

Improved Focusing Using Deconvolution Within a Concrete Block

Johannes DOUMA *, Ernst NIEDERLEITHINGER **, Roel SNIEDER *

* Colorado School of Mines, Golden. Co, USA

** BAM Bundesanstalt für Materialforschung und -prüfung, Berlin

Abstract. Time reversal techniques are used in ocean acoustics, medical imaging and non-destructive evaluation to backpropagate recorded signals to the source of origin. We demonstrate experimentally a technique which improves the temporal focus achieved at the source location. The experiment consists of propagating a signal from a transducer within a concrete block to a single receiver on the surface, and then applying time reversal or deconvolution to focus the energy back at the source location. The results show that we are able to generate a focus in time at the correct location. The proposed method is simple and proven to be robust. Additionally, its costs are negligible due to deconvolution being a preprocessing step to the recorded data. The technique can be applied for detailed investigation of the source mechanisms (e. g. cracks) but also for monitoring purposes.

1. Introduction

Several methods are used to evaluate acoustic signal generated by events in media such as water, rocks, metals or concrete. Most of them are summarized as acoustic emission methods (AE), mainly travel time evaluation methods to localize the point of origin. Sophisticated methods have been developed in seismology to localize and characterize earthquakes. Time Reversal (TR) has been the focus of much research in acoustics due to its ability to compress the measured scattered waveforms back at the source point in both space and time [1][2][3][4]. This has led to TR being applied in a wide variety of fields such as medicine, communication or nondestructive evaluation. However, continued work is being done to improve TR ability to focus energy. Some newly developed techniques use an array of input transducers, measure the wave field with an array near the desired focal spot, and then optimize the spatial and temporal focusing [5][6][7][8][9][10][11]. Other methods use an array of input transducers and optimize the temporal focusing at an output transducer [12][13][14][15][16]. However, these techniques can require/benefit from large arrays while simultaneously losing spatial localization in order to enhance temporal focusing.

In this paper, we design and execute an evaluation experiment to compare conventional time reversal to an improved variant which uses deconvolution (DC). We explore the application of DC, which is a primitive though robust version of the inverse filter [5][8], to calculate the optimal signal for backpropagation. The experiment consists of a concrete block which has a source embedded within. Instead of using a large array of receivers, the experiment uses only a single receiver to record the scattered waveform. TR



or DC is then applied to the measured scattered waveform to calculate the TR and DC signal. The calculated signals are then backpropagated from a transducer on the surface of the block into the medium and recorded at the original source location transducer. By this experiment, we are able to explore and compare the capabilities of TR and DC to focus the measured waveforms at a point in both space and time. We show that DC significantly improves the temporal focus compared with TR.

2. Theory: Deconvolution

Time reversal (TR) is a process used to compress the measured scattered waveforms both in space and time back at their source point, ideally to a Dirac delta function $\delta(t)$. It uses the recorded impulse response which can be represented by a Green's function G_{AB} between two points A and B. TR then simply reverses the signal in time and propagates it back from the receiver location into the same medium. By doing so, one expects the energy to focus at the source location. The TR process can be represented by the following equation:

$$\int_{-\infty}^{\infty} G_{AB}(\tau)G_{AB}(\tau - t)d\tau = \delta(t) \quad (1)$$

where reciprocity has been used to replace the Green's function G_{BA} with G_{AB} . According to equation 1, the TR process, which is the autocorrelation of $G_{AB}(t)$, should equal a delta function. In order for it to work perfectly, one must record for infinite time, Green's functions are assumed to contain flat, infinite bandwidth (meaning that the original source is a $\delta(t)$ as well), and one must have full coverage of the wave field. These requirements are not upheld during an experiment. This led us to explore the application of deconvolution. Going back to Eq. 1, we can rewrite this (using a convolution notation, rather than the integral form) as

$$F(t) = g(t) * R(t) \approx \delta(t) \quad (2)$$

where $F(t)$ is the focal signal or source reconstruction, $R(t)$ is the recorded signal measured at the receiver location B from the initial source propagation, and $g(t)$ is the signal necessary to be back propagated for focusing. We are able to go from Eq. (1) to Eq. (2) because we only investigate signals between the two points A and B, and remove the Green's function notation to indicate we do not have infinite bandwidth. Thus, we remove some of the unrealistic conditions that Eq. (1) required. For a TR process, the signal for backpropagation is purely the time reversed recorded signal $g(t) = R(-t)$. Our goal is to calculate the optimal signal $g(t)$ such that the focal signal $F(t)$ approximately equals a Dirac delta function $\delta(t)$.

Deconvolution equates to inverse filtering by transforming to the frequency domain, thus Eq. (2) becomes

$$F(\omega) = g(\omega)R(\omega) \approx 1 \quad (3)$$

Equation (3) is used to solve for $g(\omega)$:

$$g(\omega) = \frac{1}{R(\omega)} = \frac{R^*(\omega)}{|R(\omega)|^2} \quad (4)$$

where * denotes a complex conjugate operation. This expression gives a mathematical expression for $g(\omega)$. However, this result is unrealistic for experimental use in the event that there is a limited bandwidth, significant background noise, or more specifically, if $R(\omega)=0$ at any frequency. To avoid this singularity issue, we add a constant to the denominator to ensure that we never divide by 0. Hence Eq. (4) becomes:

$$g(\omega) = \frac{1}{R(\omega)} = \frac{R^*(\omega)}{|R(\omega)|^2 + \varepsilon} \quad (4)$$

where ε is a constant related to the average amplitude of the original received signal by

$$\varepsilon = \gamma \overline{|R(\omega)|^2} \quad (5)$$

The quantity γ , which is sometimes referred to as the waterlevel parameter [17], is an arbitrary constant chosen to optimally reduce the effect of noise introduced through the DC procedure. In our research we have used $\gamma = 0.9$ for all experiments. The value 0.9 was chosen based on optimizing the focus energy in a process similar to that developed by Clayton et al. [17]. Eq. 4 provides one with the solution for $g(\omega)$. One only has to inverse Fourier transform this result to retrieve the "optimal" DC signal in the time domain to be backpropagated such that one gets an approximate Dirac delta function focus.

3. Experimental Set Up

The purpose of our study is to explore the application of the deconvolution variant compared to conventional time reversal in focusing energy at a source location within a sample. In order to make such comparison, we created the following experimental set up. A 30 by 30 by 37 cm³ concrete block had been casted from 72 kg Quickcrete mix (No. 1101, max aggregate grain size < 4 mm), about 60 l water and 5 kg additional gravel (5-15 mm grain size). Three ultrasonic piezo transducers (proprietary type Acsys S0807, center frequency 60 kHz, "ES" in figure 1) were positioned inside the formwork in various orientations before concreting. The block contains only minimal reinforcement, mainly to hold the embedded sensors in place while pouring the concrete. Broadband Acsys point contact sensors type S1803 (center frequency about 100 kHz, "PT" in figure 1) were used as external transducers. They are piezo based as well and feature a spring loaded 2 mm diameter ceramic tip for contact to the concrete. They are sensible to acceleration vertical to the concrete surface. The transmitter signal is generated by custom made rectangular signal generator/amplifier ("BAM US" in figure 1) triggered by a TTL impulse issued by our data acquisition device (National Instruments model 6366). Signals received by the external sensors are 1 kHz low pass filtered and amplified by a Stanford Research low noise preamplifier (SR 566) before being digitized and recorded. The workflow and set up used for acquiring the data is shown in Fig. 1(a). For backpropagation, the setup is reversed. The BAM US device is removed. The transmitter signal generated is replaced by the digital/analog converter integrated in the data acquisition device, sending the computed, time reversed/deconvolved waveforms to the external sensor. The embedded sensor is used as receiver, again using the preamplifier before AD conversion and recording. This reversed set up is shown in Fig. 1 (b).

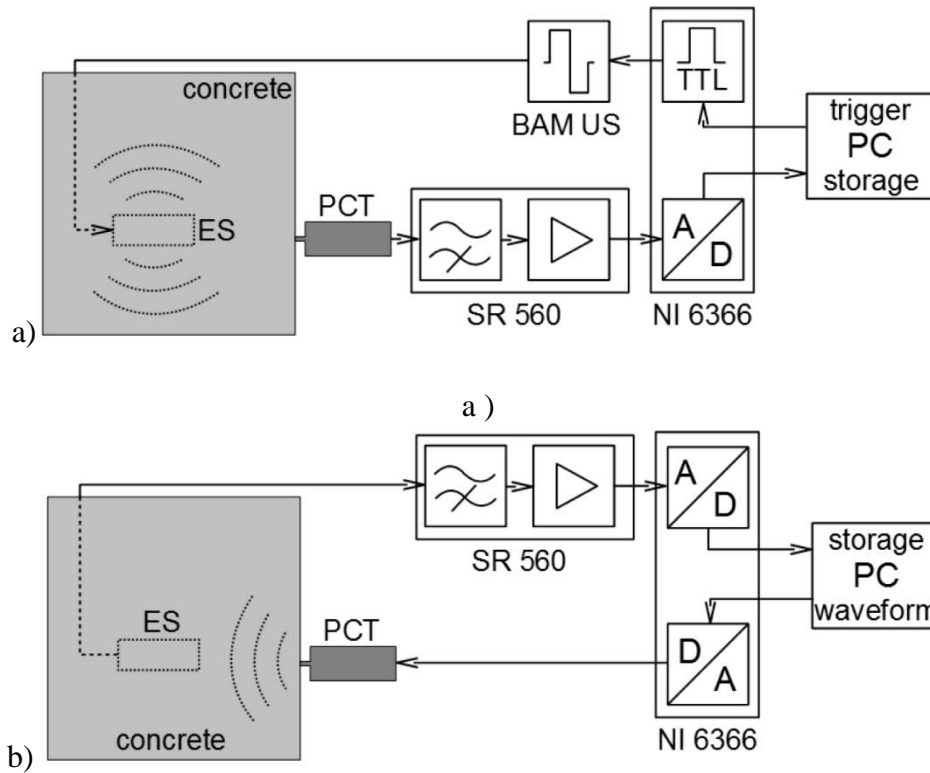


Fig. 1. Diagram indicating tools and methods used during acquisition and backpropagation.

We have used a sampling frequency of 2 MHz and 20000 samples per trace (10 ms recording time). A 4000 sample (2 ms) pretrigger interval was set. Amplitude resolution is 16 bit. True zero time of the transmitter could be identified by electromagnetic crosstalk between transmitter and receiver cables, generating a small but easy to recognize impulse in the receiver data.

Note, that due to a high noise lab environment and a lack of a power amplifier for the backpropagated transmitter signal we had to apply an additional 2 kHz low-pass Butterworth filter on all data.

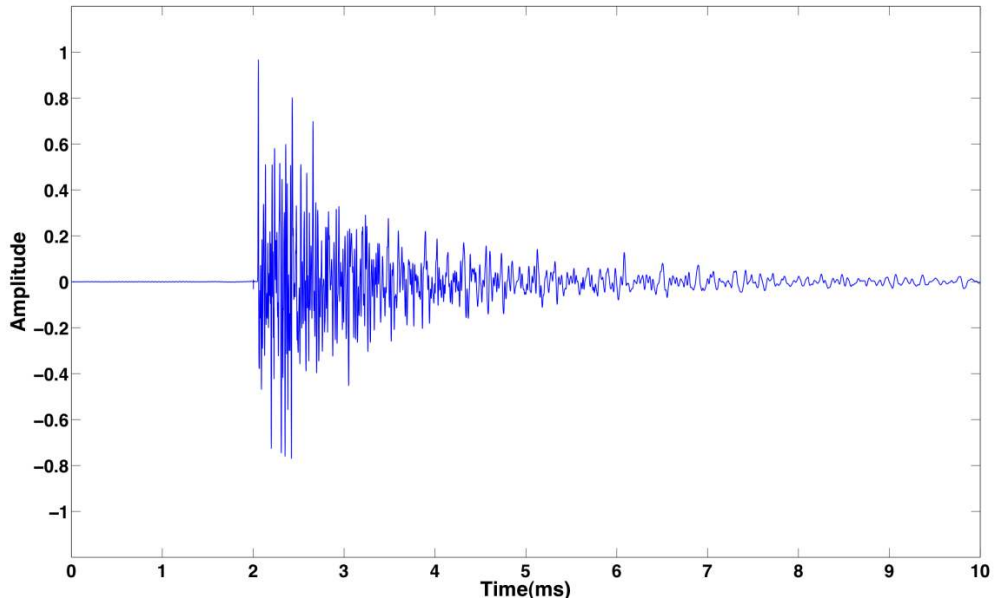


Fig. 2. Recorded scattered waveform at a single receiver on the surface of a concrete block due to our source function generation from the embedded source transducer.

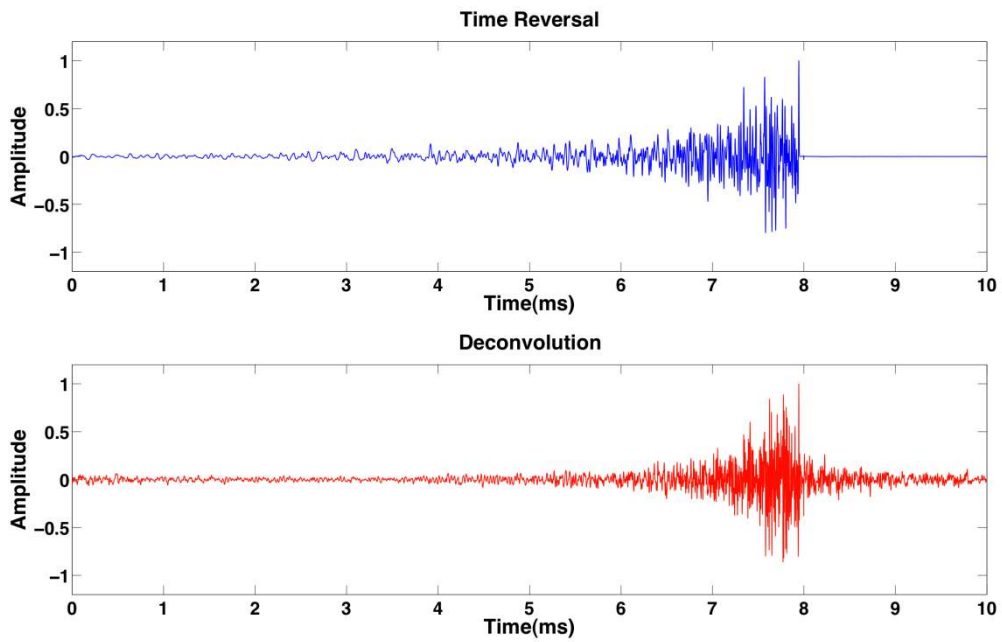


Fig. 3. Back propagation signals calculated using Time Reversal (top) and Deconvolution (bottom) using only the recorded data at the single receiver.

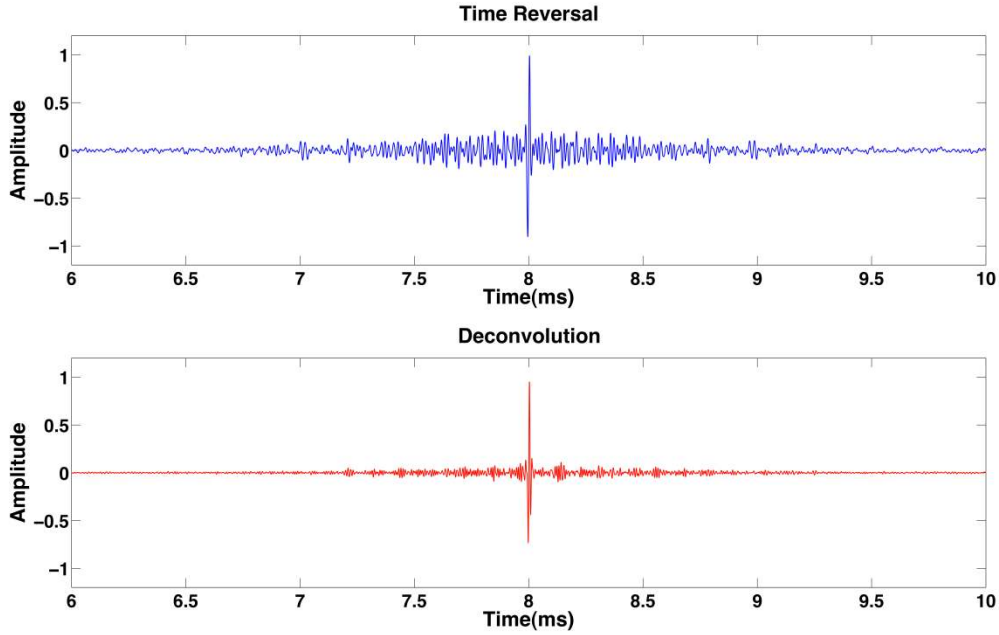


Fig. 4. Temporal focus measured at the embedded source location using Time Reversal (top), and Deconvolution (bottom).

4. Results and Discussion

Our experiments started with propagating a defined 60 kHz source function from the embedded source towards the external receiver. Note the pretrigger time present in recorded signal shown in Figure 2. This pretrigger time was proven by Ulrich et al. [18] to be necessary if one desires to use DC for any application where high signal fidelity is important or where multiple impulses may be focused successively with little separation. Additionally, it was shown by Ulrich et al. [18] that the acausal portion of the signal is necessary in order to create a symmetric focus.

Once our wave field was recorded at the single receiver, TR or DC was applied to calculate the back propagating signals. Applying these two methods, one achieves the results shown in Figure 3 where (a) highlights the backpropagating signal calculated using TR while (b) shows the DC back propagation signal. These two signals shown in Fig. 3 differ significantly in one feature: TR has zero values past approximately 8 ms while DC's backpropagation signal is nonzero for this time range. This is due to the acausal nature of the recorded signal.

These signals were then backpropagated from the receiver location into the same medium where the receiver on the surface of the concrete block now acted as a source. Propagating these calculated TR and DC signals back into the medium, one would expect a focus at the source location. Figure 4 shows the focuses recorded at the source location by using the embedded transducer as a receiver during the backpropagation. Figure 4 (a) shows the temporal focus recorded using the TR calculated signal while Figure 4 (b) represents the temporal focus achieved using the DC calculated signal. The temporal focus achieved using TR has significant side lobes present away from the time of focus. However, the temporal focus achieved using DC has suppressed most of these side lobes and was able to produce a better focus. In order to quantify this improvement, we calculate the amount of energy in a .02ms window around the time of focus compared to the total energy of the signal. The temporal focus achieved using TR only had 41 % of the total

energy within this window while DC's temporal focus had 80 % of the total energy within this window. Thus, DC is clearly able to generate a significantly better temporal focus than TR.

In order to proof the robust nature of this method, we reran the experiment using a different location for the receiver (placing the receiver on a different side of the block). The purpose of this experiment was to not only test and make sure DC still had an improved temporal focus compared to TR but to also demonstrate our decision for γ which was the regularization constant. For this set up, DC's temporal focus was 79 % while TR had a temporal focus of 47 %. We would not expect to see the exact same temporal focusing numbers as before because we changed the direction of displacement we record and the distance between the source and receiver. We reran the experiment numerous times, recalculating the DC signal using different values for γ , and recording the temporal focus at the source location. The experiment showed that the optimal value to be $\gamma = 0.9$. However, even for different γ values, one still achieves some form of a temporal focus until the γ values becomes too small where too much noises gets included into the focus.

The purpose of using time reversal (TR) and deconvolution (DC) processes is to generate a signal such that it will focus at the source location. One can use this feature of the methods for a range of applications in order to characterize the medium. For example, after the time of focus, the wave field will propagate away from the source location with the characteristic as if it were generated by a source mechanism at the focused event location. This is defined as a "virtual" source. This "virtual" source can then be used to for a wide variety of applications from multiple suppression, to medium characterization [19][20][21][22][23]. Additionally, one can continuously monitor and backpropagate signals to investigate the changes occurring within the medium. Finally, using DC, one can define the type of source function focus that will occur at the event location. This was shown to work in Ulrich et al. [18]. Therefore, one could determine the frequency of the focused wave field and allow different frequency focuses to occur. One then records the scattered wave field generated by the virtual sources consisting of different frequencies to characterize the medium. Therefore, by using DC, we could potentially improve the characterization of the medium compared with TR. In addition, the amplitude can be varied to study nonlinear effects.

5. Conclusion

We have introduced a simple though robust method for determining the optimal signal for backpropagation such that one gets an improved temporal focus at the source location. This was proven to hold true for an experimental set up having the source embedded within a concrete block and using only a single receiver. The method does not require any information about the medium. It only needs the recorded signal in order to generate the optimal signal for back propagation. Due to the simplicity, low cost, and robust nature of this method, one could easily implement this technique into pre-existing workflows. This method may then be used to characterize the medium through use of "virtual" sources, repeated backpropagation or backpropagating with different source function focuses.

6. Acknowledgements

We would like to thank BAM (specifically F. Mielentz and R. Feldmann) for providing equipment and software for the experiment, and the civil engineering lab at CSM (M. Mooney, M. Gutierrez and L. Frash) for providing us with space and resources to make the concrete specimen and to carry out our experiment.

References

- [1] Parvulescu and C. Clay. Reproducibility of signal transmission in the ocean. *Radio Elec. Eng.*, 29: 223-228, 1965.
- [2] M. Fink. Time reversed acoustics. *Physics Today*, 50(3):34-40, 1997.
- [3] B.E. Anderson, M. Gri_a, C. Larmat, T.J. Ulrich, and P.A. Johnson. Time reversal. *Acoustics Today*, 4(1): 5-16, 2008.
- [4] C.S. Larmat, R.A. Guyer, and P.A. Johnson. Time-reversal methods in geophysics. *Physics Today*, 63(8): 31-35, 2010.
- [5] M. Tanter, J.-L. Thomas, and M. Fink. Time reversal and the inverse filter. *J. Acoust. Soc. Am.*, 108: 223-234, 2000.
- [6] M. Tanter, J.-F. Aubry, J. Gerber, J.-L. Thomas, and M. Fink. Optimal focusing by spatio-temporal filter. I. Basic principles." *J. Acoust. Soc. Am.*, 110:37-47, 2001.
- [7] G. Montaldo, M. Tanter, and M. Fink. Real time inverse filter focusing through iterative time reversal. *J. Acoust. Soc. Am.*, 115: 768-775, 2004.
- [8] T. Gallot, S. Catheline, P. Roux, and M. Campillo. A passive inverse filter for Green's function retrieval. *J. Acoust. Soc. Am.*, 131: EL21-EL27, 2011.
- [9] V. Bertaix, J. Garson, N. Quieffin, S. Catheline, J. Derosny, and M. Fink. Time-reversal breaking of acoustic waves in a cavity. *Am. J. of Phys.*, 72(10): 1308, 2004.
- [10] P. Roux and M. Fink. Time reversal in a waveguide: study of the temporal and spatial focusing. *J. Acoust. Soc. Am.*, 107(5 Pt 1): 2418-2429, May 2000.
- [11] J.-F. Aubry, M. Tanter, J. Gerber, J.-L. Thomas, and M. Fink. Optimal focusing by spatio-temporal filter. II. Experiments. Application to focusing through absorbing and reverberating media. *J. Acoust. Soc. Am.*, 110: 48-58, 2001.
- [12] R. Daniels and R. Heath. Improving on time reversal with MISO precoding. In *Proceedings of the Eighth International Symposium of Wireless Personal Communications Conference, Aalborg, Denmark, P.VI-124 - P.VI-129, 2005.*
- [13] R.C. Qiu, C. Zhou, N. Guo, and J.Q. Zhang. Time reversal with MISO for ultrawide-band communications: experimental results. *IEEE Antennas and Wireless Propagation Lett.*, 5:1-5, 2006.
- [14] P. Blomgren, P. Kyritsi, A. Kim, and G. Papanicolaou. Spatial focusing and intersymbol interference on multiple-input-single-output time reversal communication systems. *IEEE J. Oceanic Eng.*, 33: 341-355, 2008.
- [15] Zhou, N. Guo, and R.C. Qiu. Experimental results on multiple-input single-output (MISO) time reversal for UWB systems in an office environment. In *MILCOM'06 proceedings of the 2006 IEEE conference on military communications*, p. 1299-1304, Piscataway, NJ, 2006. IEEE Press.
- [16] Zhou and R.C. Qiu. Spatial focusing of time-reversed UWB electromagnetic waves in a hallway environment. In: *Proceedings of the Thirty Eighth symposium on System Theory*, p. 318-322, 2006.
- [17] R. Clayton and R. Wiggins. Source shape estimation and deconvolution of teleseismic bodywaves. In: *Geophys. J. Royal Astron. Soc.*, 47: 151-177, 1976.
- [18] T. J. Ulrich, J. Douma, B. E. Anderson and R. Snieder. Improving spatio-temporal focusing and source reconstruction through deconvolution. In: *Wave Motion*, currently under review, 2013.
- [19] K. Wapenaar, F. Broggini, and R. Snieder. Creating a virtual source inside a medium from reflection data: heuristic derivation and stationary-phase analysis" In *Geophysical Journal International*, 190: 1020-1024, 2012.
- [20] J. Behura, and R. Snieder. Virtual Real Source: Source signature estimation using seismic interferometry. *Geophysics*, 78: Q57-Q68, 2013.
- [21] K. Mehta, J. Sheiman, R. Snieder, and R. Calvert. Strengthening the virtual-source method for time-lapse monitoring. *Geophysics*, 73: S73-S80, 2008.
- [22] R. Snieder, J. Sheiman, and R. Calvert. Equivalence of the virtual-source method and wave-field deconvolution in seismic interferometry. *Physical Review E*, 73, 2006.
- [23] K. Mehta, R. Snieder, R. Calvert, J. Sheiman. Acquisition geometry requirements for generating virtual-source data" In *The Leading Edge*, May, 2008.