



HAL
open science

Depth and range shifting of a focal spot using a time-reversal mirror in an acoustic waveguide

Philippe Roux, Stéphane Conti, Mathias Fink

► **To cite this version:**

Philippe Roux, Stéphane Conti, Mathias Fink. Depth and range shifting of a focal spot using a time-reversal mirror in an acoustic waveguide. *Applied Physics Letters*, 2002. hal-04000667

HAL Id: hal-04000667

<https://hal.science/hal-04000667>

Submitted on 22 Feb 2023

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.

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/253148374>

Depth and range shifting of a focal spot using a time-reversal mirror in an acoustic waveguide

Article in Applied Physics Letters · May 2002

DOI: 10.1063/1.1479208

CITATIONS

7

READS

100

3 authors, including:



Philippe Roux

University Grenoble Alpes

494 PUBLICATIONS 12,931 CITATIONS

SEE PROFILE



Mathias Fink

École Supérieure de Physique et de Chimie Industrielles

1,029 PUBLICATIONS 55,461 CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:



Imaging and Monitoring with Ambient Seismic Noise [View project](#)



time materials [View project](#)

Depth and range shifting of a focal spot using a time-reversal mirror in an acoustic waveguide

Stéphane Conti, Philippe Roux, and Mathias Fink

Citation: [Applied Physics Letters](#) **80**, 3647 (2002); doi: 10.1063/1.1479208

View online: <http://dx.doi.org/10.1063/1.1479208>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/80/19?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[Focal depth shifting of a time reversal mirror in a range-independent waveguide](#)

J. Acoust. Soc. Am. **118**, 1341 (2005); 10.1121/1.1940447

[Real-time focusing using an ultrasonic one channel time-reversal mirror coupled to a solid cavity](#)

J. Acoust. Soc. Am. **115**, 1955 (2004); 10.1121/1.1699396

[A time-reversal mirror with variable range focusing](#)

J. Acoust. Soc. Am. **103**, 3234 (1998); 10.1121/1.423040

[Phase conjugation in the ocean: Experimental demonstration of an acoustic time-reversal mirror](#)

J. Acoust. Soc. Am. **103**, 25 (1998); 10.1121/1.423233

[Time-reversal in an ultrasonic waveguide](#)

Appl. Phys. Lett. **70**, 1811 (1997); 10.1063/1.118730



2014 Special Topics

PEROVSKITES

2D MATERIALS

MESOPOROUS MATERIALS

BIOMATERIALS/ BIOELECTRONICS

METAL-ORGANIC FRAMEWORK MATERIALS

AIP | APL Materials

Submit Today!

Depth and range shifting of a focal spot using a time-reversal mirror in an acoustic waveguide

Stéphane Conti,^{a)} Philippe Roux,^{b)} and Mathias Fink

Laboratoire Ondes et Acoustique, ESPCI, 10 rue Vauquelin, 75005 Paris, France

(Received 23 October 2001; accepted for publication 18 March 2002)

We present a technique based on time reversal to focus an acoustic field at any depth and range in a waveguide. We take advantage of the signal received from an acoustic beacon in the guide to build a time-reversed modified version of the field that refocuses at a different point in the waveguide. This method is based on the application of the images theorem in the guide and, as in the classical time-reversal experiment, it does not require *a priori* knowledge of the waveguide characteristics. Ultrasonic laboratory experiments and underwater acoustic simulations are presented and compared to classical time-reversal focusing results. © 2002 American Institute of Physics.
[DOI: 10.1063/1.1479208]

Time reversal is a well-known technique to refocus an acoustic field on its original source. A time-reversal experiment implies the use of a source-receiving array—the so-called time-reversal mirror (TRM)—that will transmit back into the propagation medium a time-reversed version of the incident field. The advantage of this technique is to naturally create a set of signals that refocus at the source while taking into account the heterogeneity of the propagation medium. Time-reversal focusing has been demonstrated in ultrasonics^{1,2} and in underwater acoustics.³ The robustness of this technique leads to interesting applications in noisy or fluctuating environments such as the ocean.⁴

The aim of this work is to go beyond a classical time-reversal experiment by adding another step. Knowing the incident field from a point source in a waveguide, how could we refocus not only at the source but also at any other point in the waveguide? In other words, we look for a set of signals that will shift the time-reversed focal spot in depth and range in the waveguide. Such a result would be of great interest in underwater acoustics as far as imaging or detection is concerned. The ability to focus at any point in a waveguide is a first step in making an image of the medium. A second step would be target detection in the studied zone.

Song *et al.*⁵ have experimentally achieved at sea a 10% range shift of the focal spot along the axis of the waveguide by translating the center frequency of the incident field before time reversal. In ultrasonics, a technique based on time-reversal has also been developed to steer an acoustic beam around the focal spot through an aberrating layer.⁶ Our ambition is to shift the focal spot in range and depth in a waveguide without changing the frequency bandwidth of the incident field.

The idea of this work comes from the application of the method of images in the waveguide. The incident field received from the source on the time-reversal mirror in the guide is equivalent to the field generated in free space by a set of virtual sources that are the images of the actual source with respect to the waveguide interfaces. The advantage of

this representation is that the wave front issued from a point source in free space and received on the time-reversal mirror can be approximated by a parabola whose curvature depends on the source location. By changing the parabola before time reversal, we then create a set of signals that refocus at another point in the waveguide.

The first stage to get this result is the extraction of the parabola from the field received on the time-reversal mirror in the waveguide. Experiments have been done with 116 transducers centered at 1.5 MHz with a 50% frequency bandwidth. The waveguide, limited by a steel-water and an air-water interface, is 6 cm deep and 45 cm long. Figure 1(a) is a spatial temporal representation of the field issued from a point source and received on the TRM. The successive reflections of the incident field on the interfaces correspond to

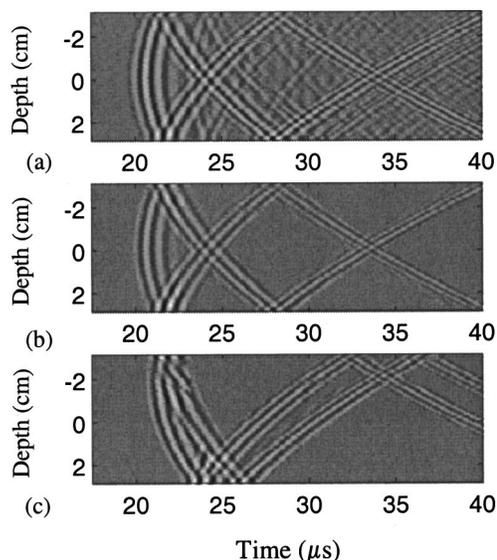


FIG. 1. Spatial temporal representation of the field after propagation in the waveguide. Time is along the x axis, the position of the TRM transducers is along the y axis. The guide length and depth are, respectively, 45 and 6 cm; (a) field received on the TRM after emission of a short pulse from the source; (b) field obtained after having extracted the parabolic wave front and folded the parabola back in the waveguide for a focus on the initial source; (c) field obtained after having extracted the parabolic wave front and folded the parabola back in the waveguide for a focus at +2 cm compared to the initial source.

^{a)}Work partly done while at the Marine Physical Laboratory, UCSD, La Jolla.

^{b)}Electronic mail: philippe@mpl.ucsd.edu

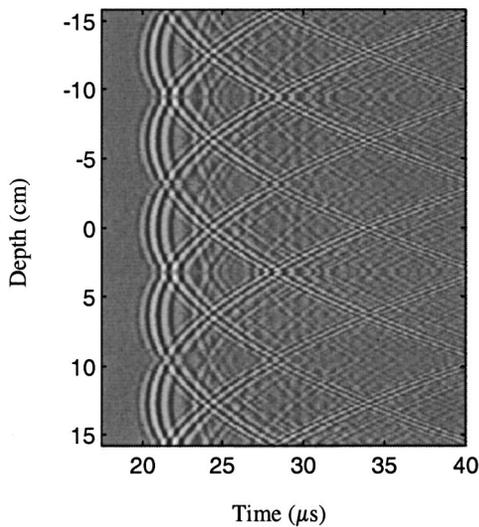


FIG. 2. Spatial temporal representation of the field emitted by the source and its images and received by the TRM and its images with respect to the waveguide interfaces. Time is along the x axis, the position of the TRM transducers and its images is along the y axis. The guide length and depth are respectively 45 and 6 cm.

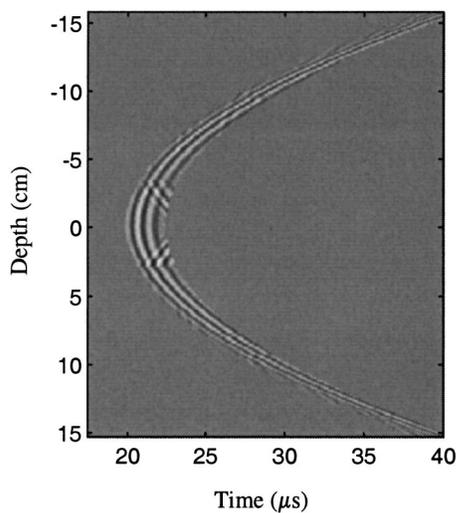


FIG. 3. Spatial temporal representation of the “useful” parabolic wavefront after application of a parabolic time window on the replica matrix (see Fig. 2). This parabola corresponds to the field issued from the source and received on the TRM images in a free space medium. Time is along the x axis, the position of the TRM transducers and its images are along the y axis. The guide length and depth are, respectively, 45 and 6 cm.

the two branches of the parabola that are folded in the waveguide. To unfold the parabola, the idea is to place side by side the replicas of the field received on the TRM in the waveguide (Fig. 2). In other words, we obtain on the images of the actual TRM the field emitted by the images of the actual source with respect to the waveguide interfaces. In Fig. 2, we observe several parabolas coming from the images of the source after propagation in free space. However, we are interested in the parabola issued from the actual source in the waveguide.

We obtain this parabola by applying a parabolic temporal window on the replica matrix with the following algorithm (Fig. 3).

- (1) A first parabolic temporal window is determined on the field received on the TRM by fitting the first wave front [Fig. 1(a) between 20 and 22 μ s].
- (2) We apply this parabolic filter on the replica matrix (Fig. 2 between 20 and 40 μ s). The evaluation criterion of the temporal window is the total energy of the windowed signal.
- (3) We vary the parabola parameters and, for each set of parameters, we measure the evaluation criterion of the parabolic filter.
- (4) The best parabolic filter corresponds to the maximum of the evaluation criterion.

The next step consists in modifying the parabola parameters to change the location of the focal spot. In the far field ($R \gg y_0$), a shift in depth is achieved by delaying the signals of the filtered replica matrix $\Delta t(y_0) = (y_0/c)(\Delta y/R)$ where y_0 is the position of the transducer on the replica matrix, R is the range between the TRM and the source, Δy is the depth shift, and c is the sound speed. It is interesting to note that the time delay is linearly dependent on the transducer position. A shift in range is performed by artificially contracting or dilating the array size. The contraction parameter which modifies the parabola curvature is $\alpha = \sqrt{(R + \Delta R)/R}$ where ΔR is the range shift of the focal spot. A contraction ($\alpha < 1$) shifts the focal spot toward the TRM; a dilatation ($\alpha > 1$) moves the focal spot away from the array. With the parabola, the time-reversed field is obtained by folding the

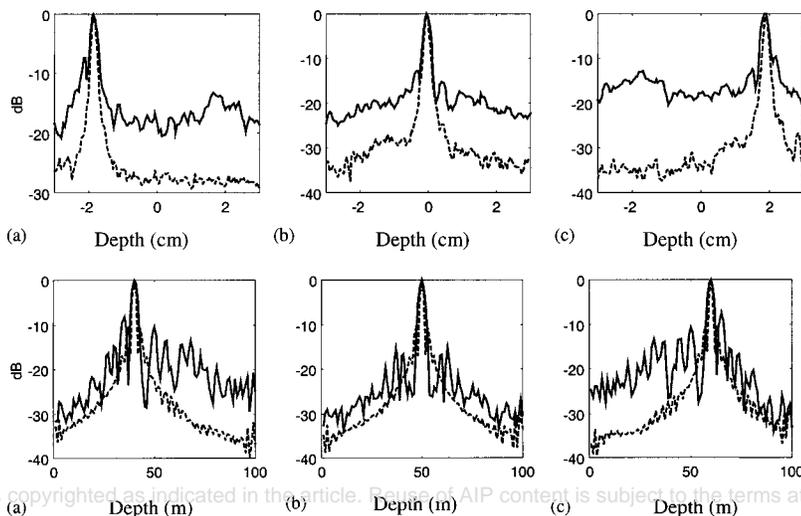


FIG. 4. Directivity pattern obtained after a classical time reversal (dashed line) and with the depth shifting technique (solid line); (a) depth shift = -2 cm; (b) depth shift = 0; (c) depth shift = +2 cm. The guide length and depth are, respectively, 45 and 6 cm.

FIG. 5. Directivity pattern obtained after a classical time-reversal (dashed line) and with the depth shifting technique (solid line); (a) depth shift = -10 m; (b) depth shift = 0; (c) depth shift = +10 m. The guide range and depth are, respectively, 2500 and 100 m.

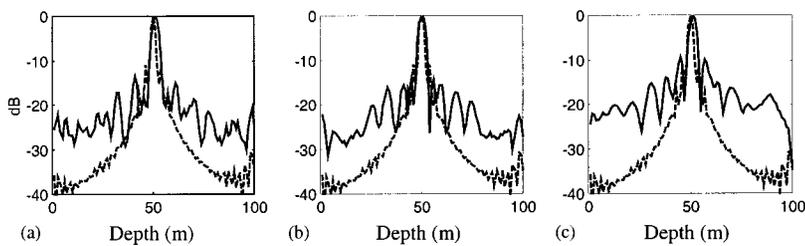


FIG. 6. Directivity pattern obtained after a classical time reversal (dashed line) and with the range shifting technique (solid line); (a) range shift = +500 m, (b) range shift = -500 m; (c) range shift = +1000 m. The initial guide range and depth are, respectively, 2500 and 100 m.

parabolic wave front back inside the waveguide [Figs. 1(b) and 1(c)]. After time reversal, the field naturally refocuses at the desired point.

Two kinds of results follow. First, we show experimentally a ± 2 cm depth shift of the focal spot in a 6 cm deep, 45 cm long ultrasonic waveguide (Fig. 4). These results are to be compared to the focal spot classically obtained by time reversal when the source is placed at ± 2 cm. Even if the focusing quality is degraded (e.g., the focal spot is larger and the side lobes are higher), the interest of this technique relies in its ability to focus at any depth in the waveguide with only one point source. Second, we performed numerical simulations in a shallow water environment. The acoustic channel is range independent, 100 m deep and the sound speed profile is constant in the water column. The source-array range is 2500 m. The TRM is made of 50 transducers centered at 1500 Hz with a 50% bandwidth. The array spans the whole water column. Figures 5 and 6 show two examples of the depth shift and range shift of the focal spot. Once again, these results are compared to classical time reversal when the source is placed at the shifted position. We observe a degradation of the focal spot compared to those obtained with a classical time reversal at these positions. Last, in the case of a down-refracting sound speed profile, a ± 10 m depth shift is still achievable but the level of sidelobes is higher.⁷

We can also investigate a more complicated problem: what happens when the TRM does not span the whole water column? Results obtained recently show that this focusing technique is still workable if we add an information to the system: for a depth limited array, you need to know the position of the array in the water column. Similarly, in a range-dependent waveguide such as a wedge, the knowledge of the slope of the bottom relative to the surface should be sufficient to achieve depth and range focusing. Practically speaking, the shift of the focal spot in the waveguide is based on the measure of the parabolic wave front as described in Fig.

3. The larger the frequency bandwidth and the smaller the source-array range, the easier is the determination of this parabola. Indeed, in a narrow-band regime or when the source-array range is large, acoustic propagation in shallow water is better described by modes than by rays. It then becomes difficult to separate in time the successive reflections of the incident field on the waveguide interfaces and the parabolic wave front as described in free space is not observable. The analysis of the time arrival of the successive echoes in the waveguide shows that depth and range focusing is possible when $H^2 B/Rc \gg 1$, where H is the depth of the guide and B is the frequency bandwidth of the acoustic signal.

In conclusion, we have shown that the field issued from an acoustic beacon provides enough information to refocus the field at any depth and range in a waveguide. This relies on time-reversal invariance and does not require *a priori* knowledge of the waveguide characteristics. This technique could be a way to perform acoustic imaging in an oceanic shallow water environment.

The authors are appreciative of William Kuperman, Director of Scripps Institution of Oceanography's Marine Physical Laboratory, for sponsoring S.C. during his internship at the Marine Physical Laboratory.

¹M. Fink, Phys. Today **50**, 34 (1997).

²M. Fink, Sci. Am. **281**, 67 (1999).

³W. A. Kuperman, W. S. Hodgkiss, H. C. Song, T. Akal, C. Ferla, and D. R. Jackson, J. Acoust. Soc. Am. **103**, 25 (1998).

⁴G. F. Edelmann, T. Akal, W. S. Hodgkiss, S. Kim, W. A. Kuperman, and H. C. Song, IEEE J. Ocean. Eng. (to be published).

⁵H. C. Song, W. A. Kuperman, and W. S. Hodgkiss, J. Acoust. Soc. Am. **103**, 3234 (1998).

⁶C. Dorme and M. Fink, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **43**, 167 (1996).

⁷S. Conti, Master degree, Paris University, 2001 (unpublished).