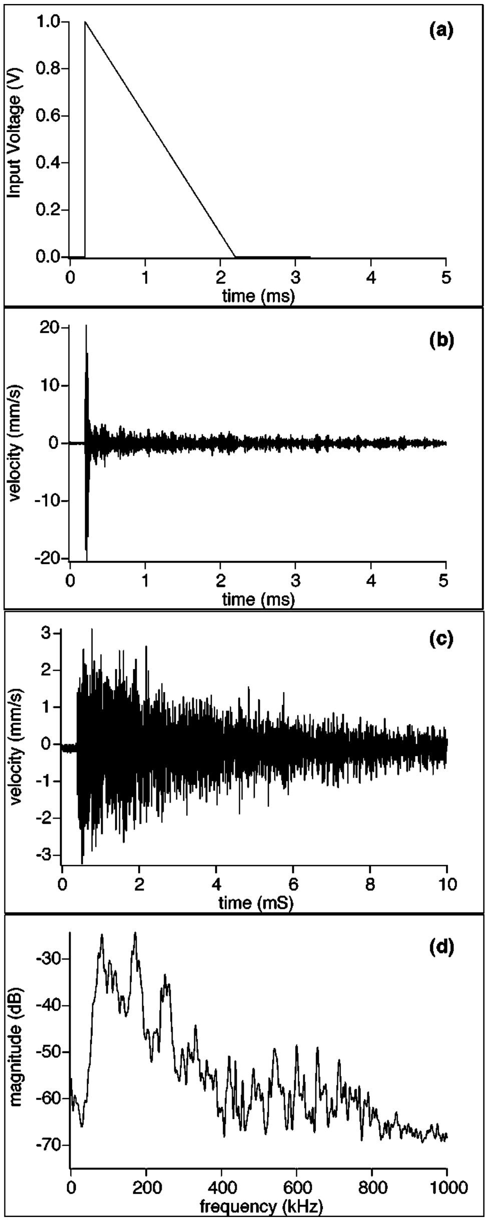

FIG. 2. Input and detected waves in the doped glass sample: (a) the electrical input into the ceramic; (b) the signal detected using the laser vibrometer on the back side of the ceramic; (c) the detected signal after traversing the sample, measured with the laser vibrometer and (d) the spectrum of the detected signal.

frequency bands used. The wave speed was measured by a standard time-of-flight method, and the Q from resonance peak width. The doped-glass sample was selected as a standard to compare with the (granular) sandstone because the wave speeds are similar but the structure is much less complex. A 50-mm-diameter, 2.8-mm-thick piezoceramic disk was epoxied with its center 28 mm from the corner of two sides of the sample, as shown in Fig. 1.

A short, triangular-shaped pulse was applied to the transducer [Fig. 2(a)]. The resulting signal broadcast into the solid was measured on the backside of the transducer using the laser vibrometer and is shown in Fig. 2(b). The signal that arrived on the opposite side (not far from the sample center in this particular case) was measured by the laser vibrometer and is shown in Fig. 2(c). The detected signal was then bandpass filtered from 100–700 kHz to eliminate low- and high-frequency noise; its frequency spectrum is shown in Fig. 2(d). Notice that the direct signal consists of the first few arrivals and almost 10 ms of coda (which includes over 300 reflections directly back and forth within the sample and a host of side-wall reflections as well). It is known that coda consists of primarily shear wave energy[18] and, as mentioned later, appears to be the case in these experiments as well.

The recorded signal was time reversed, Fig. 3(a), normalized to 1 V p-p, and rebroadcast using a $\times 100$ fixed amplification. The resulting refocused signal [shown in Fig. 3(b); zoom shown in Fig. 3(c)] was nicely reconstructed. The refocused signal was also highly compressed, 50 μs in contrast with the 6000-μs-long time-reversed signal. The noticeable ''echoes'' shown on either side of the refocused signal are possibly due to the geometry of the sample or perhaps due to the size of the transmitter. It is also well known that with additional transducers the echoes will be minimized, but that is not the purpose of these experiments. In any case, it is normal that one does not recreate a perfect pulse, since the TR field is not recorded everywhere. For instance, similar, but much smaller, echoes are shown in results in Draeger and Fink.[16]

Identical measurements were carried out for several different receiver points (on the remaining five sides), and it was found that the TRA focusing did not depend on the point of measurement. In fact, we have shown elsewhere that TRA focusing does not depend on the form of the resonator either; TRA focusing was observed in cylinders, diamond shapes, and other complex forms of acoustical resonators being tested for various medical applications.[19]

Application of a filter with center frequency near one of the coupled source/sample resonances on either the time-reversed signal or the final refocused signal greatly improved the amplitude and signal-to-noise ratio of the time reversal as one might anticipate from the spectrum shown in Fig. 2(d). When we chose to bandpass filter the received signal before reinjecting it at two of the spectral peaks—210 to 310 kHz (center frequency 260 kHz) and 700 to 800 kHz (center frequency 750 kHz)—time reversal was improved for the higher frequency bandpass-filtered signal [see Figs. 3(d)–(i)]. The resulting refocused pulses have durations of 15 μs for the 260-kHz bandpass filter and 10 μs for 750-kHz bandpass filter. The spatial distribution of the TR focused signal amplitude is presented in Fig. 4 for the horizontal [4(a) and vertical 4(b)] directions using the three bandpass filters. Amplitudes are measured peak amplitudes of the TR signal at each position, normalized to the maximum measured amplitude. The points are the actual data values and the lines are smooth fits to each measurement group. The width measured at -3 dB is approximately 3.6 mm for the 100–700-kHz bandpass signal, 2.8 mm for the signal bandpass filtered at a center frequency of 260 kHz, and about 1.2 mm for the signal bandpass filtered at a center frequency of 750 kHz. Note that the longitudinal (compressional) and shear wavelengths for these two frequencies are 12 mm (6.4 mm shear) and 4 mm (2.3 mm shear), respectively. Since the field of a symmetric spherical converging wave is described by $\sin(kr)/kr$, where the wave number $k=2\pi/\lambda$, the diffraction limit of the

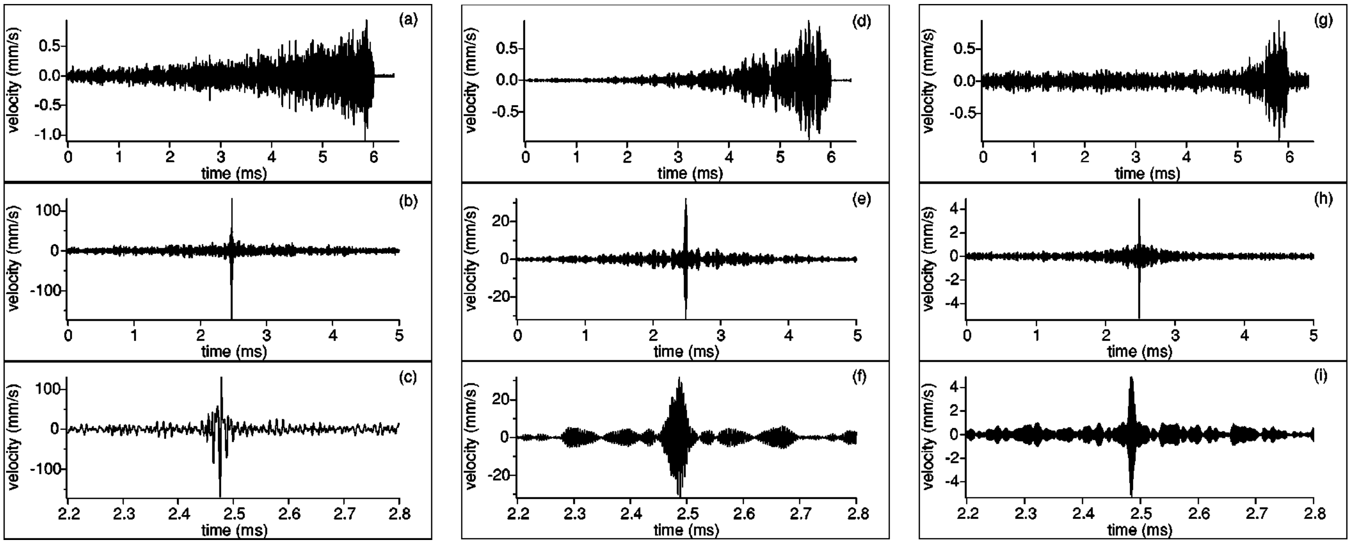

FIG. 3. Time-reversal results in doped glass for select frequency bands. Column 1 shows the (a) detected signal (time reversed); (b) the resulting time-reversed signal; and (c) its zoom for 100–700-kHz bandwidth. Column 2 (d)–(f) shows the same results for a 220–280-kHz bandwidth. Column 3 (g)–(i) shows the same results for a 700–800-kHz bandwidth.

focal spot is 0.44λ, quite close to what is observed in the experiment in all frequency bands studied.

The observed high degree of focusing is due to the numerous reflections of the acoustic signal from the walls of the solid, and is surprisingly good. We assume that the focusing is due to the large number of virtual sources from back-wall and side-wall reflections that exist in the material, and may well have to do with the fact that shear waves dominate in the coda.

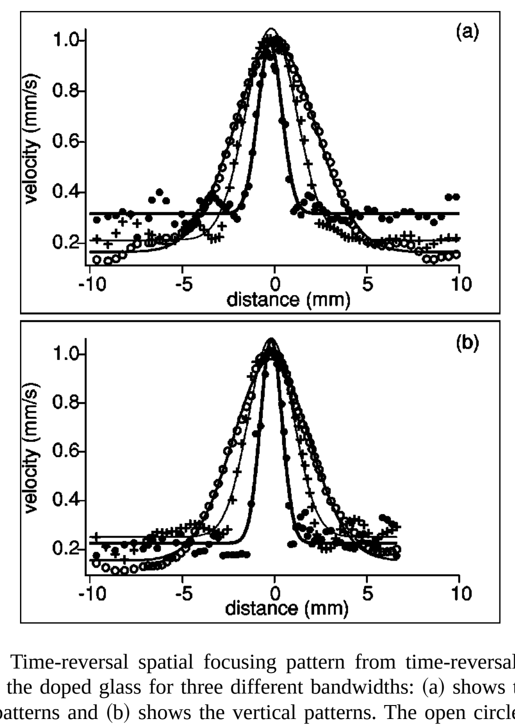

FIG. 4. Time-reversal spatial focusing pattern from time-reversal experiment in the doped glass for three different bandwidths: (a) shows the horizontal patterns and (b) shows the vertical patterns. The open circles correspond to a 100–700-kHz bandwidth, the crosses correspond to a 220–280-kHz bandwidth, and the solid circles represent a 700–800-kHz bandwidth. The solid lines are Gaussian fits to the beam patterns. Amplitudes were obtained by measuring the peak amplitude of the detected, time-reversed signal in each case. All values are normalized to the maximum detected amplitude for each bandpass interval.

B. Berea sandstone

A similar experiment was conducted for a sample of slightly different geometry and much larger dissipation, a long rough parallelepiped of Berea sandstone of dimensions $75\times75\times254$ mm. The Berea sandstone sample is a porous material composed primarily of quartz (85%) and a small fraction of feldspar (8%) grains, with kaolinite and other clays in the interstices. The wavelength in this sandstone was nearly 13 mm at the frequencies of interest, much greater than the average grain size of 100 μm, so scattering from the medium was not an issue. The bulk wave speed was around 2.2 km/s and the Q is 50—an equivalent attenuation much larger than that of the glass block.

The source signal was identical to that of the glass, and the signal emitted at the source is shown in Fig. 5(a). Figure 5(b) shows the received signal—much smaller in amplitude and shorter in duration because of high attenuation in the sample—corresponding in time to only 20 back and forth transversal before the signal is overcome by noise; the corresponding frequency spectrum is shown in Fig. 5(c). The time-reversed signal for a frequency band between 70 and 700 kHz is shown in Fig. 6(a), and the refocused signal is shown in Fig. 6(b) with its zoom in Fig. 6(c). Time reversal worked well even in the case of extremely large attenuation. As in the glass block, the spatial distribution of the TR focused signal—filtered in the frequency band between 130–200 kHz—in the sandstone was also measured and is shown in Fig. 7. The focal width at -3 dB was about 8 mm, wider than that in the glass sample and almost equal to the shear wavelength in this sample (7.8 mm). It is clear that higher attenuation and fewer reflections—and thus fewer virtual sources—restricted the focusing properties of the TR system in the sandstone, and, one can assume, in low-Q materials in general.

It is remarkable that one can virtually ignore the complications of mode conversion and treat the TR process blindly. Due to mode conversion between compressional and

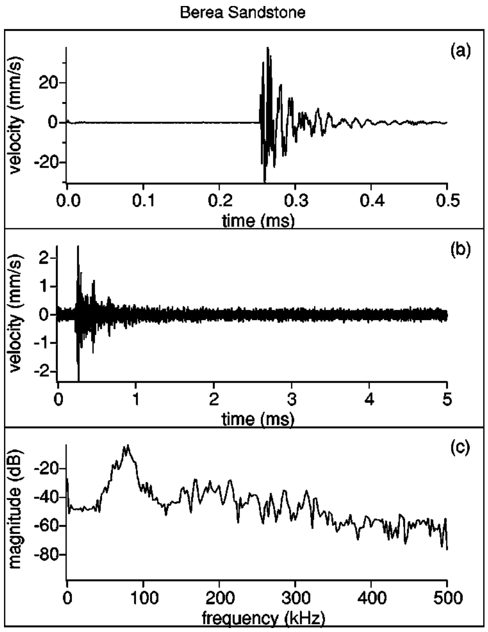

FIG. 5. Input and detected waves in Berea sandstone [the electrical input was identical to that shown in Fig. (2a)]: (a) the signal measured on the backside of the source ceramic with the laser vibrometer without filtering; (b) the direct signal that has propagated across the sandstone sample; (c) the unfiltered spectrum of the detected signal.

shear waves, reciprocity may not hold as it does in acoustical media;[20] however, this point still needs rigorous study. Nonetheless, time reversal works remarkably well in terms of spatial and temporal focusing. This is an extremely promising result because it implies that solids can be treated without concern for mode conversion that might normally be expected to complicate the problem.

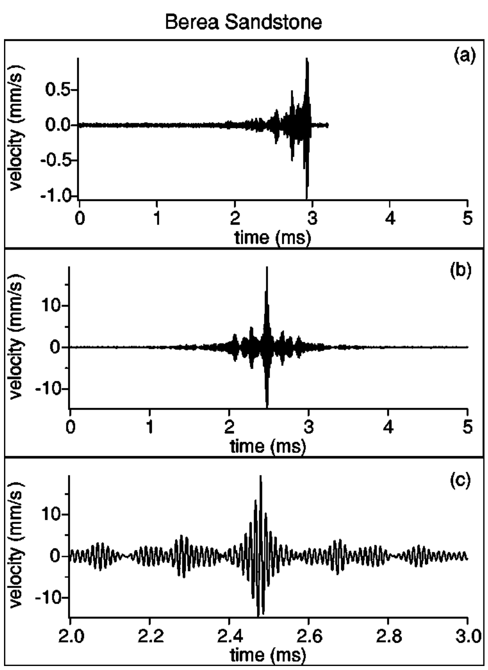

FIG. 6. Time-reversal results in Berea sandstone. (a) The detected, band-passed (70–700 kHz) signal that has been time-reversed; (b) the resulting time-reversed signal, and its zoom (c).

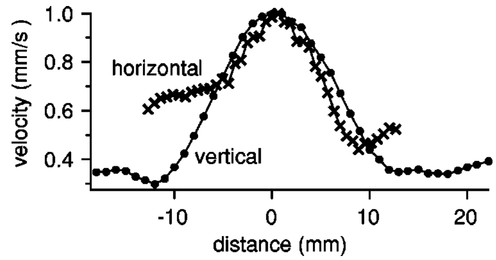

FIG. 7. The spatial distribution of the time-reversed signal amplitude in the sandstone for the vertical (closed circles) and horizontal (x's) directions. Lines serve to connect the points. Amplitudes were obtained by measuring the peak amplitude of the detected, TR signal in each case. All values are normalized to the maximum detected amplitude for each bandpass interval.

IV. SUMMARY AND CONCLUSIONS

The single-channel time-reversal experiment demonstrated extremely effective focusing of acoustic energy in time and space at an arbitrary point in three-dimensional solids where multiple compressional to shear wave conversions could have potentially destroyed the process. The role of frequency is extremely important as one might expect: filtering the TR signal, we observe focusing to a degree that is surprising (better than one would expect using the diffraction limit set by the compressional wavelength). Focusing in a lower-Q material (sandstone) is still very good, in between the compressional and shear wavelength. To our knowledge these are the first demonstrations of time reversal in granular solids.

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