INCOMPLETE PHASE CONJUGATION

KD Ridley DERA Malvern, Malvern, Worcestershire, UK
E Jakeman University of Nottingham, School of Electrical and Electronic Engineering, Nottingham, UK.
DC Jones DERA Malvern, Malvern, Worcestershire, UK

1. INTRODUCTION

In recent years, the technique of time reversal has been applied to underwater acoustic propagation (see refs [1],[2],[3]). An array of transducers senses an incoming acoustic pulse. The signal from each transducer is recorded and, after all of the pulse has been received, a time reversed replica of each individual signal is transmitted back via the transducer that detected it. The time reversed pulse propagates back through the water reproducing the high spatial and temporal concentration of acoustic power in the vicinity of the original emitter. One possible application of this technique is its use in an iterative mode, whereby multiple transmit and receive operations maximise the signal from the strongest reflector.

This time reversal technique has an analogue in laser optics, which predates, and partially inspired, the work in acoustics. In laser physics the technique is more commonly referred to as phase conjugation. This does not involve complete time reversal of the waveform, but rather reversal of the relative phases of points on the wavefront. Never-the-less, the underlying concept is the same, based on the time reversal symmetry inherent in the wave equation which describes both acoustic and optical waves. In the present paper we discuss some optical experiments that are equally relevant to acoustics. These experiments assess the impact of incomplete sampling of the wavefront (in this case due to restricted aperture size) on the ability of phase conjugation to reconstruct the original source configuration.

2. Comparison of acoustic and optical regimes

As mentioned previously, the scalar wave equation can be used to describe both optical and acoustic propagation. However, there are some important differences. As far as phase conjugation/time reversal is concerned, two differences stand out: First, acoustic wavelengths are much longer than optical ones, this means that, for the same scale of experiment, diffraction effects are more significant for acoustic waves, and it is more likely in acoustics that only a part of the wavefront is sensed. Second, optical frequencies are very much higher than acoustic ones, making direct measurement of the field oscillations impractical. Thus, in optics, only relative phases can be reversed, either by coherent, nonlinear, interactions or by electrical, or mechanical phase shifters (adaptive optics techniques). This means that, in optics, one is restricted to working in a pseudo-steady-state regime. In practice, this is rarely a serious restriction for laser applications.

3. Incomplete phase conjugation

If only part of the wavefront is reversed we have incomplete phase conjugation. This happens, for example, when the aperture over which the wavefront is sensed (we refer to this as the phase conjugate mirror (PCM) aperture) only intercepts part of the wavefront. In this case it has been shown ([4],[5],[6]) that the phase conjugation is only partial, and that the fraction of the emitted wavefront that can be considered to be truly reversed with respect to the incoming wave is simply equal to the fraction of the incoming wave that is intercepted by the aperture (these fractions are in terms of the power contained in the part of the wavefront under consideration). What happens to the non-conjugate fraction depends on the details of the propagation geometry. In general, the more distorting the medium through which the wave propagates, the more dispersed is the non-conjugate fraction that returns to the source. This has been well demonstrated in acoustics in ref [7], and in laser optics in ref [8] (from which the experimental data in the present paper is taken). This effect raises the interesting possibility of achieving a resolution which is better than the diffraction limit of the PCM aperture. The scattering medium can be thought of as increasing the effective aperture size. This is shown in the next section (and was reported for acoustic time reversal in ref [7]).

4. Experiments

The experiments used an injection-seeded, Q-switched, Nd:YAG laser giving frequency doubled output at 532nm in a 10ns long pulse. The experimental arrangement is shown schematically in figure 1. The laser beam is directed onto a pinhole of diameter 300μm. The pinhole (PH) provides a point at which the phase conjugate content of the returning beam can be assessed. In the case of perfect phase conjugation all of the light reflected from the PCM would return through the pinhole.

After the pinhole the beam (referred to now as the signal beam) has a top-hat profile with a uniform phase front. The total energy in the signal is monitored using a beam-splitter (BS2) and photodiode (PD1). The signal passes through a beam expanding telescope (L1 focal length -50mm, L2 focal length +250mm) to give a collimated beam with an Airy spatial profile of diameter (central lobe) of 1.6cm. The effective focal length of the lens combination was 3.7m. The expanded signal beam propagates along a 2.5m path, into which aberrators can be inserted, to the PCM. The energy reaching the PCM is monitored using another beam-splitter (BS3) and photodiode detector (PD2). This beam-splitter sits behind an aperture (A1) which defines the aperture of the PCM, so, in conjunction with PD1, the fraction of the signal falling upon the PCM can be measured. This fraction varied from 10^{-1} to 10^{-4} depending on the strength of the aberrators used. The PCM used the non-linear optical effect of stimulated Brillouin scattering as the phase conjugation mechanism.

The total phase conjugate energy leaving the PCM is monitored using a photodiode (PD3), and the phase conjugate energy passing back through the pinhole is monitored using a fourth photodiode (PD4). The ratio of readings PD4 to PD3 gives the fraction of the phase conjugate energy reaching the original source (pinhole) which can be used to define the fidelity of the phase conjugation process. A CCD camera (CCD) is used to record the spatial profile of the central region of the conjugate beam in the plane of the pinhole.

We now turn to quantitative measurements of the phase conjugation fidelity, which we define as the fraction of the phase conjugate power which passes back through the pinhole. As discussed in section 2, for an ideal PCM, one expects this fidelity to be equal to the fraction of the signal beam that goes through the PCM aperture. By varying the focussing of the telescope, we changed the amount of light passing through A1. Results for the fidelity are plotted in figure 2. This shows that the points do indeed lie on a straight line with unity slope, but that this line lies below the expected line for ideal phase conjugation. We interpret this as being due to imperfections in the stimulated Brillouin scattering process, that produces a non-ideal conjugate return.

In this experiment the phase conjugation is incomplete even in the absence of aberration because even when the telescope is set for optimal collimation it expands the signal beam so that its starting diameter is greater than the PCM aperture size. This allows us to investigate how the structure of the returning beam at the pinhole changes depending on the degree of aberration of the signal beam. Figure 3a shows the beam returning to the pinhole when there is no aberration. The beam profile is smooth but many times larger than the pinhole diameter (the diffraction rings arise from an attenuating filter in front of the camera). This is because beam size is determined by the diffraction limit of the PCM aperture. Figure 3b shows how the central spot narrows when a random aberrator (a thin phase screen) is introduced. This narrowing was discussed in section 3. It occurs because the scattering by the aberrator allows some light to enter the PCM aperture from parts of beam which would otherwise miss it. The aberrator thus increases the effective aperture of the PCM.

Figure 3c shows a result for a stronger phase screen, in this case the central spot is very close in size to the pinhole. It is interesting to note that the "signal to background ratio" for the central peak actually increases as the degree of aberration increases, even though the intensity of this peak drops (attenuating filters in front of the camera were changed to keep the peak intensity on the camera constant). This is because the non-conjugate part is spread out over a greater area, which reduces its intensity relative to the conjugate part, even though a greater fraction of the total power is contained within it.

It is interesting to examine the enhancement in resolution when the signal has a somewhat more complicated form. This was done by replacing the single pinhole with a double pinhole of separation 0.6mm. The separation here is less than the diffraction limit of the PCM aperture so that the phase conjugate, figure 4a, shows just a single broad, slightly elliptical, shape. When aberrators are introduced into the signal path, the resolution of the conjugate component is improved and it exhibits two peaks centred on the two pinholes. Figures 4b and 4c show the beam profiles for moderate and strong phase screens respectively, located at a distance of 2.5m. These profiles show the appearance of the non-conjugate background after aberration, and the decrease in its intensity, and the increase in the resolution of the conjugate part, as the aberrator strength increases.

5. Summary

We have reviewed the phenomenon of incomplete phase conjugation, and presented some experimental results from laser optics. These results are also relevant to phase conjugation in underwater acoustics, which is based on the same underlying principle of time reversal symmetry. It is interesting to note that very similar effects are seen in optical and acoustic experiments, despite the very different frequencies and velocities involved (the results presented here are similar to those in the acoustic experiments in [7]). It is to be hoped that useful cross-fertilisation between these two areas of physics will continue in the future.

6. References

[1] W.A. Kuperman, W.S. Hodgkiss and H.C. Song, "Phase conjugation in the ocean: Experimental demonstration of an acoustic time-reversal mirror", J. Acoust. Soc. Am. **103**, pp25-40 (1998).
[2] H.C. Song, W.A. Kuperman, W.S. Hodgkiss, T.A.kal, C. Ferla and D.R. Jackson, "A long-range and variable focus phase-conjugation in shallow water", J. Acoust. Soc. Am. **105**, pp1597-1604 (1999).
[3] M. Fink, "Time reversal in acoustics", Contemporary Physics, **37**, pp95-109 (1996).
[4] D.R. Jackson and D.R. Dowling, "Phase conjugation in underwater acoustics", J. Acoust. Soc. Am., **89**, pp171-181 (1991).
[5] C. Gu and P. Yeh, "Partial phase conjugation, fidelity, and reciprocity", Opt. Commun., 107, pp353-357 (1994).
[6] E. Jakeman and K.D. Ridley, "Incomplete phase conjugation through a random phase screen I. Theory", J. Opt. Soc. Am. A, **13**, pp2279-2287 (1996).
[7] A. Derode, P. Roux and M. Fink, "Robust acoustic time reversal with high-order multiple scattering", Phys. Rev. Lett., **75**, pp4206-4209 (1995).
[8] D.C. Jones and K.D. Ridley, "Experimental investigation by stimulated Brillouin scattering of incomplete phase conjugation", J. Opt. Soc. Am. B., **14**, pp2657-2663 (1997).

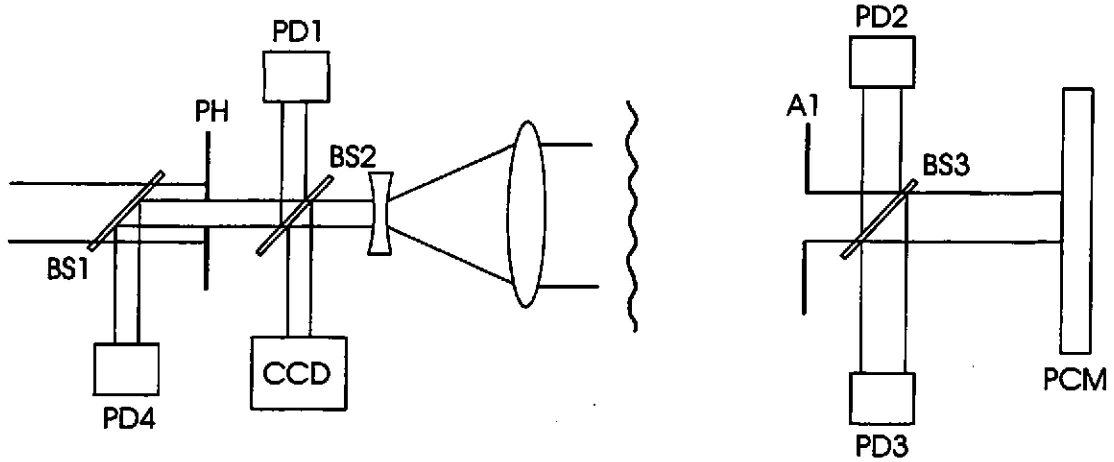

FIGURE 1

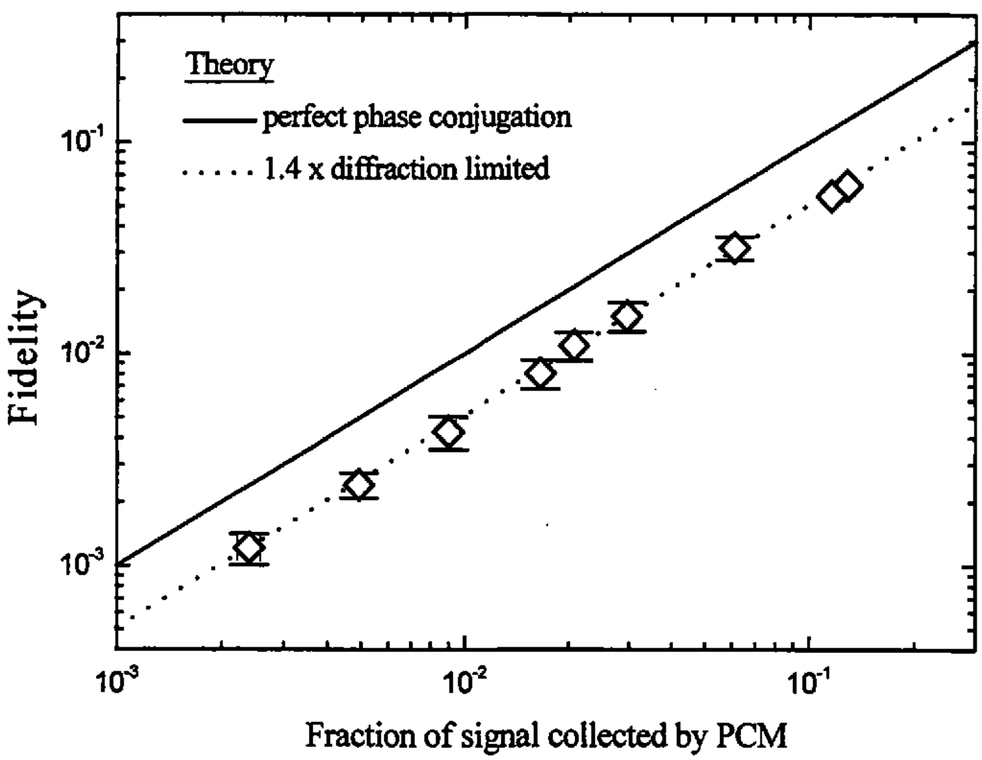

FIGURE 2

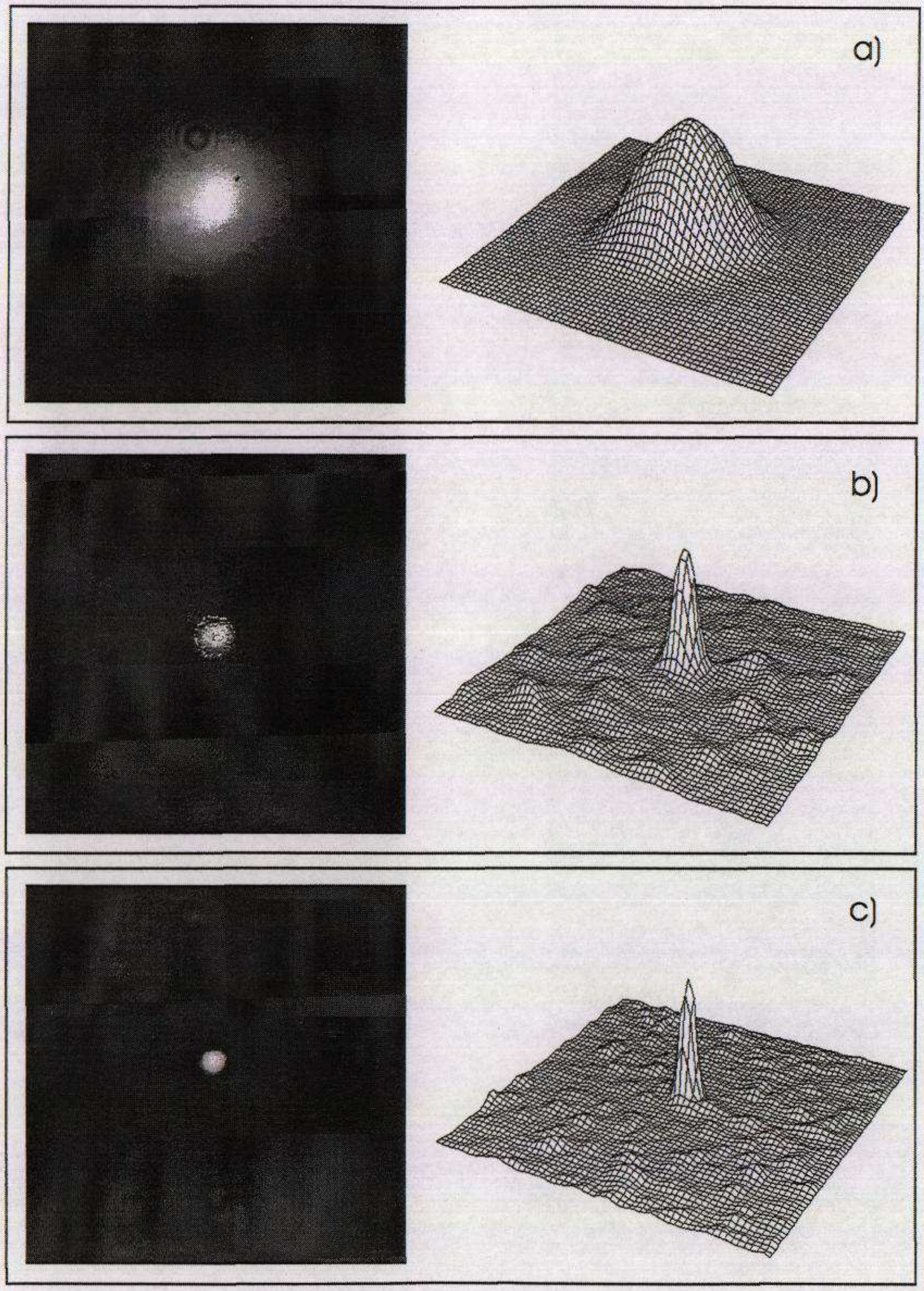

FIGURE 3

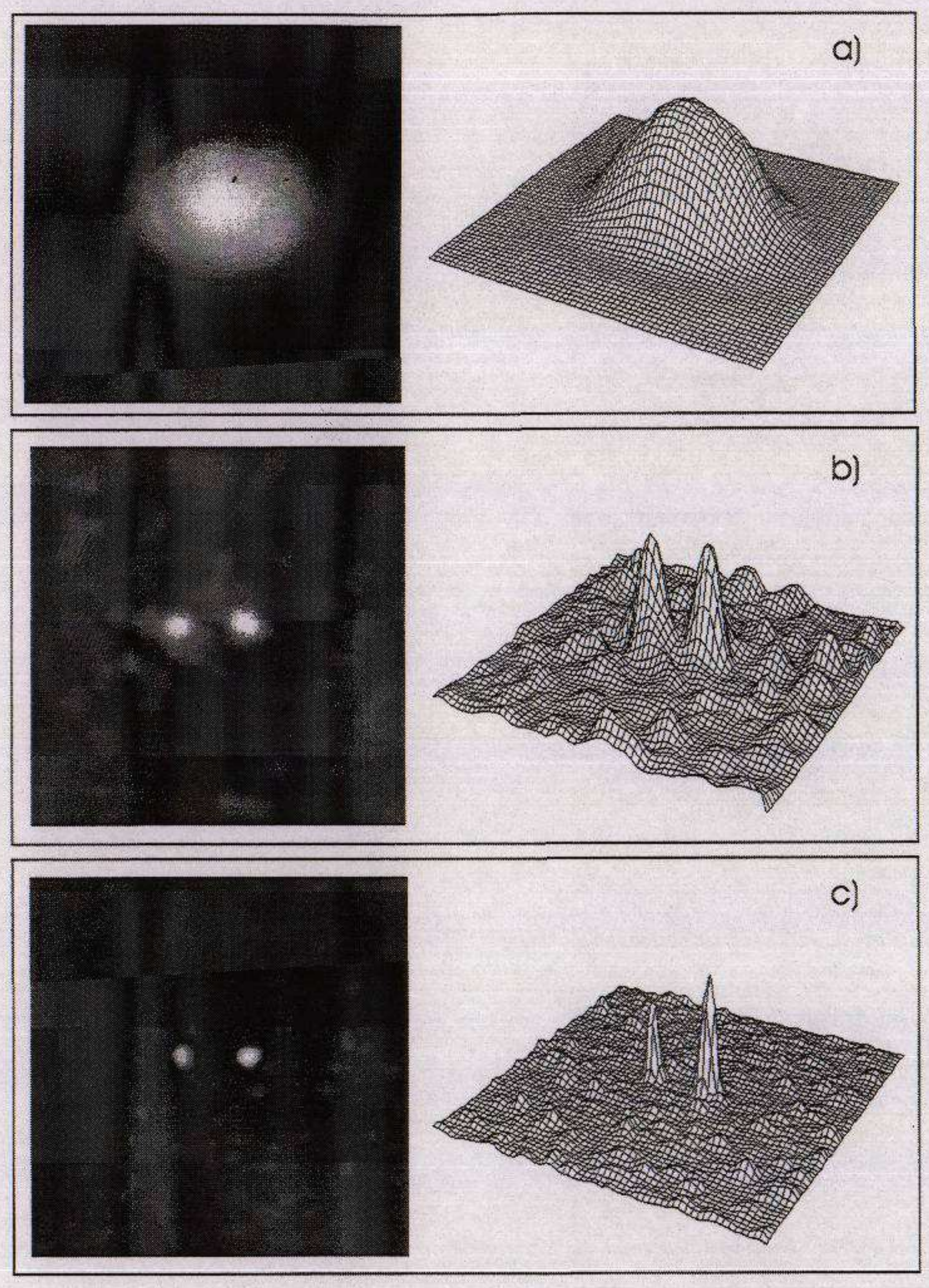

FIGURE 4