

A New Synthetic Aperture Sonar Design with Multipath Mitigation

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Abstract. Sonar performance in shallow water is severely degraded by multipath which reduces image contrast and degrades the performance of interferometric processing. This is an important limitation for high resolution applications such as minehunting, where target recognition exploits chiefly the shape and size of the target shadow. Experimental data showing the nature and importance of the multipath is presented together with a new sonar design, optimized to achieve a high level of multipath rejection at large range to water depth ratio.

INTRODUCTION

As is well known, synthetic aperture sonar (SAS) has the potential to provide very high cross-track resolution at long ranges. In practice, however, multipath interference can be a dominant cause of performance degradation, especially in shallow water. Multipath, besides the well known effect of ghost targets, leads to loss of image contrast (with consequent filling in of shadows) and degrades the quality of bathymetric estimates when interferometry is used. These effects, which are not SAS-specific, have nonetheless enhanced relevance in synthetic aperture imaging, since SAS aims naturally to extend the range of a sonar to fully exploit the gain in cross range resolution.

In addition, multipath affects specifically SAS performance because of the influence on the data-driven methods, such as the Displaced Phase Centre Array (DPCA) micronavigation, used to estimate the platform trajectory. The DPCA technique makes use of the correlation of the sea bottom direct backscatter to estimate the displacement of the SAS between pings, and depends critically [1] on a generalized Signal to Noise Ratio (SNR), where the signal is the seafloor backscatter coming from the direct path, while the noise consists of background noise of the sea, system noise, surface and volume reverberation and, last but not least, multipath interference of various orders.

We will adopt the convention of naming a multipath by the a combination of letters 'b' (for bottom) and 's' (for surface), with a lower letter indicating a specular bouncing and a capital letter indicating a non-specular scattering. In Fig. 1 first and second order multipaths from bottom scattering are shown.

Note that these plots show the trajectories for the same arrival time, and not, as it is more usual, for multiple returns from the same target. The focus will be, unlike in [2], on the multipath effects on the sea bottom direct backscatter, i.e., on the generalized SNR at a given range, which has direct implications on the DPCA technique and, at certain conditions, on the shadow contrast. In other words, this paper will investigate

how multipath affects SAS even in the absence of targets.

It will be argued that the second order multipath 'bsB' and its reciprocal 'Bsb' constitute a major obstacle for obtaining high generalized SNR at large range to waterdepth ratios, both for physical and synthetic aperture imaging. Note that because of the different spatial correlation properties, no SNR gain due to synthetic aperture processing of the kind described in [2] for targets is expected in the case of sea bottom backscatter, except when the SAS is oversampled (i.e., it moves less than half of the sonar length between pings).

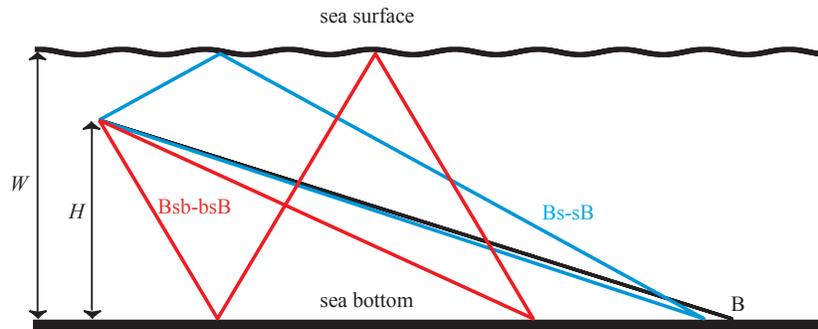


FIGURE 1. Multipath from bottom backscatter.

EXPERIMENTAL SETTING

To investigate the importance of higher order multipath for SAS performance, two experiments were conducted in June 2002 and November 2003.

In the first experiment, a 100 kHz sonar was deployed vertically on a fixed tower at a height H of 10.7 m and in a water depth W of about 20 m, in the vicinity of La Spezia. The seafloor was hard mud and the sea was calm during the experiment. No targets

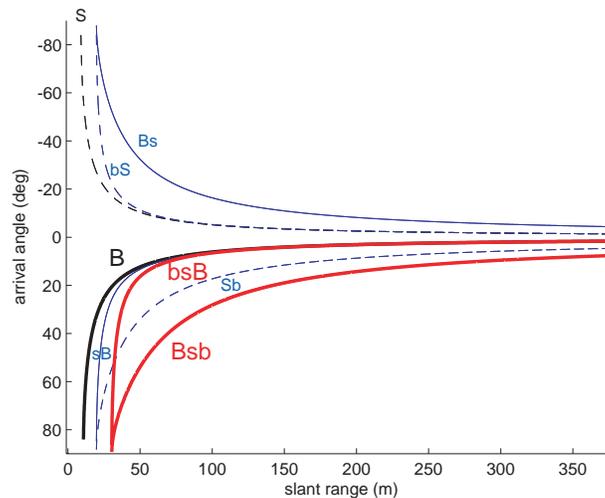


FIGURE 2. Direct and multipath returns as a function of range and arrival angle at the sonar, for the geometry of the experiment.

were deployed. In Fig. 2 the arrival angle in function of arrival time (expressed in terms of slant range of the direct bottom return) is plotted for this geometry, assuming a flat bottom.

The sonar array consisted of 256 receiver elements spaced at 7.5 mm to form an aperture of 1.92 m. When the sonar is mounted in vertical configuration, the vertical and horizontal beamwidths of the elements are about 40 degrees and 100 degrees respectively. The 64 channels at the center of the array formed a fully programmable transmitter, allowed different vertical transmission beampatterns to be synthesized (Fig. 3). The waveform used was a 95-105 kHz, 10 ms chirp. A previous experiment [3] with the same sonar deployed vertically had been conducted in 2001, but unlike this experiment, no tower was used, the sonar being lowered with ropes from the R/V Alliance. Therefore, the sonar moved horizontally too much to allow studying the ping-to-ping correlation of the data, since the horizontal beamwidth of 100 degrees gives, in fact, a spatial correlation length of only 0.8 cm. To begin, a broad transmission beam, shaped

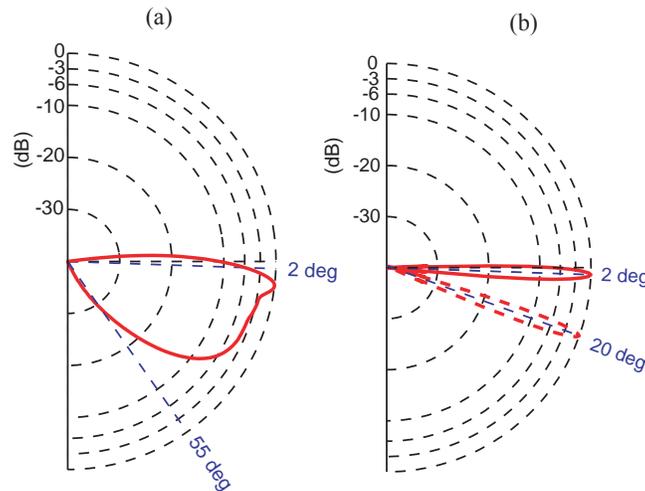


FIGURE 3. Vertical transmission beampatterns used in the experiment: (a) Wide beampattern (b) Narrow beampatterns.

to encompass a wide swath of the seafloor while avoiding surface direct ('S') and first order multipaths ('Sb', 'sB'), was synthesized using the flexibility of the programmable transmitter. The beam, shown in figure Fig. 3(a), captures the main features of a typical conventional sonar design. In Fig. 4(a) the beamformed data are presented as a function of slant range and arrival angle. A time-varying gain has been applied to the data. A comparison with Fig. 2 indicates that it is impossible at long range to separate the arrival direction of the direct return 'B' from the second order multipath 'bsB'.

A 7 degree vertical beam with -20 dB sidelobes was synthesized in reception. The SNR, derived from the ping to ping correlation, is plotted in Fig. 5(a) as a function of time (expressed as equivalent slant range distance) and the receive depression angle. The white line represents the direct bottom return arrival.

The SNR is seen to fall off with range, well before the range where noise is dominant, indicating that there are other contributions than the direct seafloor return 'B'.

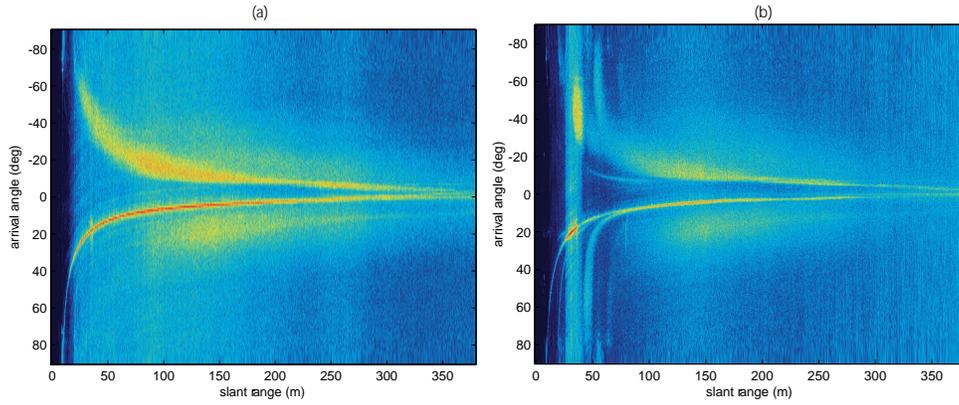


FIGURE 4. Direct and multipath returns as a function of slant range and arrival angle. Figures (a) and (b) correspond to transmission beampatterns as in Fig. 3(a) and (b), dashed line, respectively. The total dynamic range is 60 dB.

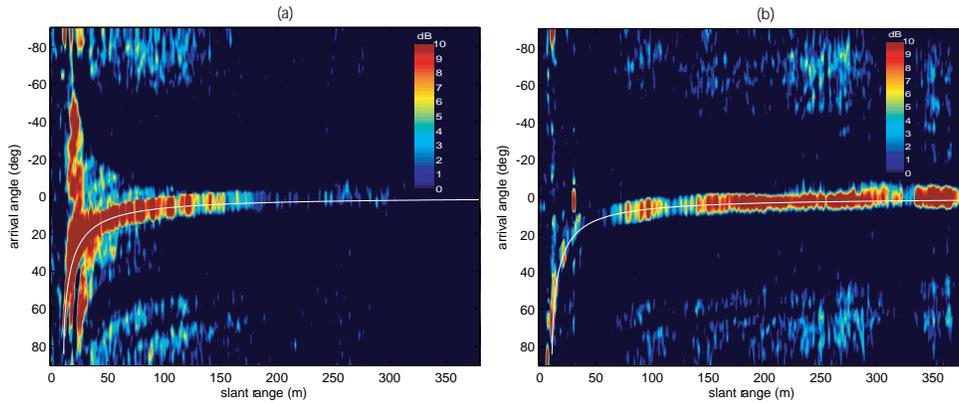


FIGURE 5. Generalized SNR as a function of range and the depression angle of the 7 degree receive beam. Figures (a) and (b) correspond to transmission beampatterns as in Fig. 3(a) and (b), continuous line, respectively.

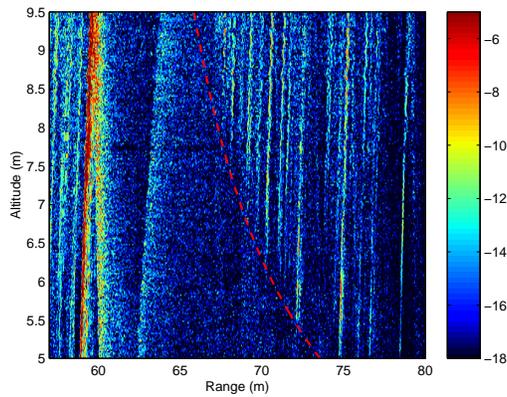


FIGURE 6. Direct and multipath returns from a sphere at 59 m range (Klein 5500 data), plotted for several sonar altitudes in the water column. The dashed red line shows the maximum shadow range, according to the geometry of the experiment.

The assumption is that the drop in SNR is due to high order multipath, excited at short range. To validate this assumption, a narrow transmission beam (3 degrees at 3 dB) steered at close range (32 m) was synthesized (Fig. 3(b), dashed line) and the corresponding data are plotted in Fig. 4(b). The ‘bsB’ multipath whose bottom specular reflection is at 32 m is clearly visible in the region around 145 m. Other multipath returns of first, second, third and fourth order are also visible, but the ‘bsB’ return is by far the most important, because its reception angle is nearly the same as that of the direct returns at far range. This explains the drop in correlation shown in Fig. 5(a) for the broad sector ensonification.

Thus, to achieve high SNR at very large relative ranges $r = R/W$, where R is the slant range, it is necessary not to ensonify the seafloor at short ranges, to avoid ‘bsB’ multipath whose arrival angle is impossible to separate in reception (similarly, a narrow receive beam is required to rule out the reciprocal ‘Bsb’ multipath).

To validate this assumption, the 3 degree transmission beam was steered at far range, as in the continuous line of Fig. 3(b). The corresponding SNR, obtained as above, is plotted in Fig. 5(b). The increase in SNR at long ranges over Fig. 5(a) is evident.

In the second experiment, conducted jointly with Defense Research & Development Canada (DRDC), Atlantic, a Klein 5500 sidescan sonar was deployed in 12 m water depth on a telescopic tower. The 455 kHz sonar was then moved vertically from 5 m to 9.5 m height while pinging in the direction of a 1 m diameter sphere placed at 59 m range. Figure 6 shows the sonar data with the strong direct return from the sphere followed by the multipath returns ‘Bs’ and ‘Bsb’. The multipath intensity is shown to be approximately constant with the sonar altitude and comparable to the reverberation level after the end of the sphere shadow, indicated by the red dashed line. In this case, the first order multipath is stronger than second order one because of the wide vertical beam pattern both in transmission and in reception.

MUTIPATH-REJECTING SONAR DESIGN

To design a sonar with high generalized SNR at long range, a key parameter is, therefore, the difference between the angle of the direct signal and the second order multipath signals (‘Bsb’, ‘bsB’) arriving at the same time.

By geometric considerations, we have

$$u_{Bsb} = \frac{H(H + 2W)}{H^2 + (H + W)W} u_B^2, \quad (1)$$

where u_B and u_{Bsb} are the sines of the receive angles of the bottom direct and the second order ‘Bsb’ multipath. Defining the relative height $h = H/W$ and the In terms of relative range r , we have,

$$u_{Bsb} = \frac{(2 + h)r}{1 + h + r^2}. \quad (2)$$

Therefore for relative range $r \gg 1$, $u_{Bsb} \cong (2 + h)/r$ and

$$u_B - u_{Bsb} \cong 2/r. \quad (3)$$

This formula gives an important design criterion for the beamwidth necessary to achieve high SNR at long range. For example, at a relative range $r = 10$, it gives an angular separation of less than 8 degrees. Given the narrowness of the beams required at large r and the need to maintain a full swath imaging, a sonar design allowing different beamwidths at different ranges seems necessary.

To address these issues, a novel sonar design has been devised by Nato Undersea Research Centre. Besides incorporating all the experience in synthetic aperture sonar the Centre has developed, it provides multipath mitigation in order to fully exploit the gain in cross range resolution even in very shallow water. The aim is to achieve good shadow contrast up to a range of more than 10 times the water depth. The multipath suppression is achieved by transmitting two beams, a wide one steered at short range and a narrow one steered at long range, with two disjoint 30 kHz frequency bands to be transmitted simultaneously. Similarly, two different receive beams with null-to-null beamwidth of 28 and 14 degrees, respectively, and a 4 degree difference in depression angle, are used (Fig. 7). In other words, the sonar design is similar to a ‘two sonar in one’

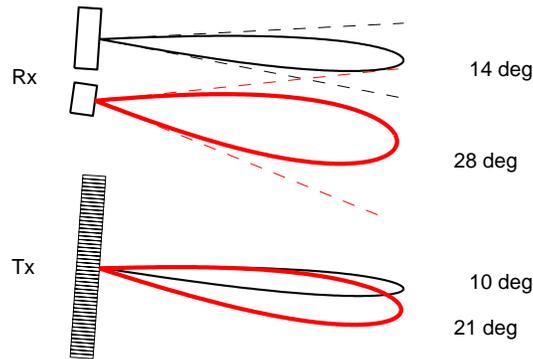


FIGURE 7. Vertical receive and transmit beam patterns for the NATO Undersea Research Centre. The wider beam is for short range while the narrow beam is for long range, up to more than 10 times the water depth. The two beams use disjoint sub-bandwidths of the signal.

design, with at least two important differences. The first is that only one transmitter is used, albeit a quite flexible one. The second is that a time-switched acquisition between the two staves of the receiver is implemented, reducing the incoming data rate.

The performance of this type of sonar was assessed using the ESPRESSO sonar performance prediction tool [4]. An SNR in excess of 10 dB is obtained out of at least one of the two beams up to 220 m range in 20 m water depth (Fig. 8). The sonar altitude in this example is 15 m above the sea bottom. The SNR which corresponds to a vertical beam pattern similar to Fig. 3(a) is shown for comparison and indicated as ‘conventional’, and gives results with a good qualitative match with Fig. 5(a). It is worth mentioning that this agreement is obtained although ESPRESSO uses a model of multipath for which each reflection is purely specular. Figure 9 gives the direct and multipath returns modeled by ESPRESSO for a narrow beam steered at 20 degrees. It is evident from the comparison with the experimental data of Fig. 4(b) that the model

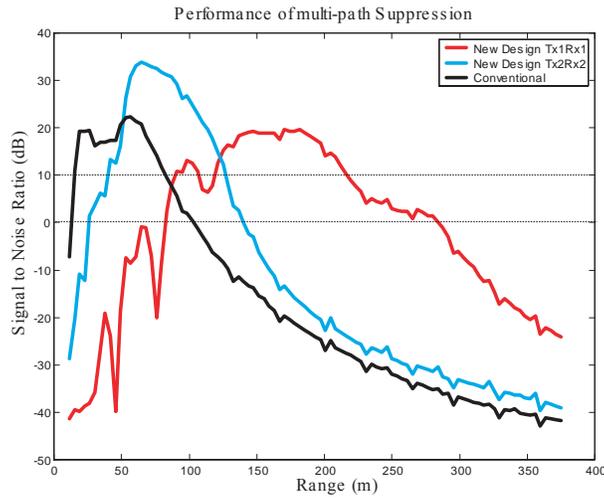


FIGURE 8. Performance prediction of the sonar design.

is only a first order approximation and that considerable spreading in angle due to non-specular reflections on the sea and bottom interfaces.

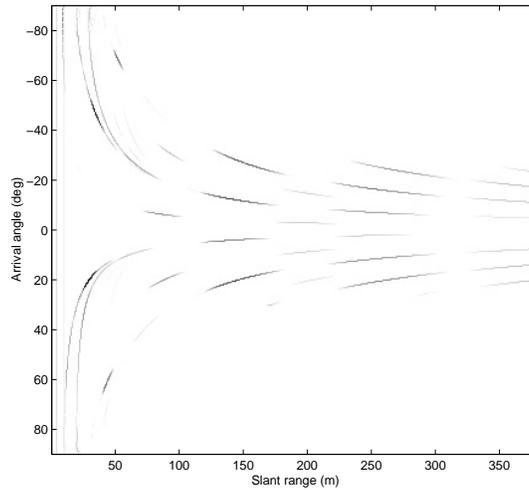


FIGURE 9. Direct and multipath returns for the transmission beam as in Fig. 3(b), steered at 20 degrees, according to the sonar performance prediction tool ESPRESSO.

CONCLUSIONS

Experimental evidence for the importance of (second order) multipath in degrading the SNR at large range to water depth ratios has been provided. This suggests that in shallow water, it is not enough to shape the beams in such a way to reject signal coming from the surface, and that a narrow beam pointing at long range can provide significant improvement. A synthetic aperture sonar design which achieves full swath imaging

transmitting two beams, a wide one steered at short range and a narrow one steered at long range, with two different frequency bands to be transmitted simultaneously is discussed.

ACKNOWLEDGMENTS

The authors are grateful to John A. Fawcett and Terrance L. Miller, DRDC Atlantic, Canada, for the use of the Klein 5500 sonar.

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