Enabling Shallow-Water Sidescan Sonar Surveys: Using Across-Track Beamforming on Receive to Suppress Multipath Interference

by

Stephen K. Pearce
M.A.Sc., Simon Fraser University, 2010
B.S., Washington State University, 2006

A Thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in the

School of Engineering Science
Faculty of Applied Sciences

© Stephen K. Pearce 2014
SIMON FRASER UNIVERSITY
Summer 2014

All rights reserved.
However, in accordance with the Copyright Act of Canada, this work may be reproduced without authorization under the conditions for “Fair Dealing.” Therefore, limited reproduction of this work for the purposes of private study, research, criticism, review and news reporting is likely to be in accordance with the law, particularly if cited appropriately.
APPROVAL

Name: Stephen K. Pearce
Degree: Doctor of Philosophy
Title of Thesis: Enabling Shallow-Water Sidescan Sonar Surveys: Using Across-Track Beamforming on Receive to Suppress Multipath Interference

Examining Committee:
Dr. Carlo Menon, Associate Professor
Chair

Dr. John Bird,
Professor, Senior Supervisor

Dr. Ivan Bajic,
Associate Professor, Supervisor

Dr. Paul Ho,
Professor, Supervisor

Dr. Jie Liang,
Associate Professor, Internal Examiner

Dr. Jonathan Preston,
External Examiner, Adjunct Professor
School of Earth and Ocean Sciences
University of Victoria

Date Approved: June 25, 2014
Partial Copyright Licence

The author, whose copyright is declared on the title page of this work, has granted to Simon Fraser University the non-exclusive, royalty-free right to include a digital copy of this thesis, project or extended essay[s] and associated supplemental files (“Work”) (title[s] below) in Summit, the Institutional Research Repository at SFU. SFU may also make copies of the Work for purposes of a scholarly or research nature; for users of the SFU Library; or in response to a request from another library, or educational institution, on SFU’s own behalf or for one of its users. Distribution may be in any form.

The author has further agreed that SFU may keep more than one copy of the Work for purposes of back-up and security; and that SFU may, without changing the content, translate, if technically possible, the Work to any medium or format for the purpose of preserving the Work and facilitating the exercise of SFU’s rights under this licence.

It is understood that copying, publication, or public performance of the Work for commercial purposes shall not be allowed without the author’s written permission.

While granting the above uses to SFU, the author retains copyright ownership and moral rights in the Work, and may deal with the copyright in the Work in any way consistent with the terms of this licence, including the right to change the Work for subsequent purposes, including editing and publishing the Work in whole or in part, and licensing the content to other parties as the author may desire.

The author represents and warrants that he/she has the right to grant the rights contained in this licence and that the Work does not, to the best of the author’s knowledge, infringe upon anyone’s copyright. The author has obtained written copyright permission, where required, for the use of any third-party copyrighted material contained in the Work. The author represents and warrants that the Work is his/her own original work and that he/she has not previously assigned or relinquished the rights conferred in this licence.

Simon Fraser University Library
Burnaby, British Columbia, Canada

revised Fall 2013
Abstract

Sidescan sonars are used to provide a high resolution 2D image of the seafloor, but when used in shallow water these side-looking systems are vulnerable to multipath interference. In some cases, this interference affects image interpretation and downstream processing such as target recognition or bottom classification. However, it is possible to suppress multipath interference by using a small array featuring a vertical stack of receivers. This thesis investigates the extent to which conventional beamforming techniques, used on receive, can suppress multipath interference. Two novel techniques are proposed, one that suppresses surface interference and one that suppresses bottom-bounce multipath. Experimental data are presented which illustrate the impact that multipath interference has on sidescan images. To establish the effectiveness of the proposed methods, the methods are applied to theoretical models of the experimental data, and are applied to the experimental data as well.

This thesis proposes the use of a fixed broad beam to suppress interference arriving from the surface. A sidescan array utilizing a vertical stack of six receive elements was constructed, and is shown to be effective at providing a clear view of the seafloor when surface interference is present. Experimental data collected with the experimental array are presented. A theoretical analysis examines the relative path strengths of the received signals for different across-track beam patterns, and examines how these signals are affected when beamforming is applied on receive. The experimental data are processed using the proposed method and are significantly improved, revealing a shipwreck that was not visible in the original image.

Suppressing bottom-bounce multipath signals is more difficult, and this thesis proposes the use of time-varying conventional beamforming techniques as a method to realize this second goal. Two sidescan images, both contaminated with bottom-bounce multipath, are
presented and modeled. The experimental data are processed using the proposed methods, and a clear view of the seafloor is provided. It is concluded that a sidescan sonar which employs across-track beamforming on a receive array is a valuable tool for suppressing the multipath and surface interference which arise in shallow water surveys.
Acknowledgments

Many people have helped me to complete this project. While only one name goes on the title page, the truth is that many others have helped make this possible. Firstly, I’d like to thank my Supervisor, Dr. John Bird. John runs his lab in a manner designed to create independent researchers, and this is no easy task but it is a significant contribution to his students’ professional development. I am truly grateful for his instruction.

I’d also like to thank my entire examining committee for their time spent evaluating my thesis and suggesting improvements to make it a better document. In particular, I would like to thank my External Examiner, Dr. Jonathan Preston, for his insightful feedback. I truly enjoyed our discussions during my defense, and I appreciate his effort reviewing not only my dissertation but also reviewing the works I cited.

Funding for my research has come from a few places. A sincere “Thank You!” to Steven Wright of EdgeTech for funding a year of my research and providing some interesting experimental data that forms a key component of my thesis. During my degree I enjoyed a 6-month MITACS internship, and I want to thank Peter Gross, Jason MacNamee, and MITACS for making this possible. The Graduate Student Society provided me with a small grant to fund the Pam Rocks survey, Sewell’s Marina was kind enough to provide us with free moorage during the survey, and Dr. Sean Cox of SFU-REM provided us access to the R/V C.J. Walters.

I owe major thanks to the survey crew for ignoring the gale warnings and the rain to help conduct the survey nevertheless. Dr. Brett Favaro skippered the boat and helped organize the survey, and provided entertaining commentary along the way. Dr. Geoff Mullins assisted with the planning and conducting of the survey, and has also been a mentor throughout my program. Pavel Haintz debugged electronics issues under a tarp (on the back of the boat) in the rain. Ryan Goldade helped with the dropcam work. Dr. Sabir Asadov is an expert on
transducer design and fabricated the transducer used in the survey. Sabir has also argued with me at length about crime/punishment, European history and the former Soviet Union, and has provided enlightening perspectives on many other topics just as closely related to sonar. Spasibo, Tovarish.

Lastly, I want to thank my friends and family (Mom, Dad, and Michael) for their unconditional love and support. I especially want to thank Elaine. Elaine has lived with me through the ups and downs of grad school, and her support has never wavered; she is a true companion.
# Contents

Approval ii  
Partial Copyright License iii  
Abstract iv  
Acknowledgments vi  
Contents viii  
List of Figures xi  

## 1 Introduction  
1.1 Sidescan Sonar ......................................................... 2  
1.1.1 2D Sidescan Images ........................................ 5  
1.2 The Problem ......................................................... 7  
1.2.1 Origin of the Problem .......................................... 9  
1.2.2 Part 1: Interference Arriving from the Surface ............. 14  
1.2.3 Part 2: Interference Arriving from the Bottom .............. 15  
1.2.4 Why Explore Additional Solutions? ........................... 17  
1.3 Contributions of the Thesis ....................................... 18  
1.4 Organization of the Thesis ........................................ 19  

## 2 Problem 1: Surface Interference  
2.1 Surface Effects in Shallow Water Sidescan Images .............. 24  
2.1.1 Geometry of Shallow Water Sidescan Sonar Deployment ...... 24  
2.1.2 Relative Levels .................................................. 26
5.4 Recommendations for Future Work ........................................... 115

Bibliography ................................................................. 117

Appendix A Bottom Masking From Along Track Beam ...................... 121

Appendix B Derivation of Equation for Footprint Shift ....................... 125

Appendix C Supplementary Sidescan Images .................................. 128
  C.1 Additional Images From Bedwell Bay ...................................... 128
  C.1.1 Example 1 .................................................................. 129
  C.1.2 Example 2 .................................................................. 129
  C.2 Additional Images From Pam Rocks ........................................ 132
  C.2.1 Example 1 .................................................................. 132
  C.2.2 Example 2 .................................................................. 135

Appendix D Cosine Beampattern Model .......................................... 143
List of Figures

1.1 Diagram of sidescan sonar operation. The side-looking sonar is mounted on a platform that moves (in the along-track) perpendicularly to the look direction of the sonar (the across-track). The broad “fan beam” beampattern is shown, and when the sonar transmits a pulse it ensonifies a wide area of the seafloor. The projection of the pulse on the seafloor at any given time, its footprint, is shown. Echoes return from the footprint to the transducer array, composed of a vertical stack of receivers. As the platform moves through the water, the process of a ping (transmitting a pulse and receiving its echoes) is repeated many times, creating the image of the seafloor. 

1.2 Simple block diagram of prototype 3D sidescan sonar system employing beam processing. The signals from a number of receivers are amplified, digitized, filtered, and then sampled. The beam processing stage combines the signals from each channel in a manner designed to produce a single “cleaned-up” signal which is then sent downstream for additional processing (e.g. identification, classification) or to create a “cleaned-up” sidescan image.

1.3 Sidescan sonar image created from data that were collected during a survey of the Pam Rocks area in Howe Sound, B.C.

1.4 Sidescan sonar image created from data that were collected during a survey of the Pam Rocks area in Howe Sound, B.C. Multipath interference contaminate this image, obscuring important details by introducing “false” highlights and also filling in shadows.

1.5 The same sidescan image shown in Fig. 1.4 but with multipath interference suppressed, leaving a clear view of the bottom.
1.6 Sidescan sonar image created from data that were collected during the same survey of the Pam Rocks area in Howe Sound, B.C., also showing strong multipath interference contamination. The rugged seafloor in pings 1 through 300 is obscured by strong surface interference, and the shadows in pings 300 to 900 behind the rocky outcroppings are filled in.

1.7 The same sidescan image shown in Fig. 1.6 but with multipath interference suppressed, leaving a clear view of the bottom.

1.8 Side-by-side comparison of Figs. 1.6 (left) and 1.7 (right). By suppressing multipath interference a clear view of the seafloor is provided, with false highlights removed and with shadows deepened.

2.1 Diagram of side-scan deployment showing a typical signal structure and typical across-track beam pattern with the transducer located at a depth of 30 m. The direct surface return (S) is given by the thin solid line, and the direct seafloor return (B) is given by the thick solid line. The surface-bottom-surface (sBs) multipath is shown by the dashed line. The bottom-surface (Bs) and surface-bottom (sB) multipath signals trace the same path in opposite directions, given by the dotted line. The transducer beam pattern is shown by the oval, with intensity decades shown by the concentric half-circles.

2.2 Relative intensity levels of the returning signals as a function of range. The signals are represented in a manner consistent with Fig. 2.1, but for clarity are now described in terms of the range at which they first appear. The bottom (B) signal appears at a range of 10 m, and the surface signal (S) appears at a range of 30 m. The sBs multipath appears at a range of approximately 75 m, and the Bs and sB multipath signals lie on top of one-another and are both given by the dotted curve which is first seen at a range of 50 m. Between 30 m and 65 m, the surface signal lies on top of a curve that represents the sum of all interfering signals (S, sB, Bs, and sBs) and is seen to closely follow the S signal until a range of approximately 65 m. The surface signal is given by the thinner of the two curves; the sum of interfering signals is given by the thicker of the two.
2.3 Relative intensity levels of the returning signals as a function of range, with signals defined as they were in Fig. 2.2 and a narrower $42^\circ$ beamwidth. The ranges at which the component signals appear in the Figure have changed due to the narrower beam pattern assumed in this Figure; the S signal becomes visible at 40 m, the sB/Bs signals at approximately 62 m, and the sBs signal at 100 m.

2.4 Simulated received signal for a target at a horizontal range of 100 m, followed by its shadow. The thin solid curve is the received signal when the B, S, sB/Bs, and sBs signals are present; the thick solid curve is the received signal when the surface signal is absent (B, sB/Bs, and sBs are received).

2.5 Side-scan image from a field deployment showing dominant surface returns that obscure the image of the seafloor. There is a shipwreck present in this image, but the shipwreck highlight and its shadow are also obscured by the interference. Fig. 2.24 is created from the same data as this Figure but with the interference attenuated, leaving the seafloor and shipwreck visible.

2.6 Diagram of parameters to be used in beamforming. Angles $\theta_1$ and $\theta_2$ define the desired extent of the beam on the bottom, and angle $\gamma_t$ is the tilt angle of the array.

2.7 Diagram of typical side-scan deployment, as shown in Fig. 2.1, but with the beamformed beam pattern now given by the thick solid curve and the “raw” beam pattern given by the thin solid oval. As with Fig. 2.1, the B signal is given by the thick solid line and the S signal is given by the thin solid line. The sBs multipath is given by the dashed line, and the dotted line represents the sB/Bs paths.

2.8 Relative received signal intensities when beamforming is used on receive. Signals are represented in a manner consistent with Fig. 2.2 but now the dotted curve represents the Bs path only, and the dash-dot curve represents the sB path. Note that the curve representing the sum of the interfering signals (S, Bs, sB, and sBs) lays directly on top of the surface signal from 30 m range to about 50 m range, and then on top of the dash-dot curve (sB multipath) beyond approximately 55 m slant range.

2.9 Received signal intensities when beamforming is applied on both transmit and receive. The sB and Bs signals are now both given by the dotted curve.
2.10 Levels determined from the simulated received signal when beamforming is applied on receive only (thin curve) and on transmit and receive together (thick curve). ................................................................. 41

2.11 Three beam patterns to choose from: the “raw” array beam pattern (thin solid oval), the equiripple pattern (thick solid curve), and the spot beam pattern (dashed curve). The sonar array is now at a depth of only 1 m, which corresponds to the shallow pole-mount deployment employed during the collection of experimental data. ................................................................. 42

2.12 Diagram of the prototype array. There is a vertical stack of receive elements, and the elements have a center-to-center spacing of 0.41 cm, or λ/2, and each receiver is 55.8λ long. Receive elements are narrow (0.29 cm or 0.36λ) and have a wide beampattern. The transmitter is composed of two separate elements that are wired together to act as a transmit array. Both transmit elements are 55.8λ long and have center-to-center spacing of λ/2, but the elements are wider (0.35 cm or 0.43λ) than receive elements. The result is a narrower transmit beampattern than that of a receive element. ............... 43

2.13 Pole mount deployment with the prototype array that features a vertical stack of receivers at half-wavelength spacing potted in black polyurethane. ......... 44

2.14 Close-up view of the prototype array used in the thesis. The housing of the array is stainless steel. ................................................................. 45

2.15 Measured receive pattern of the experimental array (thin solid oval) and measured transmit pattern (thick solid curve) compared to theoretical transmit pattern (dashed curve). The theoretical transmit pattern is mostly covered by the measured transmit pattern. The array is tilted at an angle of 15°, consistent with its standard deployment position. ................................. 46

2.16 Measured receive pattern of the experimental array (thin solid oval) and measured receive beamformed pattern (thick solid curve) compared to theoretical receive beamformed pattern (dotted curve). The dotted curve is almost completely covered by the thick solid curve. Again, array is tilted at an angle of 15°. ................................................................. 47
2.17 Deployment scenario described in Fig. 2.1 but with the measured transmit beam pattern shown by the dash-dot curve, the measured receive pattern given by the thin solid curve, and the measured receive pattern when beamforming is applied shown by the thick solid curve. As before, sBs multipath signals are shown by the dashed line, and sB/Bs multipath signals are shown by the dotted line. Direct surface returns are shown by the thin solid line, and bottom returns are shown by the thick solid line.

2.18 Signal intensities as a function of slant range when the measured beam patterns of the experimental array are used and beamforming is not applied. The composite signal intensity when all interfering signals (S, sB, Bs, sBs) are added together is initially given by the surface signal (first received at a range of about 30 m) and then increases beyond the surface signal after about 60 m range. The bottom signal is given by the thick solid curve which comes in at a range of 10 m. The thin solid curve is the surface signal, the dotted curve is the Bs signal, the dash-dot curve is the sB signal, and the dashed curve is the sBs signal.

2.19 Signal intensities for the experimental array but with equiripple beamforming applied on receive. The sum of interfering signals now lays on top of the S path at close range, then on top of the Bs signal, and then lays on top of the sB path at longer range. This behavior indicates which interference source is dominant at a given range, and how much the other interfering signals contribute to the total interference.

2.20 Levels determined from the simulated received signal using measured beam patterns from the experimental array, when beamforming is applied on receive (thick solid curve) and when it is not (thin solid curve).
Signal intensities corresponding to the situation in which the data shown in Fig. 2.5 were collected, using the measured beam patterns of the experimental array. Surface and seafloor scatterers were assumed to have equal strengths. Because the transducer is now at a depth of 1 m, the surface signal arrives at a range of 1 m and is the only substantial source of interference until a range of 100 m. Accordingly, the curve corresponding to the sum of all interfering signals lays on top of the surface signal until approximately 100 m range. Beyond 100 m range, the surface signal lays slightly below the bottom signal (which is present beyond approximately 70 m range). The thickest solid curve is the bottom signal, the dotted curve is the Bs multipath signal, the dash-dot curve is the sB multipath signal, and the dashed curve is the sBs multipath signal.

Similar to Fig. 2.21 except that beamforming is applied on receive.

Comparison of primary (S and B only) signal intensities between the prototype array (thick curves) and the ordinary sidescan sonar modeled in Fig. 2.3 (thin curves). For both cases, the B signal is given by the solid curves first present at 70 m range, and the S signal is given by the dashed curves that appear at 1 m range. The situation being modeled is the field deployment that is presently under consideration, with the transducer at a depth of 1 m and the seafloor 70 m below the boat. The prototype array uses the beam processing method as in Fig. 2.21 with a tilt angle of 15°, and the ordinary sidescan uses its comparatively narrow beams and a tilt of 25°.

Sidescan image shown in Fig. 2.5 but after beamforming is applied on receive. Surface reflections have been sharply attenuated, leaving a clear view of the seafloor and revealing a shipwreck towards the center of the image.

Close-up view of the shipwreck shown on the side-scan image in Fig. 2.24.

Side-by-side comparison of Figs. 2.5 (left) and 2.24 (right), showing a sidescan image before and after the fixed broad beam is used to suppress the surface interference that was otherwise obscuring a shipwreck.

Measured receive signal intensity from ping 220 in the side-scan data, when beamforming is applied on receive (thick curve) and when it is not applied (thin curve).
2.28 Sidescan image shown in Fig. 2.5 after a realization of MVDR beamforming is applied on receive. Surface interference has been attenuated, and the shipwreck towards the center of the image is now visible. However, a “grainy” image has resulted.

2.29 Side-by-side comparison of Figs. 2.24 (left) and 2.28 (right).

3.1 Field data collected by EdgeTech showing strong bottom-surface-bottom multipath at a range of approximately 25 m. The seafloor is roughly 13 m below the surface, and the transducer is deployed at a depth of about 1 m.

3.2 Field data collected by EdgeTech showing strong surface interference and bottom-bounce multipath. A boat wake is clearly visible at a range of approximately 45 m on ping number 400, followed by two delayed replicas of this signal.

3.3 Diagram of relevant deployment parameters. Angle $\gamma_t$ is the tilt angle of the array, with inter-element spacing $d$, deployed at depth $T$ m below the surface and $h$ m above the seafloor. The method of images is used to show the path of a bSb signal, characterized by physical angle $\theta_j$.

3.4 Diagram of the relevant beams shown with survey geometry. The receive element intensity pattern is approximated by a $\cos^{5.5}(\theta)$ (thin solid oval), and the transmit intensity pattern is approximated by a $\cos^{8.5}(\theta)$ pattern (dash-dot oval). The fixed broad beam used on receive to suppress surface signals is given by the thick solid curve. Intensity decades in dB are given by the concentric half-circles.

3.5 Diagram of the experimental setup for the location where the data shown in Fig. 3.1 were collected. The seafloor is 13 m below the surface, and the transducer is located 1 m below the surface at location (0, -1) m. The dashed line shows the path traveled by the Bsb signal at nadir, and it is extended to indicate the range (time) at which it is received. The fixed broad beam (proposed in [28] to suppress surface signals is given by the thick curve, the transmit intensity pattern is given by the dash-dot curve, and intensity decades are given by concentric half-circles.
3.6 Calculation of the relative intensity of the primary signals (B and Bsb) which were present when the data for Fig. 3.1 were collected. The transducer is assumed to be at 1 m depth, the flat seafloor is 12 m below the transducer. The intensity of the bottom signal (B) is given by the thick solid curve, and the intensity of the Bsb multipath signal is given by the dashed curve. The sum of both the B and Bsb signals is given by the solid curve that separates from the B signal at approximately 25 m slant range.

3.7 Diagram of the beampatterns and experimental setup for the location where the data shown in Fig. 3.2 were collected. The model assumes that the seafloor is 13 m below the surface, and the transducer is 1 m below the surface. The Sb signal follows the entire dashed line; it leaves the transducer and travels directly to the wake, then scatters and returns via a bottom bounce. The bSb signal travels a reciprocal course via the bottom bounce shown by the dashed line and does not take the direct route to the wake (along the surface). The fixed broad beam proposed in [28] to suppress surface signals is given by the thick curve, the transmit pattern is given by the dash-dot curve, and intensity decades are given by concentric half-circles.

3.8 Calculation of the relative intensity of the signals that were present when the data for Fig. 3.2 were collected. The transducer is assumed to be at 1 m depth, and the flat seafloor is 12 m below the transducer. The bottom signal (B) is given by the thick solid curve, the S signal is the thin solid curve, the Sb signal is the dotted curve, and the bSb signal is the dashed curve. No beamforming is used.

3.9 Calculation of the relative intensity of the signals that were present when the data for Fig. 3.2 were collected, as with Fig. 3.8. In this case, the fixed broad beam is used to attenuate surface signals.

3.10 Diagram of parameters to be used in beamforming. Angles $\theta_1$ and $\theta_2$ define the desired extent of the beam on the bottom, and angle $\gamma_t$ is the tilt angle of the array. In this figure, angles and depths are arbitrary.
3.11 Diagram of the relevant beam patterns and multipath interference. The seafloor is the rough black line at a depth of 13 m. The transducer is taken to be at a depth of 1 m, and the concentric half-circles indicate the intensity decades of its beam patterns. The dash-dot curve shows the receive beampattern which is used to process the first 24 m of each ping, and the solid curve shows the beampattern which is used to process the remainder of each ping. The dashed black line shows the route taken by the bsB and Bsb signals at nadir, when they are strongest and most visible in Fig. 3.1...

3.12 Calculation of the intensity of the received signals which were present when the data for Fig. 3.1 were collected, but when processed using the time-varying approach for bsB/Bsb signal removal. The intensity of the B signal is given by the thick solid curve, the intensity of the Bsb signal is given by the dashed curve, and the sum of both signals is given by the thin solid curve. At a range of 24 m (given by the vertical dashed black line) the beam parameter $\theta_2$ is altered as described. The intensity of the Bsb signal is initially attenuated by the processing, but beyond 45 m range its intensity approaches that of the B signal.

3.13 Calculation of the intensity of the received signals which were present when the data for Fig. 3.1 were collected. The parameters of the receive beam are altered twice (once at a range of 24 m, and once at a range of 34 m) during the processing of the ping. Greater separation between the B signal (thick curve) and the Bsb signal (dashed curve) is achieved than in Fig. 3.12.

3.14 Field data collected by EdgeTech (the same data used to create Fig. 3.1) processed using the time-varying beamforming approach which simply alters the parameters of the equal ripple beam. The Bsb signal is removed and a sharp view of the seafloor is provided.

3.15 Side-by-side comparison of Figs. 3.1 (left) and 3.14 (right). A Bsb signal contaminates a sidescan image (left) but is removed by using time-varying conventional beamforming (right) that alters the extent of the receive beam.
3.16 Diagram of the relevant beampatterns and multipath interference, now showing the beampattern which uses null-steering. The seafloor is at a depth of 13 m, the transducer is at a depth of 1 m, and the concentric half-circles indicate the intensity decades of its beampatterns. The dash-dot curve shows the receive beampattern created by the initial beamforming for S signal rejection, and the thick solid curve shows the beampattern when a null is applied to reject the interference. The dashed lines shows the route taken by the interfering signals. The thin solid line shows the route traveled by the B signal at 46 m range. ................................................................. 88

3.17 Calculation of the intensity of the received signals which were present when the data for Fig. 3.2 were collected. The fixed broad beam is used to reject S (thin solid curve) interference for the first 46 m of the ping, and a null is introduced to suppress the Sb (dotted curve) and bSb (dashed curve) interference for the remainder of the ping. B signal intensity (thick solid curve) is reduced 3 dB when the beams are switched. ................................................................. 89

3.18 Field data collected by EdgeTech (the same data used to create Fig. 3.2) processed using the time-varying beamforming approach which utilizes null-steering. The masking effects of the surface interference and of the bottom-bounce multipath are removed, leaving a clear view of the seafloor. ............... 91

3.19 Side-by-side comparison of Figs. 3.2 (left) and 3.18 (right). Originally, surface interference created by a passing vessel resulted in S, Sb, and bSb signal contamination of a sidescan image (left). Using the fixed broad beam to remove the S signal and using time-varying beamforming to remove the Sb and bSb signals, a “cleaned up” sidescan image is obtained (right). .......... 92

3.20 Field data collected by EdgeTech (the same data used to create Fig. 3.2) processed using MVDR where three adjacent time samples to estimate the correlation matrix. The Bsb signal is largely removed, although faint remnants remain, but some textural information appears to have been lost. The resulting image has a more “grainy” appearance than Figs. 3.1 and 3.14. .... 93

3.21 Side-by-side comparison of Figs. 3.14 (left) and 3.20 (right), where the proposed time-varying beamforming methods and MVDR (respectively) are used to remove a Bsb signal. ................................................................. 94
3.22 Field data collected by EdgeTech (the same data used to create Fig. 3.2) processed using MVDR using five adjacent times samples to estimate the correlation matrix. The image has a more “grainy” quality than in Fig. 3.18, and additionally there is horizontal striping visible. Although some (not all) of the multipath interference has been removed, this striping pattern is an artifact that has been added by the algorithm.

3.23 Side-by-side comparison of Figs. 3.18 (left) and 3.22 (right). The combination of a fixed broad beam with time-varying beamforming as proposed in this thesis is used to remove S, Sb, and bSb signals (left image) and is compared against the results of using MVDR to suppress those same signals (right image).

4.1 Diagram of relevant deployment parameters. Angle $\gamma_t$ is the tilt angle of the array, with inter-element spacing $d$, deployed at depth $T$ m below the surface and $h$ m above the seafloor. The method of images is used to show the path of a bSb signal, characterized by physical angle $\theta_j$.

4.2 Diagram of the relevant beampatterns and location of a null (dashed line) applied at $0^\circ$ for an $N = 8$ element receive array. The dashed curve is the $\cos^{5.5}$ element pattern, the thin solid curve is the composite beampattern after equal ripple beamforming is applied, and the thick curve is the composite beampattern when null steering is employed. Footprint shift is disregarded, and the signal to thermal noise ratio is 40 dB.

4.3 Diagram of the relevant beampatterns (solid curves) and location of a null (dashed line) applied at $0^\circ$ and when a signal arrives from endfire with $\rho_1(\gamma) \approx 0.9993$. As before, the dashed curve is the element pattern, the thin solid curve is the composite beampattern after equal ripple beamforming is applied, and the thick curve is the composite beampattern employing null steering.
4.4 Beamformer response (dB) versus the number of receive elements $N$ when footprint shift is disregarded, with a null placed at $0^\circ$. The thermal noise level is at $-40$ dB (given by the thin line). When interference arrives from boresight and from $AOA_j = -35^\circ$, the beamformer response is given by the thick solid line. When interference arrives from boresight and $AOA_j = -60^\circ$ the beamformer response is given by the dotted line. The equal ripple beam has been formed according the parameters suggested in [28] that suppress surface interference.

4.5 Beamformer response (dB) versus the number of receive elements $N$ when footprint shift is considered, with a null placed at $0^\circ$. The thermal noise level is at $-40$ dB (given by the thin line), and this is the beamformer response when $AOA_j = 0^\circ$. When interference arrives from $AOA_j = -35^\circ$, the beamformer response is given by the thick solid line, and when $AOA_j = -60^\circ$ the beamformer response is given by the dotted line. The equal ripple beam has been formed according the parameters suggested in [28] that suppress surface interference.

A.1 Diagram of a target with angular extent $\psi_{ao}$ rad centered in the main along-track lobe in Fig. A.1 (a), and diagram of a target offset from the main along-track lobe by $\psi_t$ rad in Fig. A.1 (b).

A.2 Shadow depth as a function of target width for uniformly shaded transmit and receive element (thick solid curve), triangle-shading on transmit and receive (dashed curve), and with triangle shading on transmit coupled with uniform shading on receive (dotted curve).

A.3 Shadow depth as a function of target offset for all three element shading schemes (as with Fig. A.2) for a target of width 1, 3, and 9 times the two-way far-field beamwidth. Wider targets produce a deeper shadow.

B.1 Diagram of relevant deployment parameters. Angle $\gamma_t$ is the tilt angle of the array, with inter-element spacing $d$, deployed at depth $T$ m below the surface and $h$ m above the seafloor. The method of images is used to show the path of a bSb signal, characterized by physical angle $\theta_j$. 
C.1 Sidescan image from a field deployment to Bedwell Bay in British Columbia showing dominant surface returns. ........................................... 130
C.2 Sidescan image from a field deployment to Bedwell Bay (the area shown in Fig. C.1) but when the fixed broad beam is used on receive to suppress the surface interference. .................................................... 131
C.3 Side-by-side comparison of Figs. C.1 (left) and C.2 (right). In this example, surface interference contaminates a sidescan image (left image) that contains two shipwrecks. Using the fixed broad beam, the surface interference is suppressed (right image). ........................................... 132
C.4 Sidescan image from a field deployment to Bedwell Bay showing the same shipwreck seen in Fig. 2.24 but from a different aspect ............... 133
C.5 Sidescan image from a field deployment to Bedwell Bay (the area shown in Fig. C.4) but when the fixed broad beam is used on receive to suppress the surface interference. .................................................... 134
C.6 Side-by-side comparison of Figs. C.4 (left) and C.5 (right). A shipwreck sits on an otherwise featureless portion of the seafloor but the image is contaminated with surface interference (left image). Using the fixed broad beam to remove this S interference leaves a clear view of the shipwreck that sits prominently on a muddy seafloor (right image). ........................................... 135
C.7 Sidescan image from a field deployment to the Pam Rocks Rockfish Conservation Area in Howe Sound, B.C. Surface interference is seen to introduce false highlights (intermittently from ping 500 and up) and to reduce target highlight/shadow contrast around ping 400. ........................................... 136
C.8 Sidescan image from a field deployment to Pam Rocks, but when the fixed broad beam is used on receive. The S interference is suppressed, removing the false highlights and deepening the shadow behind the large rock around ping 400. ........................................... 137
C.9 Side-by-side comparison of Figs. C.7 (left) and C.8 (right). The complex bottom in the Pam Rocks area, featuring rock highlights and accompanying shadows, is masked by surface interference (left image). Once again using the fixed broad beam to remove this interference, the shadows behind rocks are deepened and false highlights are removed (right image). ........................................... 138
C.10 Sidescan image from a field deployment to the Pam Rocks area. Subtle surface interference is present in the image, appearing mostly as streaking and also as some false highlights around pings 200-400.

C.11 Sidescan image from a field deployment to the Pam Rocks area but when the fixed broad beam is used on receive. The S interference is removed, providing a clear view of the seafloor.

C.12 Side-by-side comparison of Figs. C.10 (left) and C.11 (right). This final pair of images shows a portion of the Pam Rocks area where the seafloor is mostly gravel (rather than large rocks), but the image on the left is contaminated by surface interference that creates a subtle streaking and introduces some false highlights. The fixed broad beam removes this interference (right image).
Chapter 1

Introduction

As I begin to write this thesis, I find myself searching for a beginning that provides the reader with an accessible, qualitative description of “The Problem” that my thesis addresses. Outside my window, I can see an old bridge crossing the Fraser River. This year, the New Westminster Rail Bridge marks its 100th birthday. While it is easy to see the portion above water, how has the portion below water fared over the years? The bridge is still in active use, so it is (hopefully) doing just fine - but what if we wanted to check, just to make sure? The surface of the water represents a significant boundary, and to make observations below this boundary is a difficult matter. Because the bridge is in shallow water, this difficulty is compounded.

There are other reasons why it may be necessary to “see” below the surface of the river: What if a sunken ship must be recovered? What if a portion of the river bed must be monitored from one year to the next, and changes quantified (e.g. inspecting a pipeline or a cable)? A sidescan sonar system would be a good tool to “look” below the surface, but a number of issues would need to be addressed. Since the water is shallow, there are many boundaries within the view of the sonar system. Sonar signals will scatter and/or reflect off the many boundaries encountered, such as the river bottom, the surface of the water, and any bridge supports. The transmitted sound will bounce around, and some of it will return to the sonar system. When the sonar system receives these “multipath” signals, returning from different boundaries and arriving from different directions, how will it sort out this mess of signals to provide a clear picture of the river bottom (and how will it exclude those signals that interacted with other boundaries)?

This basic problem - multipath interference contaminating sidescan sonar signals and
subsequent images - often occurs when sidescan sonar systems are used in shallow water. The problem can occur in rivers, in lakes, and especially in busy harbors where boat traffic causes strong surface scattering to occur. Is there anything that can be done to enable an existing sidescan sonar system to survey in shallow water without suffering from this problem? The purpose of this thesis is to address that question.

1.1 Sidescan Sonar

Monostatic, active sonar systems such as sidescan sonar operate by transmitting sound and then receiving the echoes that return. In contrast to the well-known echosounder type sonar that is characterized by conical beampatterns that (usually) point downwards, sidescan sonar systems use fan-shaped beampatterns that point sideways to give them a wide field of view in one dimension (across-track) and a narrow field of view in another dimension (along-track). Sidescan sonars may be mounted on the side of a moving survey vessel like a boat or an autonomous underwater vehicle, and they may also be towed behind these vessels when mounted on a towfish. Sidescan sonars are commonly oriented so that they transmit and receive sound from a direction orthogonal to the direction of motion.

Fig. 1.1 illustrates sidescan sonar operation and relevant concepts. The side-looking sonar is mounted on a moving platform that travels perpendicularly to the look direction of the sonar. The side-looking sonar has a broad “fan beam”, as opposed to the thin conical beams of echosounders. As the sonar moves through the water, an image is created by repeating the process of a “ping”: transmitting a pulse, and receiving the echoes that return from the ensonified portion of the seafloor. After the pulse is transmitted, the pulse moves along the seafloor and ensonifies an area known as a “footprint” from which echoes return. After the echoes return from the maximum range of Ping 1, the platform has moved forward to a new location, and the process is repeated when Ping 2 is transmitted.

The sidescan sonar uses a transducer to convert electrical signals to acoustic signals on transmit (and vice-versa on receive), and this transducer features one or more elements in a vertical stack. These elements are each characterized by individual beampatterns, or directional sensitivities, and may be combined into an array. The array has its own beampattern that can change depending upon how the array is designed.

Ordinary sidescan sonar systems have a single receive element and provide high-resolution 2D images. 3D sidescan sonar systems (e.g. the EdgeTech 4600 or the Benthos C3D, known
Figure 1.1: Diagram of sidescan sonar operation. The side-looking sonar is mounted on a platform that moves (in the along-track) perpendicularly to the look direction of the sonar (the across-track). The broad “fan beam” beampattern is shown, and when the sonar transmits a pulse it ensonifies a wide area of the seafloor. The projection of the pulse on the seafloor at any given time, its footprint, is shown. Echoes return from the footprint to the transducer array, composed of a vertical stack of receivers. As the platform moves through the water, the process of a ping (transmitting a pulse and receiving its echoes) is repeated many times, creating the image of the seafloor.
as bathymetric sidescan sonars) have multiple receive elements in a vertical stack, and can provide bathymetric information (a 3D map) in addition to the high resolution 2D image. However, the bathymetric map is generally of lower resolution than the 2D image (henceforth referred to simply as a “sidescan image” implying 2D), and does not necessarily include textural information. To get around this issue, once the bathymetric map is created, the sidescan image may be “draped” over the bathymetric map so that textural information is available in addition to the bathymetry.

Sidescan sonar systems are used in many applications because they return high resolution images that cover large swaths of terrain, and because sometimes looking at things from the side (rather than from directly above) is very useful. Mine counter measures are one application where sidescan sonars are used. When a sidescan sonar images a target (a mine, for instance) that sticks up above an otherwise flat seafloor, the combination of the target’s highlight and accompanying acoustic shadow are used for target recognition [1].

Sidescan sonar is also used in applications such as bottom classification (either with 2D sidescan images [2], [3], [4] or 3D maps [5]) and for marine habitat classification [6]. Other uses have included detecting schools of herring at sea [7], [8] and detecting migrating salmon in the Fraser River [9]. As already mentioned, mine counter measures are an additional use of sidescan sonar systems [10], [11]. The importance of sidescan images is that even if not used directly in one of these applications, the sidescan images can be used to augment the bathymetric maps created by a bathymetric sidescan sonar.

This thesis proposes a method to “clean up” these sidescan images and remove interference that may be present. In this manner, downstream processing (such as mine counter measures, fish detection, seafloor imaging, or the visual interpretation of sidescan images by a user) is facilitated. A simple block diagram helps to explain where the proposed methods fit into the processing stream of a sonar such as the prototype array that is used in this thesis.

Fig. 1.2 provides a simple block diagram of the prototype 3D sidescan system (introduced in Chapter 2) that features an array of receivers. The electrical signals output from the receivers are amplified, digitized, filtered, and then sampled. As discussed later in this Chapter, sometimes these signals are contaminated with interference. This thesis introduces beam processing (the red box in the processing stream) that is designed to produce a single channel of “cleaned-up” signal that can be used for downstream processing or to create a “cleaned-up” sidescan image.
CHAPTER 1. INTRODUCTION

1.1.1 2D Sidescan Images

A sidescan sonar image represents the intensity of received signals as a function of the:

- time (or range) at which they were received,
- sonar’s position (ping number).

In other words, each pixel in a sidescan image has its 2D position given by these two axes and its color determined by the intensity of the received signal. A sample sidescan image is shown in Fig. 1.3 to illustrate this concept. Bright colors indicate a high intensity return, and dark colors indicate a low intensity return. In the sidescan images to follow, white indicates the highest intensity return, then colors transition from yellow to green to blue as intensity decreases, and black pixels indicate the weakest returns.

Fig. 1.3 was created from data collected during a survey of the Pam Rocks Rockfish Conservation Area in Howe Sound, British Columbia. The survey area was chosen because the seafloor in this area is quite rugged (a “complex” bottom). On ping 1, little to no signal is received in the first 80 m, indicating that the water depth was at least 80 m. By ping 1000 signal is being received at around 50 m range; the depth was decreasing as the boat moved into shallower water.

The survey area in Fig. 1.3 appears to show two different seafloor types: a relatively flat seafloor for the first 500 pings, and an increasingly rocky seafloor for the remainder of the image. A large rock appears to stand up from the seafloor around ping 600 at 120 m range, and its acoustic shadow is visible between roughly 140 m and 150 m range. Around the
Figure 1.3: Sidescan sonar image created from data that were collected during a survey of the Pam Rocks area in Howe Sound, B.C.
rocky portion of the seafloor (ping 600 onward, beyond a range of 120 m) a ripply pattern is seen - possibly indicating an undulating sand or gravel bottom. A scar along the bottom, stretching from roughly ping 800 at 140 m until it disappears in the shadow in ping 850 at 70 m range, is suspected to be an anchor drag mark.

This example sidescan image from Pam Rocks is used to introduce the reader to the interpretation of sidescan imagery. Textural details such as the undulating seafloor in one portion of the image (but not another portion), or the anchor drag mark, may be lost in the process of creating a 3D map of the area. As mentioned, preserving this resolution and texture information can be important when creating 3D maps or for applications like mine countermeasures. However, the usefulness of sidescan imagery depends upon it actually representing the location that the user is trying to image. If multipath interference is received, it contaminates the sidescan image and may obscure the image of the bottom and mask important bottom features such as target highlights and shadows.

1.2 The Problem

The problem is that when a sidescan sonar is used in shallow water, defined here as when both the surface and the seafloor are simultaneously within “view”, multipath interference may contaminate sidescan images. To simplify the discussion it is assumed that the objective is to image the seafloor (a common objective). In this Introduction, Fig. 1.3 is presented first because it is a clear image of the seafloor, but the problem is that sometimes sidescan images look more like Fig. 1.4. Fig. 1.4 is also created from data collected during the Pam Rocks survey, so the seafloor type is again complex and rugged, but now spurious target highlights are visible and shadows are filled in by interference.

Looking at Fig. 1.4 in pings 700 and above, it is difficult for the human eye to distinguish between the rugged seafloor (with its many highlights from objects like large rocks) and the multipath interference. In the day that this survey was conducted, there was a large amount of floating debris above the survey area, and some sidescan data were largely free of interference while other data were not. To the user, this translates into a problem because floating surface debris does not have anything to do with the seafloor, yet it shows up intermittently in the sidescan images nevertheless.

Using the processing that is proposed in this thesis, Fig. 1.4 is cleaned up and a clear view of the bottom is seen in Fig. 1.5. While spurious targets have been removed throughout
Figure 1.4: Sidescan sonar image created from data that were collected during a survey of the Pam Rocks area in Howe Sound, B.C. Multipath interference contaminate this image, obscuring important details by introducing “false” highlights and also filling in shadows.
the image, the effect is most pronounced in pings 700 and above. Another result is the deepening of shadows, especially in pings 800 and above.

The above Figures (1.4 and 1.5) are presented because they illustrate the behavior in question and provide a gentle introduction to sidescan image interpretation. A more dramatic example of multipath interference contamination of sidescan sonar data (and images) is presented in Fig. 1.6. In this area, the ship was moving into shallower water (the depth changes throughout the image from roughly 100 m depth at ping 1 to roughly 20 m depth at ping 700) and the sonar was looking towards a rocky seafloor with long acoustic shadows behind the rocks. Towards the bottom of the image in pings 1 to 300, dominant surface interference obscures the view of the seafloor by providing “false” highlights. Throughout the rest of the image in pings 300 to 900, the shadows behind the rocky outcroppings are filled in.

Fig. 1.7 shows a processed version of Fig. 1.6 where the surface interference has been suppressed. The false highlights in pings 1 to 300 have been removed, and the shadows throughout pings 300 to 900 have been deepened. The floating debris that was present in the surface area was returning signal to the sonar, and the signal from this debris contaminated the sidescan image. By removing this interference which has nothing to do with the seafloor, image interpretation and subsequent downstream processing is facilitated.

To assist in visualizing the difference between the “before” and “after” sidescan images, Figs. 1.6 and 1.7 are shown side-by-side (although at reduced size) in Fig. 1.8. Through the examples of sidescan images showing data that have been contaminated by interference, the existence of the problem is seen. If the highlight/shadow clues in an image (highlights from rocks, and the accompanying acoustic shadow), are obscured or distorted by interference, the difficult problem of image interpretation becomes significantly more difficult, resulting in poor detection performance and misclassifications. To retain good image clues it is necessary to eliminate multipath effects from the image before image analysis takes place. Having established the existence of the basic problem, attention is now turned to considering the origin of the problem.

1.2.1 Origin of the Problem

Sonar signals scatter or reflect off of either the sea surface or off the bottom, depending upon the nature of the boundaries. A calm sea surface acts as a reflector, complicating the signal structure by reflecting either transmitted signals or signals that have already scattered on
Figure 1.5: The same sidescan image shown in Fig. 1.4 but with multipath interference suppressed, leaving a clear view of the bottom.
Figure 1.6: Sidescan sonar image created from data that were collected during the same survey of the Pam Rocks area in Howe Sound, B.C., also showing strong multipath interference contamination. The rugged seafloor in pings 1 through 300 is obscured by strong surface interference, and the shadows in pings 300 to 900 behind the rocky outcroppings are filled in.
Figure 1.7: The same sidescan image shown in Fig. 1.6 but with multipath interference suppressed, leaving a clear view of the bottom.
Figure 1.8: Side-by-side comparison of Figs. 1.6 (left) and 1.7 (right). By suppressing multipath interference a clear view of the seafloor is provided, with false highlights removed and with shadows deepened.
CHAPTER 1. INTRODUCTION

the bottom. Multipath signals of this sort appear as delayed versions of the bottom signal, with the delay depending upon the number of reflections and the total path length, and the result is a masking of the seafloor.

The sea surface can also act as a scatterer when wave action is sufficiently rough, when boat wake is present, or when floating scatterers such as logs/debris and tide lines are present. Direct surface returns deteriorate the quality of sidescan imagery by introducing signals that have nothing to do with the seafloor. This thesis divides “The Problem” into two sub-problems: removing interference that arrives from the surface, and removing interference that arrives from the bottom.

1.2.2 Part 1: Interference Arriving from the Surface

Multipath interference that arrives from the surface may originate as a direct surface return or as a signal that originated below the surface but reflects off it enroute to the transducer. For the sake of simplicity, the group of multipath signals arriving from the direction of the surface will be referred to as “surface interference”. In subsequent chapters, multipath signals under consideration are identified and individually labeled.

Does This Problem Really Exist?

In the literature, the issue of surface interference affecting sidescan sonar data and images is widely known. Denbigh discusses this problem and its impact on bathymetric sidescan sonar in [12], published in 1983, and later in [13] where surface interference is said to be one of the main causes of depth error. Since then, numerous researchers have noted the existence of this problem in the context of sidescan sonar and also in other contexts. For instance, in [2] the problem of “baffling images” created from boat wakes is discussed. In [14], a model of surface interference impacts on synthetic aperture sonar was created, and in [15] the issue of signal interactions with the sea surface was investigated in the context of underwater communication. Sea state (wind, wave action) strongly affects 2D sidescan images by affecting the propagation of multipath interference, and this behavior is discussed in [16].
Does Anyone Care?

Surface interference is a problem that has been discussed in the sidescan sonar literature, but there have only been a few attempts to address this problem. In [12], a physical baffle was introduced near the transducer to reduce sensitivity to surface signals. In [17], a receive array was used to modify the beamwidth of the receiver (by modifying the number of elements used to form the array) and a steering vector was used to point the beam in the desired direction. Beamforming on transmit is used by some sonar companies (for instance, [18]) to achieve surface interference suppression by not transmitting sound towards the surface.

Recently, adaptive beamforming methods have been investigated for use by a receive array to suppress multipath interference of all sorts (not only surface interference, but also bottom-bounce interference as well) [19], [20]. The problem of surface interference affecting the performance of sidescan sonars exists and is problematic for a range of users.

1.2.3 Part 2: Interference Arriving from the Bottom

Multipath interference arrives not only from the direction of the surface, but also from the direction of the bottom. To reject surface interference, it is sufficient to greatly reduce the sonar’s response to all signals coming from the direction of the surface. However, this same approach must not be applied to the rejection of bottom-bounce multipath signals because it would also reject the direct bottom return (i.e. the one signal that must be preserved). The challenge in this case is to somehow receive one of the signals that comes from the direction of the bottom, and to reject all others.

Does This Problem Really Exist?

The rejection of bottom-bounce multipath (while preserving the direct bottom return) is not a simple problem to solve, and when this problem occurs it can substantially affect sidescan sonar signals and images. Many authors have discussed the presence of this problem in contexts involving side-looking sonars in shallow water, such as sidescan sonar and synthetic aperture sonar. Both bottom-bounce and surface interference were noted in [9] in the context of sidescan sonar used to monitor salmon as they migrated up a river. In [7], multipath signals (including bottom-bounce multipath) received by a sidescan sonar caused overestimates of herring school density, and in a related study also using a sidescan sonar, bottom bounce multipath again caused overestimates of herring school density [8].
Simulations were used by the authors to model this behavior in an attempt to correct for it.

Additional examples reference to this problem exist in other contexts as well. In [21], the problem of multipath interference lowering the quality of the bathymetric information obtained by an interferometric sonar is discussed, and a 3-element receiver is proposed that can estimate the direction of arrival of up to two signals. The studies cited in Section 1.2.3 where sidescan sonar is used in the context of mine countermeasures are additional examples of the existence of the problem of bottom-bounce multipath signals, and of the deleterious effects this problem has on an application of sidescan sonar.

**Does Anyone Care?**

Multipath signals arriving from the seafloor are more difficult to suppress than multipath signals that arrive from the surface. This difficulty arises because the direct bottom return must be permitted while all other signals from the direction of the bottom must be rejected. Although the existence of this problem has been discussed in the literature, few solutions have been proposed.

In [22], the use of a large array (256 elements) to implement transmit beamforming coupled with two receive beams (one comparatively narrow, one comparatively wide) is investigated for the purpose of suppressing bottom-bounce multipath to facilitate the use of synthetic aperture sonar in applications like mine countermeasures. It is mentioned in [22] that additional measures beyond suppressing surface interference are necessary; bottom-bounce multipath must also be suppressed somehow. Related studies explored similar concepts (narrow transmit beams, two separate receive beams) with a smaller array, also in the context of synthetic aperture sonar for use in mine countermeasures [11], [23]. As mentioned in Section 1.2.2, recent efforts have turned to using adaptive beamforming with an array of receivers to suppress multipath signals (including bottom-bounce multipath) [19], [20].

The problem of bottom-bounce multipath exists, and the effect it has on sidescan sonar signals and images is non-trivial. Surface interference also has a significant impact on sidescan sonar signals and images. Both of these problems have received attention in the literature, and some solutions have been proposed, however there is still room for improvement. The purpose of this thesis is to propose robust solutions that are simple to implement, and to investigate the effectiveness of those solutions.
1.2.4 Why Explore Additional Solutions?

Each solution to this problem comes with its own tradeoffs. The use of a physical baffle reduces the sonar’s response to surface interference, but it also provides an object off of which sonar signals may reflect (complicating the interpretation of receive signals). Transmit beamforming allows for signals to be sent only towards the bottom (as opposed to towards the surface), making it less likely to “see” a boat wake or other surface returns. However, beamforming on transmit requires additional hardware to be designed and constructed that complicates the sonar design, increases cost, and is less flexible than beamforming implemented on receive in post-processing software. Some sidescan sonars are already designed with an array of receivers for use making 3D bathymetric maps, and these systems require no additional hardware to implement beamforming on receive - why not make use of these arrays? Additionally, beamforming only on transmit and not on receive could potentially leave the sonar vulnerable to bottom-bounce multipath.

To be most effective, the sonar system would employ not only transmit beamforming but also receive beamforming. However, the use of receive beamforming within the present context (a sidescan sonar system that suppresses multipath interference) has not received sufficient attention. The adaptive beamforming method used on receive proposed in [17] truncates the main lobe as range increases during each ping but does not control sidelobe levels, leaving the system vulnerable to strong multipath interference arriving from certain directions. An extensive analysis of other adaptive beamforming methods (used on receive) has been conducted and is available in [19], including an investigation into minimum variance distortionless beamforming (or MVDR). These adaptive methods such as MVDR use a “look direction” to determine where the beam will have an undistorted response (commonly unity) to arriving signals, and attempt to adaptively place nulls in the beampattern corresponding to angles from which all other signals arrive. However, under some circumstances the use of adaptive techniques risks the introduction of artifacts from the processing into the signal.

With conventional beamforming techniques, the user is in direct control over the beampattern. When adaptive beamforming is used, such as MVDR, the algorithm is in control of the beampattern - subject to certain constraints such as unity gain in the look direction. If an interfering signal arrives within the Rayleigh beamwidth of the array, the gain in the look direction (constrained to be unity) may be less than the gain outside of the look direction [24, pp. 458-465]. Under some circumstances, this can introduce unwanted artifacts to the
sidescan data and subsequently into the “cleaned up” sidescan image.

When using MVDR, multiple time samples may be averaged to improve the estimate of the correlation matrix, which is used to calculate the weight vector. However, the angles of arrival for the signal and any interference may not be constant within this window of samples. Artifacts result if there is a mismatch between the specified look direction and the actual arrival angle of the signal, or if the arrival angle of an interferer is not constant within the averaging window and the interference arrives within the Rayleigh resolution limit. The adapted weight vector is either applied to the average of the time samples (which reduces resolution) or it is applied to the individual time samples (which introduces artifacts). Since the overall objective is to remove unwanted artifacts from the sidescan image without decreasing image resolution, this thesis compliments existing research in the area (such as [19]) by exploring time-varying conventional beamforming techniques.

1.3 Contributions of the Thesis

The significant and original contribution of this thesis is an investigation into and analysis of the effectiveness of conventional beamforming techniques used with a vertical stack of receivers to suppress multipath interference effects in sidescan sonar data. In particular, this thesis proposes two novel solutions:

- the use of a fixed broad beam to suppress surface interference ("Problem 1"), and
- the use of conventional beamforming techniques used in a time-varying manner to suppress bottom-bounce multipath ("Problem 2").

To solve Problem 1 and suppress surface interference, this thesis proposes the use of a fixed (i.e. non time-varying) receive beam that has a broad response in the direction of the bottom and a significantly reduced response in the direction of the surface. The effectiveness of this proposed solution is analyzed by modeling the multipath signals under consideration, modeling the beampatterns of the array in question, and by calculating the relative intensity of received signals under different conditions. Simulations are performed to analyze the improvement made in target highlight/shadow contrast by employing the proposed method. Additionally, the proposed method is shown to be effective when applied to “real” data from a field survey where both the highlight and shadow of a large shipwreck
CHAPTER 1. INTRODUCTION

were completely obscured by surface interference. A realization of the adaptive MVDR beamformer is used to process the sidescan data, and the results are compared to those obtained when the fixed broad beam is used. The importance of the problem of surface interference contamination of sidescan imagery is emphasized in [25], and this research has resulted in publications [26] and [27]. The research presented in the journal article [28] forms the majority of this body of work.

To solve Problem 2 and suppress bottom-bounce interference, this thesis proposes that conventional beamforming techniques be used in a time-varying manner. This general approach to removing bottom-bounce multipath signals is novel, and is shown to be effective. Common bottom-bounce multipath signals are modeled, transducer beampatterns are also modeled, and relative intensity level calculations are again performed to demonstrate the effectiveness of this method in theory. Field data that are contaminated by bottom-bounce multipath interference are presented, and the proposed processing techniques are used to remove these multipath effects from the sidescan images. Additionally, a realization of the adaptive MVDR beamformer is used to process the sidescan data, and the resulting images are compared to the results obtained using the proposed conventional methods. The majority of the research discussed in this section of the thesis is taken from [29].

Additional analysis is also performed. The performance limitations imposed on the array processing methods by footprint shift are investigated. Additionally, an investigation into the impact of increasing the number of receivers in the array is conducted. The impact of the along-track beam on target highlights/shadow contrast is also investigated. Lastly, a general equation describing the footprint shift experienced by a signal originating from an arbitrary (x,y) location is derived.

1.4 Organization of the Thesis

Following this introduction, this thesis proceeds by addressing the problem of surface interference in Chapter 2. The chapter begins with a description of the sonar array, the geometry, and multipath signals that are under consideration. The beampatterns of the array in question are presented, and the relative intensity levels are calculated for these signals. Simulation is used to illustrate the loss in target highlight/shadow contrast that is possible with surface interference contamination, and real data in the form of a sidescan image are presented that illustrate the significance of this problem. An experimental array
CHAPTER 1. INTRODUCTION

featuring a vertical stack of receivers is introduced and its beampatterns are measured. A novel solution is proposed (the “fixed broad beam”) and the performance of this solution is analyzed in theory, in simulation, and is then applied to experimental data. The performance of the fixed broad beam is compared to one realization of an MVDR beamformer, where both methods are used to process experimental data. The fixed broad beam is seen to be highly effective at suppressing surface interference.

Next, the problem of bottom-bounce multipath is addressed in Chapter 3. The geometry under consideration is presented, and experimental data (collected by EdgeTech) that illustrate the problem of bottom-bounce multipath are shown in the form of sidescan images. The approximate beampatterns of EdgeTech’s 4600 transducer are shown, the multipath signals under consideration are modeled, and relative intensity levels are calculated. Time-varying conventional beamforming techniques are introduced as a novel method to suppress the multipath signals. The performance of the proposed solutions is analyzed in theory and also when applied to the experimental data. The proposed solutions are seen to be effective at suppressing the bottom-bounce multipath interference. Again, the proposed conventional methods are compared to a realization of the adaptive MVDR beamformer when processing the experimental data.

In Chapter 4, theoretical performance limitations imposed by footprint shift are considered. Signals across array elements are decorrelated when signals arrive from off-boresight but are received simultaneously. This decorrelation limits the effectiveness of array processing methods at suppressing interference. After introducing the concept of footprint shift in the context of interference removal from a sidescan sonar system, its impact on the proposed processing methods is investigated via examples. Finally, the beamformer response to interference is investigated as the number of elements in the array is varied. For the array sizes under consideration, it is found that the greater sidelobe control afforded by increased array size is preferable despite the increased decorrelation of signals across the array.

Finally, a summary and concluding remarks are presented in Chapter 5 along with recommendations for future work. There are four appendices to this thesis. First, an analysis into the impact of the along-track beampattern at determining target highlight/shadow contrast is presented. Second, a general equation describing the footprint shift experienced by a signal originating from an arbitrary (x, y) location is derived. The third appendix contains supplementary sidescan images, providing additional evidence of the existence and importance of “The Problem” and of the effectiveness of the processing. The fourth appendix
provides the rationale for the cosine beampattern model (for sidescan transducer elements) that is used in this thesis.
Chapter 2

Problem 1: Surface Interference

The content of this chapter concerns the removal of surface interference, and is drawn from [28]. As has been mentioned, when sidescan sonar is used in shallow water where the surface and bottom are simultaneously within view, multipath interference may contaminate the signal (and subsequent image) of the seafloor. The nature of the interference is influenced by the sea state (how calm the surface is). If the surface is glassy smooth, multipath signals dominate the masking in an orderly way in the sense that the multipath signals are approximately delayed replicas of the bottom signal. If the surface is rougher, multipath signals can still dominate the masking but they are less orderly and produce a grainy effect on the image. If the surface itself is a scatterer because of the presence of boat wake [25], “chop” on the surface of the water or other turbulence, the major masking effect comes from direct surface scattering.

Key image clues used for target detection and bottom classification include spatial amplitude statistics, shadows, and highlights [1]. If these clues are obscured or distorted by surface effects, a difficult problem becomes significantly more difficult, resulting in poor detection performance and misclassifications. To retain good image clues it is necessary to eliminate surface effects from the image before the detection and classification process takes place.

Commercial sidescan sonar systems are unique to each manufacturer, but some systems provide a degree of surface interference mitigation by offering comparatively narrow across-track beams (relative to the prototype array, discussed in Section 2.2) or adjustable transducer tilt angles, allowing reduced sensitivity to surface generated interference. While it is possible to reduce sonar sensitivity to surface interference by tilting the sonar system
away from the surface or by narrowing the across-track beam, these solutions are not optimal because sensitivity to bottom signals is also affected. The sonar’s maximum range is influenced by the configuration of its receive and transmit beams, and this is especially evident when operating in shallow water. It is desirable to simultaneously maintain maximum imaging range while also eliminating the surface interference which becomes problematic when the surface is within the sonar’s view.

This Chapter investigates the ability of a vertical stack of a small number of sidescan sonar transducer elements forming an array to eliminate or greatly reduce surface effects in sidescan sonar images while preserving the bottom signal. The interference suppression of the array is compared to that of a representative ordinary sidescan sonar. This comparison is necessary because the array has narrower transducer elements thereby producing a wider across-track beam, making the array more sensitive to surface interference than ordinary sidescan transducers. However the plurality of transducer elements allows for beam shaping to alter this sensitivity. The reason for using a small number of elements is to maintain the simplicity of the sidescan configuration and to avoid unnecessary complexity. Specifically, it is found that six array elements are sufficient, and with this number of elements the array can still be deployed in the same physical space as a conventional sidescan transducer.

The Chapter begins with this introduction followed by a detailed description of the problem of bottom masking including an example from sidescan sonar data (Section 2.1). In Section 2.2, a solution to the bottom masking problem is then presented that includes a six element array which introduces minimal complexity to the sonar but yields significant improvements in the resulting images. Measured across-track beam patterns for an experimental sidescan transducer array are presented in Section 2.3, along with a discussion of advantages and disadvantages associated with the use of such an array. In Section 2.4 field data are presented that illustrate the effectiveness of an array to significantly reduce bottom masking. In Section 2.5 a realization of the adaptive MVDR beamformer is used to process the experimental sidescan data, facilitating a qualitative comparison with the non-adaptive beamforming approach proposed in this Chapter. Finally, a brief summary and discussion of results is presented in Section 2.6.

Throughout the thesis it is assumed that the objective of the sonar survey is to image the seafloor. In practice this is not always the case, but the ideas presented are also applicable to the removal of seafloor interference in the case of an upward-looking sonar where the surface - or an object floating on the surface such as an iceberg - is the objective of the
CHAPTER 2. PROBLEM 1: SURFACE INTERFERENCE

2.1 Surface Effects in Shallow Water Sidescan Images

When a sidescan sonar is used in shallow water the wide fan beam in the across track direction may intersect the surface as well as the primary target: the bottom. The effect of this intersection with the surface varies depending on the character of the surface. As was indicated in the introduction, the effect of a glassy smooth surface is the potential for the injection of a well ordered multipath structure. A choppy surface generally results in a less orderly multipath structure. If the surface itself is a significant scatterer due to the presence of boat wake or surface chop, the multipath structure in that area tends to be attenuated and the dominant signal comes from the surface. In addition to these specific situations there can also be any situation in between. The net result of the multipath and surface scattering is a masking or obscuring of the bottom image. In this section these detrimental effects are described for a typical sidescan sonar deployment.

2.1.1 Geometry of Shallow Water Sidescan Sonar Deployment

Fig. 2.1 shows a diagram of a typical sidescan sonar deployment in the across track plane. In this figure the sonar is deployed at a depth of 30 m in water that is 40 m deep. The tilt angle from the horizontal is 20°. Shown in the figure is a representative one-way across-track beam pattern for the transducer equivalent to a \( \cos^2 \theta \) voltage beam pattern which has a one-way beamwidth of 66° (see Appendix D for justification of the exponentiated cosine beampattern model). The three concentric circles around the transducer location indicate the response level of the beam in -10 dB steps with the outermost circle representing 0 dB. It is seen from this figure that the beam effectively covers the area of interest on the bottom with little loss, but it also has a significant response towards the surface. It is this response towards the surface for both transmit and receive that causes a masking of the bottom return by multipath returns and surface scattering.

The direct bottom return, the three primary multipath returns and the surface scattering source are illustrated in Fig. 2.1 for a total path length of 180 m, or equivalent slant range of 90 m. The notation is similar to that in [22] with the uppercase letter referring to the scattering boundary and the lower case letter referring to a reflection. For example, the path that travels from the transducer to the bottom (where it is scattered) and then reflects off
Figure 2.1: Diagram of side-scan deployment showing a typical signal structure and typical across-track beam pattern with the transducer located at a depth of 30 m. The direct surface return (S) is given by the thin solid line, and the direct seafloor return (B) is given by the thick solid line. The surface-bottom-surface (sBs) multipath is shown by the dashed line. The bottom-surface (Bs) and surface-bottom (sB) multipath signals trace the same path in opposite directions, given by the dotted line. The transducer beam pattern is shown by the oval, with intensity decades shown by the concentric half-circles.
of the surface on its way back to the transducer is designated as Bs. The following paths are shown in the figure, B (direct bottom return), Bs (bottom-surface multipath), sB (surface-bottom multipath), sBs (surface-bottom-surface multipath), and S (direct surface return). The paths Bs and sB lie on top of one another, but are traveling in opposite directions. It is assumed that paths that are scattered twice are sufficiently attenuated that they may be ignored as a significant source of masking.

As was mentioned in the previous paragraph the paths shown in Fig. 2.1 all have a total length of 180 m, or equivalent slant range of 90 m. Because of the geometry and the constant equivalent range, the multipaths and the direct path intersect the bottom at different locations. When the transducer is receiving backscatter from the intersect location of the direct B path, it is also receiving backscatter from the intersect locations of the Bs, sB, and sBs paths. Therefore, the image formed is actually a coherent sum of separate B, Bs, sB, and sBs signals. If the direct bottom image has a shadow at a given location, that shadow may be filled in by the multipath images, reducing the contrast ratio of the shadow. Similarly, if the surface is a significant scatterer, surface scattering will fill in the shadow, also reducing the contrast ratio.

2.1.2 Relative Levels

Fig. 2.2 shows the relative levels of the various paths as a function of slant range for the deployment shown in Fig. 1. To create this figure it was assumed that the bottom and the surface have equal and constant scattering strengths, independent of grazing angle. This assumption facilitates comparisons between the intensity of bottom returns and surface return. The pulse length for each signal (its footprint) is a primary factor in determining its relative intensity; these relative levels hold for arbitrary pulse length. The sB and Bs paths are indistinguishable from one-another in this figure for two reasons: because they follow the same route (albeit in opposite directions) and because the transmit and receive beam patterns are the same.

In Fig. 2.2 the sum of all interfering signals initially lies on top of the surface signal (which is first received at 30 m range) and increases beyond the level of the surface signal at approximately 65 m range. The contrast ratio between the desired bottom signal (first received at 10 m range) and the sum of the interfering signals is the difference between their respective intensity levels. The contrast ratio due to surface scattering is the difference between the level for the bottom return and the surface return. For this deployment, in
Figure 2.2: Relative intensity levels of the returning signals as a function of range. The signals are represented in a manner consistent with Fig. 2.1, but for clarity are now described in terms of the range at which they first appear. The bottom (B) signal appears at a range of 10 m, and the surface signal (S) appears at a range of 30 m. The sBs multipath appears at a range of approximately 75 m, and the Bs and sB multipath signals lie on top of one another and are both given by the dotted curve which is first seen at a range of 50 m. Between 30 m and 65 m, the surface signal lies on top of a curve that represents the sum of all interfering signals (S, sB, Bs, and sBs) and is seen to closely follow the S signal until a range of approximately 65 m. The surface signal is given by the thinner of the two curves; the sum of interfering signals is given by the thicker of the two.
which the sonar is relatively close to the bottom, the difference between the surface and bottom returns decreases to about 4 dB at 130 m range. At this range, the difference between the bottom signal and the sum of interfering signals decreases to 1 dB.

Although the shadow contrast ratio is important, it is not just the shadows that are of interest. Good bottom classification depends on obtaining relevant statistics of the bottom in one area compared to statistics in another, irrespective of shadows. If irrelevant signals from other parts of the bottom or the surface are contaminating the bottom return, class separation becomes fuzzy and classification ability suffers. For example, many target detection and bottom classification methods rely on textural clues which in turn depend on signal statistics. From the levels shown in Fig. 2.2 there is significant potential for the image of the bottom to be masked or distorted by both surface scattering or multipath signals, effectively destroying textural clues. Nevertheless, much of the following discussion focuses on the shadow contrast ratio, or alternatively the shadow depth as measured in dB, because the masking effect is most readily observed for shadows.

The reference for the vertical dB axis in Fig. 2.2 is arbitrary. The model which is used in this Chapter (and throughout this thesis) to calculate the intensity of the received signals is primarily designed to facilitate a meaningful analysis of relative intensity levels. While there are many factors which influence the intensity of received signals, the approach taken is to limit the complexity of the model while capturing the essence of the problem.

The seafloor is assumed to be composed of scatterers at a uniform density and with the same scattering strength. When modeling surface interference, the surface is modeled in the same manner. While the entire physical sea is certainly not always characterized by such properties, these assumptions are made to facilitate a meaningful comparison between the intensity levels of various signals. Because the model is designed to explore the impact of receive beam shape on the intensity of various signals, the assumption of equal scattering strength (between the surface and the seafloor) allows for results to be extrapolated to other settings. For instance, results can be extrapolated to describe a setting where direct surface returns are estimated to be 3 dB weaker than direct bottom returns by simply subtracting 3 dB from the calculated values.

The model takes spherical spreading loss into account, and the footprint of the signal is calculated as a function of range. Signals are assumed to either completely scatter or completely reflect off any boundary (sea surface or seafloor) they encounter. In this sense the signals under consideration are shown at maximum relative intensity. In actual practice,
CHAPTER 2. PROBLEM 1: SURFACE INTERFERENCE

Signals can undergo partial reflections where some intensity is lost at a boundary, thereby causing the received signal to be weaker than what the model predicts, but its maximum relative intensity will not be greater than predicted. This Chapter illustrates a simple and effective methodology for multipath suppression realized by altering the shape of the receive beam, and the effectiveness of this methodology is examined by considering multipath signals at maximum relative intensity. It is also useful to compare the proposed methodology against what is attainable under favorable circumstances using a commercial system with less sensitivity to surface interference.

Some commercial sidescan sonar systems employ narrower across-track beams than the 66° assumed thus far. The EdgeTech 4200 has an across-track beam width of 50° and a tilt angle of 20° [30], while the Klein 3000 has an across-track beamwidth of 40° and a maximum tilt angle of 25° [31]. Fig. 2.3 shows a plot of the intensity of the received signals assuming an ordinary sidescan transducer with a voltage beam pattern described by $\cos^5(\theta)$ for both transmit and receive (42° beamwidth) and with the transducer tilted 25° below the horizontal. Signals are defined as in Fig. 2.2, but now the surface signal appears in the Figure at 40 m range, the sB/Bs signals at around 62 m, and the sBs signal at 100 m. These changes to the range at which the component signals become visible result from the narrowing of the beam pattern; the signals are still present at their previous ranges, but have intensity below the -20 dB cutoff on the Figure.

The reduced beamwidth and slightly steeper tilt angle improve the contrast between the bottom signal and the interfering signals. The B signal is now approximately 13 dB above the sum of interfering signals and 15 dB above the S signal at a range of 130 m. As Fig. 2.3 shows, it is possible to achieve substantial interference suppression (of surface signals) using an ordinary sidescan sonar. However, it is easy to imagine scenarios where this amount of contrast is not realizable, such as if the sonar is closer to the surface or if the beams are wider. This result represents a favorable scenario for an ordinary sidescan sonar, and is later compared against the result attainable using the proposed beam processing.

Some interfering signals, such as Sb/bS signals and bSb signals, are not included in the analysis. These signals require a different set of circumstances than are presently considered (namely that the seafloor acts as a reflector for surface scattering signals). Because these interfering signals arrive from the same direction as the desired bottom signal their removal is more complicated and is discussed in Chapter 3.
Figure 2.3: Relative intensity levels of the returning signals as a function of range, with signals defined as they were in Fig. 2.2 and a narrower 42° beamwidth. The ranges at which the component signals appear in the Figure have changed due to the narrower beam pattern assumed in this Figure; the S signal becomes visible at 40 m, the sB/Bs signals at approximately 62 m, and the sBs signal at 100 m.

Example of Reduced Shadow Contrast and Interference (Simulation)

A simulator was developed to illustrate reduced shadow contrast caused by interfering surface and multipath signals. The simulated receive signal provides a useful tool for visualizing the impact of multipath interference, and compliments calculated intensity levels that are presented throughout the Chapter. In simulation, target highlights are seen to appear multiple times as the direct signal arrives first, followed by delayed replicas, and target shadows are seen to be filled in by interference. The motivation for emphasizing target highlights and shadows is that these features play a prominent role in classification.

The situation described in Fig. 2.2 was simulated using a bottom composed of random Gaussian scatterers at a density of 200 scatterers/m; with each ping the realization (both the location and complex amplitude) of the scatterers is changed. A target highlight response and subsequent shadow have been modeled by simulating the presence of a linear ramp on the bottom. The ramp is located on the seafloor at a horizontal distance of 100 m from the array; it has a horizontal extent of 1 m, and begins at a height of 0 m above the seafloor and ends at a height of 0.5 m above the seafloor. The target strength for the ramp scatterers
Figure 2.4: Simulated received signal for a target at a horizontal range of 100 m, followed by its shadow. The thin solid curve is the received signal when the B, S, sB/Bs, and sBs signals are present; the thick solid curve is the received signal when the surface signal is absent (B, sB/Bs, and sBs are received).

was 6 dB above the flat bottom scatterers.

Fig. 2.4 shows the relative levels of the simulated receive signal for the sidescan image after correction for spherical spreading. The intensity of the received signal for 20 pings is averaged for the data shown in the figure to reduce the variation so that the levels are readily observed. The thick solid curve is the level for the bottom plus multipath signals, the thin solid curve is for bottom plus multipath plus surface signals. This figure shows the target on the bottom at a slant range just past 100 m followed by its shadow. At 112 m the sB and Bs multipath image of the target is received with its shadow, and at 122 m there is a small peak due to the sBs multipath signal. If the multipath and surface signals were not there the bottom shadow would fall to the system noise level. However, the multipath signals fill in the shadow reducing the contrast ratio to 7.5 dB, and when the surface signal is included the contrast ratio is further reduced to 4.5 dB. It is also evident that the multipath target signal highlights mask the bottom return at a range of 112 m.
Example of Dominant Surface Scattering (Field Data)

Fig. 2.5 shows a sidescan image of a small wreck on a muddy seafloor obscured by surface scattering resulting from residual wake due to significant boat traffic in the area. The sidescan sonar transducer was mounted at a depth of 1 meter (shallow mount) over the side of the boat and tilted downward at an angle of 15 degrees from horizontal. The pulse was a CW pulse of length 20 cycles at a 182 kHz carrier frequency. This 20 cycle square pulse was approximately matched filtered by a bandpass filter with a bandwidth equal to the inverse of the pulse length. The boat was traveling up the left side of the figure looking to the right. The range was set at 265 m. There is an obvious rock outcrop at the bottom of the figure giving way to a mud bottom upon which the small wreck is sitting. The mud bottom gives very little return compared with the wake-contaminated surface, the scattering from which dominates the image and almost completely obscures the wreck.

The purpose for showing this figure is to illustrate the difficulty of locating a target in a sidescan image that is contaminated by strong surface scattering. If one does not know where the wreck is located, it is difficult to identify it in the image. If the task is difficult for a human who knows the wreck is somewhere in the image, the task would be nearly impossible for an automatic detection algorithm. It is shown in Fig. 2.24 that it is possible to obtain a clear image of the bottom in this situation if the data are recorded with a six element array as described in the introduction. Interested readers may refer to Fig. 2.24 to see the true seafloor and the shipwreck, but the purpose for the moment is to illustrate the masking mechanism of surface scattering and the image contamination it causes.

2.2 Multi-Element Array for Controlling Surface Effects

The previous section presented the geometry relevant to shallow water sidescan sonar deployment and illustrated the fact that surface interactions can hinder (or possibly prevent) effective target and bottom classification. The resulting multipath signals and surface scattering fill in shadows and mask the bottom. The exact nature of the interference depends on deployment depth and surface characteristics.

The deployment depth also influences the multipath structure. As the depth decreases the path length differences between interfering signals decrease, bringing the phantom images into closer registration with the bottom image. Ultimately, for very shallow deployments, multipath targets may be nearly co-registered with direct-return bottom targets
Figure 2.5: Side-scan image from a field deployment showing dominant surface returns that obscure the image of the seafloor. There is a shipwreck present in this image, but the shipwreck highlight and its shadow are also obscured by the interference. Fig. 2.24 is created from the same data as this Figure but with the interference attenuated, leaving the seafloor and shipwreck visible.
(depending on the nature of the multipath). If this behavior occurs, it leads to increased shadow depth, as multipath and direct returns follow nearly identical paths. Indeed, one method to increase shadow contrast is to employ a very shallow deployment. An additional benefit of a shallow deployment is that objects standing proud of the seafloor cast shorter shadows, allowing for textural information to be available from a larger portion of the seafloor. However, even though the shadow contrast is improved with shallow deployments, the target highlight bottom statistics are contaminated by the multipath.

Reducing or eliminating surface interaction effects requires the sonar to discriminate between signals that are due to the presence of the surface and signals due to interaction with bottom only. For removing the multipath and surface signals shown in Fig. 2.1 it is sufficient to employ an ideal sidescan sonar beam on both transmit and receive that has zero response in the direction of the surface and full response in the direction of the bottom. While it is impossible to construct such a beam with a small number of array elements, it is possible to construct beams that sufficiently approximate the ideal that significant discrimination is obtained.

Ordinary sidescan sonar systems are capable of realizing interference suppression (of surface signals) by employing comparatively narrow beams. This thesis investigates the ability of a different sort of sidescan sonar that employs a vertical stack of receive elements to achieve this same goal. 3-D sidescan sonars (bathymetric sidescan sonars) such as the EdgeTech 4600 [32] or Benthos C3D [33] are examples of sonar systems which employ this vertical stack of receivers. Such systems are commonly used to collect bathymetric data, but in this thesis attention is focused on the potential of improving sidescan images with such arrays.

An experimental transducer has been constructed and tested, its properties are discussed in detail in Section 2.3. Certain design constraints are imposed upon the system because of the vertical stacking of array elements which must be noted. An important design constraint is that the receive elements are kept at half-wavelength spacing, which provides optimal spatial resolution and results in a single main beam. This element spacing constraint affects array performance by requiring that the receive elements must employ uniform shading (as opposed to triangular shading) to maintain uniform inter-element spacing, and by requiring the elements to be narrower than the inter-element spacing. As previously mentioned, the prototype array has a significantly wider across-track beam than an ordinary sidescan sonar, leaving it inherently more sensitive to surface signals than an ordinary sidescan with
2.2.1 Beam Shaping

There are many techniques that can be employed to construct a beam that is suitable for a particular deployment. The objective in the beam design is that the beam be wide enough to cover the bottom and yet have very little response in the direction of phantom targets like wakes or surface bounce multipath. Fig. 2.6 shows a useful diagram for defining parameters for the beam design. In the figure the sidescan array is tilted at an angle $\gamma_t$ from the horizontal and angles $\theta_1$ and $\theta_2$ define the desired extent of the beam on the bottom in terms of the physical angles. These physical angles are then transformed into electrical angles $\alpha_1$ and $\alpha_2$ through the expression

$$\alpha = \frac{2\pi d}{\lambda} \sin(\theta - \gamma_t) \quad (2.1)$$

where $d$ is the distance between array elements, $\lambda$ is the wavelength, $\alpha$ is the electrical angle, and $\theta$ is the physical angle.

Once the electrical angles are defined, FIR filter design techniques can be used to determine the element weights that define the beam. For example, the electrical angle beamwidth $\alpha_w$ (filter width) and offset from broadside $\alpha_o$ (filter offset from zero frequency) are defined respectively by

$$\alpha_w = \frac{\alpha_2 - \alpha_1}{2} \quad (2.2)$$

$$\alpha_o = \frac{\alpha_2 + \alpha_1}{2}. \quad (2.3)$$

A filter is then designed with width $\alpha_w$ centered around broadside (zero frequency) using a FIR filter design algorithm. For this thesis the filter design method of least squares and
equal ripple (also referred to as a “minimax” filter in [24, pp. 156-165]) was employed and is implemented with MATLAB’s function “fircls1” [34]. To create the desired filter in MATLAB using this function, the filter order was specified as $n = 5$ (describing a filter of length $n + 1$), the normalized cutoff frequency was $\alpha_w/\pi$, passband ripple was constrained to be less than 0.2 from an amplitude of 1, and stopband ripple was constrained to be less than 0.03 from an amplitude of 0.

The filter was then shifted to the offset angle by multiplying the element weights by the following vector element by element (Hadamard product).

$$
\mathbf{b} = \begin{pmatrix}
1 \\
\exp(-j\alpha_o) \\
\exp(-j2\alpha_o) \\
\exp(-j3\alpha_o) \\
\exp(-j4\alpha_o) \\
\exp(-j5\alpha_o)
\end{pmatrix}
$$

(2.4)

This product amounts to a frequency shift for filter design, or in this application, an electrical angle shift for the array beampattern. This technique implements beamforming using a phased array (phase shifts are used to approximate time delays between the elements) and yields a wide beam pattern covering the bottom and low sidelobes in the stop band region.

Figure 2.6: Diagram of parameters to be used in beamforming. Angles $\theta_1$ and $\theta_2$ define the desired extent of the beam on the bottom, and angle $\gamma_t$ is the tilt angle of the array.
covering the surface.

2.2.2 Gains From Beam Shaping

The objective of shaping the across-track beam is to reduce the multipath and surface scattering signals while keeping the direct bottom return. For a flat bottom a good choice of the angles $\theta_1$ and $\theta_2$ to obtain this objective is to set $\theta_1$ to the angle corresponding to the depth at maximum range (assuming a flat seafloor), and to set $\theta_2$ to 90 degrees. These angles ensure that the beam has its major response along the bottom with the signals coming from directly below the array and from the bottom at maximum range suffering the attenuation associated with the filter width limits. If the bottom slopes up at far range, then the signal would be attenuated more, but the scattering strength from such a slope is usually stronger than for a flat bottom, partially offsetting the reduced return level.

The proposed fixed broad beam creates a wide beam pointing at the seafloor so that bottom signals are preserved when they arrive through a wide range of angles; the beam does not need to be “swept” along the seafloor. The beam has some ripple which is tolerated in favor of a sharp transition between the passband and the stopband that results in strong suppression of surface signals.

Fig. 2.7 shows both the original element pattern from Fig. 2.1 (thin solid oval) and the one-way composite beam pattern shaped according to the above procedure for a six element array with half-wavelength spacing (thick solid curve). It is evident that the shaped pattern has a much reduced response in the direction of the surface but maintains a good level of response in the direction of the bottom, which is the desired result. However, if this shaped beam is employed only on receive there is still an issue with the surface-bottom (sB) multipath signal in that for this particular multipath the signal going towards the surface receives significant transmit strength, and then the return from the bottom is received with the strong bottom response of the shaped beam. Accordingly, the intensity of this particular multipath signal is not reduced. Fig. 2.8 shows the relative path levels for using the shaped beam only on receive. Note that the sB multipath return is not reduced by beam shaping on receive and is quite similar in level to that shown in Fig. 2.2. However, the contributions from the other multipath signals and surface scattering are greatly reduced.

With beamforming employed, the contrast ratio between the bottom signal (first received at 10 m range, and given by the thick solid curve) and the sum of interfering signals is now at least roughly 6 dB for ranges around 130 m. If beamforming is not applied, this contrast
CHAPTER 2. PROBLEM 1: SURFACE INTERFERENCE

Figure 2.7: Diagram of typical side-scan deployment, as shown in Fig. 2.1, but with the beamformed beam pattern now given by the thick solid curve and the “raw” beam pattern given by the thin solid oval. As with Fig. 2.1, the B signal is given by the thick solid line and the S signal is given by the thin solid line. The sBs multipath is given by the dashed line, and the dotted line represents the sB/Bs paths.

ratio reduces to about 1 dB. As before, the intensity of the sum of interfering signals is initially given by a curve which lays on top of the surface signal (the surface signal is first received at 30 m range). However, the beamforming strongly attenuates the surface signal, so beyond about 55 m range the sum of interfering signals is given by a curve which lays almost directly on top of the sB path.

If the shaped beam is employed on both transmit and receive, all multipath and surface scattering signals are greatly attenuated, while leaving the bottom levels relatively untouched as shown in Fig. 2.9. The separation between the bottom signal and the sum of the interfering signals has increased to approximately 28 dB at 130 m range, due mostly to the attenuation of the sB path, which had remained fairly strong even after beamforming on receive.

The gain that can be achieved in shadow contrast and multipath highlight removal illustrated in Fig. 2.9 is also shown via simulation in Fig. 2.10. At a slant range of 100 m the difference between the combined interfering signals and the bottom signal is 38 dB in Fig. 2.9, which corresponds to the 38 dB contrast ratio shown in Fig. 2.10 for the shaped beam shadow (thick solid curve). Also evident is that the curve for the bottom alone in Fig.
Figure 2.8: Relative received signal intensities when beamforming is used on receive. Signals are represented in a manner consistent with Fig. 2.2 but now the dotted curve represents the Bs path only, and the dash-dot curve represents the sB path. Note that the curve representing the sum of the interfering signals (S, Bs, sB, and sBs) lays directly on top of the surface signal from 30 m range to about 50 m range, and then on top of the dash-dot curve (sB multipath) beyond approximately 55 m slant range.
Figure 2.9: Received signal intensities when beamforming is applied on both transmit and receive. The sB and Bs signals are now both given by the dotted curve.

2.9 (shaped beam on both transmit and receive) is lower at the farther ranges than that for Fig. 2.8 (shaped beam on receive only), and both are lower than that in Fig. 2.2 (no shaped beam). These different relative levels for the same bottom scattering strength indicate that the shaped beam is attenuating the bottom signal at the longer ranges. This attenuation is a problem only if the noise floor is sufficiently high that thermal noise begins to contaminate the return. This lower level for the bottom signal when using the shaped beam is also the reason for the difference in level for the thin curve (shaped beam on receive only) and the thick curve in Fig. 2.10 where the composite simulated signal levels are shown.

While it is desirable to both transmit and receive with a shaped beam, it is not always practical. Typically, it is much easier to beamform on receive than it is on transmit because the beamforming can be done on the receive signals after the fact in software. However, beamforming on transmit requires that hardware be designed and constructed that executes this function, complicating the sonar design and increasing cost.

It is possible, however, to mitigate the contribution of the sB multipath (the only one that requires beam shaping on transmit) by adjusting the element pattern of the transmit element such that little energy is launched into the sB multipath. This procedure does require a separate transmit element, but such a configuration is preferable for a number of reasons as will be outlined in the next section where characteristics of a prototype transducer
Figure 2.10: Levels determined from the simulated received signal when beamforming is applied on receive only (thin curve) and on transmit and receive together (thick curve).

are discussed.

Masking that can be caused by the along-track beampattern is discussed in Appendix A within the context of a practical array. Bathymetric sidescan sonars have certain design constraints (such as using approximately half-wavelength element spacing to avoid ambiguity when estimating angles of arrival) that limit the ability to shape the along-track receive beam. Since it is not practical to have triangular shading on a receive array of vertically stacked elements, a reasonable compromise is to employ triangular shading on transmit and uniform shading on receive. This combination has a slightly wider main beam than uniform shading, but lower sidelobes and hence is a good compromise between two-way uniform or triangle shading. It is concluded (in Appendix A) that two-way uniform shading does not perform badly and is sufficient for most applications.

2.2.3 Spot Sidescan

In addition to the masking mechanisms of multipath signals and surface scattering, water column targets can interfere with clearly imaging the bottom. When using a multi-element array to obtain sidescan records, an operator can further enhance certain areas of interest in the record by moving a spot beam to that area after the fact, if the data from each element have been stored. This spot beam focuses on the area of interest by narrowing the
CHAPTER 2. PROBLEM 1: SURFACE INTERFERENCE

Figure 2.11: Three beam patterns to choose from: the “raw” array beam pattern (thin solid oval), the equiripple pattern (thick solid curve), and the spot beam pattern (dashed curve). The sonar array is now at a depth of only 1 m, which corresponds to the shallow pole-mount deployment employed during the collection of experimental data.

field of view in the across track direction. Fig. 2.11 illustrates a spot beam (dashed curve) that fits inside the shaped beam (thick solid curve). This particular spot beam assumes half-wavelength element spacing and is formed using a Chebyshev window which gives the narrowest beam for a given sidelobe level. The sidelobes for this beam were set at -30 dB. The objective of using a spot beam is to further reduce the masking effects of multipath signals and surface scattering while removing any water column targets that fall outside the spot beam.

2.3 Beam Patterns and Performance of Experimental Transducer

As indicated above reducing the contributions of surface scattering and multipath signals is best done by beamforming on both transmit and receive. However, beamforming on transmit, unlike on receive, requires specialized hardware which tends to increase the cost of sonar systems. In addition, simple one element sonar transducers tend to be sufficiently wide that stacking them vertically with half wavelength spacing is not possible. The width
Figure 2.12: Diagram of the prototype array. There is a vertical stack of receive elements, and the elements have a center-to-center spacing of 0.41 cm, or λ/2, and each receiver is 55.8λ long. Receive elements are narrow (0.29 cm or 0.36λ) and have a wide beampattern. The transmitter is composed of two separate elements that are wired together to act as a transmit array. Both transmit elements are 55.8λ long and have center-to-center spacing of λ/2, but the elements are wider (0.35 cm or 0.43λ) than receive elements. The result is a narrower transmit beampattern than that of a receive element.

of these elements is required to shape the beam so that it is reasonably narrow to reject as much multipath as possible, while maintaining sufficient beamwidth to cover the bottom. A typical beam for a simple one element sidescan sonar transducer is illustrated in Fig. 2.1. Also, the wider elements are employed to increase transmit and receive sensitivity.

Therefore, to construct a vertically-stacked array of six sidescan elements spaced at one half wavelength, it is necessary to make the individual elements narrower, widening the beam in the across-track direction. This wider beam increases the contribution of surface effect signals, both multipath and surface scattering. However, if the transmit element is separate from the vertically-stacked receive elements then it can be wider, reclaiming the sensitivity and two way beam shape.

An experimental sidescan transducer which employs a vertical stack of six rectangular receive elements was constructed, its beam patterns were measured, and it was used to collect field data. The center frequency of the experimental array is 182 kHz. Fig. 2.12 illustrates the basic layout of the prototype array. The six receive elements are 18 inches long (45.72 cm, or 55.8λ). In the vertical dimension, each receive element is 0.116 inches wide (0.29 cm or 0.36λ), and the elements have a center-to-center spacing of 0.161 inches (0.41 cm, or λ/2). The transmitter is composed of two elements of length 18 inches (45.72
cm, or 0.41 cm, or \( \lambda/2 \). Fig. 2.13 shows the prototype array about to be deployed in a lake via pole mount, and Fig. 2.14 shows a close-up view of the transducer and its stainless steel housing.

For the transducer employed in this research, the transmit element was constructed from two vertically-stacked elements that were adjusted in width and spacing so that the one way transmit voltage pattern is described by a cosine raised to the power of 4, resulting in a transmit beamwidth of 47° (see Appendix D for justification of the exponentiated cosine beampattern model). Fig. 2.15 shows this \( \cos^4 \theta \) transmit pattern along with the measured pattern for the combined transmit element. Also shown for reference is the average receive power pattern for the elements in the six element receive array. The measured transmit
Figure 2.14: Close-up view of the prototype array used in the thesis. The housing of the array is stainless steel.
Figure 2.15: Measured receive pattern of the experimental array (thin solid oval) and measured transmit pattern (thick solid curve) compared to theoretical transmit pattern (dashed curve). The theoretical transmit pattern is mostly covered by the measured transmit pattern. The array is tilted at an angle of 15°, consistent with its standard deployment position.

The receive array was designed so that the receive elements have consistently smooth wide beams. To establish that a beam of a desired shape could be obtained on receive, an equal ripple beam vector (as described in Section 2.2.1) was designed and applied both to an ideal array with element patterns as shown in Fig. 2.16, and to experimental data from a six channel coherent beam pattern measurement system. The resulting patterns are compared in this figure with the dotted curve associated with the ideal array and the thick solid curve associated with applying the beam shaping vector to data from the beam pattern measurement system. The resulting patterns are a close match, with the experimental pattern having a 2 dB higher sidelobe pointing towards the surface. However, this sidelobe is still 22 dB down from the maximum response. It is therefore concluded that when the equal ripple beamforming technique is applied to the physical transducer, the resulting beam pattern is in close agreement with theory. These measured transmit and receive beampatterns (and not their approximations) are used throughout this thesis to model the prototype array.
Figure 2.16: Measured receive pattern of the experimental array (thin solid oval) and measured receive beamformed pattern (thick solid curve) compared to theoretical receive beamformed pattern (dotted curve). The dotted curve is almost completely covered by the thick solid curve. Again, array is tilted at an angle of $15^\circ$.

Fig. 2.17 shows the same deployment scenario as Fig. 2.1 but with beam shapes associated with the experimental array. The dash-dot curve illustrates the $\cos^4 \theta$ transmit pattern, the thin solid curve the element receive pattern for the six element array, and the thick solid curve shows the shaped receive pattern. If there is no beam shaping, the transmit pattern and the element pattern determine the relative strengths of the signals, resulting in the curves shown in Fig. 2.18. The results are similar to those of Fig. 2.2 for the surface scattering and the Bs and sBs multipath. However, because the transmit pattern is different, the level for the sB multipath is different. The sB multipath level is determined by the amount of energy that is launched towards the surface by the transmit element, and since the transmit pattern is relatively narrow and tilted downward less energy is launched into this path. Hence the sB path level is reduced from that of the Bs path because the Bs path does not experience the attenuation of the transmit pattern (on transmit this path is launched towards bottom) and on receive it is attenuated only by the wide receive element pattern.

The increase in the width of the receive beam is of little consequence to the sB path, as this path returns from the seafloor and experiences minimal attenuation by the receive
beam. However, the S and sBs paths do not arrive from the seafloor, but from the sea surface. This means that the increase in width of the receive beam impacts these signals. With the narrower receive beam seen in Fig. 2.1, the S signal arriving from a range of 90 m is attenuated approximately 5 dB when it is received, and the sBs signal is attenuated approximately 20 dB. With the wider receive beam pattern of the experimental transducer, as seen in Fig. 2.17 (when no beamforming is applied), the S signal from that same range is now attenuated approximately 1 dB upon receive, and the sBs signal is attenuated approximately 12 dB. However, because the experimental array employs a narrow transmit pattern the S and sBs signals receive less transmit strength than if a \( \cos^2 \theta \) transmit beam is employed. From Fig. 2.18 it can be seen that the experimental array’s beam patterns do change the intensity of the S and sBs signals compared to the levels seen in Fig. 2.2, but that these changes are most pronounced when the signals are arriving from close range and become less pronounced as range increases.

At ranges beyond 100 m, the sum of the interfering signals has actually surpassed the intensity of the bottom signal. This behavior is influenced by the increased strength of the Bs signal compared to Fig. 2.2, caused by the wide receive beam pattern. However, the surface scattering and the Bs and sBs paths all approach the array from the surface and therefore can be attenuated by beam shaping (i.e. employing the thick solid curve in Fig. 2.17 on receive).

Fig. 2.19 shows the relative levels of the various paths when the shaped beam is employed on receive. Both the surface scattering and the sBs path levels are greatly reduced because they suffer the attenuation from both the tilted transmit pattern and the shaped receive pattern. The sB path is attenuated by the tilted transmit pattern, and the Bs path is attenuated by the shaped receive pattern. The contrast between the bottom signal and the combined interfering signals is greatly increased. The bottom signal is now approximately 13 dB above the sum of interfering signals instead of approximately 0 dB when no beamforming is used. The surface signal is now approximately 30 dB below the level of the bottom signal at a range of 130 m.

Attention is now turned to comparing the results (as shown in Fig. 2.3) obtained by an ordinary sidescan sonar that uses relatively narrow beams to the results of the experimental transducer employing receive beamforming. In both cases the contrast between the B signal and the sum of interference is approximately 13 dB, but the experimental array employing beamforming increases the contrast between the B signal and the S signal. The ordinary
CHAPTER 2. PROBLEM 1: SURFACE INTERFERENCE

Figure 2.17: Deployment scenario described in Fig. 2.1 but with the measured transmit beam pattern shown by the dash-dot curve, the measured receive pattern given by the thin solid curve, and the measured receive pattern when beamforming is applied shown by the thick solid curve. As before, sBs multipath signals are shown by the dashed line, and sB/Bs multipath signals are shown by the dotted line. Direct surface returns are shown by the thin solid line, and bottom returns are shown by the thick solid line.
Figure 2.18: Signal intensities as a function of slant range when the measured beam patterns of the experimental array are used and beamforming is not applied. The composite signal intensity when all interfering signals (S, sB, Bs, sBs) are added together is initially given by the surface signal (first received at a range of about 30 m) and then increases beyond the surface signal after about 60 m range. The bottom signal is given by the thick solid curve which comes in at a range of 10 m. The thin solid curve is the surface signal, the dotted curve is the Bs signal, the dash-dot curve is the sB signal, and the dashed curve is the sBs signal.
sidescan transducer provides a significant contrast ratio (approximately 15 dB) between B and S signals, but as shown here and later in Fig. 2.23, in situations where strong surface scattering is anticipated it is preferable to employ the proposed beam processing.

The effect the experimental array’s attenuating of the surface scattering and multipath signals on the highlight interference and shadow contrast is shown by simulation results in Fig. 2.20. The thin solid curve represents the total signal as it is received using the tilted transmit pattern and the wide single element pattern (i.e. the situation for the performance shown in Fig. 2.18). The highlight for the target is evident along with a second highlight from the Bs multipath signal, and the shadow behind the target highlight is filled in by the Bs multipath signal. The thick solid curve shows the total signal level after the shaped beam is applied. Although the bottom return is somewhat attenuated by the shaped beam at the farther ranges, the target highlight is evident along with the deep shadow (approximately 18 dB with beamforming, compared to approximately 4 dB without beamforming), and there is no evidence of the multipath signals. Hence, a sidescan transducer constructed to have a relatively narrow transmit beam and an array of six receive elements to shape the receive beam provides significant attenuation to surface scattering and multipath signals. This
Figure 2.20: Levels determined from the simulated received signal using measured beam patterns from the experimental array, when beamforming is applied on receive (thick solid curve) and when it is not (thin solid curve).

2.4 Field Results

In this section results from a field deployment of the experimental array are presented illustrating improvement in the sidescan images by employing a multi-element sidescan transducer. Theoretical calculations accompany the presentation of experimental data to help explain the results of the field survey and the effect of the beam processing. A comparison is made between the theoretical performance predictions of the prototype transducer array and an ordinary sidescan sonar.

2.4.1 Removing Strong Surface Interference

The sidescan image of Fig. 2.5 shows an image of a small wreck almost totally obscured by surface scattering. Surface scattering dominates the image due to the relatively strong backscatter from boat wake and surface chop compared to backscatter from the muddy bottom and the small wreck. Fig. 2.21 represents the situation under which the data
Figure 2.21: Signal intensities corresponding to the situation in which the data shown in Fig. 2.5 were collected, using the measured beam patterns of the experimental array. Surface and seafloor scatterers were assumed to have equal strengths. Because the transducer is now at a depth of 1 m, the surface signal arrives at a range of 1 m and is the only substantial source of interference until a range of 100 m. Accordingly, the curve corresponding to the sum of all interfering signals lays on top of the surface signal until approximately 100 m range. Beyond 100 m range, the surface signal lays slightly below the bottom signal (which is present beyond approximately 70 m range). The thickest solid curve is the bottom signal, the dotted curve is the Bs multipath signal, the dash-dot curve is the sB multipath signal, and the dashed curve is the sBs multipath signal.

for Fig. 2.5 were recorded, and helps explain the results that were obtained in the field by showing the relative intensity levels obtained for equal bottom and surface backscatter strengths. The assumption of equal backscatter strengths allows the contributions from each source to be compared. To be consistent with the field data, the transducer is modeled to be at a depth of 1 m and tilted at 15°, and the bottom depth is 70 m.

Since the transducer is close to the surface, the surface return enters immediately and decreases with increasing slant range due to spreading losses. The bottom return enters at a slant range of 69 m, corresponding to the height of the transducer above the bottom, and reaches an intensity level that is approximately the same as that for the surface scattering returns. This equality of bottom and surface scattering strength roughly represents the highlights of the wreck as compared with the backscatter strength of the surface. It is also evident from Fig. 2.21 that the sB multipath (if present during data collection) contributes
to the experimental return, although it is weaker than Bs multipath and surface scattering. Multipath may not have been present during data collection because strong surface backscatter has a tendency to hinder multipath propagation. As was discussed earlier the intensity of the sB multipath (if present) may be reduced by the tilt of the transmit beam. However, the tilt here is only 15° so the sB multipath is not attenuated as much as in Figs. 2.18 and 2.19.

In the sidescan image of Fig. 2.5 the far end of the shipwreck is located at approximately 125 m range, and in Fig. 2.21 the sum of interfering signals is approximately 3 dB stronger than the bottom signal at and beyond 125 m range, thus explaining the difficulty in visually identifying the wreck. If, however, the beam is shaped on receive to reduce the intensity of surface interference, the wreck becomes visible. Fig. 2.22 shows the effect of beam shaping on receive to reduce the surface scattering. The Bs multipath level is reduced by beam shaping because it arrives from the surface direction. The sB multipath level, however, remains the same, being attenuated only by the tilted transmit beam. The bottom signal at 265 m range, instead of being approximately 3 dB weaker than the sum of interfering signals, is now approximately 5 dB stronger than the sum of the interfering signals. The surface interference level drops by 26 dB as a result of beamforming, thus leaving a significant contrast between the wreck highlights and the surface interference. At a range of approximately 125 m, the B signal is now approximately 15 dB stronger than the sum of the interfering signals.
Figure 2.23: Comparison of primary (S and B only) signal intensities between the prototype array (thick curves) and the ordinary sidescan sonar modeled in Fig. 2.3 (thin curves). For both cases, the B signal is given by the solid curves first present at 70 m range, and the S signal is given by the dashed curves that appear at 1 m range. The situation being modeled is the field deployment that is presently under consideration, with the transducer at a depth of 1 m and the seafloor 70 m below the boat. The prototype array uses the beam processing method as in Fig. 2.21 with a tilt angle of 15°, and the ordinary sidescan uses its comparatively narrow beams and a tilt of 25°.

The prototype array is predicted to be significantly better than an ordinary sidescan sonar at attenuating S signals, as shown in Fig. 2.23. The ordinary sidescan is modeled at a tilt of 25° and achieves substantial S signal suppression using only its tilt angle and comparatively narrow beams. Different from Fig. 2.3 is that the ordinary sidescan is now modeled at a depth of 1 m (pole-mount deployment) in water 70 m deep. Accordingly, S signals arrive at a range of 1 m and B signals arrive at a range of 70 m in Fig. 2.23. At 250 m range the contrast between the B and S signals is 8 dB for the ordinary sidescan sonar, and the B signal intensity is 5 dB above the B signal intensity received with the prototype array when it uses beamforming. The prototype array is modeled as in Fig. 2.22. Surface signal rejection is significant when using the prototype array with the beam processing method outlined, resulting in a contrast ratio of 25 dB. Fig. 2.23 indicates that in situations where strong surface interference is anticipated to be a major concern, the prototype array and beamforming approach is preferred to an ordinary sidescan.
Fig. 2.24 shows the improvement that can be made to Fig. 2.5 if equal ripple beamforming, as previously described, is applied on receive using the prototype array. Surface interference is strongly suppressed, leaving a much clearer view of the seafloor and of the shipwreck. Due to the shallow depth of the transducer in the water (only 1 m below the surface) and also the 70 m depth of the seafloor, the sB multipath follows a path which has a similar, albeit non-identical, length to the direct B return. For this reason, if sB multipath is indeed present in the image shown in Fig. 2.24 then it is in very close registration with the bottom signal and would be difficult if not impossible to notice visually. Furthermore, because the surface produced significant scattering at most ranges, it is quite possible that the sB path was mostly absent from the data.

Some artifacts from the surface interference remain, but now the details of the seafloor are visible whereas before beamforming these details (such as the rocky outcropping or the shipwreck) were heavily obscured. This figure illustrates the need for an effective surface interference rejection technique, and also demonstrates that a small vertical array coupled with across-track beamforming is one such technique. Surface scattering rejection is especially important in shallow water environments such as this one because the muddy seafloor is a weak scatterer, hence the surface scattering (as seen in Fig. 2.5) was stronger than that of the seafloor.

Fig. 2.25 shows an expanded image of the wreck showing a shadow at the tail of the wreck and centered approximately at ping 220. A side-by-side comparison of Figs. 2.5 and 2.24 is shown in Fig. 2.26. Although the size of each Figure must be reduced in order to fit the page, the difference between the two images is evident.

To see the impact of the beam processing, the backscatter recorded for ping 220 is presented in Fig. 2.27, showing both the backscatter before the surface interference was removed (thin curve) and after (thick curve). The thick curve clearly shows the two edges of the wreck and the shadow behind it. On ping 220, the first edge of the wreck is at a range of roughly 100 m, the second edge is at a range of 125 m, and the acoustic shadow occurs immediately following this second edge. After beamforming, the shadow depth on this ping is increased by approximately 15 dB. As previously mentioned, shadows can be a useful tool in classification - in this case the shadow yields information about the height of the shipwreck relative to the seafloor.
## Problem 1: Surface Interference

**Figure 2.24:** Sidescan image shown in Fig. 2.5 but after beamforming is applied on receive. Surface reflections have been sharply attenuated, leaving a clear view of the seafloor and revealing a shipwreck towards the center of the image.
Figure 2.25: Close-up view of the shipwreck shown on the side-scan image in Fig. 2.24.

Figure 2.26: Side-by-side comparison of Figs. 2.5 (left) and 2.24 (right), showing a sidescan image before and after the fixed broad beam is used to suppress the surface interference that was otherwise obscuring a shipwreck.
2.5 Qualitative Comparison: MVDR

To illustrate the potential for the introduction of artifacts into the sidescan signals and images by MVDR, a brief comparison is given between the results obtained using the proposed fixed broad beam with results obtained using one realization of MVDR beamforming. This comparison is limited in scope because only one realization of MVDR is given, and is qualitative in nature. As seen in the sidescan images created using MVDR, this comparison illustrates the potential for the introduction of artifacts into the sidescan image by the MVDR algorithm. Although other realizations of the MVDR beamformer are possible, the present comparison illustrates the possibility for a data-dependent beamformer to introduce data-dependent artifacts into the sidescan signal or image.

The MVDR weight vector is obtained via

\[
\mathbf{w}_{\text{mvdr}} = \frac{\mathbf{\hat{R}}^{-1} \mathbf{b}_{\text{mvdr}}}{\mathbf{b}_{\text{mvdr}}^H \mathbf{\hat{R}}^{-1} \mathbf{b}_{\text{mvdr}}} \quad (2.5)
\]

Figure 2.27: Measured receive signal intensity from ping 220 in the side-scan data, when beamforming is applied on receive (thick curve) and when it is not applied (thin curve).
where $b_{mvdr}$ is the steering vector

$$
\begin{align*}
    b_{mvdr} &= \begin{pmatrix}
        1 \\
        \exp(-j\alpha) \\
        \exp(-j2\alpha) \\
        \exp(-j3\alpha) \\
        \exp(-j4\alpha) \\
        \exp(-j5\alpha)
    \end{pmatrix}
\end{align*}
$$

that “sweeps” along the seafloor during the processing of each ping. The difference between this look direction and the center of the fixed broad beam in Eq. 2.4 is that $b_{mvdr}$ changes during the processing of each ping, and $b$ in Eq. 2.4 does not change. The correlation matrix may be estimated by

$$
\hat{R} = \frac{1}{M} \sum_{m=0}^{M-1} x[m]x^H[m]
$$

where the estimate uses $M$ time samples from the data vector $x$.

Techniques such as diagonal loading may be used to essentially broaden the main lobe, and the correlation matrix estimate can incorporate different numbers of time samples [19]. Additionally, the look direction can be determined in different ways (assuming a flat seafloor at depth $D_1$, assuming a sloping seafloor that begins at depth $D_2$, etc.). Accordingly, caution must be exercised when drawing general conclusions from the limited scope of this qualitative comparison.

Fig. 2.28 shows the result of processing the data shown in Fig. 2.5 using one realization of the MVDR beamformer. In this realization of the MVDR beamformer, the correlation matrix is estimated using five adjacent time samples ($M = 5$), and diagonal loading is not used. The seafloor is assumed to be at a constant depth of 70 m, and the look direction is calculated accordingly. The surface interference has been attenuated, and the shipwreck is now visible, but the result is a “grainy” image. Some of the textural details visible in Fig. 2.24 are lost, as noted when looking at the rocky outcropping in pings 1 to 100, or at the muddy seafloor in the vicinity of the shipwreck. The loss of textural information in the region of the rocky outcropping is attributable to the use of the flat seafloor assumption and to the assumption that the depth is constant at 70 m. This result stresses the importance that the look direction be accurately known when using this adaptive algorithm. To better
## Chapter 2. Problem 1: Surface Interference

<table>
<thead>
<tr>
<th>Slant Range (m)</th>
<th>Ping Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
</tr>
</tbody>
</table>

Figure 2.28: Sidescan image shown in Fig. 2.5 after a realization of MVDR beamforming is applied on receive. Surface interference has been attenuated, and the shipwreck towards the center of the image is now visible. However, a “grainy” image has resulted.
visualize the difference in processing results, both Figures are shown at reduced size but side-by-side in Fig. 2.29.

Although this is only a single realization of the MVDR beamformer, this example illustrates the problems and potential costs (i.e. loss of textural information) that can be encountered when using this adaptive algorithm. Other researchers have conducted extensive work in the application of different adaptive algorithms to sonar data [19], and noted certain issues with MVDR that warranted consideration (such as look direction/signal direction mismatch, and the possibility that the signal could inadvertently be suppressed). However, for the suppression of surface interference, this thesis proposes the use of a simple fixed broad beam that does not require a look direction and does not destroy textural clues of the seafloor.

2.6 Chapter Summary

The Chapter addresses the improvement of shallow-water sidescan images that can be obtained using a vertically-stacked array to attenuate surface interference for purposes such as habitat and target classification. The importance of suppressing surface interference from shallow-water sidescan images was discussed, as was the ability of a small vertical array to
accomplish this goal. By utilizing a vertical stack of receive elements, beamforming may be applied on receive in post-processing to shape the across-track beam. By shaping the beam appropriately, interfering signals from sources such as surface scattering can be greatly attenuated and signals from the bottom can be preserved. The importance of suppressing surface signals was demonstrated through theory, simulation, and experimental data. The proposed method is general in the sense that the beam parameters can be changed depending upon the sonar deployment and the survey environment, and these changes can even be made after the survey has occurred.
Chapter 3

Problem 2: Bottom-Bounce

Multipath

In the previous Chapter, the problem of surface interference contaminating sidescan images (and the signals that create them) was considered. The use of a fixed broad beam is proposed as a solution to this problem, whereby the receive array’s response in the direction of the surface is minimized. However, this same approach does not solve the problem of interference that arrives from the direction of the seafloor. In this Chapter, the use of time-varying across-track beam processing (on receive) to suppress multipath signals that arrive from the direction of the bottom is investigated.

Sonar signals scatter or reflect off of either the sea surface or off the bottom, depending upon the nature of the boundaries. A calm sea surface acts as a reflector, complicating the signal structure by reflecting either transmitted signals or signals that have already scattered on the bottom. Multipath signals of this sort appear as delayed versions of the bottom signal, with the delay depending upon the number of reflections and the total path length, and the result is a masking of the seafloor. The sea surface can also act as a scatterer when wave action is sufficiently rough, when boat wake is present, or when floating scatterers such as logs and tide lines are present. Direct surface returns deteriorate the quality of sidescan imagery by introducing signals that have nothing to do with the seafloor.

It is understood that multipath interference can arrive from the direction of the sea surface, but it is also known that multipath can arrive from the direction of the seafloor (for instance, see [7], [8], [9], and [16]). To address the issue of multipath interference adversely
affecting sidescan sonar systems, it is ultimately desirable to suppress multipath signals arriving from both the surface and the seafloor. However, multipath signals arriving from the seafloor present a special challenge due to the fact that they arrive from a direction similar to the direct bottom return.

To solve this problem, recent attention has turned to implementing beamforming on an array of receivers (for instance, see [17], [20], [25], and [27]). In [19], an investigation into adaptive beamforming techniques is presented. In the previous Chapter, the feasibility of using conventional (data-independent) beamforming is explored within the context of surface signal removal using a vertically stacked array. The present Chapter builds upon the results presented in [28] by considering the removal of bottom-bounce multipath using conventional beamforming techniques applied in a time-varying manner.

The motivation for using conventional beamforming techniques in a time-varying manner is to avoid introducing artifacts into the sidescan images that result from the data and the processing. With conventional beamforming techniques, the user is in direct control over the beampattern. When adaptive beamforming is used, such as minimum-variance distortionless response beamforming (MVDR), the algorithm is in control of the beampattern - subject to certain constraints such as unity gain in the look direction. If an interfering signal arrives within the Rayleigh beamwidth of the array, the gain in the look direction (constrained to be unity) may be less than the gain outside of the look direction [24, pp. 458-465]. Under some circumstances, this can introduce unwanted artifacts to the sidescan data and subsequently into the “cleaned up” sidescan image.

When using MVDR, multiple time samples may be averaged to improve the estimate of the correlation matrix, which is used to calculate the weight vector. However, the angles of arrival for the signal and any interference may not be constant within this window of samples. Artifacts result if there is a mismatch between the specified look direction and the actual arrival angle of the signal, or if the arrival angle of an interferer is not constant within the averaging window and the interference arrives within the Rayleigh resolution limit. The adapted weight vector is either applied to the average of the time samples (which reduces resolution) or it is applied to the individual time samples (which introduces artifacts). Since the overall objective is to remove unwanted artifacts from the sidescan image without decreasing image resolution, this Chapter explores time-varying conventional beamforming techniques.

Following this introduction, Section 3.1 of this Chapter presents a description of the
problem posed by bottom-bounce multipath interference. The notation used to describe signals is consistent with that used in the previous Chapter, where upper case letters indicate that scattering occurred at a boundary and lower case letters indicate that a reflection occurred. Two examples of bottom masking by bottom-bounce multipath signals obtained from “real” sonar data are presented in the form of sidescan images, and two intensity level calculations are also presented that further illustrate the problem at hand. The first example demonstrates masking caused by a bottom-surface-bottom (Bsb) signal, and the second example shows masking caused by surface (S), surface-bottom (Sb), and bottom-surface-bottom (bSb) signals. In Section 3.2, a solution is presented that eliminates the Bsb signal by altering the parameters of the fixed beam prior to the arrival of the Bsb signal. In Section 3.3 a solution is presented that eliminates the Sb and bSb signals from the second example sidescan image by introducing a null in the receive beampattern that rejects this interference. These approaches proposed in this chapter are compared against two realizations of the adaptive MVDR technique in Section 3.4. Finally, in Section 3.5, conclusions are drawn and recommendations for future work are presented.

3.1 Bottom-Bounce Multipath: Defining the Problem

Multipath signals arriving from the direction of the bottom are difficult to remove because they arrive from a direction in which the desired signal (the B signal) also arrives. The challenge is to receive the B signal at full intensity, yet reject the interference. Utilizing a vertically stacked array of receivers to implement beamforming techniques, it is possible to realize this objective.

EdgeTech provided some of their field data to the author, and these data illustrate the bottom-bounce multipath that is not simple to address. Figs. 3.1 and 3.2 have been created from data collected by EdgeTech using an EdgeTech 4600 sonar (8-receive staves, carrier frequency of 540 kHz) on a pole-mount deployment. The data were recorded in areas where the seafloor is relatively flat and the water shallow. Fig. 3.1 contains a strong bottom-surface-bottom (Bsb) multipath, and Fig. 3.2 contains multiple interfering signals which are all caused by the presence of a boat wake on an otherwise calm sea surface. Multipath signals have been identified using the angle of arrival estimation method developed by Kraeutner and Bird [35], which determines the arrival time (range) and angle of the received signals. From the single ping profiles created by this method, the nature of the interfering signals
has been determined. Specifically, bottom bounce multipath are identifiable because they appear to originate from beneath the seafloor. In other words, bottom bounce multipath arrive from the same angle as a direct B return but have a much greater travel time. A bSb signal, for instance, arrives from an angle consistent with a portion of the seafloor but takes a longer path than a direct B return from that location; the bSb signal initially reflects off the bottom, travels to the surface and scatters, and then returns via the same route.

Fig. 3.1 shows an image of the seafloor where a noticeable Bsb multipath signal is present. The seafloor is roughly 13 m below the surface of the water, and the transducer is deployed at a depth of roughly 1 m. The Bsb signal is seen at a range of approximately 25 m; this multipath is a delayed replica of the bottom (B) signal which arrives at a range of approximately 12 m. The interference is strongest in the vicinity of 25 m range, and appears to attenuate as range increases. The receive processing that was outlined in [28] is insufficient to remove Bsb interference because this interference arrives from the direction of the bottom.

The second EdgeTech data file clearly illustrates the problems caused by direct surface interference and bottom-bounce multipath. In Fig. 3.2, at a range of approximately 45 m on ping number 400, a boat wake is seen in the image. This boat wake is seen in subsequent pings at greater than 45 m range. The primary interfering S signal appears once, followed by two delayed replicas of this signal. Multipath signals produce these delayed replicas of the S signal; on ping 400 the first replica appears at a range of approximately 48 m and the second replica appears around 51 m range. These two delayed replicas of the interfering signal are the surface-bottom (Sb) and bottom-surface-bottom (bSb) signals. Note that in this case, the scattering event takes place primarily at the sea surface rather than at the seafloor (as in Fig. 3.1).

To better characterize the problem at hand, it is important to consider the geometry of the deployments and the beampatterns of the system (which are different from the prototype array discussed in Chapter 2). This is done in the following subsection, where relevant beampatterns and angle conventions are also defined. With this information, it is possible to create relative intensity level plots for the received signals after some simplifying assumptions have been made. As in Chapter 2 the intensity level plots facilitate a meaningful discussion about changes to the intensity of received signals as a result of changes to the receive beampattern.
### Figure 3.1: Field data collected by EdgeTech showing strong bottom-surface-bottom multipath at a range of approximately 25 m. The seafloor is roughly 13 m below the surface, and the transducer is deployed at a depth of about 1 m.
Figure 3.2: Field data collected by EdgeTech showing strong surface interference and bottom-bounce multipath. A boat wake is clearly visible at a range of approximately 45 m on ping number 400, followed by two delayed replicas of this signal.
Figure 3.3: Diagram of relevant deployment parameters. Angle $\gamma_t$ is the tilt angle of the array, with inter-element spacing $d$, deployed at depth $T$ m below the surface and $h$ m above the seafloor. The method of images is used to show the path of a bSb signal, characterized by physical angle $\theta_j$.

### 3.1.1 Sonar System and Deployment Geometry

Fig. 3.3 shows some of the relevant system parameters and terms that are used to describe the system geometry. An array is deployed $T$ m below the surface and $h$ m above the seafloor, and is tilted at an angle of $\gamma_t$ below horizontal. Inter-element separation is given by $d$, and an interfering signal is seen to arrive from angle $\theta_j$. For clarity, the geometry is exaggerated (in particular, the deployment depth $T$ and the inter-element separation $d$ are greatly increased for this diagram) and only two elements are shown. In this case, the return paths of both the Sb and bSb signals are shown (both signals follow the same return path). The method of images is used to reflect the surface about the seafloor to clearly show the path taken by the multipath signals. While the bSb signal also traveled this path in the opposite direction (from the transducer, down to the seafloor, then up to the boat wake) before following a reciprocal path back to the transducer, the Sb signal did not. Instead, the Sb signal traveled directly from the transducer to the boat wake, where it scattered and then returned to the transducer along the path shown.

The sonar system that was used to collect the experimental data shown in Figs. 3.1 and 3.2 is an EdgeTech 4600 [30]. This sonar system uses eight vertically stacked receive
staves, and the receive stave intensity pattern is approximated by $\cos^{5.5}(\theta)$ for a beamwidth of $\approx 56^\circ$. The transmitter is approximated by a $\cos^{8.5}(\theta)$ intensity pattern for a beamwidth of $\approx 46^\circ$. The standard tilt angle for an EdgeTech 4600 is $\gamma_t = 30^\circ$ below horizontal. Fig. 3.4 shows a diagram of these transmit and receive patterns, with intensity decades in dB given by the concentric half-circles. The fixed broad beam that is used to suppress S signals on receive is given by the thick solid curve.

As discussed in [28] a direct surface return can be suppressed using the array of receivers to form a fixed broad beam that rejects S signals. However, the fixed broad beam in [28] is insufficient to reject the bottom-bounce multipath shown in Figs. 3.1 and 3.2. To facilitate a discussion about the impact of these interfering signals on the resulting sidescan images, it is necessary to characterize the relative intensity levels of the received signals.

### 3.1.2 Intensity Level Calculations

Having described the multipath signals which are under consideration, the signals that were observed are now defined in terms of their relative intensity. The interfering Bsb signal
present in Fig. 3.1 is treated first due to its simplicity, followed by the Sb and bSb signals shown in Fig. 3.2. The model that is used to calculate the intensity of the received signals is the same as in Chapter 2; it is primarily designed to facilitate a meaningful analysis of relative intensity levels. While there are many factors which influence the absolute intensity of received signals, the approach taken is to limit the complexity of the model while capturing the essence of the problem.

The seafloor is assumed to be composed of scatterers at a uniform density and with uniform scattering strength. When modeling interference resulting from boat wake, surface scatterers are modeled in the same manner as seafloor scatterers. Because the model is designed to explore the impact of receive beam shape on the intensity of various signals, an assumption of equal scattering strength (between the surface and the seafloor) is made so results can be extrapolated to other settings. As in the previous Chapter, results can be extrapolated to describe a setting where direct surface returns are estimated to be 3 dB weaker than direct bottom returns by simply subtracting 3 dB from the calculated values.

The model takes spherical spreading loss into account and does not correct for it, and the footprint of the signal is calculated as a function of range. Thermal noise is not included in the model so that attention can be focused on changes in signal intensity level that result from changes in the receive beampattern. Signals are assumed to either completely scatter or completely reflect off any boundary (sea surface or seafloor) they encounter. In this sense the signals under consideration are shown at maximum relative intensity. In actual practice, signals such as the Bsb signal may undergo partial reflections where some intensity is lost at a boundary, thereby causing the received signal to be weaker than what the model predicts, but its maximum relative intensity will not be greater than predicted.

**Bsb Signal**

In order to calculate relative intensities, it is necessary to describe the relevant system geometry. Fig. 3.5 presents a diagram of the experimental setup for the location where the data shown in Fig. 3.1 were collected. The dashed line is the route taken by the Bsb signal, extended below the bottom to indicate the range (time) at which it was received. The thick curve is the fixed broad beam proposed in [28] for S signal suppression, and its intensity decades in dB are given by the concentric half-circles.

The survey area in Fig. 3.1 is known to have a relatively constant depth, therefore the flat seafloor assumption is used to simplify the problem at hand while still allowing
Figure 3.5: Diagram of the experimental setup for the location where the data shown in Fig. 3.1 were collected. The seafloor is 13 m below the surface, and the transducer is located 1 m below the surface at location (0, -1) m. The dashed line shows the path traveled by the Bsb signal at nadir, and it is extended to indicate the range (time) at which it is received. The fixed broad beam (proposed in [28] to suppress surface signals is given by the thick curve, the transmit intensity pattern is given by the dash-dot curve, and intensity decades are given by concentric half-circles.
Figure 3.6: Calculation of the relative intensity of the primary signals (B and Bsb) which were present when the data for Fig. 3.1 were collected. The transducer is assumed to be at 1 m depth, the flat seafloor is 12 m below the transducer. The intensity of the bottom signal (B) is given by the thick solid curve, and the intensity of the Bsb multipath signal is given by the dashed curve. The sum of both the B and Bsb signals is given by the solid curve that separates from the B signal at approximately 25 m slant range.

for an effective solution to be found. Fig. 3.6 shows the relative intensity of the primary signals that were present when the data for Fig. 3.1 were collected, assuming the fixed broad beam is used in processing. (The “no beamforming” intensity levels are omitted because there is little difference in the relative intensity between signal and interference with and without the fixed broad beam in the case of the Bsb signal.) In the next Section, these calculations of relative intensity levels are repeated when the proposed time-varying beamforming methodology is implemented that modifies the fixed broad beam during the processing of each ping.

Fig. 3.6 shows the intensity of the bottom (B) signal in the thick solid curve being approximately equalled by the intensity of the bottom-surface-bottom (Bsb) signal in the dashed curve. The sum of both the B and Bsb signals is given by the solid curve that separates from the B signal at approximately 25 m slant range. Because of the system geometry, the direct B signal appears at a range of 12 m and the Bsb signal appears at a range of 25 m (consistent with Fig. 3.1). This intensity level calculation assumes that the Bsb signal continues to be received after a range of 25 m. The bottom masking that
is possible from a Bs signal is clearly evidenced: the intensity of the Bs signal quickly reaches a level similar to the B signal, and gradually surpasses it throughout the remainder of the ping.

In Fig. 3.1 the Bs signal appears to lose intensity quickly after it is received. This discrepancy between the model and the physical data is likely attributable to the model’s assumption that signals either completely scatter or completely reflect. Nevertheless, it is necessary to develop a methodology that suppresses such a potentially strong bottom-bounce multipath signal.

**Sb and bSb Signals**

Having described the interference which is present in Fig. 3.1, attention is turned to the interference which is present in Fig. 3.2. The survey area represented in Fig. 3.2 is a relatively flat seafloor, but it not perfectly flat. Although the bottom is 10 m below the transducer at nadir, the interfering signals (Sb and bSb) reflect elsewhere in a location where the bottom is roughly 2 m deeper. Therefore, the following analysis assumes the seafloor to be at a constant depth of 13 m with the transducer located 1 m below the surface. Although the true seafloor is not perfectly flat, these assumptions simplify the analysis and allow focus to be maintained on evaluating the effectiveness of the proposed beam processing methods.

Fig. 3.7 depicts the route taken by the interfering signals as they return to the transducer. The dashed line indicates the paths traveled by both the Sb and bSb signals. The Sb signal travels directly from the transducer to the wake (along the surface), then returns via a bottom bounce. The bSb signal travels a reciprocal course via a bottom bounce both to and from the wake. The two-way path length of the Sb signal is calculated as 96.4 m and the total path length of the bSb signal is 103 m. These two signals are therefore expected to appear in the sidescan image at ranges of approximately 48.2 m and 51.5 m from the array, respectively. The scattering event for each signal occurs at a similar location on the surface (a horizontal distance of 45 m from the array). These calculations are consistent with the experimental data that are being modeled.

The transmit beampattern and fixed broad beam receive pattern are shown in Fig. 3.7, with the signal paths superimposed. Looking at the signal paths, it is clear that the fixed broad beam is insufficient to reduce the sensitivity to the bottom-bounce multipath signals since they arrive through the main lobe. The S signal follows a direct route along the surface, and is attenuated by the fixed broad beam, but the Sb and bSb signals are not attenuated.
Figure 3.7: Diagram of the beampatterns and experimental setup for the location where the data shown in Fig. 3.2 were collected. The model assumes that the seafloor is 13 m below the surface, and the transducer is 1 m below the surface. The Sb signal follows the entire dashed line; it leaves the transducer and travels directly to the wake, then scatters and returns via a bottom bounce. The bSb signal travels a reciprocal course via the bottom bounce shown by the dashed line and does not take the direct route to the wake (along the surface). The fixed broad beam proposed in [28] to suppress surface signals is given by the thick curve, the transmit pattern is given by the dash-dot curve, and intensity decades are given by concentric half-circles.
A calculation of the relative intensity of the signals that were received when the data shown in Fig. 3.2 were collected is shown in Fig. 3.8. The intensity of the B signal is given by the thick solid curve; it is first received at 12 m range and is the only signal present until the direct surface return from the wake (given by the thin solid curve) arrives at 45 m range. Multipath signals that are replicas of the S signal are received at roughly 48.2 m range and 51.5 m range, the Sb (dotted curve) and bSb signal (dashed curve) respectively. To model the wake in Fig. 3.2 the multipath signals are taken to have a finite duration. Surface scattering is assumed to only occur between 45 m and 45.5 m horizontal range (at a depth of 0 m) to model the boat wake. Accordingly, all interfering signals have a small duration in time (range). When the fixed broad beam is not used, the S signal is 7.5 dB weaker than the B signal (again, under the assumption of equal scattering strength of the surface and the seafloor). As illustrated by the sidescan image in Fig. 3.2, sometimes surface scattering is significantly stronger than bottom scattering, therefore it is desirable to implement the fixed broad beam to achieve significant discrimination.

When the fixed broad beam is used, the relative intensity levels of the signals are given by Fig. 3.9. The fixed broad beam attenuates the S signal 32 dB below the intensity of
the bottom signal at 45 m range. However, as expected this approach does not eliminate multipath signals that return from the direction of the seafloor. The intensity of the Sb signal is 1 dB stronger than the bottom signal (at 48.2 m range), and the bSb signal arrives last because of its longer path length and its intensity is approximately 8 dB greater than that of the bottom signal at 51.5 m range. These differences in intensity result from differences between the arrival angle and transmission angle for each signal as they “pass through” the transmit beam and receive beam. The intensity of the Sb and bSb signals in Fig. 3.2 is lower than predicted by the model because the model primarily explores the effect of beampatterns on received intensity; the model does not allow for partial seafloor reflections that would reduce the intensity of the received signals.

Additional measures beyond the fixed broad beam are necessary in order to reveal the true characteristics of the seafloor by removing the masking effects of the multipath. This problem is addressed by altering the shape of the beam to achieve the desired interference suppression. By carefully controlling the manner and timing by which the beam is altered, the interference is suppressed and the desired bottom return is preserved.
3.2 Removal of Bsb Signal

In the previous Section, the nature of the interfering signals was established. They were characterized in terms of the time (range) at which they are observed, their relative intensity, and also in terms of their direction of arrival. By using the knowledge of the time (range) and estimate of the AOA at which the multipath signals are observed, it is possible to suppress them by using this information to guide the time-varying beamforming procedure.

The impact of time-varying beamforming is seen through changes in the relative intensity of the signals. By varying the characteristics of the receive beam at the right time, it is shown that the multipath signals are attenuated while leaving the desired bottom signal nearly unaltered. First, intensity level calculations are presented to illustrate the potential for bottom-bounce interference suppression that can be realized. Second, the sidescan image presented in Fig. 3.1 is “cleaned up” using time-varying beamforming, illustrating the effectiveness of the proposed method at removing interference in a field setting.

3.2.1 Intensity Level Calculations

The interference caused by Bsb signals may be removed from a sidescan image by altering the parameters of the beam at the appropriate time. These multipath signals must travel twice the distance of the direct B return that they replicate, so by altering the shape of the beam at (or slightly before) a range/time corresponding to twice the water depth, these signals may be attenuated. In Fig. 3.10 the parameters used for beamforming are described. For this analysis, it is assumed that a fixed broad beam is employed (as specified in Chapter 2) for surface signal rejection. The desired vertical extent of the across-track beam is given by angles $\theta_1$ and $\theta_2$ (again, the tilt angle is $\gamma_t$) for an array located 1 m below the surface. In Fig. 3.10 the angles and depths are arbitrary and were chosen to aid with illustration. In reality, the tilt angle of the EdgeTech 4600 is 30°.

In the case of the Bsb signal shown in Fig. 3.1 the water is 13 m deep and the seafloor is 12 m below the transducer, so the beam should change shape at a range/time before 25 m (at which point the Bsb signal is received). Accordingly, 24 m is chosen as the range at which to alter the beampattern. At this range in the processing of each ping, $\theta_2$ is changed from its previous value of $\theta_2 = 90^\circ$ (as specified in [28]) to a new value of $\theta_2 = 50^\circ$.

Fig. 3.11 provides a diagram of the physical setup and beampatterns under consideration. The beampattern which is used to process the first 24 m of each ping is given by the
CHAPTER 3. PROBLEM 2: BOTTOM-BOUNCE MULTIPATH

Figure 3.10: Diagram of parameters to be used in beamforming. Angles $\theta_1$ and $\theta_2$ define the desired extent of the beam on the bottom, and angle $\gamma_t$ is the tilt angle of the array. In this figure, angles and depths are arbitrary.

Figure 3.11: Diagram of the relevant beam patterns and multipath interference. The seafloor is the rough black line at a depth of 13 m. The transducer is taken to be at a depth of 1 m, and the concentric half-circles indicate the intensity decades of its beam patterns. The dash-dot curve shows the receive beampattern which is used to process the first 24 m of each ping, and the solid curve shows the beampattern which is used to process the remainder of each ping. The dashed black line shows the route taken by the bsB and Bsb signals at nadir, when they are strongest and most visible in Fig. 3.1.
Figure 3.12: Calculation of the intensity of the received signals which were present when the data for Fig. 3.1 were collected, but when processed using the time-varying approach for bsB/Bsb signal removal. The intensity of the B signal is given by the thick solid curve, the intensity of the Bsb signal is given by the dashed curve, and the sum of both signals is given by the thin solid curve. At a range of 24 m (given by the vertical dashed black line) the beam parameter $\theta_2$ is altered as described. The intensity of the Bsb signal is initially attenuated by the processing, but beyond 45 m range its intensity approaches that of the B signal.

dash-dot black curve, and the beam pattern which processes the remainder of each ping is given by the solid curve. Concentric half-circles indicate the intensity decades of the beam responses, and the direction of arrival (at nadir) of the Bsb signals is given by the vertical dashed line. The Bsb signal travels a vertical route at nadir and appears to arrive from range of 25 m below the array.

Fig. 3.12 is a calculation of the intensity of the received signals when $\theta_2$ is altered to be $\theta_2 = 50^\circ$ immediately before the Bsb signal arrives. As in Fig. 3.6, the B signal is given by the thick curve, the Bsb signal is given by the dashed curve, and the sum of both signals is given by the thin solid curve. The dashed vertical line at a range of 24 m indicates the point at which the beam is altered. Because of the modified beampattern, the Bsb signal is significantly attenuated beyond a range of 30 m, while the B signal is preserved. The Bsb signal strength increases beyond this range and is eventually comparable to the B signal at a range of approximately 45 m, however.
Figure 3.13: Calculation of the intensity of the received signals which were present when the data for Fig. 3.1 were collected. The parameters of the receive beam are altered twice (once at a range of 24 m, and once at a range of 34 m) during the processing of the ping. Greater separation between the B signal (thick curve) and the Bsb signal (dashed curve) is achieved than in Fig. 3.12.

It is possible to alter the beam parameters a second time, to achieve better separation between the interfering signals and the B signal. This is desirable because by 50 m slant range the interfering Bsb signal has greater intensity than the B signal. Fig. 3.13 shows the intensity levels of the relevant signals when the beam is altered not only at a range of 24 m (as previously described) but also altered at a range of 34 m. When the beam is altered the second time, $\theta_2 = 40^\circ$ and $\theta_1 = 15^\circ$. Note that these parameters have been chosen so the B signal intensity is nearly continuous across the transition points and is not subject to an abrupt change. Using a knowledge of the direction of arrival of the B signal at the time the beam is adjusted, the beam is adjusted in such a way that the response to the B signal is preserved.

By altering the beam parameters a second time, the Bsb signal is greatly suppressed and B signal intensity is preserved. Note that the model does not correct for spherical spreading loss (there is no time varying gain), causing signal intensity to diminish with range. Attention is now turned to seeing this method applied to “real” field data. The field data have been corrected for spherical spreading, and in field deployments signal intensity also depends upon many factors including grazing angle and bottom substrate in addition
to the beampatterns of the sonar. While the model for Fig. 3.13 shows decreasing signal strength with range, field data may exhibit different behavior. In the following subsection, the data used to create the sidescan image in Fig. 3.1 are processed using the time-varying method that preserves the B signal and suppresses the Bsb signal.

### 3.2.2 Field Data

By applying the time-varying beamforming approach that was described in the preceding subsection which simply alters the parameters of the fixed broad beam, the Bsb signal is attenuated. Fig. 3.14 provides a clear look at the seafloor which had previously been obscured in Fig. 3.1. In keeping with the processing described in [28], the first 24 m of the ping are processed with the lower extent of the beam equal to $\theta_2 = 90^\circ$. Between 24 m range and 34 m range, the lower extent of the beam changes to $\theta_2 = 50^\circ$. Beyond 34 m range, the remainder of each ping is processed with $\theta_2 = 40^\circ$ and $\theta_1 = 15^\circ$.

For easier comparison, Figs. 3.1 and 3.14 are presented side-by-side in Fig. 3.15. The resulting image created using the proposed processing method is a significant improvement over Fig. 3.1, with no obvious remnants of the Bsb signal. The time-varying beamforming method successful removes the interfering signals from Fig. 3.1. In the following section, time-varying beamforming is used to address the Sb and bSb interference that was shown in Fig. 3.2.

### 3.3 Removal of Sb and bSb Signals

As with the removal of the Bsb signal, by changing the receive beam before bottom-bounce (Sb and bSb) signals arrive, a clear image of the seafloor can be obtained. The Sb and bSb signals shown in Fig. 3.2 arrive through the main lobe near boresight, which makes it more difficult to suppress the interference while preserving the B signal. In this case, the interference does not arrive from a wide range of angles (as the Bsb signal does in the previous example) but rather from a very small range of angles such that a single null placed inside the receive beam is capable of rejecting both signals.

Null-steering is the signal processing technique that is used to accomplish the multipath rejection. This approach to interference removal is employed in radar and communications for suppressing jamming signals, but has yet to receive much attention in the sidescan sonar literature. Harry Van Trees [24, pp. 165-173] provides a wealth of information about this
Figure 3.14: Field data collected by EdgeTech (the same data used to create Fig. 3.1) processed using the time-varying beamforming approach which simply alters the parameters of the equal ripple beam. The Bsb signal is removed and a sharp view of the seafloor is provided.
CHAPTER 3. PROBLEM 2: BOTTOM-BOUNCE MULTIPATH  

<table>
<thead>
<tr>
<th>Ping Number</th>
<th>Slant Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>350</td>
<td>400</td>
</tr>
<tr>
<td>450</td>
<td></td>
</tr>
</tbody>
</table>

Adaptive beamforming techniques such as MVDR give control of the beampattern to the algorithm. The proposed conventional beamforming techniques differ from adaptive techniques by placing control of the beampattern in the hands of the user. As previously mentioned, the author’s approach is motivated out of a desire to prevent artifacts from being introduced into the resulting sidescan image by the processing. A single null is introduced inside the main lobe, and the gain is then manually adjusted so that beamformer response in the B signal’s arrival angle is unchanged by the processing. In this way, the introduction of artifacts to the sidescan image is avoided.

3.3.1 Null-Steering

The first step in the application of null steering to sidescan sonar data is to calculate the angle of arrival of the interfering signal(s), $\text{AOA}_j$, from the difference between the physical angle $\theta_j$ and the tilt angle $\gamma_t$. The seafloor in the location where the data shown in Fig. 3.2 were collected is not perfectly horizontal, however the arrival angle of both the multipath signals is approximately the same. The flat seafloor assumption is used only to model the intensity of the multipath signals, but is not required when applying the null-steering approach to experimental data.

Figure 3.15: Side-by-side comparison of Figs. 3.1 (left) and 3.14 (right). A Bsb signal contaminates a sidescan image (left) but is removed by using time-varying conventional beamforming (right) that alters the extent of the receive beam.
As previously mentioned, bottom-bounce multipath signals are identified when looking at single ping profiles created using the method described in [35]. Because bottom bounce multipath arrive from an angle consistent with a portion of the seafloor, but travel a longer course than a direct B signal from that location, the multipath signal(s) appear to originate significantly below the seafloor. The multipath signals in Fig. 3.2 arrive from a perceived location of approximately (40, -28.5) m, or (40, -27.5) m relative to the array at a deployment depth of 1 m, which makes the arrival angle equal to

\[
AOA_j = \theta_j - \gamma_j \\
= \tan^{-1}(27.5/40) - 30 \\
= 4.5^\circ
\]

which corresponds to a signal arriving from just “below” the boresight of the transducer. This location is termed the ‘perceived location’ because the angle of arrival estimation algorithm assumes that signals travel a reciprocal path, when in reality some multipath signals (for instance, the Sb signal) do not.

The corresponding electrical angle between receiver elements is then computed from \( AOA_j \). For a sidescan sonar where the elements are spaced at intervals of \( d \) meters, the electrical angle of the interfering signal is

\[
\alpha = \frac{2\pi d}{\lambda} \sin(AOA_j)
\]

where \( \lambda \) is the wavelength and \( \alpha \) is the electrical angle of the interfering signal. Note that it is possible to specify multiple \( AOA_j \) angles if multiple interfering signals are present, but the number of elements in the array \( N \) constrains the maximum number of constraints to be \( N - 1 \) or fewer [24, pp. 167-168]. If only a single interference angle is specified, then a constraint vector \( C \) is created as such:

\[
C = \begin{pmatrix} 
1 \\
\exp(j\alpha) \\
\exp(j2\alpha) \\
\vdots \\
\exp(j(N-1)\alpha) 
\end{pmatrix}.
\]

If multiple interference angles are specified, the constraint vector \( C \), being an \( (N \times 1) \) vector, becomes a concatenation of similar vectors such that it forms a matrix of dimensions \( (N \times 1) \).
where \( m_j \) is the number of interference angles specified and obeys the constraint 
\[ m_j \leq (N - 1). \]

If beamforming has already been applied, which is the case that is currently under 
consideration, the \((1 \times N)\) element weight vector which shaped the beam (without null-
steering) is \( w_0 \). To modify the original weight vector so that the beam is constrained to 
have a null at angle(s) \( \text{AOA}_j \), the following operation is performed:

\[
\begin{align*}
   w_n H &= w_0 H \left[ I_N - C (C^H C)^{-1} C^H \right] 
\end{align*}
\]

where \( H \) indicates a Hermitian transpose and \( I_N \) is the \((N \times N)\) identity matrix. The 
resulting weight vector is null-constrained and modifies the receive transducer beam accord-
ingly.

Null-steering significantly alters the shape of the receive beam. Fig. 3.16 shows the 
result of constraining the fixed broad beam (dash-dot curve) to have a null such that the 
interfering signals (dashed line) are suppressed, with the null-steered beam pattern given 
by the thick solid curve. The beam has a significantly altered shape which now has greatly 
reduced sensitivity in the direction of the interference (path shown by the dashed lines). 
The thin solid line shows the route taken by the B signal at a range/time of 46 m.

If the beampattern employing null-steering is used by the receiver for the duration of 
each ping, then the presence of the null not only rejects the multipath signals, but also rejects 
a portion of the desired seafloor signal (the B signal). The solution is to change the shape of 
the beam during the processing of each individual ping, immediately before the interference 
arrives. The B signal which arrives from the location of the bottom bounce is received much 
sooner than the multipath signals (48.2 m and 51.5 m for Sb and bSb, respectively) and 
has already been received by the time the interference arrives. It is possible to use the fixed 
broad beam without nulls to process the ping until a range (time) of approximately 46 m, 
and to then change the beam pattern to implement null-steering for the remainder of the 
ping.

Changing the beam pattern in this manner may introduce an artifact into sidescan images 
by altering the response in the direction of the B signal. To avoid this effect, the gain can 
be adjusted to compensate for the discrepancy between the response of the original pattern 
and the new pattern. This effect is observed and is addressed in the following discussion.
Figure 3.16: Diagram of the relevant beampatterns and multipath interference, now showing the beampattern which uses null-steering. The seafloor is at a depth of 13 m, the transducer is at a depth of 1 m, and the concentric half-circles indicate the intensity decades of its beampatterns. The dash-dot curve shows the receive beampattern created by the initial beamforming for S signal rejection, and the thick solid curve shows the beampattern when a null is applied to reject the interference. The dashed lines show the route taken by the interfering signals. The thin solid line shows the route traveled by the B signal at 46 m range.
3.3.2 Intensity Levels

To characterize the improvements that are gained by using the proposed null-steering approach, signal intensity levels are again calculated, but this time using the proposed processing method. Fig. 3.17 shows a calculation of the relative signal intensities when the proposed methodology is used to suppress interference. For the first 46 m of the ping, the fixed broad beam (proposed in [28]) is used to suppress the S signal (thin solid curve), and a null is introduced to suppress the Sb (dotted curve) and bSb signals (dashed curve) for the remainder of the ping. B signal intensity (thick solid curve) is reduced 3 dB when the beams are switched.

S signal intensity is reduced by 32 dB, while Sb and bSb signals are suppressed more than 50 dB below their previous levels. The B signal undergoes a 3 dB drop in its intensity when the fixed beam is replaced with the null-steered beam. As previously mentioned, this sudden change in B signal intensity would leave an artifact in a sidescan image. To compensate, the gain is increased by this amount (3 dB) shown by the dashed line for the B signal; although this solution also increases the intensity of the Sb and bSb signals by the same amount, their relative intensity is still 50 dB weaker than the B signal.
this method in practice, it is sufficient to identify the arrival angle of the B signal at the
time/range the beam will be changed, compute the difference between the old and new array
responses to the B signal from its arrival angle, and to compensate accordingly.

3.3.3 Field Data

The angle of arrival method in [35] is able to provide all necessary information for the precise
application of the null-steering technique and any gain adjustment that ensures a smooth
transition between these beams. By placing a null at 4.5° the bottom bounce interference
is rejected, and a clear view of the seafloor is obtained. To maintain consistent beamformer
response in the direction of the B signal when the null is introduced, gain is increased 3 dB
for the remainder of each ping.

Fig. 3.18 shows the multipath-contaminated field data presented in Fig. 3.2 but when
the proposed time-varying beamforming is used to suppress the multipath interference. A
side-by-side comparison of Fig. 3.18 with Fig. 3.2 is shown in Fig. 3.19. The time-varying
beamforming approach is seen to be effective at suppressing bottom bounce multipath sig-
nals, and at preserving B signal intensity. By keeping the user in control of the beampattern,
it is possible to reject multipath interference in a way that avoids introducing artifacts into
the sidescan image.

3.4 Qualitative Comparison: MVDR

As in Chapter 2, it is now useful to compare the results obtained using the proposed conven-
tional beamforming approaches with results obtained using two realizations of the (adaptive)
MVDR algorithm. A complete, general, quantitative comparison of the methods is beyond
the scope of this thesis, but a simple qualitative comparison between results facilitates the
discussion. The sidescan data that created Figs. 3.1 and 3.2 are processed using realiza-
tions of the MVDR algorithm. As explained in Chapter 2.5, caution must be exercised when
drawing general conclusions from the limited scope of this qualitative comparison.

Fig. 3.20 shows the result of MVDR processing on the Bsb-contaminated sidescan data
shown in Fig. 3.1, and was created using three adjacent time samples to estimate the
correlation matrix that is used to calculate the MVDR weight vector. To calculate the look
direction at any given time sample, the seafloor is assumed flat at a constant depth of 12 m.
No diagonal loading is used. The result is that the Bsb signal appears largely attenuated,
Figure 3.18: Field data collected by EdgeTech (the same data used to create Fig. 3.2) processed using the time-varying beamforming approach which utilizes null-steering. The masking effects of the surface interference and of the bottom-bounce multipath are removed, leaving a clear view of the seafloor.
CHAPTER 3. PROBLEM 2: BOTTOM-BOUNCE MULTIPATH

| Ping Number | Slant Range (m) |
|-------------|----------------|---|
|             | 0              | 10 |
|             | 20             | 30 |
|             | 40             | 50 |
|             | 60             | 70 |
|             | 80             | 100|

Figure 3.19: Side-by-side comparison of Figs. 3.2 (left) and 3.18 (right). Originally, surface interference created by a passing vessel resulted in S, Sb, and bSb signal contamination of a sidescan image (left). Using the fixed broad beam to remove the S signal and using time-varying beamforming to remove the Sb and bSb signals, a “cleaned up” sidescan image is obtained (right).

although a faint remnant is still visible in the neighborhood of 25 m range. However, the image also has a more “grainy” appearance than Figs. 3.1 and 3.14. To facilitate a comparison between the proposed processing methods and MVDR, Fig. 3.21 shows a side-by-side comparison. These smaller Figures (half normal size) facilitate a comparison on a large scale, but to see the finer details such as the grainy quality of an image, these Figures are best viewed at full size.

Fig. 3.22 was created using an MVDR realization to process the data shown in Fig. 3.2 that is contaminated with wake interference. In this realization, five adjacent time samples are used to estimate the correlation matrix that is used to determine the weight vector, and no diagonal loading is used. The resulting image appears to be free from boat wake and the associated multipath interference. Again, a grainy appearance is noted in the image, but textural details are preserved at the longer ranges (≈ 50 m and beyond). However, artifacts from the processing appear to have been introduced. In Fig. 3.2, no prominent horizontal “stripes” were visible, except for on ping 400 beyond 45 m range. When these data are processed using the MVDR realization, the “stripe” on ping 400 is now highlighted from 10 m to 45 m. Additionally, faint horizontal stripes are visible throughout the image, mostly between ranges 20 m and 45 m on all pings. The textural details that were present in this
Figure 3.20: Field data collected by EdgeTech (the same data used to create Fig. 3.2) processed using MVDR where three adjacent time samples to estimate the correlation matrix. The BsB signal is largely removed, although faint remnants remain, but some textural information appears to have been lost. The resulting image has a more “grainy” appearance than Figs. 3.1 and 3.14.
Figure 3.21: Side-by-side comparison of Figs. 3.14 (left) and 3.20 (right), where the proposed time-varying beamforming methods and MVDR (respectively) are used to remove a Bsb signal.

Fig. 3.23 shows a side-by-side comparison between Figs. 3.18 and 3.22. Again, these smaller figures facilitate a comparison of the more obvious features, like the interference stripe at ping 400, but finer details such as a grainy quality to the image are lost when the size of the image is reduced.

The proposed time-varying conventional beamforming techniques do assume knowledge (for null-steering) or estimates (for Bsb removal) of signal angles- and times-of-arrival, and therefore require somewhat similar knowledge as MVDR. However, the proposed conventional methods introduce known and constant changes in the beampattern that can be compensated for if the B signal’s angles-of-arrival are known. MVDR beampatterns are designed specifically so that they do not remain constant with respect to time, and the possibility exists that the resulting sidescan images may contain artifacts that were introduced by the algorithm.

The sidescan images created using MVDR (shown in Figs. 2.28, 3.20 and 3.22) are all characterized by a comparatively more “grainy” appearance than their respective images that were created using the proposed conventional techniques. In addition, Fig. 3.22 shows artifacts from the MVDR processing; a horizontal striping pattern is visible in the image. Although the MVDR realizations have removed some of the interference from the data used to create each image, the proposed conventional techniques yield results that are
Figure 3.22: Field data collected by EdgeTech (the same data used to create Fig. 3.2) processed using MVDR using five adjacent times samples to estimate the correlation matrix. The image has a more “grainy” quality than in Fig. 3.18, and additionally there is horizontal striping visible. Although some (not all) of the multipath interference has been removed, this striping pattern is an artifact that has been added by the algorithm.
CHAPTER 3. PROBLEM 2: BOTTOM-BOUNCE MULTIPATH

Figure 3.23: Side-by-side comparison of Figs. 3.18 (left) and 3.22 (right). The combination of a fixed broad beam with time-varying beamforming as proposed in this thesis is used to remove S, Sb, and bSb signals (left image) and is compared against the results of using MVDR to suppress those same signals (right image).

more visually pleasing as they retain textural clues and are free from algorithm-introduced artifacts.

3.5 Summary and Conclusion

The Chapter introduces a new method for the removal of bottom-bounce multipath interference from sidescan sonar signals and images, and analyzes the method’s effectiveness. This general approach involves modifying the shape of the receive beam one or more times during the processing of each individual ping so that the bottom signal is preserved and the interference is rejected.

Two examples of the problem presented by bottom-bounce multipath were given, and the proposed method was used to suppress the interference in both cases. The examples were modeled to demonstrate the effectiveness of the proposed method in theory, and the effectiveness of the method was also demonstrated when applied to experimental sidescan data. It is concluded that conventional beamforming techniques used in a time-varying manner are capable of rejecting bottom-bounce multipath, leaving the user with a clear view of the seafloor.

In Chapters 2 and 3, conventional beamforming techniques are proposed to mitigate the
effects of interference on sidescan sonar signals (and subsequent images). However, there are relevant theoretical performance limitations that must be discussed. In Chapter 4, the impact of footprint shift on the array processing is discussed.
Chapter 4

Footprint Shift and Performance Limitations

While the beam processing methods discussed in Chapters 2 and 3 are shown to work in theory and in practice with field data, the performance limitations that are imposed by the footprint shift effect were not discussed. Footprint shift is the decorrelation of a signal between receivers in an array which results from their spatial offset. Because the receivers are not exactly co-located, signals received simultaneously by the array from off-boresight must have originated from slightly different locations on the scattering surface (i.e. the signals are not entirely similar). The footprint shift effect is discussed in the context of B signals arriving at a 3D sidescan sonar array in [36], and is presently extended to include multipath signals as well.

When using the proposed beamforming methods to suppress multipath interference, footprint shift can introduce decorrelation that reduces the effectiveness of the beamforming. While the coherent portion of an interfering signal may be rejected by the proposed beamforming, the incoherent portion cannot be rejected in this manner and is responsible for the reduction in performance. As the number of elements in the array increases (assuming a constant inter-element spacing $d$), so does the footprint shift across the array. However, using more elements allows for greater precision when forming the beam. It is therefore relevant to investigate this performance tradeoff and see how performance changes as the number of receive elements used to implement beamforming is varied.
The change in array gain versus the number of sensors forming an array has been investigated in the cases where signal coherence decays linearly (see [38]) and exponentially (see [37]). In the present context, the manner of decay in signal coherence depends upon the type of pulse that is transmitted. Since the beamforming in this thesis is implemented via phase shifts and not true time delays, there will necessarily be a loss of signal coherence when signals arrive off-broadside (as mentioned, the mechanism in the present context is footprint shift).

In this Chapter, the impact of footprint shift on the proposed array processing methods is discussed. First, an equation for calculating the footprint shift of a signal is presented. Next, the implications of footprint shift are discussed in mathematical terms. Changes (due to footprint shift) to the beampatterns of an array employing the proposed beam processing methods are then presented visually.

4.1 Calculating Footprint Shift

In [35] and [36] a discussion of footprint shift is presented in the context of B signals. The latter reference presents equations for calculating the correlation coefficient of the B signal between receive elements in the case of either a square pulse or triangular pulse (such as a matched filtered square pulse). To extend these results to multipath signals, it is first necessary to consider the geometry in question.

Fig. 4.1 shows the path of the bSb signal (dashed line) when the method of images is used to project the surface about the seafloor, showing the signal traveling in a straight line (this Figure is repeated from Chapter 3). Two adjacent receive elements are shown (solid dots) with their inter-element spacing $d$ exaggerated to aid in illustration. A plane wave traveling the course of the bSb signal is not received at exactly the same time by both receivers; the two receivers have two partially different footprints, therefore footprint shift occurs. As in previous figures, the array tilt angle is given by $\gamma_t$ and the multipath signal travels a path given by $\theta_j$ from horizontal. $T$ is the depth of the first receive element below the surface, $h$ is the height of this element above the seafloor, and water depth is $T + h$.

A general expression for calculating the footprint shift of a signal arriving at the receive array has been derived (see Appendix B) by considering the return path geometry shown in Fig. 4.1. The orientation of the transducer elements (tilt angle $\gamma_t$ and inter-element spacing $d$) and the return path of the signal provide sufficient information to describe the footprint.
Figure 4.1: Diagram of relevant deployment parameters. Angle $\gamma_t$ is the tilt angle of the array, with inter-element spacing $d$, deployed at depth $T$ m below the surface and $h$ m above the seafloor. The method of images is used to show the path of a bSb signal, characterized by physical angle $\theta_j$.

shift. By assuming that the returning signal is a plane wave and that angle $\theta_j$ describes both footprints, the equivalent range delay between reception at successive receivers is calculated using the equation

$$\delta r = -\frac{d}{2\sqrt{x^2 + y^2}} [y \cdot \cos(\gamma_t) + x \cdot \sin(\gamma_t)]$$  \hspace{1cm} (4.1)

where $x$ is the horizontal distance from the scattering location back to the array, and $y$ is the vertical component of this distance. The variable $y$ is taken to be positive if the interfering signal arrives from above the receive array. This equation is simple to evaluate if the geometry of the system in question is known, or can be approximated. Profiles of individual pings offer the necessary information. Caution should be exercised when applying this model to signals that scatter at nadir, because such signals arrive from a range of angles and cannot adequately be described by a single angle $\theta_j$.

In the case of the bSb signal and the data shown in Fig. 3.2, where the transmit frequency was 540 kHz and $d = 0.435\lambda$, Eq. 4.1 evaluates to $\delta r \approx 4.75 \cdot 10^{-5}$ m. The experimental data being modeled (seen in Fig. 3.2) indicate that the bSb signal arrived from roughly $(40, -28.5)$ m, as previously discussed. The variable $x$ denotes the horizontal component (40 m) of this location and $y$ denotes the vertical component referenced to the location of
the array (-27.5 m, since the array is 1 m below the surface). Note that $x$ and $y$ in Eq. 4.1 correspond only to the components of the return path that is traveled by the signal, which is not necessarily the same as the transmit path (such as when the signal does not follow a reciprocal course). However, as long as the angle of arrival is correctly determined, the calculation of footprint shift is unaffected (see Appendix B).

Eq. 4.1 provides a numerical value of the footprint shift experienced by the signal when considering its two-way travel distance, hence the factor of 2 in the denominator. The maximum value attainable by $\delta r$ is then half the inter-element spacing, or for a sonar such as the EdgeTech 4600, $\delta r_{\text{max}} \approx 6.04 \cdot 10^{-4}$ m. The footprint shift experienced by the bSb signal seen in Fig. 3.2 is approximately 8% of the maximum value.

Converting the footprint shift experienced by a signal into a correlation coefficient as shown in [35] requires knowledge of the pulse length and type, and equations 19 and 20 on page 310 of the reference describe the calculation of correlation coefficients for two common waveforms. These results were derived in the appendices of [35], and build upon an expression of footprint shift for B signals that was derived in the appendix of [36]. Applying the results of [35] to an example, consider a representative waveform: a 20-cycle square pulse that is matched filtered, and to be consistent with the example of the bSb multipath shown in Fig. 3.2 the carrier frequency is assumed to be 540 kHz. If this pulse experiences the maximum footprint shift of $\delta r_{\text{max}} \approx 6.04 \cdot 10^{-4}$ m (corresponding to a signal arriving from endfire) then the correlation coefficient is $\rho_1(\gamma) = 0.9993$. The subscript denotes that the correlation refers to adjacent elements. For the bSb signal that is under consideration, where $\delta r \approx 4.75 \cdot 10^{-5}$ m and again assuming a 20-cycle square pulse that has been matched filtered, the correlation coefficient is $\rho_1(\gamma) \approx 1$. To better understand the implications of footprint shift and of these correlation coefficients, a discussion of the relevant theory is presented next.

4.2 Theory

The decorrelation imposed by footprint shift has two important implications. The first implication, as previously stated, is that as the number of receivers increases (assuming constant $d$) the decorrelation across the array also increases. The second implication is that even if thermal noise levels are low, decorrelation may lower the effective SNR of the system using the proposed beamforming methods. Footprint shift can affect not only interfering
signals, but also desired signals (like the B signal). To illustrate the impact of footprint shift in a clear manner, the problem at hand is simplified by considering footprint shift in the context of the B signal only. In this Subsection, results from [36] are presented, and in the next Subsection these results are extended.

The first implication of footprint shift is evident when examining a representative 3x3 correlation matrix. Consider a 3-element array with an arriving complex Gaussian signal, where the variance of its amplitude is \(2\sigma_s^2\) and it arrives with electrical angle \(\gamma_e\) between adjacent elements. The correlation matrix of the signal is \(R_s\). Assuming additive white Gaussian noise, characterized by variance \(2\sigma_n^2\), that is uncorrelated between different elements (a correlation matrix \(R_n\) with diagonal elements \(2\sigma_n^2\)) the 3x3 correlation matrix is

\[
R = R_s + R_n
\]

\[
= \begin{bmatrix}
2\sigma_s^2 + 2\sigma_n^2 & 2\sigma_s^2\rho_1(\gamma)e^{-j\gamma} & 2\sigma_s^2\rho_2(\gamma)e^{-j2\gamma} \\
2\sigma_s^2\rho_1(\gamma)e^{j\gamma} & 2\sigma_s^2 + 2\sigma_n^2 & 2\sigma_s^2\rho_1(\gamma)e^{-j\gamma} \\
2\sigma_s^2\rho_2(\gamma)e^{j2\gamma} & 2\sigma_s^2\rho_1(\gamma)e^{j\gamma} & 2\sigma_s^2 + 2\sigma_n^2
\end{bmatrix}
\]  

(4.2)

where \(\rho_1(\gamma)\) is the correlation coefficient between adjacent elements that is associated with footprint shift, and likewise \(\rho_2(\gamma)\) is the correlation coefficient between the first and third element (also associated with footprint shift). The first and second elements in the array are decorrelated by an amount associated with \(\delta r\), the first and third elements are decorrelated by an amount associated with \(2\delta r\), and accordingly \(\rho_1(\gamma) \geq \rho_2(\gamma)\). As the number of receivers in the array increases, so does the decorrelation across the array that results from footprint shift. This behavior does not change if additional interfering signals are received, and is seen easily in the context of the B signal.

Footprint shift also causes what is essentially a raising of the noise floor. This effect is easily seen by considering a 2-element array receiving a B signal and thermal noise. Defining \(\rho_n = 2\sigma_s^2/(2\sigma_s^2 + 2\sigma_n^2)\) as the correlation coefficient associated with noise, the 2x2 correlation matrix \(R\) can be rewritten as

\[
R = \left(2\sigma_s^2 + 2\sigma_n^2\right) \cdot \begin{bmatrix}
1 & \rho_n\rho_1(\gamma)e^{-j\gamma} \\
\rho_n\rho_1(\gamma)e^{j\gamma} & 1
\end{bmatrix}.
\]

(4.3)

Let \(\rho_n\rho_1(\gamma)\) be treated as an effective correlation coefficient \(\rho_e\) and the effective signal-to-noise ratio be defined as

\[
\text{snr}_e = \frac{\rho_e}{1 - \rho_e}
\]

(4.4)
as in [36]. The correlation matrix may be rewritten as

$$\mathbf{R} = (2\sigma^2_s + 2\sigma^2_n) \cdot \begin{bmatrix} 1 & \rho_e e^{-j\gamma} \\ \rho_n e^{j\gamma} & 1 \end{bmatrix}. \quad (4.5)$$

Because the correlation coefficients associated with noise and with the signal are acting as a product which determines the effective SNR, a high effective SNR requires both correlation coefficients to be high. In other words, even if thermal noise is kept to a minimum the effective SNR is limited by footprint shift.

To illustrate this point, consider the following example. If the signal to thermal noise ratio, defined as $10 \cdot \log_{10}(2\sigma^2_s/2\sigma^2_n)$, equals 40 dB then $\rho_n = .9999$. Considering a signal with the maximum decorrelation of $\rho_1(\gamma) = .9993$ the effective correlation coefficient is $\rho_e = .9992$ and the effective signal to noise ratio is $\text{snr}_e = 1249$, or equivalently 31 dB. If thermal noise is completely disregarded (that is, if $\rho_n = 1$) then the effective signal to noise ratio shows a very modest increase to $\text{snr}_e = 1427.6$ or 31.5 dB. This example clearly illustrates that footprint shift-induced decorrelation can limit the effective SNR when thermal noise is low.

The example of the 2x2 matrix where only the B signal and thermal noise are considered shows how the effective SNR is determined by footprint shift and thermal noise. By considering $N$ receivers, a single effective SNR cannot be used because the decorrelation between elements depends on their spacing (that is, a single correlation coefficient $\rho_1(\gamma)$ does not describe the decorrelation between any two array elements) and therefore this precise SNR of 31 dB does not represent the maximum null depth for any arbitrary array. To treat the problem at hand, where the array receives the B signal and thermal noise as well as an interfering signal, a more complicated calculation is necessary and is provided in the following analysis. However, this simple example illustrates in principle how interference can lower the effective SNR. As the effective signal to noise ratio drops the beampattern of the receive array is affected, decreasing the depth of nulls.

To continue this analysis, it is now necessary to illustrate how footprint shift affects the beampattern of a receiver employing beamforming. The preceding analysis was general in nature, and the following analysis models a sonar such as the EdgeTech 4600 that employs the specific beam processing methods that have been suggested in Chapters 2 and 3 for use on this sonar system.


4.3 Beampattern Changes

When footprint shift affects the received signals, the beampattern of a receiver employing beamforming is altered. For monostatic systems where two-way travel is considered, it is expected that signals arriving from boresight experience no footprint shift and signals arriving from endfire experience the greatest footprint shift, which for adjacent elements cannot be larger than half the inter-element spacing. For the EdgeTech 4600, this spacing is approximately \(0.435 \cdot \lambda\), and the receive element pattern is approximated as a \(\cos^{5.5}\) intensity pattern. A transducer tilt angle of 30\(^\circ\) is assumed.

If an interfering signal arrives exactly from endfire (for instance \(\theta_j = 120^\circ\), a signal originating from the seafloor “behind” the transducer) then it experiences maximum footprint shift, but the receive element pattern eliminates the signal and it does not contribute to the response of the beamformer. A signal arriving from \(\theta_j = 110^\circ\) still experiences significant footprint shift (\(\rho_1(\gamma) \approx 0.9993\)), and because it does not arrive exactly from endfire is not eliminated by the element pattern. The following analysis considers such an example signal.

Fig. 4.2 shows the receive beampatterns that are obtained using the proposed beam processing when \(\rho_1(\gamma) = 1\) (i.e. footprint shift is disregarded) and when the receiver has 8 elements. The thin solid curve shows the composite beampattern obtained via the fixed broad beam processing, the thick solid curve shows the composite beampattern obtained via null-steering with a null at 0\(^\circ\), and the location of the null is shown by the dotted line. The dashed curve shows the \(\cos^{5.5}\) receive element pattern, with a response of \(-40\) dB to signals arriving from \(\theta_j = 110^\circ\), or an angle of arrival equal to 80\(^\circ\). Because footprint shift is disregarded and the signal to thermal noise ratio is 40 dB, the null is 40 dB deep.

Taking into account the impact of footprint shift on the beampattern alters the depth of the null (seen in Fig. 4.3). Continuing the analysis, the bottom signal is now assumed to experience footprint shift and the resulting changes to the beampattern are shown. This assumption allows for simple and clear illustration of the behavior that is being investigated, namely the filling-in of nulls as a result of a decorrelated signal arriving at the array.

Fig. 4.3 shows the receive beampatterns when \(\delta r \approx 5.95 \cdot 10^{-4} m\), making \(\rho_1(\gamma) \approx 0.9993\), which corresponds to a matched-filtered 20-cycle pulse experiencing footprint shift and arriving from near endfire. The depth of the null is slightly affected (the null is now approximately 33 dB deep), and the equal ripple beampattern shows modest changes. Footprint shift is a sufficient mechanism to alter the beampatterns of proposed beamformer, although
the null is still sufficiently deep to be effective at suppressing the chosen interference.

4.4 Considering $N$ Receive Elements

By changing the number of elements in the receive array the composite beampatterns of the beamformer are altered, as is its susceptibility to footprint shift-induced decorrelation. As the number of elements in the receive array ($N$) increases, the ability to shape the beam in a desired fashion is improved. However, if a received signal experiences footprint shift then the decorrelation across the entire array increases with $N$. The following analysis investigates the behavior of the beamformer’s response to interfering signals as $N$ is varied, in order to better understand this performance trade-off as the number of receivers changes.

To analyze the response of a beamformer versus the number of elements composing the array is a difficult problem to address in a general sense. A theoretical investigation into the changes in array gain that result from loss of signal coherence was conducted by Cox and Green [37], [38]. The purpose of this analysis is not to repeat prior work but to gain a better understanding of how the proposed beamforming methods will be affected in a realistic setting. To achieve this goal, the scope of this analysis is narrowed, and a particular
CHAPTER 4. FOOTPRINT SHIFT AND PERFORMANCE LIMITATIONS

Figure 4.3: Diagram of the relevant beampatterns (solid curves) and location of a null (dashed line) applied at 0° and when a signal arrives from endfire with \( \rho_1(\gamma) \approx 0.9993 \). As before, the dashed curve is the element pattern, the thin solid curve is the composite beampattern after equal ripple beamforming is applied, and the thick curve is the composite beampattern employing null steering.

example forms the basis of the analysis.

The scope is narrowed by considering sidescan sonar arrays that vary in size from \( N = 5 \) to \( N = 30 \). This limit is imposed because while ordinary sidescan sonars have a single receive element and more complicated 3D sidescan sonars may have 6, 8, or even 10 receive elements, so a sidescan array of 30 elements represents an extreme case in these contexts. Sidescan arrays of greater than 30 elements are not considered in this analysis, although some synthetic aperture sonar systems do use arrays of 30 elements or larger. To narrow the scope further, the number of interfering signals is limited, and the angles from which these signals arrive is also limited.

It is assumed, as before, that a null is placed directly at boresight for the purpose of suppressing some interfering signal. As before, the pulse is a 20-cycle matched filtered square pulse. Under the proposed conventional beamforming techniques, the first procedure is to form the fixed broad beam such that surface interference is strongly suppressed, and then (for instance) to constrain the beam to have a null at the desired location (boresight, in this case). The fixed broad beam is designed to have a strong response in the direction of the bottom and a weak response in the direction of the surface. As the number of elements in the beamformer increases, the response in the direction of the surface is reduced. By increasing
Let the beamformer response $P$ be given by

$$P = w_n^H (R_0 + aR_{AOA_j} + R_n) w_n$$  (4.6)

where $R_0$ is the correlation matrix of a signal arriving at boresight, $R_{AOA_j}$ is the correlation matrix of a signal arriving from angle $AOA_j$, $R_n$ is the correlation matrix of the noise, and $w_n$ is the weight vector given by Eq. 3.3. Both signals are assumed to have equal intensity in the water, and the thermal noise level is $-40$ dB. The signal arriving from boresight is unattenuated by the $\cos^{5.5}$ element pattern, but the signal arriving from $AOA_j$ is attenuated by $a = \cos^{5.5}(\theta_j - \gamma_t) = \cos^{5.5}(AOA_j)$. Only the correlation matrix of the signal arriving from off-boresight, $R_{AOA_j}$, is affected by footprint shift.

Two scenarios are now considered: one where the footprint shift is assumed non-existent (that is, $\rho_1(\gamma) = 1$), and the other where footprint shift is taken into account according to Eq. 4.1. In the first scenario, changes to the beamformer response as a function of $N$ result only from changing sidelobe locations and changing sidelobe intensities. In the second scenario, footprint shift fills in nulls in the beampattern and affects the beamformer response. By comparing the results from these two scenarios, the impact of footprint shift can clearly be seen.

For both scenarios, one interfering signal arrives at boresight. In addition to this interfering signal, additional interfering signals arrive from angles that correspond to the locations of nulls in Fig. 4.3 for when $N = 8$, at $AOA_j = -35^o$ and $AOA_j = -60^o$. Signals arriving from the off-boresight angles correspond to surface interference.

Changes in null depth are readily observed when footprint shift is considered. The response of the beamformer in dB is plotted versus the number of elements in the receiver, and in Fig. 4.4 footprint shift is ignored. Fig. 4.4 shows that when $N = 8$ the beamformer response is equal to the thermal noise floor (thin line) when interference arrives from boresight and also $AOA_j = -35^o$ (thick line), and also equals the noise floor when interference arrives from boresight and $AOA_j = -60^o$ (dotted line). The changes in the beamformer response versus $N$ are due entirely to changing sidelobe locations and intensities. These off-boresight interfering signals experience footprint shift equal to $\delta r \approx 3.47 \cdot 10^{-4}$ m and $\delta r \approx 5.23 \cdot 10^{-4}$ m, respectively.

When footprint shift is considered, it is expected that the low points in the beamformer
Figure 4.4: Beamformer response (dB) versus the number of receive elements \( N \) when footprint shift is disregarded, with a null placed at 0\(^\circ\). The thermal noise level is at −40 dB (given by the thin line). When interference arrives from boresight and from \( AOA_j = -35\,^\circ \), the beamformer response is given by the thick solid line. When interference arrives from boresight and \( AOA_j = -60\,^\circ \) the beamformer response is given by the dotted line. The equal ripple beam has been formed according the parameters suggested in [28] that suppress surface interference.

response shown in Fig. 4.4 will be “filled in”. Indeed this is the behavior seen in Fig. 4.5, where the low points in the beamformer response are slightly increased but the pattern is otherwise unchanged. Considering the \( N = 8 \) element case, the beamformer response is −32.4 dB when interfering signals arrive from boresight and from \( AOA_j = -35\,^\circ \). The beamformer response increases to −38.9 dB when the interfering signals arrive from boresight and \( AOA_j = -60\,^\circ \). When footprint shift was disregarded, beamformer response equaled the noise floor at −40 dB in both cases. Therefore, footprint shift from the interfering signal arriving from \( AOA_j \) (in either case) is seen to slightly increase the beamformer response above the thermal noise floor. In other words, from Figs. 4.2 to 4.5 footprint shift is seen to fill in nulls and to increase beamformer response above the thermal noise floor.

Although in this example the interfering signals arrive from constant angles while sidelobe locations and sidelobe levels vary with \( N \), which in turn varies the beamformer response with \( N \), it is still evident that increasing the number of elements in the array has beneficial results despite footprint shift. The benefits of increasing \( N \) include increased control over sidelobe levels and a sharper transition between the passband and the stopband in
Figure 4.5: Beamformer response (dB) versus the number of receive elements $N$ when footprint shift is considered, with a null placed at $0^\circ$. The thermal noise level is at $-40$ dB (given by the thin line), and this is the beamformer response when $AOA_j = 0^\circ$. When interference arrives from $AOA_j = -35^\circ$, the beamformer response is given by the thick solid line, and when $AOA_j = -60^\circ$ the beamformer response is given by the dotted line. The equal ripple beam has been formed according the parameters suggested in [28] that suppress surface interference.

...the beampattern, as evidenced by the decreasing trend in beamformer response with $N$. Increasing $N$ implies that nulls may not extend all the way down to the noise floor, but it also allows greater control over the array’s response in the direction of the surface. A null at boresight may still extend below $-30$ dB even if it does not reach the noise floor, but now sidelobes pointing towards the surface are greatly decreased.

It is concluded that a beamformer using the proposed processing methods is robust to interference. Footprint shift does little to alter the effectiveness of the proposed processing methods. The maximum intensity of sidelobes is seen in Figs. 4.4 and 4.5 to vary the beamformer response over a wide range, and for this example is highest when $N = 5$ and the beamformer response is $32$ dB above the thermal noise floor. Footprint shift in the $N = 8$ element case is seen to increase beamformer response $8$ dB above the noise floor, a relatively small increase. For practical applications of the proposed processing methods to commercial sonars, sidelobe levels are expected to have a far more deleterious effect on performance than footprint shift. It is anticipated that in practical settings there is little difference between an interfering signal that is suppressed by $32$ dB or by $40$ dB, whereas...
an interfering signal suppressed by less than 10 dB could potentially be a concern. It is therefore evident (within the limited scope of this investigation) that using more receive elements is preferable to using fewer receive elements because of the greater control over sidelobe levels.
Chapter 5

Conclusion

Throughout this thesis, multiple examples have been given that illustrate the masking effects that multipath interference can have. The multipath interference has been identified, described theoretically in terms of their relative intensity, and multiple examples of this behavior have been shown via sidescan images. The phenomenon of multipath interference has been divided into two problems within this thesis: the problem of surface interference, and the problem of bottom-bounce multipath. These problems have been dealt with separately, but in both cases the solutions involve the use of conventional beamforming techniques (on receive) to suppress the interference and preserve the direct bottom return. To suppress surface interference the use of a fixed broad beam is proposed, and to suppress bottom-bounce interference the implementation of conventional beamforming techniques in a time-varying manner is proposed.

In this final Chapter, the conclusions from Chapters 2-4 are presented. The conclusions from each Chapter are presented separately. Following these conclusions, recommendations are made for future work.

5.1 Solving Problem 1: Conclusions

The gains which result from using beamforming to suppress surface interference are investigated for the case where beamforming is applied only on receive, and also for the case where beamforming is applied on both transmit and receive. Calculation of the relative path strengths indicates that beamforming on receive is highly effective at attenuating interfering
signals, but that beamforming on both transmit and receive is even more effective. However, because significant improvement is made by employing beamforming on receive only, and since beamforming on transmit requires the use of additional electronics (increasing the price and complexity of the system), the use of beamforming on receive is preferred.

A prototype array is introduced, featuring a vertical stack of receive elements. Comparisons between the prototype array and an ordinary sidescan sonar are made, the main difference being their respective beams. An ordinary sidescan sonar can employ triangular shading on both transmit and receive to control the along-track beamwidth, but the prototype array is constrained to have uniform shading for the receive elements. However, it is possible for an array (such as the prototype array) to use triangular shading on transmit if those elements are separate from the receive elements. The impact of the along-track beam pattern on shadow depth was explored in Appendix A, as target width and offset were varied and different element shading schemes were employed. Also in Appendix A, the uniform element shading (on both transmit and receive elements) which is featured in the prototype array is seen to be sufficient for most applications.

The measured across-track beam patterns of the prototype array were compared to predicted beam patterns, and found to be in close agreement. The calculations of relative path strengths and the simulations of the received signal were repeated using the measured beam patterns with and without beamforming implemented (on receive only). In calculation, this caused a 30 dB reduction of the surface signal intensity, and caused the bottom signal to be 13 dB stronger than the sum of interfering signals at a range of 130 m. In simulation the shadow depth was increased by approximately 14 dB (compared to the shadow depth which was obtained without using across-track beamforming) at a range of 100 m, and the effects of multipath signals were no longer visible.

Finally, field data (in the form of sidescan images) collected using the six-element prototype array were presented. A sidescan image, corrupted by surface interference which was the result of boat traffic and surface chop, was processed using the proposed fixed broad beam. The processed sidescan image was greatly improved over the unprocessed image, revealing details of the seafloor which included a previously obscured shipwreck and rocky outcropping. This processed image also showed greater shadow contrast (approximately 15 dB greater) in the area immediately beyond the shipwreck due to the attenuation of the surface interference.

A realization of the MVDR beamformer is created and is used to process the experimental
sidescan data. This facilitates a qualitative comparison between the results obtained using the proposed fixed broad beam and the results obtained via MVDR. It is seen than the chosen MVDR realization does remove much of the surface interference and successfully reveals the shipwreck, but the resulting image has a “grainy” quality that compromises textural details. To address surface interference, the fixed broad beam is therefore preferred.

Ordinary sidescan sonars which employ comparatively narrow beams and suitable tilt angles are capable of suppressing the interfering signals under consideration (the S, sBs, Bs, and sB). Theoretical analysis predicts that such a sonar is capable of achieving 13 dB separation between the B signal and the sum of interfering signals, and 15 dB contrast between B and S signals for the scenario which was modeled. Deployment depth strongly influences the interference suppression capabilities of this type of sonar, with a pole-mount deployment being the least favorable (predicted bottom-surface contrast reduces to 5 dB) if strong surface interference is anticipated. Another advantage for ordinary sidescan sonars is lower cost than a sidescan sonar with a plurality of receivers.

For the towfish deployment that was modeled, both sonars achieve the 13 dB contrast between the B signal and the sum of interference, but the prototype array is seen to be less susceptible to S signals and more susceptible to sB/Bs multipath signals. When modeled to be deployed via pole-mount where S signals were the dominant interference, the prototype array offered superior S signal suppression (25 dB, compared to 5 dB for the ordinary sidescan). The prototype array is therefore the preferred choice for shallow deployments where strong surface interference is anticipated. This finding is considered important because, as illustrated in Figs. 2.5 and 2.24, surface interference can completely contaminate a sidescan image. Other advantages of the array include the flexibility to tailor the receive beam in post-processing to suit the survey environment, and also the potential to employ other beam processing methods which are beyond the scope of this thesis.

5.2 Solving Problem 2: Conclusions

When the fixed broad beam proposed in Chapter 2 is used in a time-varying manner, the result is shown to be effective at removing Bsb interference. By altering the extent of the beam before Bsb interference arrives, the interference is suppressed. The effectiveness of this method is demonstrated through intensity level calculation and through field data collected by EdgeTech using an EdgeTech 4600. Using the knowledge of the system geometry and
the angle of arrival estimation method in [35], the beam is adjusted before the arrival of
the interfering signals such that the bottom return is received without attenuation but the
interference is suppressed.

Null steering is introduced as an approach by which specific interfering signals can be
removed from sidescan images. Unlike the fixed broad beam approach discussed in Chapter
2, which rejects surface signals and has a broad beam pointed at the seafloor, the null steer-
ing method creates precise changes which allow for the targeted removal of signals including
bottom-bounce multipath. This method is also shown to be effective via intensity level cal-
culation and through the processing of field data collected by EdgeTech using an EdgeTech
4600. After identifying the angle of arrival and also the time of arrival of the interference,
a null is introduced into the receive beam. This null is introduced after the B signal has
arrived from that angle and immediately before the interference arrives, permitting the B
signal but rejecting the interference. To avoid introducing artifacts from the processing into
the sidescan image, the gain is adjusted to maintain a consistent response to the B signal
when the null is introduced. The null steering method is shown to be effective at removing
Sb and bSb multipath which resulted from a surface scattering event caused by boat wake.

The proposed conventional beamforming methods have advantages and disadvantages
compared to adaptive beamforming methods such as MVDR. The main advantage of the
conventional beamforming approach is that interference can be rejected without decreasing
resolution and without introducing artifacts into the sidescan image. However, the conven-
tional approach - as proposed - requires a skilled operator to distinguish the interference
from the B signal. MVDR requires a look direction, similar to the requirement of the con-
tentional approach, but automatically forms the beam around this look direction so that
the user does not manually alter the pattern. While there is a clear benefit to removing
control from the user - thus removing the requirement for a skilled user - and placing con-
trol of the beampattern with the algorithm, there can also be consequences. The sidescan
images created using the MVDR realizations were seen to be less visually pleasing than
those images created using the proposed conventional techniques, and MVDR was seen to
introduce artifacts from the processing into a sidescan image. The proposed conventional
processing techniques allow textural clues to be retained and avoid introducing artifacts into
the sidescan data and subsequent images.
5.3 Theoretical Limitations: Conclusions

Footprint shift has been shown to influence the degree to which beamforming is capable of suppressing interference. A general equation for the footprint shift of incoming signals has been developed. It is shown that footprint shift does limit the depth of nulls, effectively imposing a noise floor that may be above the thermal noise floor. However, it is also concluded that the proposed beam processing methods remain effective at suppressing interference even when footprint shift occurs in the received signals. For the array sizes under consideration, the greater beam control that is afforded by an increase in the number of array elements offsets the decrease in null depth imposed by footprint shift.

5.4 Recommendations for Future Work

In the future, additional research is necessary to determine the extent to which the conventional time-varying beamforming approach can be automated so that a skilled operator is not required. In essence, the task is to create an adaptive (or semi-adaptive) algorithm from the conventional methods proposed in this thesis for bottom-bounce multipath removal. The rejection of surface signals is thought to be an easier task that does not necessitate the use of adaptive methods. However, when the B signal and bottom bounce multipath arrive from similar directions, they must somehow be distinguished from one-another. Is it possible to develop a method that yields high-quality sidescan imagery (such as obtained using the proposed conventional methods), and combines this quality with automatic interference removal (such as with adaptive methods like MVDR) to suppress bottom-bounce multipath?

As stated, the main obstacle to the automation of the proposed time-varying conventional approaches is the requirement that interference be discriminated from the direct bottom return. Indeed, one of the main benefits to using adaptive beamforming methods instead of the proposed conventional approaches is that - assuming a correct look direction is obtained - a skilled operator is not required to discriminate interference from signal. To navigate this obstacle to automation while maintaining the quality of the sidescan images that result, it may be possible to utilize the output from a bottom tracing algorithm. If the bottom can correctly be identified (not always a simple task), then the problem of identifying interference is simplified. If the interference is identified as such, and if its time- and angle-of-arrival are known, then it may also be possible to automate the gain adjustment
that ensures B signal continuity as the beam is changed to reject the interference. In the case of a Bsb signal, it may be possible to automate the proposed time-varying method by modifying the beam preemptively at a time/range corresponding to the water depth plus transducer altitude, but this also requires accurate estimates of depth and altitude.
Bibliography


[18] 3DSS DX Brochure, Ping DSP, Victoria, B.C., Canada. 15


[32] 4600 Series Brochure, EdgeTech, Boca Raton, FL. 34

[34] MATLAB version 2008a, Natick, Massachusetts: The MathWorks Inc., 2008. 36


Appendix A

Bottom Masking From Along Track Beam

Along-track beam shapes may contribute to shadow filling, which affects classification ability. Consider a transmitted pulse that is traveling along a flat seafloor when it hits a tall target that occupies the entire along-track beam at a given range. If no interfering signals are present, then a deep shadow is observed on the other side of the tall target before the pulse arrives on the seafloor beyond the target. However, if only a portion of the along-track beam is pointing at the tall target and if the remainder of the beam ensonifies the seafloor to the side of the target, then shadow depth is reduced.

Consider the diagram in Fig. A.1 which shows two scenarios: a target extended in angle is centered in the main along-track lobe (Fig. A.1a), and a target extended in angle which is offset from the main along-track lobe (Fig. A.1b). $\psi_t$ describes the angular offset of the target from the center of the main lobe, and $\psi_{a0}$ describes the angular extent of the target. The concept being depicted is that shadow depth or contrast for the target will depend on the width of the target and on the beam offset, because these factors will determine how much of the beam's intensity is directed towards the target and how much intensity is directed elsewhere.

The shadow will be deepest for a beam pointed directly at the target center, and that depth is shown in Fig. A.2. The shadow depth for a uniformly shaded transmit and receive element is given by the thick solid curve. The shadow depth for a triangularly shaded transmit and receive element is given by the dashed curve, and the combination
of a triangularly shaded transmit with a uniform receive element is shown by the dotted curve. Ordinary sidescan transducers may employ the triangular shading pattern, but the experimental array discussed in Section 2.2 uses uniform element shading because consistent half-wavelength spacing is used between elements.

If the target is very small the backscatter picked up by the beam on either side will fill in the shadow. However, wider targets eclipse the main beam and the shadow is filled in by backscatter only from the sidelobes. The uniform shaded elements have the narrowest main lobe but the highest sidelobes and therefore the shadow depth initially increases quickly with target width and then becomes dominated by the high sidelobes. Triangular shading on both transmit and receive results in a wider main beam and much lower sidelobes, hence the shadow depth increases more slowly with target width but drops to a lower level than that of the uniform shading once the sidelobes become dominant contributors.

Since it is not practical to have triangular shading on a receive array of vertically stacked elements, a reasonable compromise is to employ triangular shading on transmit and uniform shading on receive. This combination has a slightly wider main beam than uniform shading, but lower sidelobes and hence is a good compromise between two-way uniform or triangle shading. However, two-way uniform shading does not perform badly and is sufficient for
most applications.

Also of interest is the depth of the shadow as the beam moves across the target because the shadow is not as deep at the target’s edges as it is when the beam is centered on the target. Fig. A.3 shows the shadow depth as a function of beam offset for three target widths. The set of curves on the right are for the uniform, triangular, and uniform/triangle shading for the widest target. As the beam moves across the target the shadow is first shallow and then reaches its deepest value when the target is centered. Larger targets produce deep shadows and small targets produce shallow shadows.

Both Figs. A.2 and A.3 show shadow depth as a function of multiples of the two-way far-field beamwidth of a uniform aperture which is approximately

$$B_{2u} \simeq \frac{2\lambda}{\pi L}$$  \hspace{1cm} (A.1)

if $L \gg \lambda$, and where $B_{2u}$ is the two-way beamwidth (units of radians) for uniform shading, $\lambda$ is the wavelength and $L$ is the element length. Therefore, these figures represent general results in the sense that given a transducer length, and provided the conditions hold (far-field and $L \gg k\lambda$) the corresponding target size and offset can be determined by the formula
Figure A.3: Shadow depth as a function of target offset for all three element shading schemes (as with Fig. A.2) for a target of width 1, 3, and 9 times the two-way far-field beamwidth. Wider targets produce a deeper shadow.

\[ x = r k B_{2u} \]  \hspace{1cm} (A.2)

where \( x \) is the size of the target or offset in meters, \( r \) is the slant range under consideration, and \( k \) is the multiple of \( B_{2u} \) for either the size or offset.
Appendix B

Derivation of Equation for Footprint Shift

The derivation of Eq. 4.1 is relatively straightforward. The objective of the task at hand is to derive an equation that relates the footprint shift experienced by an arbitrary signal to the scattering location that returned the signal. The reason for this goal is because the angle of arrival estimation algorithm developed by Kraeutner and Bird [39] allows for multiple angles of arrival to be estimated simultaneously, facilitating quick identification of the angle and time at which multipath signals arrive. As previously stated, a multipath signal such as the bSb signal is easily identified in such single ping profiles because it appears to originate from below the seafloor. A semi-skilled operator can examine single ping profiles if multipath interference is suspected, and can search for signals appearing to arrive from below the seafloor, determining the perceived scattering location. After the multipath is identified, the precise time and angle at which to apply a null to the main lobe is now determined, facilitating removal of the signal. Accordingly, it is desirable to obtain an equation that expresses the footprint shift of that signal in terms of its perceived scattering location so that performance limitations can be estimated.

As mentioned, the perceived scattering location does specify the “true” time and angle at which the interfering signal was received and is therefore sufficient for this calculation. In fact, footprint shift can be calculated directly from the angle of arrival, so there is no need to use the coordinates of the scattering location if $AOA_j$ is available. However, since the AOA estimation algorithm developed in [39] estimates ranges and angles to scattering...
Figure B.1: Diagram of relevant deployment parameters. Angle $\gamma_t$ is the tilt angle of the array, with inter-element spacing $d$, deployed at depth $T$ m below the surface and $h$ m above the seafloor. The method of images is used to show the path of a bSb signal, characterized by physical angle $\theta_j$.

locations and subsequently converts these angles and ranges into $x$ and $y$ coordinates, this information is readily accessible without requiring any calculation. In this report, both the Sb and bSb signals are assumed to originate from (40, -28.5) m, or (40, -27.5) m referenced to the array at a depth of 1 m.

Fig. B.1 describes the geometry for determining footprint shift (repeated from Chapter 3). Recall that adjacent array elements are separated by $d$ meters, and that the type of sonar system in question is a monostatic array. When 2-way travel is considered, signals arriving at adjacent elements in the monostatic array can experience footprint shift up to a maximum of $d/2$ meters, corresponding to signals arriving from endfire. Signals arriving from boresight experience no footprint shift. The equation describing this behavior is

$$\delta r = \frac{d}{2} \sin(AOA_j) = \frac{d}{2} \sin(\theta_j - \gamma_t)$$ (B.1)

where $AOA_j = \theta_j - \gamma_t$. Invoking the trigonometric identity that

$$\sin(A - B) = \sin(A) \cos(B) - \cos(A) \sin(B)$$

Eq. B.1 becomes

$$\delta r = \frac{d}{2} \cdot [\sin(\theta_j) \cos(\gamma_t) - \cos(\theta_j) \sin(\gamma_t)].$$ (B.2)
Because it is desirable to work in the context of the perceived scattering location of the received signals, a substitution is made for \( \sin(\theta_j) = y/\sqrt{y^2 + x^2} \) where \( y \) and \( x \) are the coordinates of the scattering location referenced to the lowest receive element in the array. However, this substitution for \( \sin(\theta_j) \) implicitly assumes that \( y \) is negative. Were this formulation to be used, scattering locations below the array would be expressed as having \( y \) coordinates that are positive and locations above the array would have negative \( y \) coordinates. To avoid confusion and to opt for a more intuitive formulation let this notation be reversed, writing instead \( \sin(\theta_j) = -y/\sqrt{y^2 + x^2} \) so that perceived scattering locations are written exactly as determined in the single ping profile. For instance in the case of the bSb signal from Fig. 3.2 with a perceived scattering location of \((40, -27.5)\) m, \( x = 40 \) m and \( y = -27.5 \) m (relative to the array). Substituting for \( \sin(\theta_j) \) and for \( \cos(\theta_j) \) as well, Eq. B.2 becomes

\[
\delta r = d \cdot \left[ -y \frac{\cos(\gamma t)}{\sqrt{y^2 + x^2}} - x \frac{\sin(\gamma t)}{\sqrt{y^2 + x^2}} \right] \quad (B.3)
\]

from which Eq. 4.1 is quickly obtained:

\[
\delta r = -\frac{d}{2\sqrt{y^2 + x^2}} \cdot \left[ y \cos(\gamma t) + x \sin(\gamma t) \right]. \quad (B.4)
\]

This expression allows for the quick and easy calculation of footprint shift for an arbitrary signal arriving at the array. The geometry of the system in question does not need to be known, the only required information is the inter-element spacing \( d \), the transducer tilt angle \( \gamma_t \), the transducer deployment depth, and the coordinates of the perceived scattering location. These coordinates are then entered directly into Eq. B.4 without requiring any alteration.

Additional implicit assumptions have been made in the above derivation that are worth mentioning. When footprint shift does occur, the scattering locations that produced the signals received at two elements are slightly offset in space and angle, but it is assumed that this angular offset is negligible. It is also implicitly assumed that the scattering locations can be described by a single angle \( \theta_j \); Eq. 4.1 is invalid for signals originating from nadir. When plotting profiles via Kraeutner and Bird’s method, it is common to offset the profile in space according to the transducer deployment depth, in which case the \( y \) coordinate in Eq. B.4 needs a similar offset. Finally, as stated before, it is assumed that the signals are plane waves and that the sonar system is a monostatic system.
Appendix C

Supplementary Sidescan Images

In this Appendix, additional sidescan images are provided. These images have been chosen because they are contaminated with interference, and (as before) are presented along with the “cleaned up” version that results from the processing that this thesis proposes. The motivation for including this Appendix is simple: to convince the skeptical reader that

- the problem really does exist,
- the problem really does occur in practice (in fact, it is fairly common),
- the proposed processing really does address the problem.

The Problem (that multipath interference contaminates sidescan images when the survey is conducted in shallow water) occurs often enough that the Underwater Research Laboratory has many examples from field trials - only a small collection of which are given here. Many sidescan images have already been presented, but the ones included in this Appendix offer further evidence to support the above claims. In each of the cases to be presented, the fixed broad beam was employed to remove surface interference.

C.1 Additional Images From Bedwell Bay

Two additional images are now presented which were created from data collected during surveys in Bedwell Bay, outside Vancouver. Recall that the sidescan image shown in Chapter 2 was collected in this survey area. In Fig. 2.5 a shipwreck is masked by dominant surface interference, and although Fig. 2.5 is perhaps the most dramatic example of bottom
masking seen during this survey, other images from the same survey show similar behavior. The surface interference that resulted during this survey was caused by a combination of wind/wave action and by boat wake.

C.1.1 Example 1

In this first example, shown in Fig. C.1, dominant surface interference obscures the seafloor and partially masks two separate shipwrecks. The sidescan image is blurry in places, such as pings 100-150 between 50 m and 100 m range, and also pings 500-600 between roughly 100 m and 265 m range. Some spurious highlights are also present, lending a grainy quality to the image.

When Fig. C.1 is processed using the fixed broad beam, surface interference is attenuated and a clear view of the seafloor results. Fig. C.2 shows the result of this processing, revealing a clear view of the seafloor with two shipwrecks visible. The fixed broad beam also increased sensitivity to B signals coming from the close range (roughly less than 100 m) portion of the image. On this particular deployment, the transducer was tilted at a fairly shallow angle of about 15° below horizontal, which decreases sensitivity to signals arriving from near nadir (the close-range signals in this image) and increases sensitivity to signals arriving from long range - or from the surface.

Fig. C.3 shows a side-by-side comparison of the two sidescan images presented in this Subsection. Although both images are reduced in size to facilitate this comparison, the changes resulting from the fixed broad beam processing are evident.

C.1.2 Example 2

In this second example, the shipwreck shown in Fig. 2.5 is viewed from a different aspect during the same survey. Fig. C.4 shows the sidescan image created from these data, except in this case the shipwreck is not entirely obscured by the surface interference. The image as a whole is quite contaminated, however, even if the shipwreck is discernable. The muddy bottom that exists in much of this survey area is a weak scatterer; although the shipwreck would normally stand out from the otherwise featureless seafloor, the surface interference reduces the contrast.

Applying the fixed broad beam, the surface interference is rejected and Fig. C.5 results; the shipwreck sitting on an otherwise featureless seafloor is revealed. A side-by-side
Figure C.1: Sidescan image from a field deployment to Bedwell Bay in British Columbia showing dominant surface returns.
Figure C.2: Sidescan image from a field deployment to Bedwell Bay (the area shown in Fig. C.1) but when the fixed broad beam is used on receive to suppress the surface interference.
Figure C.3: Side-by-side comparison of Figs. C.1 (left) and C.2 (right). In this example, surface interference contaminates a sidescan image (left image) that contains two shipwrecks. Using the fixed broad beam, the surface interference is suppressed (right image).

**C.2 Additional Images From Pam Rocks**

During the Pam Rocks survey discussed in the Introduction, a combination of environmental factors resulted in unexpected surface interference. The Vancouver area was subjected to gale-force winds during the days that the survey was conducted (although the wind was comparatively mild in the survey area), and the result was that there was more floating debris on the water than is usually present. Additionally, inflow/outflow currents from Howe Sound and the Straight of Georgia were producing tidelines around the survey area, concentrating the floating debris and providing a source of strong surface interference.

**C.2.1 Example 1**

In this first example from Pam Rocks, surface interference causes a streaked appearance in the lower portion of the image (pings 1 - 100), and partially fills in a shadow in the middle of the image (around ping 400) in Fig. C.7. Strong and intermittent scattering from debris in the tideline contaminates the upper portion of the image (pings 500 and above), filling
Figure C.4: Sidescan image from a field deployment to Bedwell Bay showing the same shipwreck seen in Fig. 2.24 but from a different aspect
Figure C.5: Sidescan image from a field deployment to Bedwell Bay (the area shown in Fig. C.4) but when the fixed broad beam is used on receive to suppress the surface interference.
Figure C.6: Side-by-side comparison of Figs. C.4 (left) and C.5 (right). A shipwreck sits on an otherwise featureless portion of the seafloor but the image is contaminated with surface interference (left image). Using the fixed broad beam to remove this S interference leaves a clear view of the shipwreck that sits prominently on a muddy seafloor (right image).

In shadows and introducing “false” highlights that have nothing to do with the seafloor. In this survey area, the seafloor is more “complex” than in Bedwell Bay, making it more difficult for the human eye to discriminate between the rapidly changing B signals and the surface interference.

Fixed beam processing removes the surface interference, and yields Fig. C.8. Shadows are deepened, false highlights are removed, and the streaking in the lower portion of the image is removed. A side-by-side comparison of these images is shown in Fig. C.9.

C.2.2 Example 2

In this second example from Pam Rocks, the effects of surface interference are more subtle - hence more difficult - to distinguish from the seafloor signal. Throughout Fig. C.10 some streaking is visible, but a few spurious highlights are present around 150 m range in pings 200-400. These false highlights are not immediately recognizable from the occasional rock sticking up from the seafloor.

Fig. C.11 shows the cleaned-up version of Fig. C.10, with surface interference removed.
Figure C.7: Sidescan image from a field deployment to the Pam Rocks Rockfish Conservation Area in Howe Sound, B.C. Surface interference is seen to introduce false highlights (intermittently from ping 500 and up) and to reduce target highlight/shadow contrast around ping 400.
Figure C.8: Sidescan image from a field deployment to Pam Rocks, but when the fixed broad beam is used on receive. The S interference is suppressed, removing the false highlights and deepening the shadow behind the large rock around ping 400.
Figure C.9: Side-by-side comparison of Figs. C.7 (left) and C.8 (right). The complex bottom in the Pam Rocks area, featuring rock highlights and accompanying shadows, is masked by surface interference (left image). Once again using the fixed broad beam to remove this interference, the shadows behind rocks are deepened and false highlights are removed (right image).
Figure C.10: Sidescan image from a field deployment to the Pam Rocks area. Subtle surface interference is present in the image, appearing mostly as streaking and also as some false highlights around pings 200-400.
The subtle streaking throughout the image is removed, as are the spurious highlights. Looking at the side-by-side comparison of these images (shown in Fig. C.12), additional surface interference artifacts are identified. Beginning around range 150 m on ping 1, and continuing beyond 200 m range on ping 75, a “line” of surface interference is visible in the unprocessed image that has been removed in the processed image. The subtlety of the interference in this set of images, coupled with the complex bottom, makes recognition of the interference challenging.
Figure C.11: Sidescan image from a field deployment to the Pam Rocks area but when the fixed broad beam is used on receive. The S interference is removed, providing a clear view of the seafloor.
Figure C.12: Side-by-side comparison of Figs. C.10 (left) and C.11 (right). This final pair of images shows a portion of the Pam Rocks area where the seafloor is mostly gravel (rather than large rocks), but the image on the left is contaminated by surface interference that creates a subtle streaking and introduces some false highlights. The fixed broad beam removes this interference (right image).
Appendix D

Cosine Beampattern Model

A general model is needed for the across-track beampatterns of the individual transducer elements modeled in this thesis. Beampattern measurements for the elements in the prototype array are available (and are used in this thesis), but a model is required for all other elements. Significant research indicates that the standard sinc beampattern model for a rectangular element does not apply, and that the introduction of a cosine term is warranted, under certain conditions. This Appendix summarizes the motivation for adopting the cosine beampattern model (for transducer elements) throughout this thesis.

In [40] it was found that the baffling material around an element influences its beampattern. The authors assume infinite baffles and introduce a directivity term that takes the form of a cosine function when the baffling material is acoustically soft. It is shown that the voltage $A$ measured by a beampattern measurement system follows the form

$$A = A_0 \frac{\sin (X(\theta))}{X(\theta)} \alpha(\theta)$$  \hspace{1cm} (D.1)

where $\theta$ is the physical angle off boresight,

$$X(\theta) = \frac{2\pi w \sin(\theta)}{\lambda},$$  \hspace{1cm} (D.2)

the source width is $2w$, and the directivity term $\alpha(\theta)$ is $\alpha(\theta) = \cos(\theta)$ if the baffle is soft. If the baffle is completely rigid then $\alpha = 1$, and if the source is placed in free space then $\alpha = 0.5[1 + \cos(\theta)]$.

In [41] the authors constructed phased array transducers with narrow width (less than $\lambda$) elements and using different baffling materials. It was concluded that beamwidth depends upon baffling material impedance (as concluded in [40]). A new directivity term was
introduced that takes the form

\[
\frac{Z_2 \cos(\theta)}{Z_2 \cos(\theta) + Z}
\]  

(D.3)

where \( Z_2 \) is the acoustic impedance of the baffle and \( Z \) is the acoustic impedance of the propagation medium. Simulation and experimentation confirmed that high impedance baffles produce wide beampatterns, and low impedance baffles produce narrow beampatterns. In [42] the width of the element was seen to influence the form of the beampatterns, with narrow (less than \( \lambda \) width) elements in acoustically soft baffles being described by the product of sinc and cosine patterns rather than pure sinc patterns.

When deciding upon a general beampattern model to use in this thesis, consideration must be given to the theoretical work that has been conducted, and the model must also fit the experimental beampattern measurements. The theoretical and experimental research cited above provides a basis for rejecting the pure sinc beampattern model that may be expected (under certain conditions) from rectangular transducer elements, and supports the introduction of a cosine term. The prototype array discussed in Chapter 2 has narrow rectangular elements (less than \( \lambda \)) and uses a combination of hard and soft baffling materials. Therefore, it is reasonable to expect that the beampattern for an individual (narrow) element in the prototype array would be described by a combination of sinc and cosine terms. However, this is not what is observed.

The beampattern measurements from the elements in the array are not adequately described by either a cosine function (to the power of 1), a sinc function, or the product of the two. For the prototype array the single element beampatterns are 115 degrees wide, whereas a cosine function (raised to the power of 1 for the voltage pattern) has a beamwidth of 90 degrees; a cosine function to the power of 1 is not sufficiently wide to describe the measurement. Multiplication of the cosine by a sinc function does not widen the beampattern, so the multiplication of the two terms is inadequate to describe the beampatterns of the elements in the array. The transducer elements are observed to have maximum response at boresight, to have 0 response at endfire, and to have a wide beam that transitions monotonically and without sidelobes or nulls between these two extremes, therefore a sinc pattern is also not appropriate. A new general model that fits the experimental beampattern measurements is therefore needed.

The beampattern model that is used in this thesis is a cosine function that is exponentiated, with the exponent determined empirically. In this way, the beampattern may be widened or narrowed to best fit the measurements, and a smooth transition is ensured.
between maximum response at boresight and zero response at endfire. Although this thesis
does not present a solid theoretical foundation for the use of the exponentiated cosine beam-
pattern model, this model accurately captures the receive element beamwidth, accurately
models the transmit beampattern, and is capable of accurately describing the measured
beampatterns of not only the prototype array but of other arrays as well (such as the
EdgeTech 4600 used in Chapter 3).