



**HAL**  
open science

# How to adapt numerical simulation of wave propagation and ultrasonic laboratory experiments to be comparable - A case study for a complex topographic model

Bence Solymosi, Nathalie Favretto-Cristini, Vadim Monteiller, Dimitri Komatitsch, Paul Cristini, Børge Arntsen, Bjorn Ursin

## ► To cite this version:

Bence Solymosi, Nathalie Favretto-Cristini, Vadim Monteiller, Dimitri Komatitsch, Paul Cristini, et al.. How to adapt numerical simulation of wave propagation and ultrasonic laboratory experiments to be comparable - A case study for a complex topographic model. *Geophysics*, 2018, 83 (4), pp.T195-T207. hal-02020821

**HAL Id: hal-02020821**

**<https://hal.science/hal-02020821>**

Submitted on 15 Feb 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## GEOPHYSICS®

**How to adapt numerical simulation of wave propagation and ultrasonic laboratory experiments to be comparable? A case study for a complex topographic model**

Journal:	<i>Geophysics</i>
Manuscript ID	GEO-2017-0536.R1
Manuscript Type:	Technical Paper
Date Submitted by the Author:	19-Dec-2017
Complete List of Authors:	Solymosi, Bence; Aix-Marseille Univ., CNRS, Centrale Marseille, LMA, France Favretto-Cristini, Nathalie; Aix-Marseille Univ., CNRS, Centrale Marseille, LMA, France Monteiller, Vadim; Aix-Marseille Univ., CNRS, Centrale Marseille, LMA, France Komatitsch, Dimitri; Aix-Marseille Univ., CNRS, Centrale Marseille, LMA, France Cristini, Paul; Aix-Marseille Univ., CNRS, Centrale Marseille, LMA, France Arntsen, Børge; Norwegian University of Science and Technology Ursin, Bjørn; Norwegian University of Science and Technology
Keywords:	ultrasonic, finite element, modeling, diffraction
Area of Expertise:	Seismic Modeling and Wave Propagation

1  
2  
3  
4       **How to adapt numerical simulation of wave propagation and**  
5  
6  
7       **ultrasonic laboratory experiments to be comparable? A case study**  
8  
9  
10       **for a complex topographic model**  
11  
12  
13  
14  
15  
16  
17  
18

19       **Running head:** Comparison of synthetic and lab data  
20  
21  
22  
23

24       **Authors:**

25  
26  
27       Bence Solymosi<sup>1\*</sup>, Nathalie Favretto-Cristini<sup>1</sup>, Vadim Monteiller<sup>1</sup>,

28  
29       Dimitri Komatitsch<sup>1</sup>, Paul Cristini<sup>1</sup>, Børge Arntsen<sup>2</sup>, Bjørn Ursin<sup>2</sup>  
30  
31  
32  
33  
34

35  
36       <sup>1</sup>Aix-Marseille Univ, CNRS, Centrale Marseille, LMA, France  
37

38       <sup>2</sup>Norwegian University of Science and Technology, Trondheim,  
39  
40  
41       Norway  
42  
43

44       \*[bence.solymosi@gmail.com](mailto:bence.solymosi@gmail.com)  
45  
46  
47  
48  
49

50       **Keywords:** wave propagation, spectral-element modeling, laboratory  
51  
52       experiments, curved interfaces, diffraction, transducer characteristics  
53  
54  
55  
56  
57  
58  
59  
60

## ABSTRACT

Numerical methods are widely used in seismic exploration to simulate wave propagation, however the algorithms are based on various assumptions. The accuracy of numerical simulations is of particular interest in case of realistic geological setups. The direct comparison of numerical results can have limitations, and an alternative approach can be the comparison of synthetic results with experimental data, obtained for a small-scale physical model in laboratory conditions. Laboratory experiments are repeatable and provide high-quality data for a known configuration. The goal of this work is to provide a possible workflow to adapt the numerical simulations and the laboratory experiments to each other, such that the two can be easily compared with high accuracy. The model is immersed in a water tank and a conventional pulse-echo technique is used to collect reflection data in both zero-offset and offset configurations. We use a spectral-element method for the numerical modeling. The model geometry is implemented using a non-structured mesh and the computational cost can be optimized using larger elements and higher-order basis functions. The real source transducer characteristics are implemented based on a new approach: laboratory characterization of the impulse response, followed by an inversion step to obtain a numerically-equivalent source. The comparison of the zero-offset synthetic and laboratory results reveals an excellent fit in terms of arrival time, phase and amplitude. Minor amplitude mismatches may be attributed to the noise recorded in the laboratory data, and to the possible inaccuracy of the proposed source implementation. Comparison of simulated and laboratory offset traces also exhibits a good fit in general, but with significantly less accuracy for some arrivals than in the zero-offset case. This can be mainly attributed to the inaccuracies of the transducer positions

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

during the laboratory measurements combined with the strong topography of the model.

For Peer Review

## INTRODUCTION

Numerical simulation of seismic wave propagation is widely used for environmental and industrial applications for subsurface evaluation in seismic exploration (e.g., for survey design, data processing and interpretation) (Robertsson et al., 2007). Simulation is also a core tool of seismic imaging and inversion (Virieux et al., 2011). Conventional methods (e.g., ray-tracing, Kirchhoff integral and finite-difference methods), widely used in seismic exploration, are efficient to simulate realistic wavefields in environments with simple structures and slowly-varying material properties. However, difficulties arise for environments with large and rapid structural changes, due to shadow zones and (multiple) diffractions. Thus, different methods have been developed to improve seismic modeling in realistic geological environments, including steeply-dipping faults, curved interfaces, salt bodies, etc (e.g., Mittet, 2017). Before real applications, new methods are typically tested against other numerical methods using synthetic configurations. Several projects have focused on the comparison and validation of different numerical results (e.g., Igel et al., 2000; Moczo et al., 2006; Fehler & Kehler, 2011; Chaljub et al., 2015). Since each numerical algorithm is based on mathematical or physical assumptions, their direct comparison for realistic and complex models can have limitations, as it can be difficult to determine the one that gives the best approximation of a physically unknown solution. Therefore there is a strong interest in using physical datasets to benchmark synthetic results. However, since in real life the subsurface of the Earth is never accurately known, the synthetic results cannot be directly compared with any seismic or seismological dataset from real measurements.

An alternative approach to test and validate the performance of numerical methods in

1  
2  
3  
4 realistic cases can be the comparison of synthetic results with experimental data,  
5  
6 obtained for a small-scale physical model in laboratory conditions. This implicitly  
7  
8 assumes that the scaled physical mechanisms are identical to those at seismic scale  
9  
10 (Ebrom & MacDonald, 1994), and this assumption is fulfilled in case of the linear wave  
11  
12 equation. Considered as obsolete in the 1990's – essentially due to the drastic increase in  
13  
14 computing capacities -, laboratory experiments have recently been re-introduced into the  
15  
16 ideas-to-applications pipeline. Laboratory can be considered as a halfway house between  
17  
18 numerical modeling and field observations. Indeed, laboratory experiments are  
19  
20 repeatable, more controllable than real seismic surveys, versatile in terms of acquisition  
21  
22 setup and provide high-quality data for a known configuration. Furthermore, similarly to  
23  
24 real seismic acquisitions and unlike some numerical data, laboratory measurements  
25  
26 contain random and signal-generated noise, multiples, mode conversions, and  
27  
28 uncertainties due to position inaccuracies. As these sources of noise and uncertainties can  
29  
30 be better assessed than in case of field datasets, laboratory experiments also provide a  
31  
32 higher fidelity data than real seismic surveys. Therefore, laboratory experiments are a  
33  
34 valuable tool to validate numerical simulations against real physical datasets.  
35  
36  
37  
38  
39

40  
41 Initially, small-scale physical modeling was extensively developed for a better  
42  
43 understanding of wave propagation phenomena (e.g., Wapenaar & Berkhout, 1987; Pant  
44  
45 et al., 1992) and for the validation of theoretical predictions (Favretto-Anrès & Rabau,  
46  
47 1997). Laboratory experiments are still used nowadays to investigate physics that is not  
48  
49 sufficiently understood to be numerically modeled with confidence (Cooper et al., 2010;  
50  
51 Stewart et al., 2013; Ekanem et al., 2013; Xu et al., 2016; Chang et al., 2017). Data from  
52  
53 laboratory experiments are also used as input to inverse problems (Pratt, 1999; Favretto-  
54  
55 Anrès & Sessarego, 1999; Bretaudeau et al., 2013; Chai et al., 2016), to test new data  
56  
57  
58  
59  
60

1  
2  
3  
4 processing algorithms (Campman et al., 2005), and in time-lapse 3D studies (Sherlock et  
5 al., 2000). More recently, small-scale modeling approaches have been developed as tools  
6  
7 to validate numerical modeling and seismic imaging methods in the context of onshore  
8  
9 and offshore seismics (Bretaudeau et al., 2011; Tantsereva et al., 2014; Favretto-Cristini  
10  
11 et al., 2014). In particular, Tantsereva et al. (2014) evaluated the ability of a 3D  
12  
13 discretized Kirchhoff integral method (DKIM) to accurately simulate complex  
14  
15 diffractions using a zero-offset laboratory dataset, measured for a small-scale model with  
16  
17 strong topography, immersed in a water tank. Comparisons of numerical and laboratory  
18  
19 datasets showed that the DKIM could correctly reproduce the wavefield, except in the  
20  
21 vicinity of secondary shadow boundaries created by the interaction of the edges of the  
22  
23 topographic structures. As a follow up of the work of Tantsereva et al. (2014), Favretto-  
24  
25 Cristini et al. (2017) quantitatively analyzed the effect of multiple scattering and surface  
26  
27 curvature on the wavefield, in order to define the cases where these effects may be  
28  
29 neglected in the numerical modeling without a significant loss of accuracy. These works  
30  
31 clearly show the importance of laboratory datasets as part of the benchmarking options  
32  
33 for numerical algorithms.  
34  
35  
36  
37  
38  
39

40  
41 An efficient benchmarking procedure requires a carefully chosen and jointly-adapted  
42  
43 approach to both the laboratory experiments and the numerical modeling. On the one  
44  
45 hand, the numerical tools must be adapted to the experimental configuration (e.g.,  
46  
47 implementing the real source characteristics, material properties and acquisition  
48  
49 conditions). On the other hand, the laboratory experiments have to be carried out in  
50  
51 accordance with the capabilities of the numerical tools (e.g., choosing the acquisition  
52  
53 geometry such that the future computational cost is the lowest possible). In addition,  
54  
55 experimental uncertainties must be identified, in order to be subsequently minimized as  
56  
57  
58  
59  
60

1  
2  
3  
4 much as possible, and numerical simulations may also contribute to it.  
5

6 The goal of this paper is to address the above challenges by providing a possible way  
7 to adapt both the numerical simulations and the laboratory experiments such that the two  
8 can be easily compared with high accuracy. To achieve this goal, we resorted to spectral-  
9 element modeling (SEM) as a full-wave method, which is not based on strong underlying  
10 assumptions (such as for example the DKIM). SEM also becomes more and more  
11 popular with time in the seismic community, since it is well-suited for high-performance  
12 computing (Komatitsch et al., 2003). As it combines the accuracy of a pseudo-spectral  
13 method with the flexibility of a finite-element method, SEM allows the handling of  
14 complex geometries by using a non-structured mesh and different element sizes in the  
15 computational domain (Komatitsch & Tromp, 2002; Oliviera & Seriani, 2011). Since the  
16 necessary trade-off between accuracy and computational cost is usually sought-after, we  
17 are also interested in the ability of SEM to accurately simulate complex 3D wavefields  
18 including (multiple) diffractions at the lowest possible computational and man-hour cost.  
19 Few papers are devoted to the comparison of SEM with other numerical methods (e.g.,  
20 Capdeville et al., 2002, 2003; Moczo et al., 2010; Chaljub et al., 2015; De Basabe & Sen,  
21 2015). Pageot et al. (2017) recently compared laboratory and synthetic datasets in an  
22 onshore configuration to investigate surface wave propagation and amplitude  
23 transformation between 2D and 3D. But to the best of our knowledge, no paper uses  
24 laboratory experiments as reference datasets for comparison in offshore configuration.  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49

50 In this paper, we thus compare 3D spectral-element simulations with laboratory  
51 measurements in both 3D zero-offset and 3D offset offshore reflection configurations for  
52 the so-called Marseille-Benchie model. To our knowledge, it is the first time that such a  
53 comparison for the general offset case is presented. The Marseille-Benchie model is  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 based on French's model (French, 1974) and also includes additional structures with  
5  
6 steep flanks, sharp edges, corners and curved interfaces (Tantsereva et al., 2014). It  
7  
8 enhances multiple reflections and diffractions, as well as shadow zones and interactions  
9  
10 between different structures. This complexity provides a significant challenge to any  
11  
12 numerical method to reproduce the wavefield.  
13  
14

15 The paper is organized as the following. Section "Small-scale seismic modeling"  
16  
17 briefly describes the laboratory experiments, i.e., the small-scale model and the  
18  
19 experimental setup. The laboratory datasets obtained in zero-offset and offset  
20  
21 configurations are also presented, together with their physical interpretations. Section  
22  
23 "Numerical modeling" is devoted to a short description of SEM. More importantly, we  
24  
25 also discuss in details the input data/parameters, namely the model geometry, the  
26  
27 material properties, and the characteristics of the source and receiver transducers. In  
28  
29 "Data comparisons", we compare the laboratory and numerical datasets, and then discuss  
30  
31 the results in "Discussion".  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## SMALL-SCALE SEISMIC MODELING

We carried out several laboratory experiments in a water tank, where wave propagation occurs in small-scale conditions. A scaling factor of 1:20 000 is used to scale down the real-life dimensions of typical seismic setups to the laboratory scale. Hence, an experimental frequency of 500 kHz corresponds to a seismic frequency of 25 Hz and an experimental distance of 1 mm corresponds to 20 m at seismic scale. Material properties, such as velocity, density and attenuation are not affected directly by the scaling.

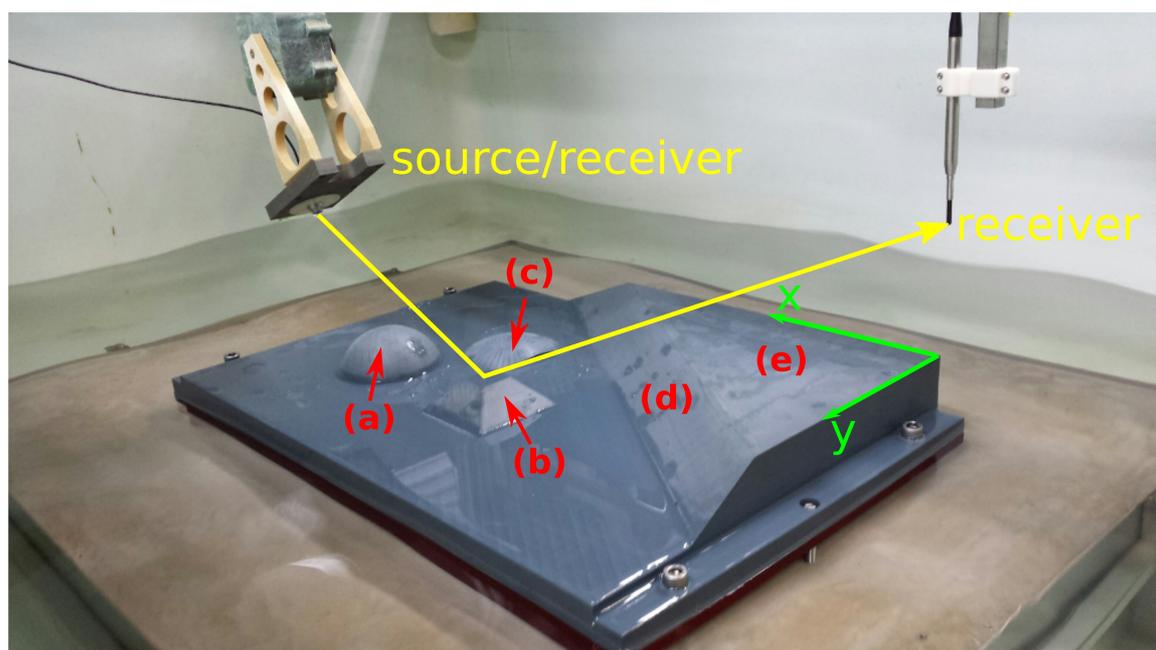
## Small-scale geological model

The Marseille-Benchie model contains various complex topographic features, such as a dome, a truncated dome, a truncated pyramid and two flat parts separated by a ramp (Figure 1). The model is made of polyvinyl chloride (PVC) and has a size of 600 mm x 400 mm, corresponding to 12 km x 8 km at seismic scale. Its thickness varies between 30 and 70 mm, depending on the geometry. The measured material properties of the PVC are  $V_p=2220\pm 10$  m/s,  $V_s=1050\pm 10$  m/s,  $\rho=1412\pm 17$  kg/m<sup>3</sup>. PVC is considered to be homogeneous and isotropic for the frequency range of interest of this work (250-650 kHz). For example the P- and S-wave velocities were found to be quasi-constant for this frequency range, suggesting a negligible dispersion. Attenuation was measured using the amplitude of transmitted monochromatic sine waves at different frequencies through different PVC samples of varying thickness. Following the measurements, the attenuation can be transformed into quality factors:  $30 < Q_p < 60$  and  $27 < Q_s < 31$  for P- and S-waves, respectively. As that is known, the measurement of attenuation is one of the most difficult laboratory tasks among all the material property characterizations. According to the measurements and accounting for the uncertainties of this parameter, we consider the PVC to have the same quality factor between 250-650 kHz which is in good agreement with the literature (Favretto-Anrès & Rabau, 1997). For further details on the model, see also Tantsereva et al. (2014).

## Experimental setup

Since our work is concerned with offshore measurements, the model was immersed in

1  
2  
3  
4 a water tank equipped with a computer-controlled acquisition system that allows for  
5 accurate positioning of the source and receiver transducers. The water temperature was  
6 continuously monitored during the measurements, providing accurate knowledge of the  
7 speed of sound waves in water (usually around 1480 m/s). Water was considered to have  
8 a density of 1000 kg/m<sup>3</sup> and negligible attenuation.  
9  
10  
11  
12  
13  
14  
15  
16  
17



18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39 *Figure 1. Illustration of the small-scale seismic experiments performed in the water tank.*  
40  
41 *The Marseille-Benchic model contains a dome (a), a truncated pyramid (b), a truncated*  
42 *dome (c), a ramp (d) and an elevated plateau (e). The model is illuminated by a*  
43 *piezoelectric transducer (on the left). In offset configuration, the wavefield is recorded by*  
44 *a hydrophone (on the right).*  
45  
46  
47  
48  
49  
50  
51

52  
53 A conventional pulse-echo technique was used to collect reflection data in both zero-  
54 offset and offset configurations (Figure 1). Zero-offset measurements were performed by  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 using a custom-made Imasonic® transducer as both the source and the receiver. It has a  
5  
6 diameter of 3 mm and was located  $180\pm 0.5$  mm above the flat part of the model  
7  
8 (corresponding to 3.6 km at seismic scale). The source signal generated by this  
9  
10 transducer and its associated frequency spectrum for the frequency range of interest of  
11  
12 this work are shown in Figure 2. The transducer has a dominant frequency of 500 kHz  
13  
14 and a broad-beam radiation pattern, as the width of the main lobe is  $35^\circ$  at -3 dB. This  
15  
16 radiation pattern allows for a large area to be illuminated and therefore more 3D effects  
17  
18 to be captured, e.g., interaction of waves with multiple topographic features and multiple  
19  
20 wave scattering (Favretto-Cristini et al., 2017).  
21  
22  
23  
24

25 Offset measurements were performed by using two transducers, namely the above-  
26  
27 mentioned transducer as the source and an omnidirectional Teledyn Reson® hydrophone  
28  
29 as the receiver. Both transducers were located  $150\pm 0.5$  mm above the flat part of the  
30  
31 model. The hydrophone has an active diameter of 4 mm and its sensitivity is constant  
32  
33 between 50-800 kHz. The source can be tilted with various angles to illuminate different  
34  
35 parts of the model or to enhance some particular effects, such as shadow zones.  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

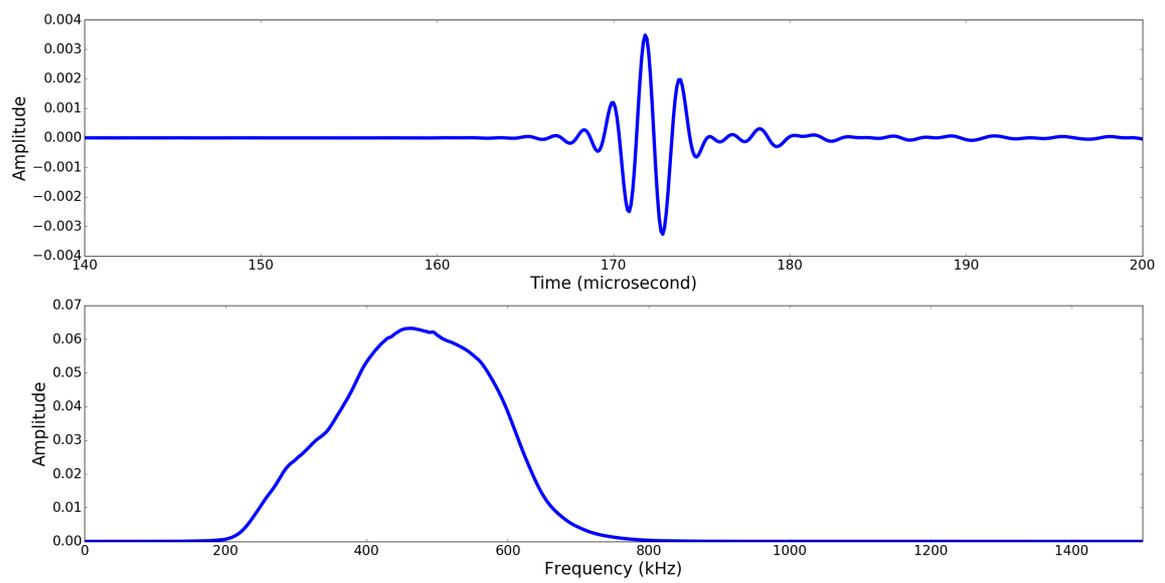


Figure 2. Top: source signal (filtered between 250-650 kHz) generated by the source transducer and recorded by the hydrophone in opposite position, bottom: associated frequency amplitude spectrum.

## Laboratory datasets

We performed acquisitions along  $x$ -lines (Figure 1) with a sampling distance of 0.5 mm (corresponding to 10 m at seismic scale). The collected dataset thus consists of numerous parallel profiles, providing a set of reflection data for a dense grid (with a receiver spacing of 0.5 mm in both directions). In order to enhance the signal-to-noise ratio, 256 acquisitions were performed at each grid point and then the individual registrations were stacked. The speed of sound in water was  $1485\pm 0.1$  m/s and  $1484\pm 0.1$  m/s for zero-offset and offset measurements, respectively, due to the different water temperatures during the two measurements. The tilt angle of the source transducer was  $39^\circ$  for the offset measurements.

For the sake of brevity, we focus only on one line in this paper, located above the full dome, the truncated pyramid and the ramp (red line in Figure 3). This acquisition line provides complex diffraction effects, multiple reflections and arrivals corresponding to curved interfaces. Figure 4 shows the laboratory zero-offset dataset for the study line, overlaid by the interpretation of the recorded events. For the sake of clarity, only the main events are shown in Figure 4. Events a) and c) represent the arrivals related to the top surface of the PVC, corresponding to the pyramid and the dome, and to the flat parts, respectively. Event a) mainly consists of reflections (see positions between 90-115 mm for the pyramid and 95-410 mm for the dome). There are also some diffraction hyperbolas corresponding to the edges of the top surface of the pyramid, for positions below 90 mm and above 115 mm. Moreover due to the angle of the truncation, there are two smaller hyperbolas in the center of the pyramid, partly overlapping with the reflections from the top flat surface of the object. Similarly to event a), event c) mainly

1  
2  
3  
4 consists of reflections, as well as some diffraction hyperbolas related to the junctions of  
5  
6 the the pyramid and the dome with the flat part. Events b) and d) correspond to  
7  
8 reflections from the bottom of the PVC, below the pyramid and the dome, and below the  
9  
10 flat part, respectively. Since Figure 4 is a time section, a classical velocity pull-up effect  
11  
12 can be seen in the different arrival times of events b) and d). Indeed, depending on the  
13  
14 overburden, reflections from the same horizontal bottom surface of the PVC arrive at  
15  
16 different times. Event e) represents reflections from the small truncated dome (Figure 1).  
17  
18 This out-of-plane arrival, which is due to the broad-beam radiation pattern of the source  
19  
20 transducer, was not considered during the simulations. Event f) shows reflections from  
21  
22 the ramp, which was partly accounted for during the simulations. Note that the  
23  
24 diffractions on the right side of the section after 200  $\mu$ s and for positions between 300-  
25  
26 420 mm, are related to the side of the model.  
27  
28  
29  
30

31  
32 Figure 5 shows the laboratory offset dataset (i.e. a common shot gather) for the study  
33  
34 line together with the interpretation of the main events. Event a) shows the direct arrival  
35  
36 from the source and event b) the reflections from the dome. All the interpretations  
37  
38 marked as event c) correspond to reflections/diffractions from the pyramid. Event d)  
39  
40 illustrates the reflections from the flat part of the PVC. Event e) is related to reflections  
41  
42 from the small truncated dome and event f) to reflections from the ramp. Event g) is not  
43  
44 related to the model, but to spurious arrivals from the acquisition system (not considered  
45  
46 during the simulations).  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

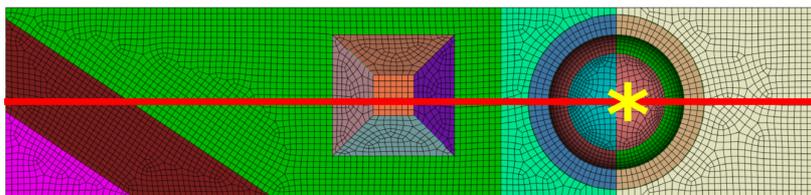


Figure 3. Part of the model used for the numerical simulations with a coarse mesh. The red line denotes the position of the study line discussed in the paper. The yellow asterisk shows the source position for the offset study line. The different colors show the subdomains necessary for the non-structured meshing.

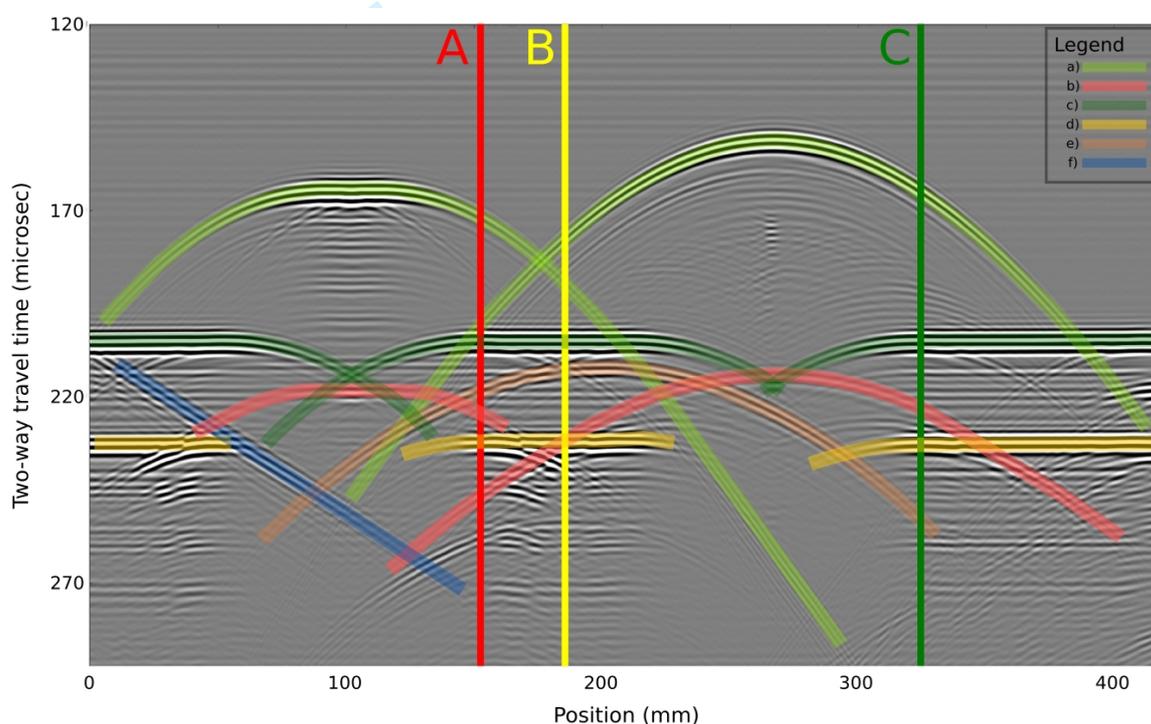


Figure 4. Cross-section of the laboratory zero-offset dataset, corresponding to the red line in Figure 3. The data was filtered between 250-650 kHz. Annotated events: (a) & (b) top & bottom of the pyramid and the dome, (c) & (d) top & bottom of the flat part, (e) truncated dome, (f) ramp. The vertical lines denote the zero-offset traces chosen for comparison.

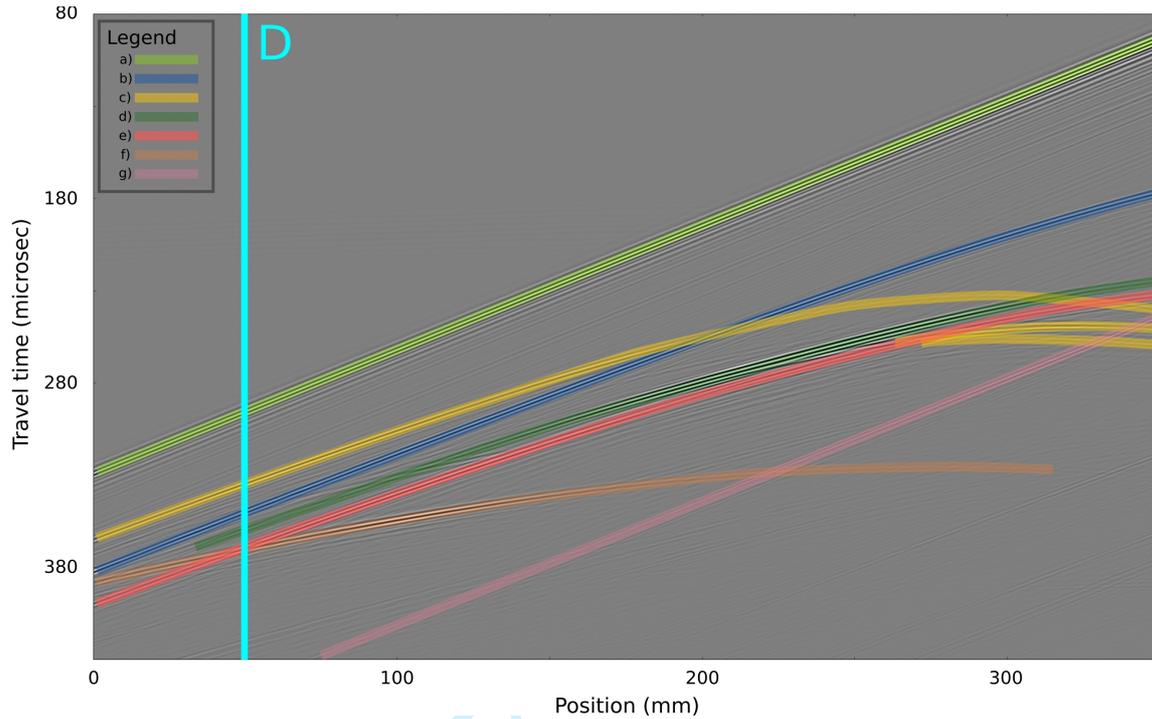


Figure 5. Cross-section of the laboratory offset dataset (i.e. common shot gather), corresponding to the red line in Figure 3. The data was filtered between 250-650 kHz. Annotated events: (a) direct arrival, (b) dome, (c) pyramid, (d) flat part, (e) truncated dome, (f) ramp, (g) spurious reflection from the acquisition system. The source position is shown in Figure 3 with the yellow asterisk. The vertical line denotes the offset-trace chosen for comparisons.

## NUMERICAL MODELING

We used a spectral-element method (SEM) for the numerical modeling of the experiments. Following a brief recall of the method, we discuss the strategy used to mesh the model geometry, the numerical implementation of the real transducer characteristics, as well as the preliminary numerical calibration of the material properties.

### Recall of the spectral-element method

Here we focus only on some of the most important features of the method, and we refer the reader to Komatitsch & Vilotte (1998), Fichtner (2010) or Peter et al. (2011) for more details.

The strong form of the wave equation for viscoelastic materials is described as

$$\rho \partial_t^2 \mathbf{u} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{f} \quad (1)$$

where  $\rho$  denotes the mass density,  $\mathbf{u}=\mathbf{u}(\mathbf{x},t)$  the displacement field,  $\mathbf{x}$  the spatial coordinates,  $t$  the time,  $\boldsymbol{\sigma}$  the stress tensor and  $\mathbf{f}$  the source term. The source term for viscoelastic materials can represent for example a point source:

$$\mathbf{f} = -\mathbf{D} \cdot \nabla \delta(\mathbf{x} - \mathbf{x}_s) S(t) \quad (2)$$

where  $\mathbf{D}$  denotes the moment tensor,  $\mathbf{x}_s$  the source position,  $\delta$  the Dirac delta distribution and  $S(t)$  the source wavelet. Under the assumption of small perturbations, the stress tensor  $\boldsymbol{\sigma}$  is linearly related to the displacement field through the constitutive relationship (Hooke's law):

$$\boldsymbol{\sigma} = \mathbf{c} : \nabla \mathbf{u} \quad (3)$$

where  $\mathbf{c}$  denotes the stiffness tensor, describing the elastic properties of the material. Since the Marseille-Benchie model is made of a viscoelastic material, equation 3 has to

1  
2  
3  
4 be modified such that the stress is determined by the entire strain history:  
5

$$6 \quad \sigma(t) = \int_{-\infty}^t \partial_t c(t-t') : \nabla \mathbf{u}(t') dt' \quad (4)$$

7  
8  
9  
10 The technique of Liu et al. (1976) is used to approximate the absorption based on a set  
11 of three Zener standard linear solids. This standard approach usually assumes that the  
12 quality factor Q does not depend on the frequency. This assumption is confirmed by our  
13 laboratory measurements, which show the same Q factor for the PVC used in the model  
14 when measured between 250-650 kHz (see section “Small-scale geological model”). In  
15 practice, the implementation of the Zener model requires fitting Q in the frequency range  
16 of interest by using a set of relaxation mechanisms (relaxation times represented by  
17 points in the frequency range, and their associated weights). A linear approach can be  
18 used by setting the optimization points at given frequencies in the frequency range of  
19 interest and then optimizing the fit for the weights (Emmerich & Korn, 1987). However,  
20 this approach does not ensure the positivity of the weights and thus the decay of the total  
21 energy.  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36

37 An alternative approach is introduced by Blanc et al. (2016) to ensure that the weights  
38 are always positive and their non-linear optimization is also more accurate in terms of  
39 fitting the constant Q approximation in the frequency range of interest. The non-linearity  
40 means that both the points and the weights are optimized to obtain a better fit of Q in the  
41 frequency range of interest. We use this approach for the simulations presented in this  
42 work.  
43  
44  
45  
46  
47  
48  
49  
50

51 SEM uses the weak form of the equations, which can be obtained by multiplying  
52 equation 1 with an arbitrary test function  $\mathbf{w}$  and then integrating by parts over the total  
53 volume of the model  $\Omega$ :  
54  
55  
56  
57  
58  
59  
60

$$\int_{\Omega} \rho \mathbf{w} \cdot \partial_t^2 \mathbf{u} d^3 \mathbf{x} = \int_{\partial\Omega} \hat{\mathbf{n}} \cdot \boldsymbol{\sigma} \cdot \mathbf{w} d^2 \mathbf{x} - \int_{\Omega} \nabla \mathbf{w} : \boldsymbol{\sigma} d^3 \mathbf{x} + \mathbf{M} : \nabla \mathbf{w}(\mathbf{x}_s) S(t) \quad (5)$$

Equation 5 can be reformulated as:

$$\mathbf{M} \ddot{\mathbf{u}}(t) + \mathbf{K} \mathbf{u}(t) = \mathbf{f}(t) \quad (6)$$

where  $\mathbf{M}$  denotes the mass matrix and  $\mathbf{K}$  the stiffness matrix. In SEM, the computational cost is optimized by combining high-degree Lagrange interpolants to represent the wavefield and Gauss-Lobatto-Legendre (GLL) quadrature to compute the integrals involved (Komatitsch & Vilotte, 1998). This combination leads to a perfectly diagonal mass matrix in equation 6, which then enables the use of an explicit time scheme that can be efficiently parallelized (Komatitsch et al., 2003; Carrington et al., 2008; Vos et al., 2010). On the one hand, SEM is efficient in handling complex geometries and fluid-solid coupling. On the other hand, the standard GLL quadrature requires a hexahedral mesh in 3D, which can be challenging to obtain in case of a non-structured mesh for realistic geological setups.

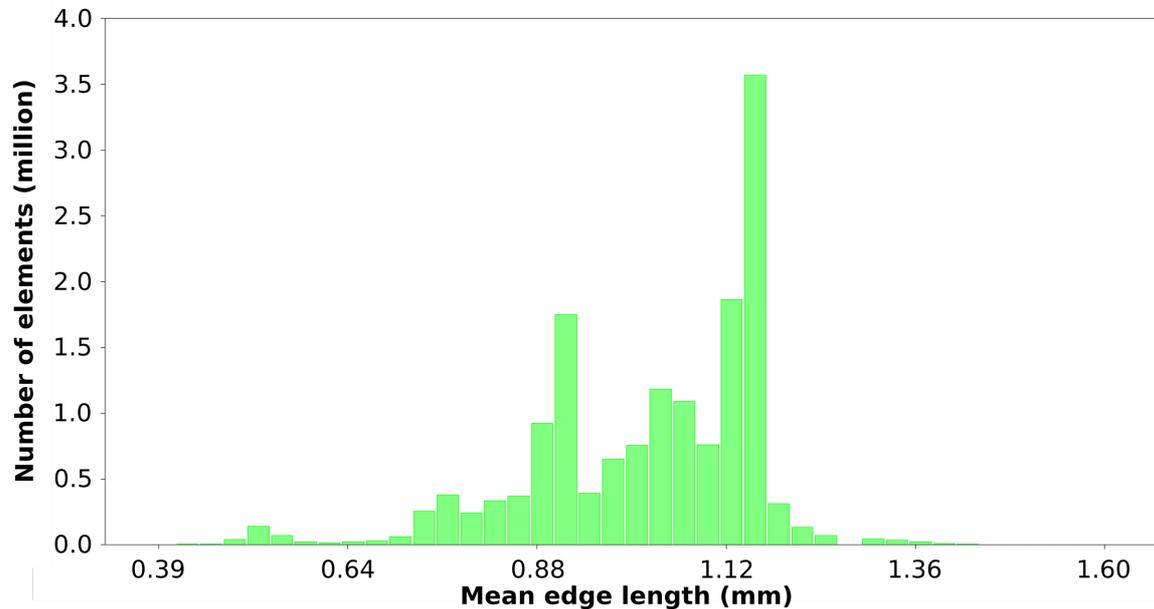
Considering only a part of the full physical domain results in the need for artificial boundaries in the simulations. In order to avoid spurious reflections from these boundaries, we use a perfectly matched layer (PML) technique (Komatitsch & Tromp, 2003; Festa et al., 2005; Kristek et al., 2009). As SEM uses the weak form of the wave equation, the PML equations have singularities, which need to be explicitly removed (Xie et al., 2016).

In our work, we used Specfem3D-Cartesian, an open-source spectral-element software package (Komatitsch & Vilotte, 1998), with explicit second-order Newmark time stepping (Hughes, 1987).

## Meshing

Creating a non-structured hexahedral mesh for a complex geometry is a challenging and lengthy task (Shepherd & Johnson, 2008; Staten et al., 2010). We used Cubit/Trelis® (Blacker, 1994) to mesh the model. In case of a non-structured mesh, we need to keep in mind the future computational cost and the accuracy by considering three points. Firstly, the element size must be small enough to accurately model the highest frequencies to be considered. Secondly, the size of the different elements in one material should be as equal as possible (depending on the geometry) to avoid too small elements. This is important because smaller elements require smaller time steps (i.e., higher computational cost) and more memory. Finally, one needs to avoid creating too distorted/elongated elements, which could result in meshes of poor quality or even containing elements with negative Jacobians, making the simulation unstable. Since the model has a complex overall geometry, fully automatic hexahedral meshing algorithms could not be used. Our solution was to cut the domain into several subdomains, which were easier to handle for the meshing algorithms (Figure 3). The challenge of the task was to find the order in which the individual subdomains had to be meshed, such that the entire computational domain could be meshed at the end. Due to these difficulties - and also to reduce the computational cost -, we considered only a part of the full model for the numerical simulations (Figure 3). As a result, the truncated dome was excluded from the simulations, as this object proved to be too complex to be meshed, mainly due to its small dimensions combined with sharp edges and narrow corners. With our decomposition strategy, we first obtained a mesh containing about 15.6 million elements, including the water layer above the PVC. Figure 6 shows a typical distribution of the element size for

1  
2  
3  
4 the model with the applied decomposition and meshing strategy. The maximum edge  
5 length is about four times bigger than the smallest one, being about 1.6 and 0.4 mm,  
6  
7 respectively. It is important to note that the accuracy of the spectral-element simulations  
8  
9 is not directly constrained by the element size, but rather by the number of GLL points  
10  
11 per wavelength. The initial meshing strategy was designed for 4<sup>th</sup> order polynomial basis  
12  
13 functions, requiring 5 GLL points per wavelength, which is approximately 5 GLL points  
14  
15 per element (Mulder, 1999). Considering the minimum velocity of the model - namely,  
16  
17 1050 m/s for the S-waves in PVC – and the maximum target frequency – namely, 650  
18  
19 kHz –, the goal was to have all the edge lengths below 1.6 mm. We present an optimized  
20  
21 meshing strategy in the Appendix, which allowed us to reduce the number of elements to  
22  
23 about 1.4 million and the computational cost by a factor of 4 to 6.  
24  
25  
26  
27  
28  
29  
30  
31



52 *Figure 6. Distribution of the element size of the mesh for the part shown in Figure 3.*

53  
54  
55  
56  
57  
58  
59  
60

## Numerical implementation of the real transducer characteristics

One of the most important task in our work was to accurately implement the real characteristics of the transducers in the numerical simulations. Since it is omnidirectional and has a frequency-independent sensitivity, the Teledyn Reson® hydrophone (used as the receiver for offset measurements) was implemented as a point receiver. However, the Imasonic® source transducer has a unique radiation pattern that cannot be described by the classical analytical formulation of Zemanek (1971) or by an approximate radiation pattern valid only for the dominant frequency (Tantsereva et al., 2014). The latter does not provide a good solution, as other frequencies also contribute to the radiation pattern. Therefore, we propose a new, two-step approach to implement the real transducer characteristics in numerical simulations, accounting for all frequencies. The procedure consists of the laboratory characterization of the source followed by an inversion step in order to obtain a numerically-equivalent source.

The characterization of the radiation pattern of the source transducer was performed in a water tank. The source transducer was connected to a pulse generator and kept fixed, while the hydrophone was moved around the source to record the impulse response of the source at every  $0.2^\circ$ , covering an angle range of  $200^\circ$  at a constant distance of 259 mm (Figure 7). The recorded dataset was the input for the subsequent inversion step. Here, we need to distinguish the procedures to obtain the numerically-equivalent source in zero-offset and offset configurations, as they require a slightly different approach (Figure 8). We first introduce the procedure for the offset case, and the differences for the zero-offset case are discussed afterwards.

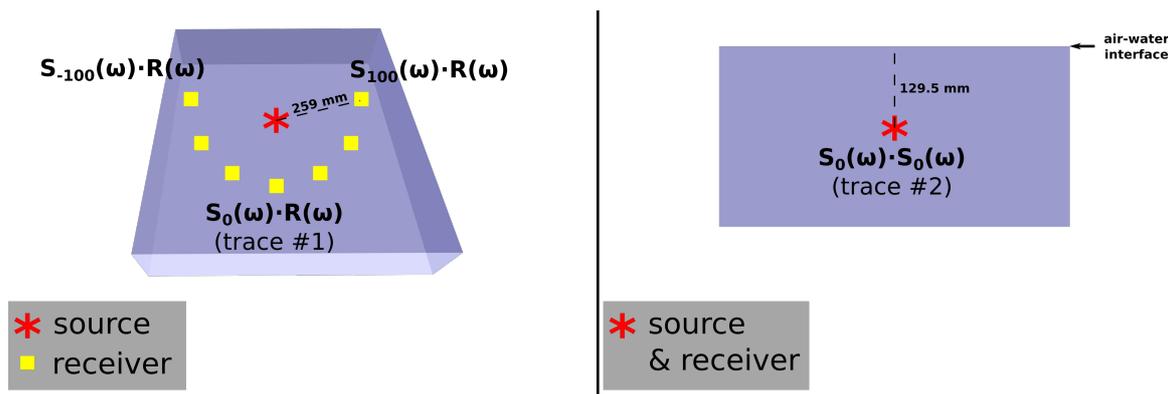


Figure 7. Schematic diagrams of laboratory characterization of the source transducer using the source and receiver transducers (left) and the source transducer illuminating the air-water interface at normal incidence (right).

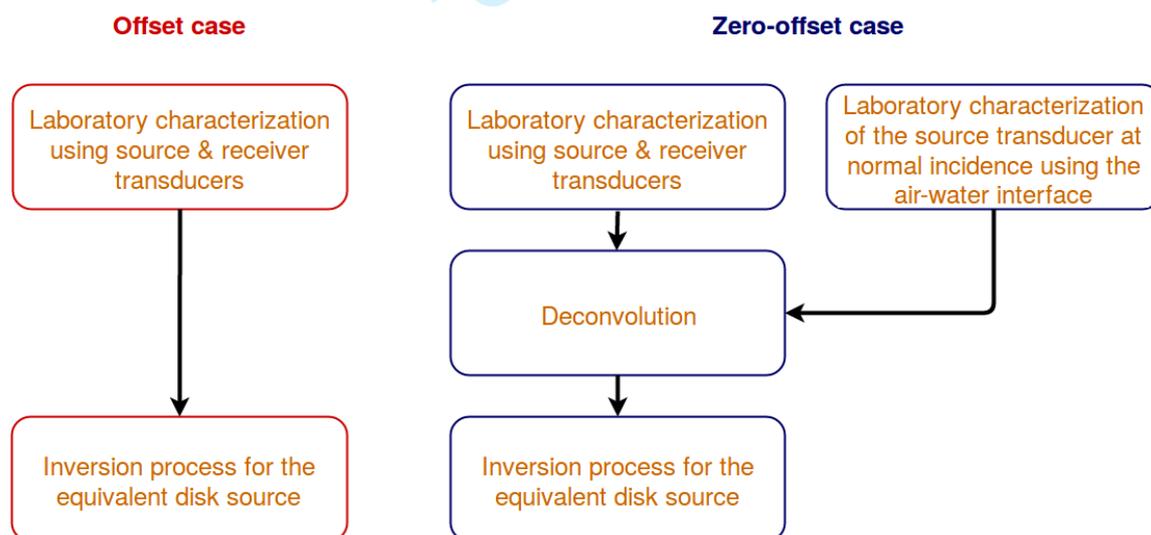


Figure 8. Workflow of the procedures used to implement the numerical equivalent of the real source transducer in offset and zero-offset configurations.

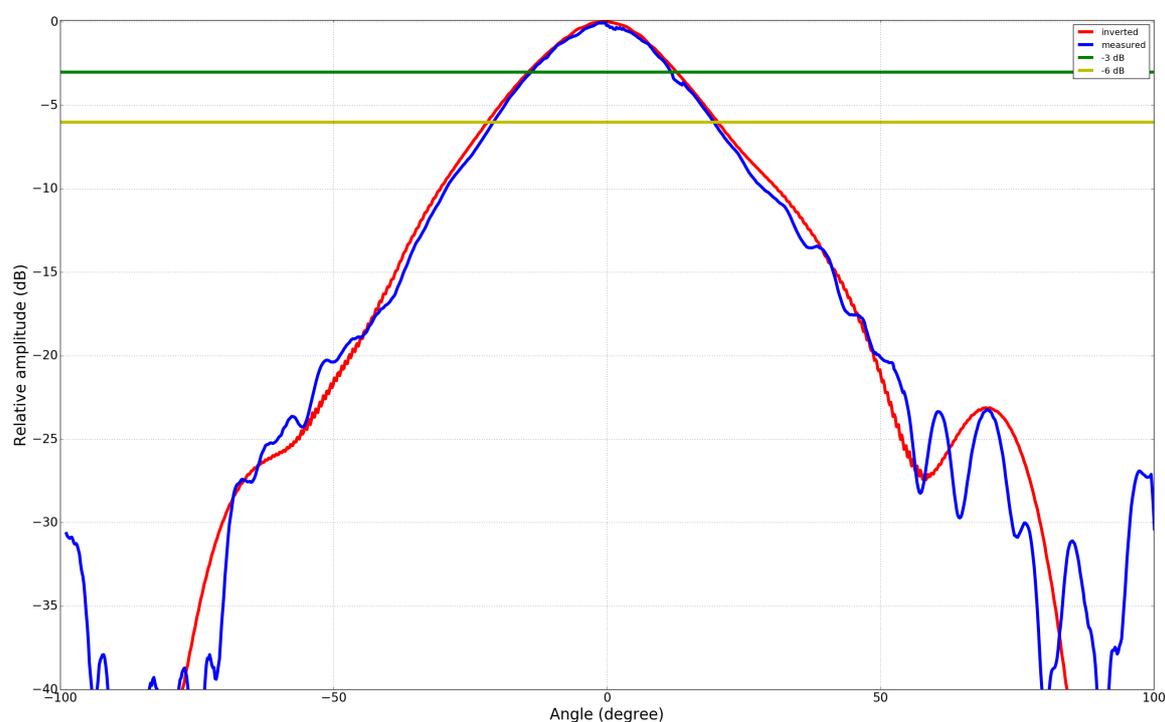
As most of the numerical tools can use point sources, we built an equivalent disk source of several point sources. This approach is based on the theory of wave superposition (Koopmann et al., 1989). The disk is described with three parameters:

1  
2  
3  
4 thickness, radius, and the number of point sources distributed on the surface. The  
5  
6 different point sources are independent, i.e., they can have any arbitrary (smooth) source  
7  
8 signal and are constrained only by the measured dataset and the inversion process. The  
9  
10 goal of the inversion was to determine the source signal of each point source, such that  
11  
12 the resulting overall source signal of the whole equivalent source is the same as the one  
13  
14 measured at each angle. The initial guess for each point source was a constant zero  
15  
16 pressure, and the cost function was computed using the L<sup>2</sup>-norm :

$$\Phi^{(k)} = \sum_i \sum_j (m_{ij} - c_{ij})^2 \quad (7)$$

21  
22  
23  
24 where  $\Phi^{(k)}$  denotes the cost function after the  $k^{\text{th}}$  iteration, and  $m_{ij}$  and  $c_{ij}$  are the recorded  
25  
26 and the calculated impulse responses at the  $i^{\text{th}}$  time sample and  $j^{\text{th}}$  hydrophone position,  
27  
28 respectively. During the inversion step, some parameters, namely the radius of the  
29  
30 equivalent disk, the number of point sources distributed on the disk, the number of layers  
31  
32 in the disk, and the number of iterations were tested to find the best fit with the measured  
33  
34 data. We found that a radius of 3 mm with 253 point sources distributed on only one disk  
35  
36 layer gives the best fit between the measured and the inverted radiation patterns (Figure  
37  
38 9). Using more than 10 000 iterations did not result in any significant change in the  
39  
40 results. The comparison of simulated traces using the inverted equivalent source with the  
41  
42 measured traces shows an angle dependency in the goodness of fit (Figure 9). Indeed,  
43  
44 the main lobe of the radiation pattern (corresponding to  $\pm 30^\circ$  around the center of the  
45  
46 transducer) is accurately recovered. For example, the correlation coefficient between the  
47  
48 measured and simulated traces at  $0^\circ$  and  $20^\circ$  are 0.99 and 0.98, respectively (Figure 10).  
49  
50 However, outside of the range of  $\pm 30^\circ$ , the goodness of fit drastically decreases with  
51  
52 increasing angle from the center of the transducer (Figure 9). For example the correlation  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 coefficient between measured and simulated traces at  $60^\circ$  is 0.64 (Figure 10). Therefore,  
5  
6 the secondary lobes of the real radiation pattern are less accurately recovered. This can be  
7  
8 explained by the fact that the recorded signals corresponding to the secondary lobes have  
9  
10 far less energy than those of the main lobe (less than -20 dB). Hence they can be  
11  
12 overshadowed by the noise recorded in the laboratory data.  
13  
14  
15  
16  
17  
18  
19



43 *Figure 9. Comparison of the measured (blue) and inverted (red) radiation patterns of the*  
44 *transducer in offset configuration. The amplitude is maximal opposite to the transducer*  
45 *( $0^\circ$ ).*  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

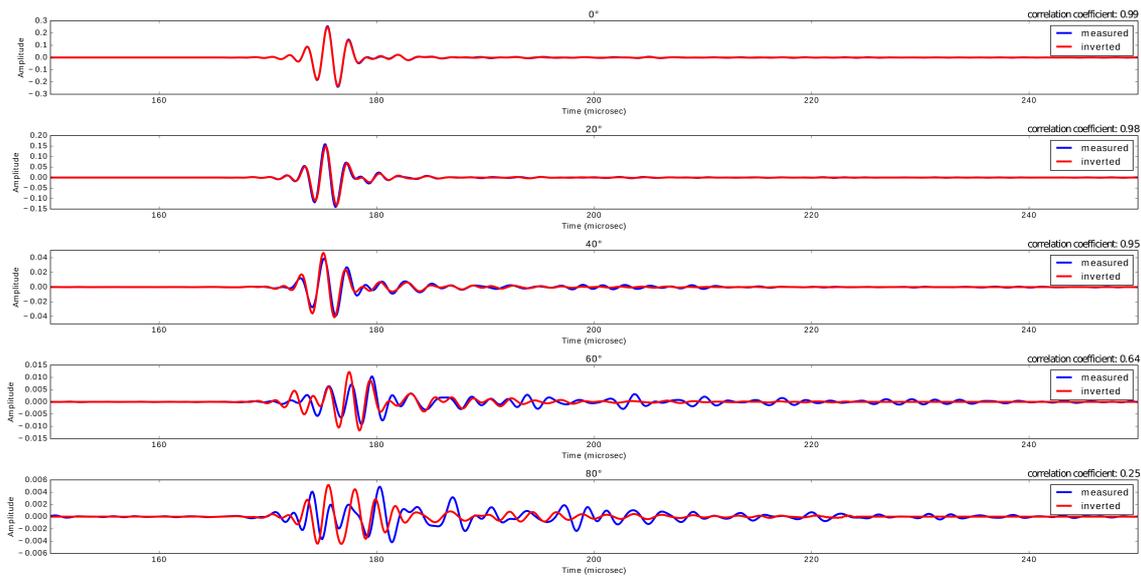


Figure 10. Comparison of the measured traces (blue) with the simulated traces (red), using the inverted equivalent source, at different angles. The correlation coefficients for the corresponding traces are shown in the top right corner of each panel.

The procedure to obtain the numerically-equivalent source in the zero-offset configuration is quite similar to the previous one, but requires a deconvolution process before the inversion step (Figure 8). This is due to the fact that for zero-offset measurements the same source transducer is used twice (first as the source, and then as the receiver). Therefore an extra measurement is needed, using only the source transducer to measure the reflected wavefield from the water-air interface at normal incidence (at a distance of half of 259 mm). The deconvolution process is done in the frequency domain after a Fourier transform of all the recorded signals. Let us denote the laboratory trace recorded by the hydrophone opposite to the source transducer as trace #1 (Figure 7), and the trace recorded by the source transducer corresponding to the reflected wavefield from the water-air interface at normal incidence as trace #2 (Figure 7). The process can be

1  
2  
3  
4 summarized as:  
5

6 - Step I: note that trace #2 is the square of the source transfer function. Therefore the  
7 square root of trace #2 gives the source transfer function at  $0^\circ$ , i.e., in the opposite  
8 position to the source,  
9

10  
11 - Step II: since the hydrophone is omnidirectional, the receiver transfer function is the  
12 same at each angle  $\alpha$ . Therefore divide trace #1 by the source transfer function (Step I) to  
13 determine the receiver transfer function ( $R(\omega)$ ),  
14

15  
16 - Step III: divide all the traces recorded by the hydrophone with the receiver transfer  
17 function (Step II) to get  $S_\alpha(\omega)$  for each angle  $\alpha$  (deconvolution in time domain),  
18

19  
20 - Step IV: take the square of  $S_\alpha(\omega)$  for each  $\alpha$  to obtain the zero-offset transfer  
21 function of the source transducer at each angle,  
22

23  
24 - Step V: inverse Fourier transform all the obtained traces to the time domain.  
25

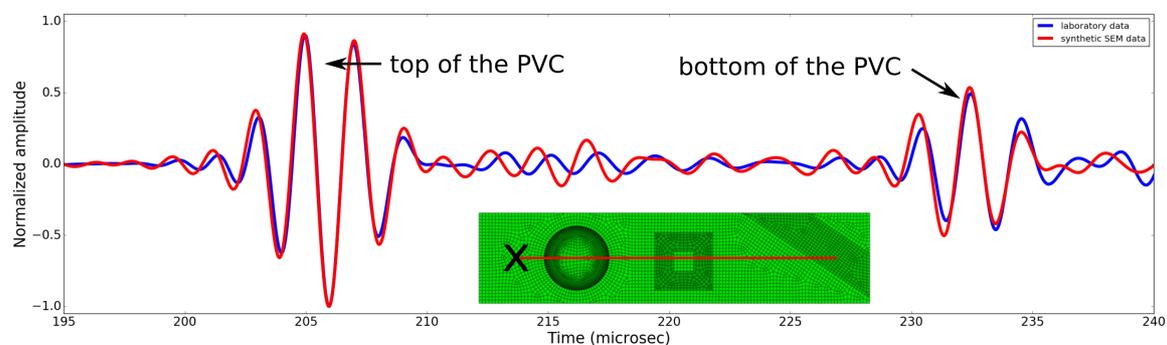
26  
27 The dataset derived using this deconvolution process is the input to the inversion  
28 process, which is the same as described above for the general offset case. According to  
29 our tests, the best fit between the measured and the inverted radiation patterns can be  
30 obtained with a disk radius of 6 mm, using 253 point sources and only one disk layer.  
31 Similarly to the offset case, using more than 10 000 iterations did not provide better  
32 results. The angle dependency in the goodness of fit is also valid for the zero-offset case.  
33 However, the range of the accurate fit is broader (about  $\pm 35^\circ$  around the center of the  
34 transducer). This is due to the fact that (relatively) more energy is focused in the central  
35 beam in this configuration, thus the outer region (with lower signal-to-noise ratio) has  
36 less influence on the inversion of the main lobe.  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## Numerical calibration of material properties

Since the characterization of material samples yields a range of values for each measured property, an initial calibration was necessary to find the values to be used for the final simulations. In order to have the least geometrical effect on the calibration, a test point above the flat part of the model was chosen (black cross in Figure 11), far from the sides of the model to avoid edge effects as much as possible. For this point the laboratory trace was considered to be the reference and the following properties were tested during the calibration simulations: velocity and Q factors for both P- and S-waves for the PVC. The densities of PVC and water, and the velocity of P-waves in water were considered to be known.

We note here that the investigated parameters have a combined effect on the amplitude, phase and arrival times, so the result of this calibration provides one possible solution in the parameter-space. First the velocities of P- and S-waves for the PVC were calibrated, then all the remaining differences between the reference laboratory trace and the simulated trace were attributed to  $Q_p$  and  $Q_s$ .

The resulting material parameters from the calibration are the following:  $V_p = 2260$  m/s,  $V_s = 1050$  m/s,  $\rho = 1412$  kg/m<sup>3</sup>,  $Q_p = 28.7$  and  $Q_s = 26$ .



1  
2  
3  
4 *Figure 11. Comparison of zero-offset laboratory trace with synthetic results for the test*  
5 *point to calibrate the material properties before the final simulations. The position of the*  
6 *test point is shown with the black cross.*  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Peer Review

## DATA COMPARISONS

### Comparison of zero-offset data

Here, we consider more specifically three traces of the laboratory zero-offset section, shown in Figure 4 and corresponding to the red line in Figure 3. These traces (labeled as A, B, and C in Figure 4) are of particular interest, as they contain diffracted waves generated by the feature edges, as well as reflections from the flat and curved surfaces of the model.

Trace A is located above the lower edge of the pyramid, where its flank meets the flat part (Figure 12). It is composed of several groups of reflections from the side of the pyramid (denoted as event A1), from the flat part (A3 and A4), from the bottom of the model below the flat part (A8 and A9) and below the dome (A10). Several groups of diffracted waves are also present, corresponding to diffractions from the upper edge (A2) and the lower edge (A7) of the pyramid, and from the edge of the dome (A6). Event A5 is related to the truncated dome, which is not included in the simulations.

Trace B is located halfway between the pyramid and the dome (Figure 13). It is composed of several groups of events associated with reflections from the side of the dome (events B1 and B2) and from the side of the pyramid (B3), from the flat part (B4), and from the bottom of the model below the flat part (B6). Event B5 is the superposition of diffractions from the upper edge of the pyramid and from the edge of the dome. Event B7 corresponds to the superposition of a reflection from the bottom of the model below the dome and a diffraction from the lower edge of the pyramid.

Trace C is located on the other side of the dome, compared to traces A and B (Figure

1  
2  
3  
4 14). It is composed of several groups of reflections from the side of the dome (C1 and  
5  
6 C2), from the flat part (C3 and C4), and from the bottom of the model below the flat part  
7  
8 (C6 and C7). Event C5 is a multiple of a diffraction from the lower edge of the dome,  
9  
10 while event C8 is a multiple reflection.  
11  
12

13 It is important to note that the laboratory data are real data, as they contain unknown  
14  
15 noise recorded by the acquisition system. Furthermore, as can be seen in Figure 2, the  
16  
17 source wavelet is a long signal, composed of a main event followed by a few tens of  $\mu$ s  
18  
19 long low-energy tail with small amplitudes (ringing effect). It may explain the fact that  
20  
21 some events are composed of two parts (for instance, events A8 and A9 in Figure 12; B1  
22  
23 and B2 in Figure 13; C1 and C2, C3 and C4, C6 and C7 in Figure 14).  
24  
25  
26

27 Qualitative comparisons between laboratory and synthetic traces show a quite good fit  
28  
29 in amplitude, phase and travel time. Regardless of the trace location, synthetic traces  
30  
31 show an almost perfect fit with the experimental data in time, phase and amplitude for the  
32  
33 reflected events from the top and bottom of the flat part of the model. The early and late  
34  
35 parts of these arrivals sometimes reveal minor amplitude misfits, most probably due to  
36  
37 the low-energy second part of the source signal, which may not be perfectly  
38  
39 reconstructed by the source inversion, as well as the uncertainties in the attenuation  
40  
41 parameters chosen for the simulations. Events associated with the side reflections and/or  
42  
43 diffractions from the topographic features are also well restored by the simulations (see  
44  
45 events A1 in Figure 12, B5 and B6 in Figure 13, C1 and C8 in Figure 14). The correlation  
46  
47 coefficients between measured and simulated traces are 0.91, 0.95 and 0.91 for traces A,  
48  
49 B and C, respectively. These good results are due to the fact that SEM has the ability to  
50  
51 honor the model geometry, even for tilted and curved interfaces by using a non-structured  
52  
53 mesh.  
54  
55  
56  
57  
58  
59  
60

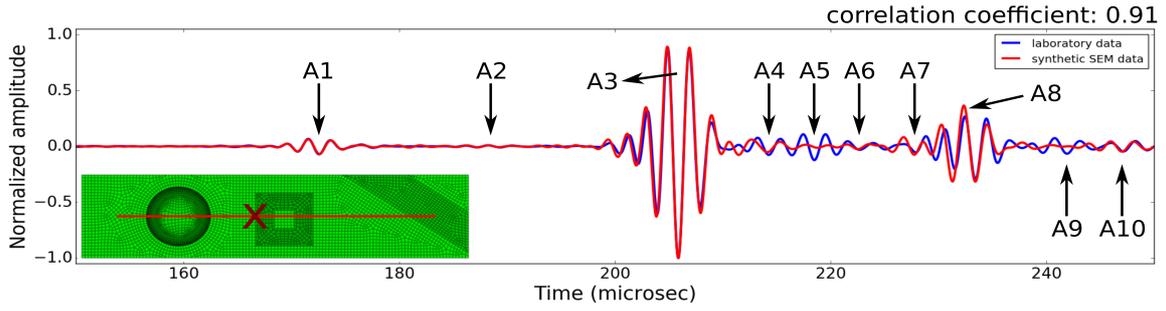


Figure 12. Comparison of zero-offset laboratory trace A with synthetic results. Physical interpretation of the annotated events is provided in the text.

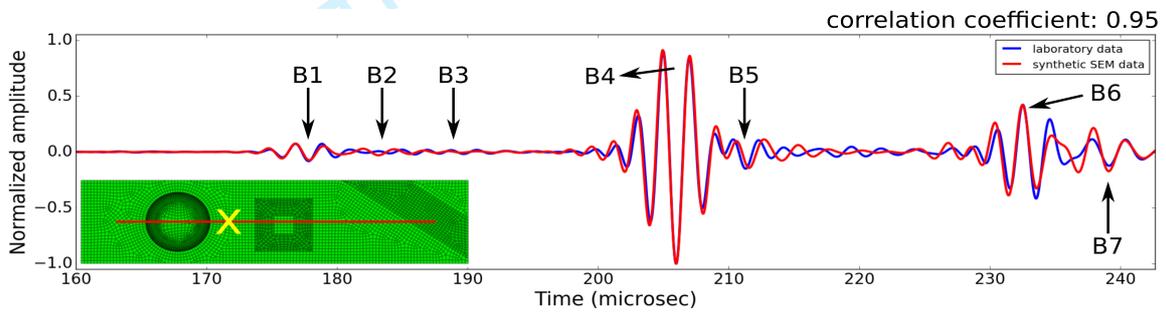


Figure 13. Comparison of zero-offset laboratory trace B with synthetic results. Physical interpretation of the annotated events is provided in the text.

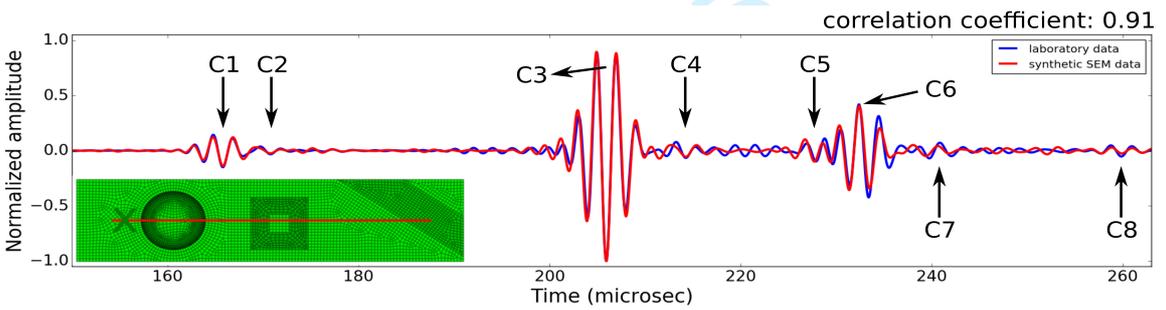


Figure 14. Comparison of zero-offset laboratory trace C with synthetic results. Physical interpretation of the annotated events is provided in the text.

## Comparison of offset data

Here, we consider more specifically one trace of the laboratory offset section, labeled as D in Figure 5. The source location (represented by the asterisk in Figure 15) is above the flank of the dome, and the receiver (represented by the triangle in Figure 15) is located close to the ramp. Trace D contains several groups of events, mainly associated with the direct source-receiver travel path (labeled as D1 in Figure 15), reflection from the top of the truncated pyramid (D2) and reflection from the curved surface of the dome (D3).

A qualitative comparison between the simulated results and laboratory data shows a good fit in arrival time, phase and amplitude for all the events pointed out, except for the reflection from the dome (D3). Some important remarks must be highlighted here. First, the offset configurations are more sensitive to noise than zero-offset ones. Due to a more complex acquisition setup, using more electric devices and transducers, the signal-to-noise ratio of the laboratory data in offset configuration is generally lower than in the zero-offset case. Furthermore, the offset configurations are more sensitive also to uncertainties in the acquisition geometry, especially in case of a model with strongly tilted and curved interfaces. Indeed, it can be analytically shown that a small uncertainty in the source position and/or in the incidence angle of the incident wave may have a significant impact on the illumination of the curved surface of the dome. As a result, it can have a huge effect on the reflected and diffracted wavefields (see section “Discussion”). It explains the fact that event D3 in Figure 15 is quite well modeled by the simulation, but with both significant time and amplitude misfits. The correlation coefficient between the measured and simulated traces is 0.76 for trace D. Finally, as

1  
2  
3  
4 mentioned above, the implementation of the numerically-equivalent source has higher  
5  
6 uncertainties for both the low-energy later part of the source wavelet and the secondary  
7  
8 lobes (due to the low signal-to-noise ratio of these events) than for the main lobe of the  
9  
10 directivity pattern. Even if they carry less energy than the main lobe, the role of these  
11  
12 higher-order lobes in the illumination of the model should not be neglected in case of  
13  
14 offset configurations.  
15  
16 offset configurations.

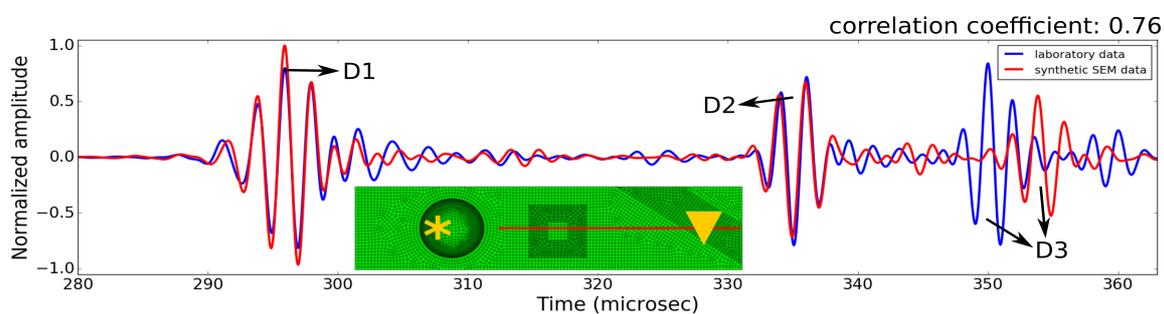


Figure 15. Comparison of offset laboratory trace *D* with synthetic results. Physical interpretation of the annotated events is provided in the text. The red line shows the acquisition line, the yellow asterisk the source position and the yellow triangle the receiver corresponding to trace *D*.

## DISCUSSION

As shown above, SEM can reproduce laboratory zero-offset data in terms of arrival time, phase and amplitude with excellent accuracy. However, the fit between synthetic results and experimental offset data is significantly less accurate. We discuss here the possible explanations for this observation, including experimental uncertainties and numerical implementation of the directivity pattern of the source transducer, as well as the computational cost.

Laboratory data always contains noise, and offset datasets have a lower signal-to-noise ratio than zero-offset ones. Moreover, uncertainties in the transducer positions also have an effect on the data. It is more significant in the offset case, since there is a non-linear combination of uncertainties in the source location, the source tilt angle and the receiver position. This non-linear combination makes it difficult to evaluate the role of one effect over the others. This effect is even more pronounced in the presence of strongly curved interfaces, causing wave defocusing. Let us analyze here this source of misfit and quantify the order of magnitude of the possible resulting error. As the problem is the most pronounced in case of strongly curved interfaces, we show an example for the Marseille-Benchie model using the dome.

The geometry of the problem is shown in Figure 16, and for now we suppose that the source is located exactly above the top of the dome. We are interested in the change in the offset of the arrival of a given ray due to an error in the tilt angle of the source ( $\gamma$ ). Based on geometrical considerations, we can obtain the following relations:

$$\delta x = \frac{R+H}{\cos^2(\theta)} \delta\theta \quad (8)$$

and

$$\delta y = \delta l_2 \frac{\sin(\alpha)}{\cos(\theta + \alpha)} + l_2 \frac{\cos(\alpha) \delta \alpha \cos(\theta + \alpha) + \sin(\theta + \alpha) (\delta \theta + \delta \alpha) \sin(\alpha)}{\cos^2(\theta + \alpha)} \quad (9)$$

where the offset change is the sum of  $\delta x$  and  $\delta y$ , while  $R$  denotes the radius of the dome,  $H$  the distance between the top of the dome and the source transducer. To quantify the order of magnitude of the error in the offset, we consider  $H = 140$  mm,  $R = 51.25$  mm, and  $\gamma = 5^\circ$ . Supposing an error of  $0.5^\circ$  in the source position, the point of illumination on the surface of the dome has an error of 1.3 mm. Using equations 8 and 9 above, we get  $\delta x = 5.2$  mm and  $\delta y = 1.5$  mm. It means that an uncertainty of  $0.5^\circ$  in the source tilt angle leads to a shift of 6.7 mm (134 m at seismic scale) in the arrival offset of the beam (i.e. in the receiver location), depending on the point of the illumination of the surface of the dome. This uncertainty may thus have a significant impact on both the arrival time and the amplitude of the reflected and diffracted events. In ongoing work, we now focus on the design of an acquisition system providing much higher accuracy of transducer positions to significantly decrease these uncertainties in the recorded data.

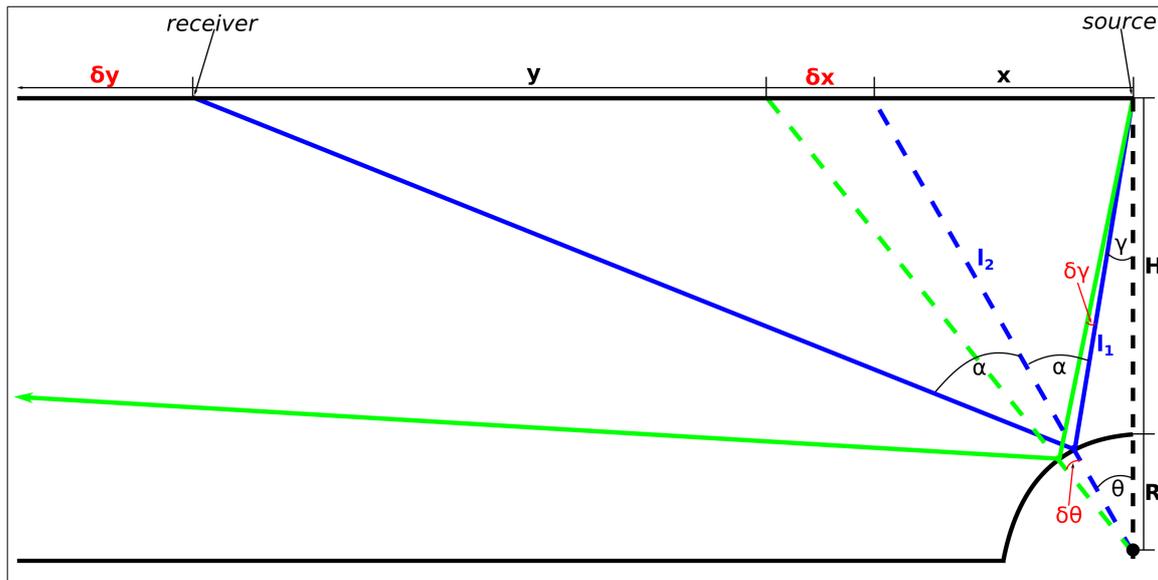


Figure 16. The effect of the uncertainties in the source position on the wavefield.

We have proposed a strategy to numerically implement the directivity pattern of the real source transducer. This strategy permits to recover the main lobe of the emitted beam, where most of the energy is concentrated. Excellent fit between synthetic results and laboratory zero-offset data shows that the strategy is efficient in zero-offset configurations, as in that case mostly the main lobe illuminates the model and contributes to the recorded data. Nevertheless, for offset data recorded in strong topographic environments, the proposed strategy is less accurate, since both the low-energy later part of the source wavelet (see Figure 2) and the secondary lobes play an important role in the illumination of the model, even if they carry far less energy than the main event of the source wavelet in the main lobe. Indeed, in our case they may interact with the dome and the pyramid (depending on the source location), influencing the amplitude and phase of the wavefield. Future work will focus on a new approach to numerically implement real transducer properties, which can accurately account for both the main lobe and the lower-

1  
2  
3  
4 energy parts of the source wavelet.  
5

6 Computational cost of numerical methods is often an important point, particularly in  
7 the operational context of seismic exploration. Here, we differentiate between the man-  
8 hour cost spent on the preparation of the simulations and the computational cost (i.e., the  
9 number of processors used for simulations times the actual running time of one  
10 simulation). In general, SEM has large man-hour cost, due to the non-structured  
11 hexahedral meshing. To illustrate this problem, it is interesting to note that we spent three  
12 weeks to find the optimal meshing strategy for the Marseille-Benchie model, without  
13 even finding a satisfying strategy for the truncated dome. Contrary to the common finite-  
14 difference gridding, there is no quick or cheap solution to non-structured hexahedral  
15 meshing in terms of man-hour cost.  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28

29 Regarding the computational cost of the method, we used 2100 Intel® Xeon® Sandy  
30 Bridge EP (E5-2680) processor cores for the simulations. The initial meshing strategy  
31 resulted in a mesh that needed 10150 core-hours to simulate 350  $\mu$ s of wave propagation  
32 (corresponding to 7 s at seismic scale). Using the optimized meshing strategy of the  
33 Appendix, this cost was reduced to 1611 core-hours with a relative element size of 2.5, or  
34 to 2538 core-hours with a relative element size of 2.25.  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## CONCLUSIONS AND FUTURE WORK

The goal of our work is to provide a possible workflow to adapt both the numerical simulations and the small-scale laboratory experiments to each other, such that the two can be easily compared with high accuracy. We are also interested in the ability of SEM to accurately simulate complex 3D wavefields including (multiple) diffractions at the lowest possible computational and man-hour cost. We have thus compared 3D SEM simulations with laboratory measurements in both 3D zero-offset and 3D offset offshore reflection configurations for a small-scale physical model. The model includes structures with steep flanks, sharp edges, corners and curved interfaces. This complexity provides a challenge to any numerical method to reproduce the wavefield.

Prior to the simulations, some works have focused on the input data/parameters, namely the material properties, the model geometry and the characteristics of the source and receiver transducers. The viscoelastic behavior of the material used in the model has been approximated with a set of Zener standard linear solids, while the other parameters are known from previous laboratory characterization of material samples. The real source transducer characteristics have been implemented based on a new approach: laboratory characterization of the impulse response, followed by an inversion step to obtain a numerically-equivalent source for the numerical simulations. The zero-offset measurement requires an additional deconvolution step before the inversion, as in that case only one transducer is used as both the source and the receiver.

We have suggested an optimization of the computational cost, by using larger elements in the non-structured mesh and higher-order polynomial basis functions. This technique helps to significantly reduce the computational cost, while obtaining a similar

1  
2  
3  
4 level of accuracy.  
5

6 The comparison of the zero-offset synthetic and laboratory results has revealed an  
7 excellent fit in terms of arrival time, phase and amplitude. Minor amplitude mismatches  
8 may be attributed to the noise recorded in the laboratory data, as well as to the inaccuracy  
9 of the proposed source implementation to restore the low-energy secondary lobes of the  
10 source transducer, and the uncertainties in the attenuation parameters chosen for the  
11 simulations. The comparison of simulated and laboratory offset traces has exhibited a  
12 good fit in terms of amplitude, arrival time and phase, but with significantly less accuracy  
13 for some arrivals than in the zero-offset case. This can be mainly attributed to the  
14 inaccuracies of the transducer positions during the laboratory measurements combined  
15 with the strong topography of the model, as well as to the smaller signal-to-noise ratio of  
16 the offset configurations.  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30

31 Future work will focus on the development of a more accurate acquisition system to  
32 reduce inaccuracies in transducer positions during the laboratory measurements.  
33 Furthermore, the noise level of the new acquisition system will have to be assessed (e.g.  
34 Valensi et al., 2015). The proposed numerical implementation of the real transducer  
35 should also be investigated further, to account more for the low-energy secondary lobes,  
36 and the low-energy later arrivals of the source signal as well, since they may also  
37 contribute to the wavefield. The reduction of the man-hour cost of SEM, due to the  
38 lengthy meshing step, will be essential in the future. A more robust and automatic  
39 meshing tool, suitable for non-structured hexahedral meshing of arbitrary 3D geometries  
40 will be required. The laboratory datasets and the obtained numerical results should be  
41 also compared with other numerical methods, such as the commonly used finite-  
42 difference method.  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## Acknowledgements

The authors thank Zhinan Xie for his help with the implementation of stable PMLs for the 3D case, Emanuele Casarotti for his advices on non-structured meshing, and Régine Guillermin, Patrick Sanchez, Guy Rabau and Vincent Long for their help with the experiments. This work received funding from the European Union Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant, agreement no. 641943. Børge Arntsen and Bjørn Ursin received financial support from the Norwegian Research Council through the ROSE project. We also thank CNRS for its financial support through the PICS BENCHIE project. This work was granted access to the French HPC resources of TGCC under allocations no. 2016-gen7165 and 2017-gen7165 made by GENCI.

We also acknowledge the Associate Editor and the four anonymus reviewers for their careful reading, helpful suggestions and questions which all improved the paper.

## Appendix

As mentioned in “Meshing”, finding the appropriate meshing strategy for a complex geometry using a non-structured hexahedral mesh is a time-consuming procedure. Thus, our goal here is to reduce the computational cost without modifying the meshing strategy. In other words, we use the same subdivision of the whole model into subdomains and the same meshing order of the different subdomains.

Our optimization takes advantage of the fact that the accuracy of the spectral-element simulations is not directly constrained by the element size, but rather by the number of GLL points per wavelength. It means that we can increase the element size and keep a similar level of accuracy of the simulations by increasing the order of the polynomial basis functions. This technique is widely discussed in the literature as  $h$ -,  $p$ -, or  $h$ - $p$  convergence, where  $h$  stands for the element size and  $p$  denotes the polynomial order of the basis functions (e.g., Hughes, 1987; Maday & Rønquist, 1990; Seriani & Priolo, 1994; Vos et al., 2010; Oliveria & Seriani, 2011). For the initial meshing of the model we used basis functions of order  $N = 4$ , meaning that  $N + 1 = 5$  GLL points are used in each element.

We consider the mesh presented in Figure 3 as the reference for this Appendix. As shown in section “Comparison of zero-offset data“, the reference mesh yields accurate synthetic results compared with the zero-offset laboratory data. When creating a non-structured mesh, the element size has a distribution as shown in Figure 6. This is due to the geometrical constraints on the meshing algorithm, resulting in various element sizes. Cubit/Trelis<sup>®</sup> uses a target element size, as the meshing algorithm aims to mesh the model such that the average of the element sizes is close to this target value. For the

1  
2  
3  
4 reference mesh, a target edge length of 1.1 mm is necessary to have the largest elements  
5  
6 below the required threshold of 1.6 mm. For the sake of brevity, we use relative target  
7  
8 element sizes hereafter, by considering the target element size of the reference mesh as  
9  
10 being equal to 1. We note that small changes in the target element size result in the same  
11  
12 distribution of the element sizes, only the size of each element is multiplied by the factor  
13  
14 of the change. According to our experience, it remains true even for such a complex  
15  
16 geometry as the Marseille-Benzie model if the change is at most a factor of 0.2-5. Since  
17  
18 our meshing strategy involves the subdivision of the model into several subdomains,  
19  
20 there is an upper limit for increasing the element size. With our decomposition strategy,  
21  
22 using about 5 times larger elements than the reference value is the upper limit. It comes  
23  
24 from the fact that above this value, the element size becomes too high compared with the  
25  
26 dimensions of some of the subdomains. We emphasize that using larger elements does  
27  
28 not result in a less accurate representation of even the curved interfaces, as curved  
29  
30 hexahedral elements are used. It means that the numerical tool can account for curved  
31  
32 edges and surfaces of each element, instead of only straight lines and planar surfaces  
33  
34 (Komatitsch & Vilotte, 1998; Fichtner, 2010).  
35  
36  
37  
38  
39

40  
41 We tested two different approaches. The first one consists of fixing the polynomial  
42  
43 order of the basis functions and changing the element size. The second one keeps the  
44  
45 element size fixed and changes the polynomial order. To evaluate the results, we ran the  
46  
47 same zero-offset simulations using the different meshes and compared the resulting  
48  
49 synthetic traces to traces obtained with the reference mesh. To evaluate the tests we use  
50  
51 zero-offset traces B and C (Figures 13 and 14). To obtain a quantitative comparison, we  
52  
53 computed the root mean square (RMS) difference between each synthetic trace and the  
54  
55 reference trace. Figure 17 shows the relative computational cost and the RMS misfit for  
56  
57  
58  
59  
60

different element sizes, using 6<sup>th</sup>-order polynomial basis functions. The results suggest that the optimum is around relative element sizes of 2.25-2.5. Using smaller elements increases the computational cost, while using larger elements increases the RMS misfit without any significant gain in the relative computational cost.

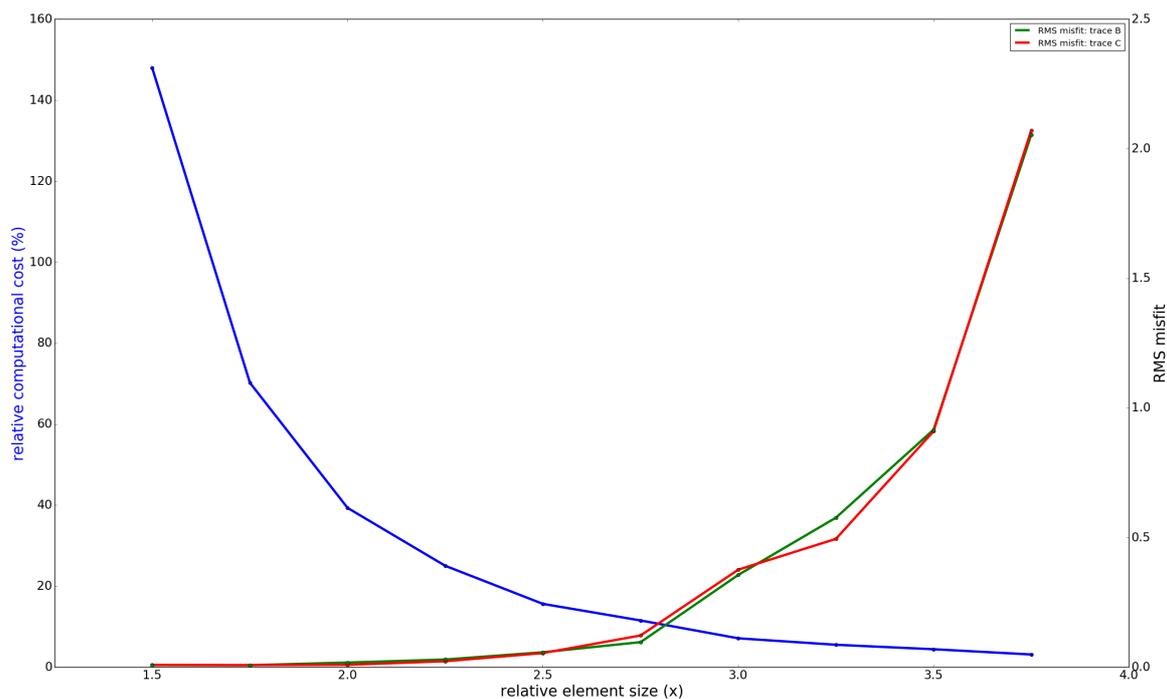


Figure 17. Relative computational cost (blue) and RMS misfit (green: trace B, red: trace C) for varying element size, using 6<sup>th</sup>-order polynomial basis functions.

Considering that the optimal element size is about 2.5 (based on Figure 17), the effect of the polynomial order has to be examined as well. Figure 18 shows the relative computational cost and the RMS misfit for different polynomial orders, using a relative element size of 2.5. The results show that the polynomial order of 8 yields the smallest RMS misfit (around 0.008). Even though the RMS misfit is somewhat higher for order 6 (around 0.05), its computational cost is more than three times lower than that of order 8.

We note that the RMS misfit does not show a monotonous trend for any of the traces, neither in Figure 17, nor in Figure 18. This is probably due to the non-structured mesh. Maday & Rønquist (1990) mathematically proved that a monotonous trend in the misfit curves can be expected only for a structured mesh, but not necessarily for a non-structured mesh.

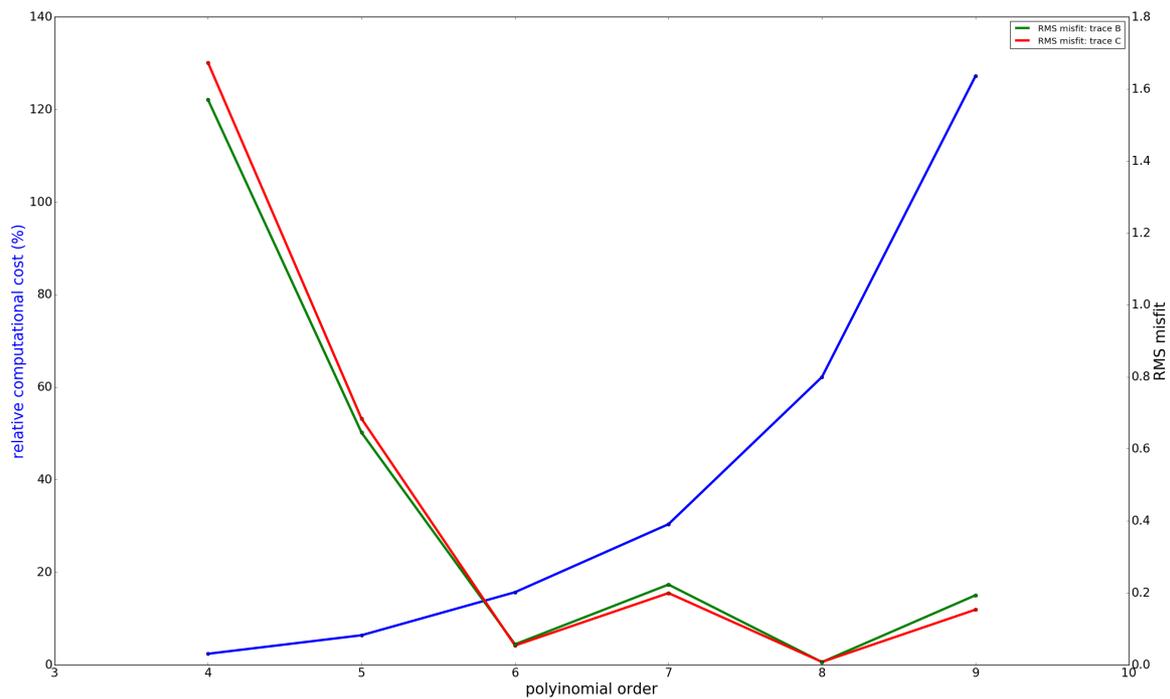
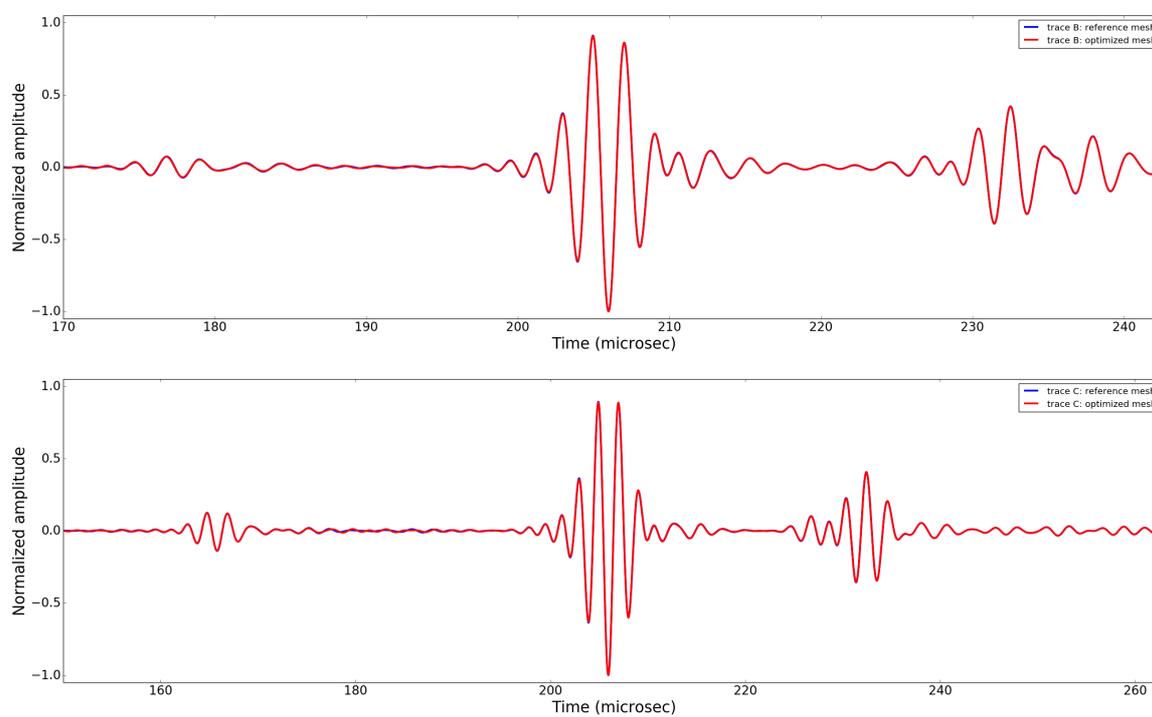


Figure 18. Relative computational cost (blue) and RMS misfit (green: trace B, red: trace C) for varying order of the polynomial basis functions, using a relative element size of 2.5.

Figure 19 shows the comparison of the traces using the optimized mesh (relative element size of 2.5) and 6<sup>th</sup> order basis functions with the reference traces. The optimized mesh provides an excellent fit with the reference solutions in general. Due to the larger elements, some minor oscillations can be seen, probably due to mesh dispersion.

1  
2  
3  
4 However their amplitude and difference from the reference solutions are negligible.  
5  
6 Considering that the relative computational cost is only 15.7 % of the reference  
7  
8 simulation, we suggest to use the optimized meshing strategy. Moreover, the effect of  
9  
10 mesh dispersion can be reduced by using a relative element size of 2.25 instead of 2.5. In  
11  
12 that case the relative computational cost is still 25 % of the reference, in return for a a bit  
13  
14 higher accuracy than with a relative element size of 2.5.  
15  
16  
17  
18  
19



45 *Figure 19. Comparison of zero-offset synthetic traces using the reference mesh (blue)*  
46 *and the optimized mesh with a relative element size of 2.5 and 6<sup>th</sup>-order basis functions*  
47 *(red): trace B (top), trace C (bottom).*  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## References

1  
2  
3  
4  
5  
6  
7  
8  
9  
10 Blacker, T., 1994, CUBIT Mesh Generation Environment Users Manual, Vol. 1, Sandia  
11 National Laboratories, Albuquerque, New Mexico, USA.

12  
13  
14 Blanc, E., D. Komatitsch, E. Chaljub, B. Lombard, and Z. Xie, 2016, Highly accurate  
15 stability-preserving optimization of the Zener viscoelastic model, with application to  
16 wave propagation in the presence of strong attenuation: *Geophysical Journal*  
17 *International*, **205**, 427-439, doi: 10.1093/gji/ggw024.

18  
19  
20  
21  
22  
23 Bretaudeau, F., D. Leparoux, O. Durand, and O. Abraham, 2011, Small-scale modeling of  
24 onshore seismic experiment: A tool to validate numerical modeling and seismic imaging  
25 methods: *Geophysics*, **76**, no. 5, T101–T112, doi: 10.1190/geo2010-0339.1.

26  
27  
28  
29  
30  
31  
32 Bretaudeau, F., R. Brossier, D. Leparoux, O. Abraham and J. Virieux, 2013, 2D elastic  
33 full-waveform imaging of the near-surface: application to synthetic and physical  
34 modelling data sets: *Near Surface Geophysics*, **11**, no. 3, pp. 307-316, doi: 10.3997/1873-  
35 0604.2012067.

36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46 Campman, X. H., K. van Wijk, J. A. Scales, and G. C. Herman, 2005, Imaging and  
47 suppressing near-receiver scattered surface waves: *Geophysics*, **70**, no. 2, V21–V29, doi:  
48 10.1190/1.1884831.

49  
50  
51  
52  
53  
54  
55 Capdeville, Y., C. Larmat, J.P. Vilotte and J.P. Montagner, 2002, A new coupled spectral  
56 element and modal solution method for global seismology: A first application to the  
57 scattering induced by a plume-like anomaly: *Geophysical Research Letters*, **29**, no. 9,  
58 doi:10.1029/2001GL013747.

59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130  
131  
132  
133  
134  
135  
136  
137  
138  
139  
140  
141  
142  
143  
144  
145  
146  
147  
148  
149  
150  
151  
152  
153  
154  
155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236  
237  
238  
239  
240  
241  
242  
243  
244  
245  
246  
247  
248  
249  
250  
251  
252  
253  
254  
255  
256  
257  
258  
259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
310  
311  
312  
313  
314  
315  
316  
317  
318  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
350  
351  
352  
353  
354  
355  
356  
357  
358  
359  
360  
361  
362  
363  
364  
365  
366  
367  
368  
369  
370  
371  
372  
373  
374  
375  
376  
377  
378  
379  
380  
381  
382  
383  
384  
385  
386  
387  
388  
389  
390  
391  
392  
393  
394  
395  
396  
397  
398  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
420  
421  
422  
423  
424  
425  
426  
427  
428  
429  
430  
431  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
460  
461  
462  
463  
464  
465  
466  
467  
468  
469  
470  
471  
472  
473  
474  
475  
476  
477  
478  
479  
480  
481  
482  
483  
484  
485  
486  
487  
488  
489  
490  
491  
492  
493  
494  
495  
496  
497  
498  
499  
500  
501  
502  
503  
504  
505  
506  
507  
508  
509  
510  
511  
512  
513  
514  
515  
516  
517  
518  
519  
520  
521  
522  
523  
524  
525  
526  
527  
528  
529  
530  
531  
532  
533  
534  
535  
536  
537  
538  
539  
540  
541  
542  
543  
544  
545  
546  
547  
548  
549  
550  
551  
552  
553  
554  
555  
556  
557  
558  
559  
560  
561  
562  
563  
564  
565  
566  
567  
568  
569  
570  
571  
572  
573  
574  
575  
576  
577  
578  
579  
580  
581  
582  
583  
584  
585  
586  
587  
588  
589  
590  
591  
592  
593  
594  
595  
596  
597  
598  
599  
600  
601  
602  
603  
604  
605  
606  
607  
608  
609  
610  
611  
612  
613  
614  
615  
616  
617  
618  
619  
620  
621  
622  
623  
624  
625  
626  
627  
628  
629  
630  
631  
632  
633  
634  
635  
636  
637  
638  
639  
640  
641  
642  
643  
644  
645  
646  
647  
648  
649  
650  
651  
652  
653  
654  
655  
656  
657  
658  
659  
660  
661  
662  
663  
664  
665  
666  
667  
668  
669  
670  
671  
672  
673  
674  
675  
676  
677  
678  
679  
680  
681  
682  
683  
684  
685  
686  
687  
688  
689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708  
709  
710  
711  
712  
713  
714  
715  
716  
717  
718  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
730  
731  
732  
733  
734  
735  
736  
737  
738  
739  
740  
741  
742  
743  
744  
745  
746  
747  
748  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759  
760  
761  
762  
763  
764  
765  
766  
767  
768  
769  
770  
771  
772  
773  
774  
775  
776  
777  
778  
779  
780  
781  
782  
783  
784  
785  
786  
787  
788  
789  
790  
791  
792  
793  
794  
795  
796  
797  
798  
799  
800  
801  
802  
803  
804  
805  
806  
807  
808  
809  
810  
811  
812  
813  
814  
815  
816  
817  
818  
819  
820  
821  
822  
823  
824  
825  
826  
827  
828  
829  
830  
831  
832  
833  
834  
835  
836  
837  
838  
839  
840  
841  
842  
843  
844  
845  
846  
847  
848  
849  
850  
851  
852  
853  
854  
855  
856  
857  
858  
859  
860  
861  
862  
863  
864  
865  
866  
867  
868  
869  
870  
871  
872  
873  
874  
875  
876  
877  
878  
879  
880  
881  
882  
883  
884  
885  
886  
887  
888  
889  
890  
891  
892  
893  
894  
895  
896  
897  
898  
899  
900  
901  
902  
903  
904  
905  
906  
907  
908  
909  
910  
911  
912  
913  
914  
915  
916  
917  
918  
919  
920  
921  
922  
923  
924  
925  
926  
927  
928  
929  
930  
931  
932  
933  
934  
935  
936  
937  
938  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
950  
951  
952  
953  
954  
955  
956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966  
967  
968  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978  
979  
980  
981  
982  
983  
984  
985  
986  
987  
988  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
999  
1000

1  
2  
3  
4 element method with a modal solution for elastic wave propagation in global Earth  
5 models: *Geophysical Journal International*, **152**(1), pp 34-67, doi: 10.1046/j.1365-  
6 246X.2003.01808.x.  
7  
8

9  
10 Carrington, L., D. Komatitsch, M. Laurenzano, M. Tikir, D. Michea, N. Le Goff, A.  
11 Snavely and J. Tromp, 2008, High-frequency simulations of global seismic wave  
12 propagation using SPECFEM3D\_GLOBE on 62 thousand processor cores, in  
13 Proceedings of the ACM/IEEE Supercomputing SC'2008 Conference, Austin, TX, pp. 1–  
14 11, Article #60.  
15  
16

17  
18 Chai, X., W. Shangxu, W. Jianxin, L. Jingnan, and Y. Hanjun, 2016, Reflectivity  
19 inversion for attenuated seismic data: Physical modeling and field data experiments,  
20 *Geophysics*, **81**(1), T11-T24, doi: 10.1190/geo2015-0250.1.  
21  
22

23  
24 Chaljub, E., M. Emeline, P. Moczo, J. Kristek, F. Hollender, P-Y. Bard, E. Priolo, P. Klin,  
25 F. de Martin, Z. Zhang, W. Zhang, and X. Chen, 2015, 3-D numerical simulations of  
26 earthquake ground motion in sedimentary basins: testing accuracy through stringent  
27 models: *Geophysical Journal International*, **201**(1), 90-111, doi: 10.1093/gji/ggu472.  
28  
29

30  
31 Chang, C.-H., Y.-F. Chang, and P.-Y. Tseng, 2017, Azimuthal variation of converted-wave  
32 amplitude in a reservoir with vertically aligned fractures – a physical model study:  
33 *Geophysical Prospecting*, **65**(1), 221-228, doi: 10.1111/1365-2478.12357.  
34  
35

36  
37 Cooper, J. K., D. C. Lawton, and G. F. Margrave, 2010, The wedge model revisited: A  
38 physical modeling experiment: *Geophysics*, **75**(2), T15-T21, doi: 10.1190/1.3309641.  
39  
40

41  
42 De Basabe, J. D., and M. K. Sen, 2015, A comparison of finite-difference and spectral-  
43 element methods for elastic wave propagation in media with a fluid-solid interface:  
44 *Geophysical Journal International*, **200**(1), 278-298, doi: 10.1093/gji/ggu389.  
45  
46

47  
48 Ebrom, D. A., and J. A. McDonald, 1994, Seismic physical modeling: SEG reprint series  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 15, 494 pages.

5  
6 Ekanem, A. M., J. Wei, X.-Y. Li, M. Chapman, and I. G. Main, 2013, P-wave attenuation  
7 anisotropy in fractured media: A seismic physical modeling study: *Geophysical*  
8  
9 *Prospecting*, **61**, 420–433, doi: 10.1111/j.1365-2478.2012.01127.x.

10  
11  
12  
13 Emmerich, H., and M. Korn, 1987, Incorporation of attenuation into timedomain  
14  
15 computations of seismic wave fields: *Geophysics*, **52**, 1252–1264, doi:  
16  
17 10.1190/1.1442386.

18  
19  
20 Favretto-Anrès, N., and G. Rabau, 1997, Excitation of the Stoneley-Scholte wave at the  
21  
22 boundary between an ideal fluid and a viscoelastic solid: *Journal of Sound and Vibration*,  
23  
24 **203**(2), 193-208, doi: 10.1006/jsvi.1996.0884.

25  
26  
27 Favretto-Anrès, N., and J.-P. Sessarego, 1999, Identification of shear wave parameters of  
28  
29 viscoelastic solids by laboratory measurements of Stoneley-Scholte waves: *Acta Acustica*  
30  
31 united with *Acustica*, **85**, 505-516.

32  
33  
34 Favretto-Cristini, N., A. M. Aizenberg, B. Ursin, P. Cristini P., and A. Tantsereva, 2017,  
35  
36 Analysis of wave scattering from a viscoelastic layer with complex shape: accepted in  
37  
38 *Journal of Computational Acoustics*.

39  
40  
41 Favretto-Cristini, N., A. Tantsereva, P. Cristini, B. Ursin, D. Komatitsch, and A. M.  
42  
43 Aizenberg, 2014, Numerical modeling of zero-offset laboratory data in a strong  
44  
45 topographic environment: results for a spectral-element method and a discretized  
46  
47 Kirchhoff integral method: *Earthquake Science* **27**(4), 391-399, doi: 10.1007/s11589-  
48  
49 014-0061-4.

50  
51  
52 Fehler, M., and P. J. Keliher, 2011, SEAM Phase I: Challenge of subsalt imaging in  
53  
54 tertiary basins, with emphasis on deepwater Gulf of Mexico. SEG, Tulsa, Oklahoma,  
55  
56 USA.

1  
2  
3  
4 Festa, G., E. Delavaud, and J.-P. Vilotte, 2005, Interaction between surface waves and  
5 absorbing boundaries for wave propagation in geological basins: 2D numerical  
6 simulations, *Geophysical Research Letters*, **32**, doi: 10.1029/2005GL024091.  
7  
8

9  
10 Fichtner, A., 2010, *Full Seismic Waveform Modelling and Inversion*, Springer-Verlag,  
11 Heidelberg, Germany, EU.  
12

13  
14 French, W. S., 1974, Two-dimensional and three-dimensional migration of model-  
15 experiment reflection profiles: *Geophysics*, **39**, 265–277, doi: 10.1190/1.1440426.  
16  
17

18  
19 Hughes, T. J. R., 1987, *The finite element method, linear static and dynamic finite*  
20 *element analysis*, Prentice-Hall International Inc., Englewood Cliffs, New Jersey, USA.  
21  
22

23  
24 Igel H., N. Takeuchi, R. J. Geller, C. Megnin, H. P. Bunge, E. Clévéde, J. Dalkolmo, and  
25 B. Romanowicz, 2000, The COSY project: verification of global seismic modeling  
26 algorithms: *Physical Earth Planet Interiors* **119**(1–2), 3–23, doi: 10.1016/S0031-  
27 9201(99)00150-8.  
28  
29

30  
31 Komatitsch, D., and J. P. Vilotte, 1998, The spectral-element method: an efficient tool to  
32 simulate the seismic response of 2D and 3D geological structures, *Bulletin of the*  
33 *Seismological Society of America*, **88**(2), 368–392.  
34  
35

36  
37 Komatitsch, D., and J. Tromp, 2002, Spectral-element simulations of global seismic wave  
38 propagation—I. Validation, *Geophysical Journal International*, **149**(2), 390–412.  
39  
40

41  
42 Komatitsch, D., and J. Tromp, 2003, A Perfectly Matched Layer absorbing condition for  
43 the second-order elastic wave equation, *Geophysical Journal International*, **154**, 146–153.  
44  
45

46  
47 Komatitsch, D., S. Tsuboi, C. Ji, and J. Tromp, 2003, A 14.6 billion degrees of freedom, 5  
48 teraflops, 2.5 terabyte earthquake simulation on the Earth Simulator, *Proceedings of the*  
49 *ACM/IEEE Supercomputing SC'2003 Conference*, Phoenix, Arizona, USA, pp. 4–11.  
50  
51

52  
53 Koopmann, G. H., L. Song, and J. B. Fahnline, 1989, A method for computing acoustic  
54  
55

1  
2  
3  
4 fields based on the principle of wave superposition: *Journal of the Acoustical Society of*  
5  
6 *America*, **86**, 2433, doi: 10.1121/1.398450.

7  
8 Kristek, J., P. Moczo, and M. Galis, 2009, A brief summary of some PML formulations  
9  
10 and discretizations for the velocity-stress equation of seismic motion: *Studia Geophysica*  
11  
12 *et Geodaetica*, **53**, 459-474, doi: 10.1007/s11200-009-0034-6.

13  
14 Liu, H.P., D. L. Anderson, and H. Kanamori, 1976, Velocity dispersion due to  
15  
16 anelasticity: implications for seismology and mantle composition, *Geophys J. R. astr.*  
17  
18 *Soc.*, **47**, 41–58.

19  
20 Maday, Y., and E. M. Ronquist, 1990, Optimal error analysis of spectral methods with  
21  
22 emphasis on non-constant coefficients and deformed geometries, *Computer Methods in*  
23  
24 *Applied Mechanics and Engineering*, **80**, 91-115.

25  
26 Mittet, R, 2017, On the internal interfaces in finite-difference schemes: *Geophysics*,  
27  
28 **82**(4), T159-T182, doi: 10.1190/geo2016-0477.1.

29  
30 Moczo, P., J. Kristek, M. Galis, and P. Pazak, 2010, On accuracy of the finite-difference  
31  
32 and finite-element schemes with respect to P-wave to S-wave speed ratio: *Geophysical*  
33  
34 *Journal International*, **182**(1), 493-510, doi: 10.1111/j.1365-246X.2010.04639.

35  
36 Moczo, P., J-P. Ampuero, J. Kristek, S. M. Day, M. Kristekova, P. Pazak, M. Galis, and  
37  
38 H. Igel, 2006, Comparison of numerical methods for seismic wave propagation and  
39  
40 source dynamics—the SPICE code validation. In: *International symposium on the effects*  
41  
42 *of surface geology on seismic motion*, Japan.

43  
44 Mulder, W. A., 1999, Spurious modes in finite-element discretization of the wave  
45  
46 equation may not be all that bad: *Applied Numerical Mathematics*, **30**(4), 425-445, doi:  
47  
48 10.1016/S0168-9274(98)00078-6.

49  
50 Oliveira, S.P., and G. Seriani, 2011, Effect of element distortion on the numerical  
51  
52

1  
2  
3  
4 dispersion of spectral-element methods, *Communications in Computational Physics*,  
5  
6 **9**(4), 937–958.

8 Pageot, D., D. Leparoux, M. Le Feuvre, O. Durand, P. Cote and Y. Capdeville, 2017,  
9  
10 Improving the seismic small-scale modelling by comparison with numerical methods:  
11  
12 *Geophysical Journal International*, **211**, 637–649, doi: 10.1093/gji/ggx309.

15 Pant, D. R., S. A. Greenhalgh, and B. Zhou, 1992, Physical and numerical model study of  
16  
17 diffraction effects on seismic profiles over simple structures: *Geophysical Journal*  
18  
19 *International*, **108**, 906–916, doi: 10.1111/j.1365-246X.1992.tb03479.x.

22 Peter, D., D. Komatitsch, Y. Luo, R. Martin, N. Le Goff, E. Casarotti, P. Le Loher, F.  
23  
24 Magnoni, Q. Liu, C. Blitz, T. Nissen-Meyer, P. Basini, and J. Tromp, 2011, Forward and  
25  
26 adjoint simulations of seismic wave propagation on fully unstructured hexahedral  
27  
28 meshes: *Geophysical Journal International*, **186**, 721-739, doi: 10.1111/j.1365-  
29  
30 246X.2011.05044.x.

33 Pratt, R., 1999, Seismic waveform inversion in the frequency domain. Part I: Theory and  
34  
35 verification in a physical scale model: *Geophysics*, **64**, 888–901, doi: 10.1190/1.1444597.

38 Robertsson, J. O. A., B. Bednar, J. Blanch, C. Kostov, and D. J. van Manen, 2007,  
39  
40 Introduction to the supplement on seismic modeling with applications to acquisition,  
41  
42 processing, and interpretation: *Geophysics*, **72**(5), SM1–SM4, doi: 10.1190/1.2755959.

45 Seriani, G., and E. Priolo, 1994, A spectral element method for acoustic wave simulation  
46  
47 in heterogeneous media: *Finite Elements in Analysis and Design*, **16**, 337-348, doi:  
48  
49 10.1111/j.1365-246X.2011.05044.x.

52 Shepherd, J. F., and C. R. Johnson, 2008, Hexahedral mesh generation constraints,  
53  
54 *Engineering with Computers*, **24**(3), 195–213.

56 Sherlock, D. H., J. McKenna, and B. J. Evans, 2000, Time-lapse 3D seismic physical  
57  
58

1  
2  
3  
4 modeling: *Exploration Geophysics*, **31**, 310–314, doi: 10.1071/EG00310.

5  
6 Staten, M. L., R. A. Kerr, S. J. Owen, T. D. Blacker, M. Stupazzini, and K. Shimada,  
7  
8 2010, Unconstrained plastering—hexahedral mesh generation via advancing-front  
9  
10 geometry decomposition, *International Journal for Numerical Methods in Engineering*,  
11  
12 **81**, 135–171.

13  
14  
15 Stewart, R. R., N. Dyaur, B. Omoboya, J. J. S. de Figueiredo, M. Willis, and S. Sil, 2013,  
16  
17 Physical modeling of anisotropic domains: Ultrasonic imaging of laser-etched fractures  
18  
19 in glass: *Geophysics*, **78**(1), D11–19, doi: 10.1190/geo2012-0075.1.

20  
21  
22 Tantsereva, A., B. Ursin, N. Favretto-Cristini, P. Cristini, and A. M. Aizenberg, 2014a,  
23  
24 Numerical modeling of 3D zero-offset laboratory data by a discretized Kirchhoff integral  
25  
26 method: *Geophysics*, **79**, no. 2, T77-T90, doi: 10.1190/GEO2013-0034.1.

27  
28  
29 Tantsereva, A., B. Ursin, N. Favretto-Cristini, P. Cristini, and A. M. Aizenberg, 2014b,  
30  
31 Errata to “Numerical modeling of 3D zero-offset laboratory data by a discretized  
32  
33 Kirchhoff integral method”, *Geophysics* 79(5), Y3-Y4.

34  
35  
36 Valensi, R., D. Leparoux, O. Durand, F. Bretaudeau, and P. Côte, 2015, Multicomponent  
37  
38 reduced scale seismic modelling: upgrade of the MUSC laboratory with application to  
39  
40 polarization observations: *Geophysical Journal International*, **202**, 1993-2024, doi:  
41  
42 10.1093/gji/ggv170.

43  
44  
45 Virieux, J., H. Calandra, and R.-E. Plessix, 2011, A review of the spectral, pseudo-  
46  
47 spectral, finite-difference and finite-element modelling techniques for geophysical  
48  
49 imaging: *Geophysical Prospecting*, **59**, 794–813, doi: 10.1111/j.1365-2478.2011.00967.x.

50  
51  
52 Vos, P. E. J., S. J. Sherwin, and R. M. Kirby, 2010, From  $h$  to  $p$  efficiently: implementing  
53  
54 finite and spectral/ $hp$  element methods to achieve optimal performance for low- and  
55  
56 high-order discretisations, *Journal of Computational Physics*, **229**, 5161–5181.

1  
2  
3  
4 Wapenaar C. P. A., and A. J. Berkhout, 1987, 3D target-oriented pre-stack migration:  
5  
6 First Break, **5**(6), 217-227.  
7

8 Xie, Z., R. Matzen, P. Cristini, D. Komatitsch, and R. Martin, 2016, A perfectly matched  
9  
10 layer for fluid-solid problems: Application to ocean-acoustics simulations with solid  
11  
12 ocean bottoms, Journal of the Acoustical Society Of America, **140**(1), 165-175, doi:  
13  
14 10.1121/1.4954736.  
15  
16

17 Xu, C., D. Bangrang, and W. Jianxin, 2016, A physical modeling study of seismic  
18  
19 features of karst cave reservoirs in the Tarim Basin, China: Geophysics, **81**(1), B31-B41,  
20  
21 doi: 10.1190/geo2014-0548.1.  
22  
23

24 Zemanek, J., 1971, Beam behavior within the near-field of a vibrating piston: Journal of  
25  
26 the Acoustical Society Of America, **49**, 181–191, doi: 10.1121/1.1912316.  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60