Comparision of Target Detection Capabilities of the Reson Seabat 8101 and Reson Seabat 9001 Multibeam Sonars

by

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Abstract

Swath multibeam sonar systems (MBSS) are commonly described as being capable of producing full-bottom coverage (100 % coverage). However, there is finite dimension to their multiple narrow beams, and therefore, this places a limit on the minimum target size that can be successfully detected. Multibeam sonars are being used more frequently to provide information regarding short wavelength features on the seafloor, and since these feautures are similar is size or smaller than the beam footprint, their adequate detection is not always possible. Numerous other issues inherent to the use of multibeams complicate the successful detection and delineation of small scale features, including but not limited to the changing size of the projected beam footprint tied to water depth, the nature of the bottom detect algorith used at nadir or obliques portions of the swath, and the difficulty of maintaining high data sounding densities from a moving platform.

This papers explores the capabilities of two different multibeam sonars to detect short wavelength features on the seafloor, whose dimensions approaches that of or are less than the beam spacing in the horizontal dimensions. The survey site was offshore of the Bamfield Marine station, in a region where an underwater pipeline had recently been installed. Due to the shallow nature of the survey region, several dives were conducted using underwater video equipment to record the actual size of the concrete collars for ground truthing purposes. This allowed for the comparison of the actual target size with the results provided from the MBSS, as a means of determining the effectiveness of target detection of these two system

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Chapter 1: Introduction

Section 1.1: Using multibeam sonar to detect targets in shallow waters

Presently, swath multibeam sonar systems (MBSS) are commonly described as being capable of producing full-bottom coverage (100 % coverage). However, the use of this term to describe the capabilities of MBSS to potential users, can be misleading. Having to ability to achieve 100% coverage of a survey area through planned overlapping swaths, is phenomenal, however, this does not ensure that all targets large and small, will be detected. This is because multibeam sonars have a finite dimension to their multiple narrow beams, and therefore, there is a limit to the minimum spatial resolution that can be achieved, and thus a corresponding minimum target size that can be detected by the sonar (Hughes-Clarke, 1998).

Multibeam sonars are being used more frequently in roles where investigators are attempting to derive information regarding short wavelength features on the seafloor, and there are great demands placed on these systems to succesfully detect these targets. Since these shorter wavelength targets are similar is size or smaller than the beam footprint dimensions of the multibeams systems being used to detect them, their adequate detection is not always possible. Their successful detection is further complicated by numerous other issues inherent to the use of multibeams, including but not limited to the changing size of the projected beam footprint tied to water depth, the nature of the bottom detect algorith used at nadir or obliques portions of the swath, and the difficulty of maintaining high data sounding densities from a moving platform (Miller et. al., 1997).

This paper explores the issue of small target detection in shallow waters, using both a Reson Seabat 8010 and a the Reson Seabat 9001 sonar. The survey site was offshore of the Bamfield Marine station, St. Andrews, NB, in the St. Croix River (Figure 1). This site was chosen because an underwater pipeline had recently been installed offshore of the Bamfield Marine Station wharf. The pipeline consisted of large diameter PVC tubing that was anchored in place by several equally spaced concrete collars. The survey consisted of conducting muliple surveys over the region where the pipeline had been installed.

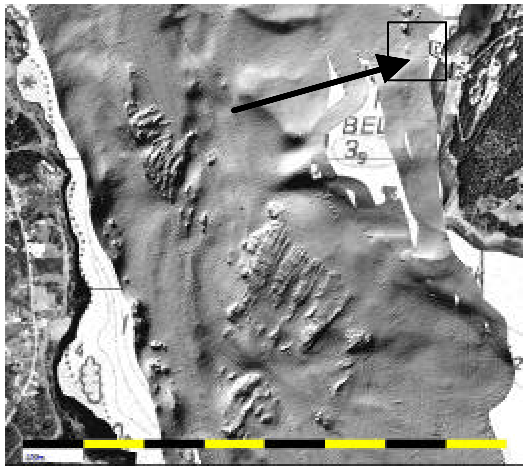

Figure 1: St. Croix River and Bamfield Marine Station. Arrow delineates area of interest.

While the plastic tubing of the pipeline offered very little acoustic impedance contrast, the concrete collars themselves were excellent targets on the seabed Figure 2. In addition, because of the shallow nature of the survey region, several dives were conducted using underwater video equipment to record the actual size of the concrete collars for ground truthing purposes. This allowed for the comparison of the actual target size with the results provided from the MBSS, as a means of determining the effectiveness of target detection of these two systems.

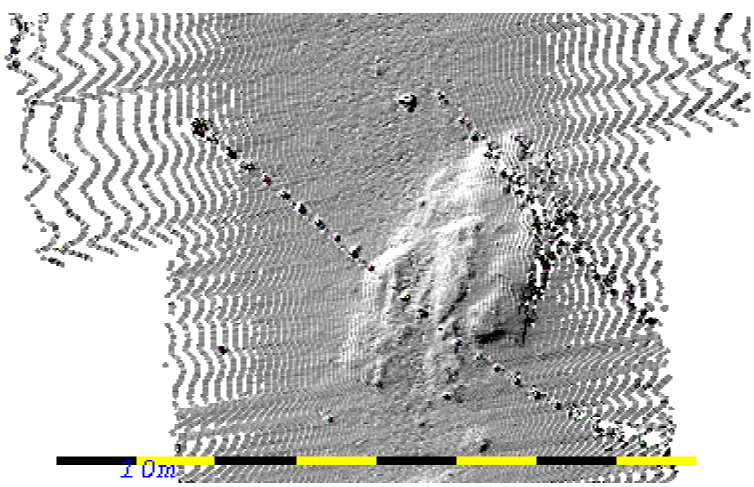

Figure 2: Sun-illuminated bathymetry over pipeline, highlighting concrete collars positions.

Section 1.2: Background: Why is this investigation important.

Before the advent of swath mapping systems, hydrographers accepted that a single beam survey could not provide complete coverage of a survey region, and such surveys were designed in a manner to provide the most amount of sounding for a reasonable period of time. This meant that only those targets, whether they be shipwrecks, or shoals, that fell within the footprint of the vertical beam echosounder, would be detected. Any targets located in regions in between where the survey lines were run, were left undetected. Furthermore, the beam angle for a typical single vertical beam echo-sounder was on the order of 5-20 °, making the ability to delineate the shape of a target virtually impossible. To overcome the shortcomings, many hydrographic organizations implemented the use of side-scan sonars to help fill in the gaps between survey lines.

With the advent a swath sonar systems, the ability to achieve 100% bottom coverage was greatly promoted, even though the meaning of 100% coverage was, and still is poorly defined (Hughes-Clarke, 1999). Initially, multibeam systems were deployed with great success in deep water. Because of the water depths, the ability to resolve small targets on the seafloor wasn't a consideration, nor was it even possible, given that the ability to detect targets is limited by the size of the beam footprints. As the size of these footprints are greatly influenced by the total water depth (generally 1-10% of water depth), the ability to detect a 5 m or even 25 m target was not of great importance when operating in waters on the order of 1000 m to 3000 m. IHO standards themselves advocate that when working in waters < 30 m deep, an error of +/- 1 % of water depth was exceptable in the vertical domain. This error budget alone is greater than the size of a 5-25 meter target, when working in ~3000 m waters.

As the capabilities of swath sonars improved, their deployment in shallow water environments became more common, and we as hydrographers have become more reliant on their ability to detect any and all targets, that may pose a potential hazard to navigation. However, the use of multibeam systems in shallow water specifically for the detection of short wavelength features raise quite a number of issues. In shallow waters, the tolerance for errors is much smaller, as shallow water targets represent potential hazards to the safety of navigation. Multibeam systems in operation in shallow waters are potential being pushed beyond the capabilities, and it behooves us as end users to have better understanding of the practical limitations with respect to their ability to resolve small scale features.

There are a number of factors that influences a MBSS ability to resolve a target. However, the most fundamental parameter that needs to be considered when attempting to resolve a target of a specific size, is the sounding density. Any factor that alters the sounding density, will have an effect on the minimum spatial dimensions of a target that can be reasonably be detected. One of the simplest factors that will alter the sounding density of a survey, is the beam footprint dimension, and its' depence on beam width and water depth. The greater the water depth, the greater the footprint size, and the fewer number of soundings that will be received from the seafloor.

While we are fairly confident that we can successfully detect targets whose physical dimensions are greater than the beam footprint, targets smaller than the beam footprint may either, remain hidden to us, or their geometry in the sounding dataset will be erroneous. This is by no means a failure of the MBSS, but highlights the importance of understanding the minimum spatial resolution of the systems, and the limitations that this may place on detecting small scale seafloor features.

Section 1.3: Quantifying the limits on Spatial Resolution of a Sonar

The intent of this paper is to explore the capability of the sonars to detect short wavelength features on the seafloor whose dimensions approaches that or are less then the beam spacing in the horizontal dimensions. In so doing, we can potential establish the spatial resolution achievable with these sonars, in these particular water depths.

When attempting to quantify a sonars ability to resolve fine-scale morphology, there are two approaches:

- synthetic modelling of the reponse of the sonar, or,
- conducting repetitive benchmark surveys over terrain of known physical dimension (rare because it require very detailed knowledge of seafloor morphology)

(Hughes-Clarke, 1998)

The St. Andrews survey, and the ability to conduct several underwater dives over the pipeline, provided a rare and unique opportunity to quantify the spatial resolution limitations of the two sonars. This was a unique opportunity because this method involves having detailed knowledge of the true morphology of a region, information that is rare to have access to, given that most morphological information derives from remote sensing techniques. Here we have the opportunity to investigate the ability of these sonars to detect targets of known size, and compare the final bathymetric data products with our knowledge of these targets dimension. In so doing, we can quantify both the horizontal and vertical extent of the detected seafloor anomaly, and compare these values with the target's actual dimensions.

Chapter 2: General Principles of Multibeam Sonar Systems

Section 2.1: Overview

Bathymetric swath sonar measure the oblique slant range to the seafloor of distances beyond the first arrival of echos from nadir, by using several beams oriented both vertically and obliquely. Typically these beams are 1 ° - 2 ° in both fore-aft and athwartship directions and are much narrower than the 5-25 ° beams employed by earlier single beam systems. This means that MBSS sonars are very capable of resolving targets that are much smaller than those detected by narrow vertical beam sonars, yet the dimensions of target capable of being detected, are limited to those targets equal to or larger than the beam footprints. As these footprint dimensions are generally 1-10% of water depth, the total water depth will have a significant impact of the ability of the sonar to detect very small seabed targets. (Hughes Clarke et. al., 1998). Those targets whose physical dimensions are smaller than the beam footprint may not be adequately resolved.

Multi narrow-beam sonar systems are typically based on a cross fan beam geometry generated by two transducer arrays mounted at right angles to each other either in an L of T configuration (Figure 3) (de Moustier, 1988). Each array produces a beam which is narrow in the direction of its short axis, and the intersection of the two results in a beam pattern that is delimited by the narrow widths of these beams (Figure 4).

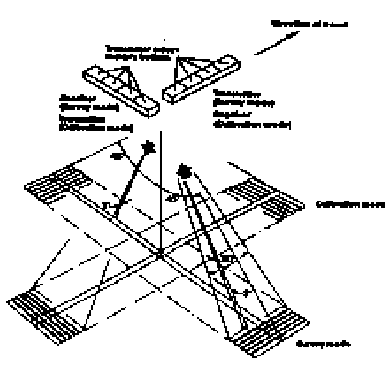

Figure 3: The orthogonal orientation of the transmit and receive beam patterns in in multibeam system (Nishimura, 1997)

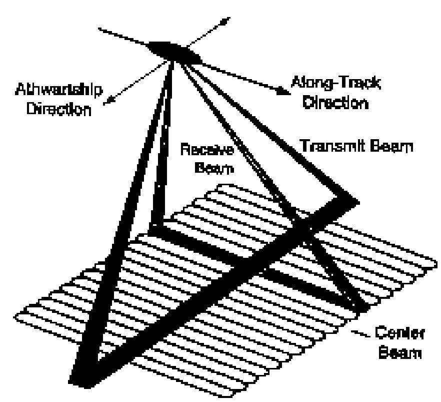

Figure 4 : The intersection between the two transducer arrays of a multi-beam system (Grant & Schreiber, 1990)

In practice, these arrays are made up of a number of identical transducer elements that are equally spaced. In the trasmit array, these element are placed parallel to the ship's keel and project a vertical fan beam, that is narrow in the along track direction and broad in the across track (Farr, 1980). The typical beamwidth for a transmit array is 1° to 3° in the along track direction and up to 150° (or more) in the across track direction.

In order to obtain the necessary angular resolution of the non-nadir beams, the receiver array consists of a series of hydrophones mounted orthogonally to ship's directions of travel. The receiver array generates a series of fan-shaped receiving beams that are in planes parallel to the ship's direction of travel, and the system is sensitive to the narrow rectangular window on the seafloor that is formed by the intersection of the transmit and receive beams (Fig. 5). Typically, the receive beamwidths are 1° to 3° in the across track direction, and 20° in the along track direction in order to accomodate the pitch attitude of the boat. The large width of the receive beam in the along-track direction ensures that the receive array will be oriented properly to detected the return signal regardless is the ship's motion.

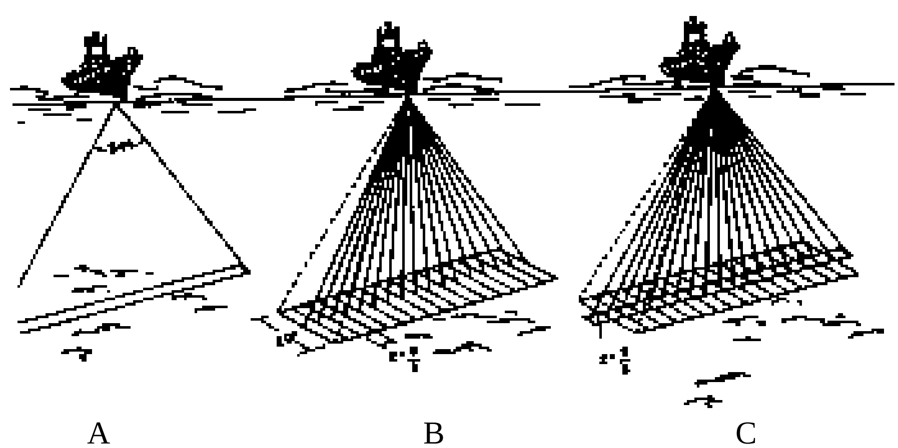

Figure 5: Relationship of the transmit and receive beams in the Sea Beam Swath Bathymetry system. A) Transmit beam B) Receive Beams C) Intersection of the two (Renard & Allenou, 1979).

Because of the finite beam width, the acoustic footprint from an oblique beam ensonifies an area of the seafloor whose size is a function of the beam angle, and the slant range distance along which the acoustic pulse must travel before interacting with the seafloor (Figure 6). The acoustic signal fluctuates in a random fashion over the area of ensonification due the random nature of the scattering of sound off of the seafloor. The object is to determine the best possible estimate of the true arrival time at the point corresponding to the boresight of the beam, determined by the specific angle of that particular beam (Figure 6) (Farr, 1980). This best estimate of time arrival is determined by the bottom detect algorithm being employed by the system. The output for each acoustic ping, is a coordinate pair for each beam, which provides the depth and the horizontal distance from the ship along a line perpendicular to the ships heading, from which a swath bathymetry map can be generated.

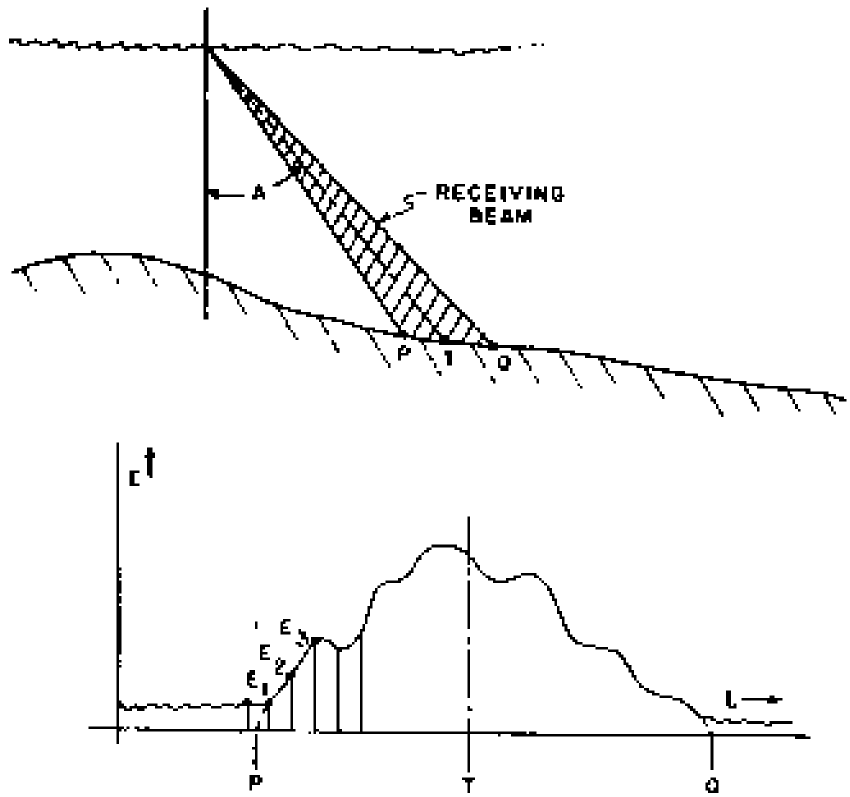

Figure 6: Receiving beam and subsequent recording of signal energy, as a function of time.

Most conventional vertical beam echo sounders determine the travel time of the acoustic pulse by detecting the position of the sharp leading edge of the returned echo (amplitude detection) (Mayer and Hughes-Clarke, 1995). Once this is determined the two-way travel, and hence depth, can be calculated. This process is much more complex with a multibeam sonar. In a MBSS, where the angle of incidence for the beams formed to each side of vertical (nadir) increases, the returned echo loses its sharp leading edge and the accurate determination of depth via amplitude detection becomes more difficult (Figure 7). An alternate solution is to use phase detection, an interferometric principle, as a means of determining the range to the seafloor for these oblique beams. In theory, this is achieved by creating several narrow beam bathymetric sidescan sonars that are in parallel with each other (de Moustier, 1998). A two row split aperture sidescan sonar configuration can be duplicated by a multibeam system by generating two beams pointing in the same direction through beamforming, and measuring the phase difference between these these beams over the duration of the return echo envelope. The point at which there is no phase difference, corresponds to the maximum response axis of the beam, providing a measure of the two-way travel time for a known angle (pointing direction) from which a depth to the seafloor can be determined (Mayer and Hughes-Clarke, 1995). Both amplitude and phase detection are performed on each beam within the swath, and the system software selects the best detection method for a given beam and uses this in calculating depth. Nadir (near-vertical) depths are primarily calculated based on amplitude detection, while oblique beam depths are usually determined through phase detection methods.

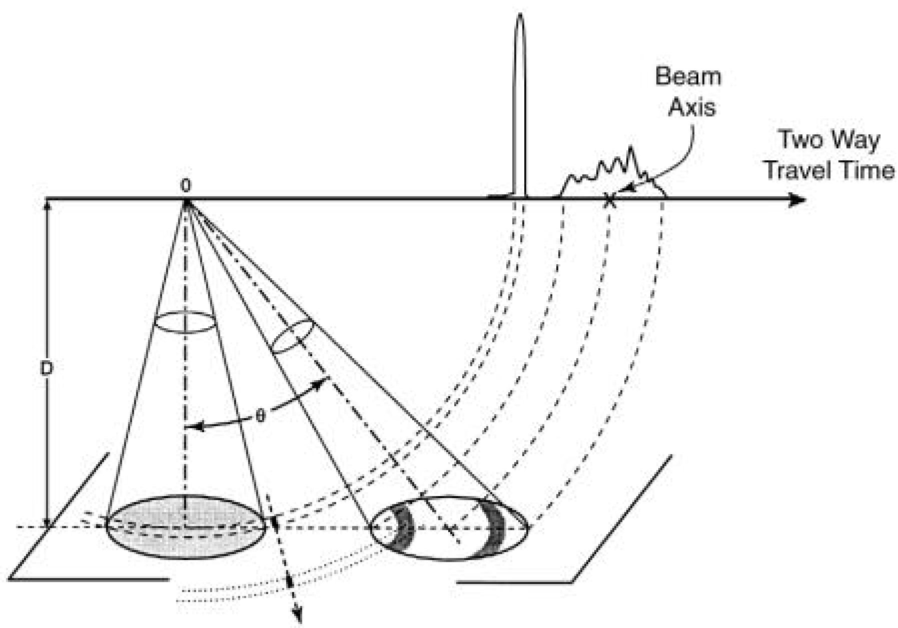

Figure 7: Nadir and Oblique Return Echo (after de Moustier, [1998, p.6]).

Section 2.2: Different Methods of Generating A Series of Beams

Although the design of multibeam transducers varies widely from manufacturer to manufacturer, the principles behind their design remains the same. Typically, multibeam sonars use different transducer arrays for generating the transmit and receive beams. The transmit array is usually mounted with its length axis parallel to the keel of the ship and the receive array is mount at right angles to the transmit array. The objective is to create beams which are narrow in both the fore-aft and athwartship directions.

However, this design requires the use of a linear array of elements to generate the required transmit and receive beams. Typically beams are formed broadside to the array through a process called beamforming. In the case of a flat linear array, through beamform, only one beam oriented broadside to the array, or nadir, will be formed. In order to generate the oblique outer beams, beam steering must be applied. This is a process of forming a beam at a given angle θ from broadside. This is achieved by incrementally phase-shifting the contribitions of the transducer element along the array so as to create a virtual array whose face is perpendicular to the desired steering direction (de Moustier, 1998)

As beams are steered away from broadside, the width of the steered beam increase in inverse proportion to the steering angle. This is because the aperture of the virtual array shortens as it is projected onto the plane perpendicular to the steering direction (de Moustier, 1998). Because the beam width of the outer beams formed through beam steering, are larger than the nadir beam width, their corresponding footprint size will also be larger. This complicates the detection a small scale features in the outer portions of the swath.

However, difficulties associated with beam steering can be avoided by using a series of elements placed along a curved array, as opposed to a linear array. Both the Reson 9001 and the Reson 8101 utilize such a configuration. Beams can be formed broadside to the tangent to the face of the array by using the subset of elements which are closest to this tangential point (Figure 8). Thus since all beams are formed broadside to the tangents around a curved array, no beam steering is required (except in the outermost portion where not enough elements exist) and all beams will have the same beamwidth. This configuration has the added advantage of being insensitive to errors in the surface sound speed at the array face, a value that needs to be rigorously monitored when applying beam steering principles.

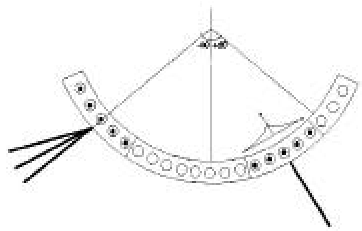

Figure 8: Illustration of the design of a curved array of elements in a multibeam sonar (Kammerer, personal communication).

Section 2.3: Description of Reson Seabat Multibeam Sonars

2.3.1 Reson Seabat 8101 Multibeam

The Reson Seabat 8101 multibeam operates at 240 khz, generates 101 beams per ping and has an angular sector of 150 °. However, the usable angular sector derived from internal quality flags generated by the sonar, typically is limited 125 ° and 130 °. In the shallow waters offshore of the Bamfield wharf, the sonar was capable of providing swath coverage up to 7 x water depth. The maximum ping rate for the 8101 system is 30 pings per second.

The beam widths in both the fore-aft direction and the port-starboard direction are 1.5 °, and are of equal angular size regardless of whether they are nadir or outer beams. This is because the design of the Seabat 8101 utilizes a curved array, and unlike a flat array, does not require the use of beam steering to generate the non-nadir beams, except in the outer most beams. The curved array allows the system to generate beams that are orthogonal to the face at all orientations (orthogonal to the tangent of the array at any given point). The 8101 is capable of both amplitude and phase detection methods, for depth to the seafloor determinations. Typically, for the inner beams, amplitude detection method is used, while the outer beams utilize phase detection to determine slant range distance.

RESON Seabat 8101 (240kHz)

- centre frequency:	240 kHz
- angular sector (deg.)	150 °
- sounding per swath:	101
- foreaft beam width	1.5 °
- port-stbd beam width	1.5 °
- active roll compensation?	No
- active pitch compensation?	No

Figure 9: Attaching the Reson 8101 transducer to poll mount, St. Andrews Hydro Field Camp (photo courtesy of Dr. D. Wells).

2.3.2 Reson Seabat 9001 Multibeam

The RESON Seabat 9001 is the most widely used high resolution bathymetric sonar on the market (Hughes-Clarke, 1997). It is designed for short range (<100m) bathymetry and backscatter imaging. Operating at 455 kHz using beams that are only 1.5 ° by 1.5 ° in size, it generates 60 soundings per swath per ping within a 90 ° wide sector. It is capable of generating 15 pings per second.The swath width indicated by the manufacturers is listed as between 2x to 4 x water depth. . Like the Reson 8101, the beam widths in both the fore-aft direction and the port-starboard direction are 1.5 °, and are generated by a curved array as well. However, unlike the Reson 8101, the 9001 makes use of only the amplitude detection method for determine the arrival time of the first return. This is because of the narrower swath width, and the magnitude of the echo return envelope of even the outer most beams, is sufficient enough to utilize the amplitude detect method.

RESON Seabat 9001 (455 kHz)

- centre frequency:	455 kHz
- angular sector (deg.)	90 °
- sounding per swath:	60
- foreaft beam width	1.5 °
- port-stbd beam width	1.5 °
- active roll compensation?	No
- active pitch compensation?	No

Figure 10: Securing the the Reson 9001 transducer to Mary O vessel, Burton bridge Hydro Field Camp (photo courtesy of J.V Martinez).

Chapter 3: Beam Footprint Dimensions

The diiferent beam footprint dimensions of multibeam system are a function of the beamwidth, the grazing angle of the transmit beam with the seabed, and the water depth. The relationship is summarized as follows: the smaller the beamwidth, the greater the grazing angle (closer to nadir), and the shallower the water, the smaller the beam footprint. These footprint dimensions play a fundamental role in controlling the overall resolution of a multibeam system. Obviously, those beams closer to nadir will be capable of better resolutions than the outer beams, because of the different beam footprint sizes.

For those system that utilize amplitude detection methods for determining bottom detection, the minimum spatial resolution can theoretically be calculated based on the footprint sizes controlled by beam spacing specifications. However, because the beam footprint size is dependent on water depths, such calculations assume a flat seafloor. Such estimations of minimum spatial dimensions based on the beam footprint dimensions can only be considered for systems that utilize amplitude detection, because defining an equivalent beam dimension for a phase detection system is much more difficult (Miller et. al.1997). This is because unlike amplitude detection, phase detection takes many measurements of the phase difference over the length of the acoustic return within an outer beam footprint. The point at which there is no phase difference corresponds to the maximum response of axis of that beam, and an estimate of arrival time for that beam pointing direction is provided (de Moustier, 1998). Since several measurements of phase are taken over an individual footprint, it is much more difficult to define a geometric size for each sample taken across the width of an individual footprint.

Section 3.1: Principles of Calculating the Footprint Size Based on Beamwidth

The transmit beam is narrow in the along track direction and broad in the across track direction in order to ensonify the full angular sector of the swath. In terms of defining the horizonal spatial resolution of a MBSS system, the fore-aft beamwidth of the transmit beam will control the along track dimensions of the beam footprint, and the port-starboard beamwidth will control the across track dimensions of the beamwidth.

Assuming a flat seafloor, the dimension of the fore-aft beam footprint is equal to twice the slant range distance times the tangent of half the beamwidth, where the slant range is a function of the beam angle and water depth.

Beam Footprint Size Along Track = (2 x (SLR(tan(½ x F/A BW)))

For those systems that use amplitude detection methods, the port-starboard beamwidth can be used in combination with the water depth and the beam angle (different for nadir or oblique beams), to determine the dimensions of individual beam footprints across the width of the swath. This across track beam footprint dimension is equal to the TAN of the beam angle + ½ P/S beamwidth minus the TAN of the beam angle – ½ P/S beamwidth, multiplied times the water depth.

Beam Footprint Size Across = Depth * ((tan(β + ½ P/S BW) - (tan(β - ½ P/S BW))

3.1.1 Determining Along Track Footprint Size

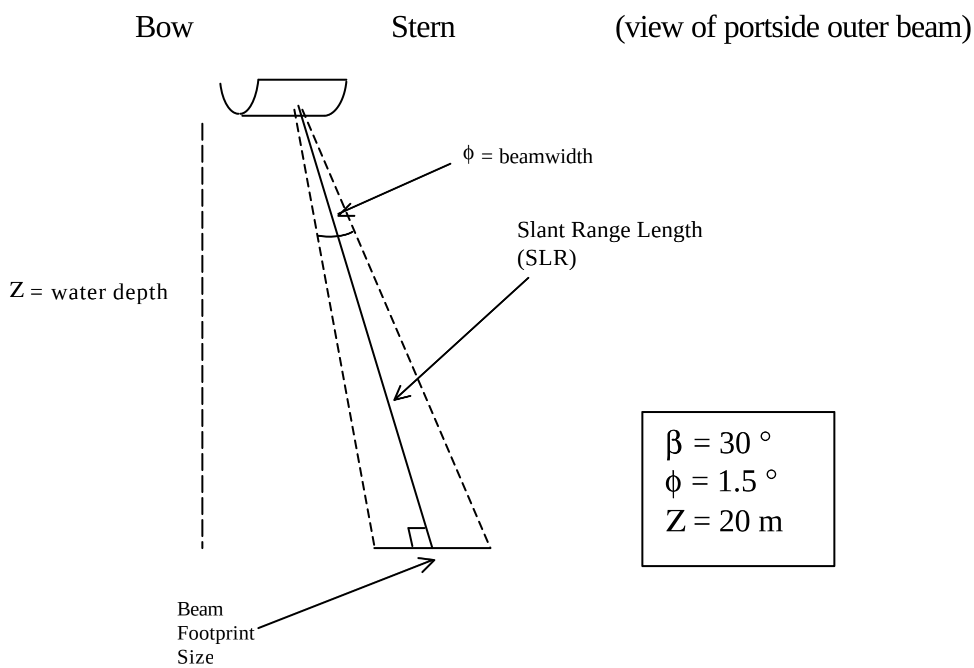

Figure 11: Calculating the dimensions of the along track beam footprint.

Beam Footprint Size in along track dimension equals:

BFS = 2 * (SLR(TAN(ϕ/2))) where the Slant Range (SLR) is a f(n) of beam angle and water depth

= 2 * ((Z / COS (β))(TAN (0.75 °)))

= 2 * ((20 / COS (30 °)(TAN (0.75 °)))

= 2 * ((23. 094)(TAN (0.75 °)))

= 0.60463433 m

So the beam footprint size in the along track direction for a beam oriented 30 ° from nadir equals 0.60 m, in 20 m of water.

3.1.2 Determining Across Track Footprint Size

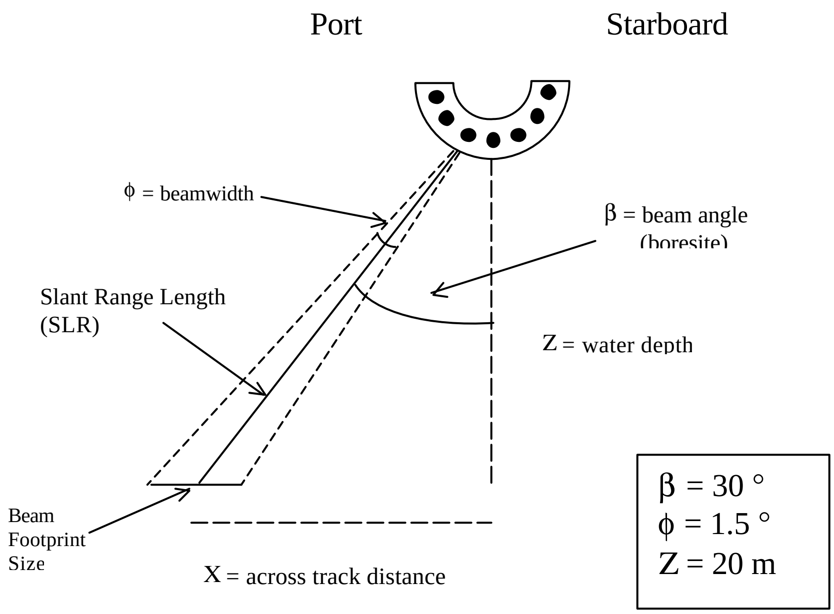

Figure 12: Calculating the dimensions of the across track beam footprint.

Beam Footprint Size equals:

BFS = ((TAN(β+(ϕ/2)) * Z) - (TAN(β-(ϕ/2))*Z))
= ((TAN(30.75)) * 20) - (TAN (29.25) * 20)
= 11.89875 - 11.200538
= 0.6982119 M

So the beam footprint size in the across track direction for a beam oriented 30 ° from nadir equals 0.70 m, in 20 m of water.

3.1.3 Footprint Dimension Calculations for Both Systems

	Beam Angle	5 m Water Depth Along x Across (in meters)	10 m Water Depth Along x Across (in meters)	15 m Water Depth Along x Across (in meters)
Limits of Reson 8101				
Outer Beam	70	0.38 **x** 1.12	0.77 **x** 2.24	1.15 **x** 3.36
	60	0.26 **x** 0.52	0.52 **x** 1.05	0.79 **x** 1.57
	50	0.20 **x** 0.32	0.41 **x** 0.63	0.61 **x** 0.95
Limits of Reson 9001	40	0.17 **x** 0.22	0.34 **x** 0.45	0.51 **x** 0.67
	30	0.15 **x** 0.17	0.30 **x** 0.35	0.45 **x** 0.52
	20	0.14 **x** 0.15	0.28 **x** 0.30	0.42 **x** 0.44
	10	0.13 **x** 0.13	0.27 **x** 0.27	0.40 **x** 0.40
Nadir Beam	**0**	**0.13 x 0.13**	**0.26 x 0.26**	**0.39 x 0.39**
	10	0.13 **x** 0.13	0.27 **x** 0.27	0.40 **x** 0.40
	20	0.14 **x** 0.15	0.28 **x** 0.30	0.42 **x** 0.44
	30	0.15 **x** 0.17	0.30 **x** 0.35	0.45 **x** 0.52
Limits of Reson 9001	40	0.17 **x** 0.22	0.34 **x** 0.45	0.51 **x** 0.67
	50	0.20 **x** 0.32	0.41 **x** 0.63	0.61 **x** 0.95
	60	0.26 **x** 0.52	0.52 **x** 1.05	0.79 **x** 1.57
Outer Beam	70	0.38 **x** 1.12	0.77 **x** 2.24	1.15 **x** 3.36
Limits of Reson 8101				

Approx Swath Width Coverage

	5 m	10 m	15 m
Reson 9001(~90°)	**10 m**	**20 m**	**30 m**
Reson 8010(~150°)	**37 m**	**75 m**	**112 m**

2 * (TAN (Angular Sector) x Water Depth

	Beam Angle	20 m Water Depth Along x Across (in meters)	25 m Water Depth Along x Across (in meters)	30 m Water Depth Along x Across (in meters)
Limits of Reson 8101				
Outer Beam	70	1.53 x 4.48	1.91 x 5.60	2.30 x 6.72
	60	1.05 x 2.10	1.31 x 2.62	1.57 x 3.14
	50	0.81 x 1.27	1.02 x 1.58	1.22 x 1.90
Limits of Reson 9001	40	0.68 x 0.89	0.85 x 1.12	1.03 x 1.34
	30	0.60 x 0.70	0.76 x 0.87	0.91 x 1.05
	20	0.56 x 0.59	0.70 x 0.74	0.84 x 0.89
	10	0.53 x 0.54	0.66 x 0.67	0.80 x 0.81
Nadir Beam	**0**	**0.52 x 0.52**	**0.65 x 0.65**	**0.79 x 0.79**
	10	0.53 x 0.54	0.66 x 0.67	0.80 x 0.81
	20	0.56 x 0.59	0.70 x 0.74	0.84 x 0.89
	30	0.60 x 0.70	0.76 x 0.87	0.91 x 1.05
Limits of Reson 9001	40	0.68 x 0.89	0.85 x 1.12	1.03 x 1.34
	50	0.81 x 1.27	1.02 x 1.58	1.22 x 1.90
	60	1.05 x 2.10	1.31 x 2.62	1.57 x 3.14
Outer Beam	70	1.53 x 4.48	1.91 x 5.60	2.30 x 6.72
Limits of Reson 8101				

Approx Swath Width Coverage

	20 m	25 m	30 m
Reson 9001(~90°)	**40 m**	**50 m**	**60 m**
Reson 8010(~150°)	**150 m**	**187 m**	**225 m**

2 * (TAN (Angular Sector) x Water Depth

Table 1: Beam Footprint dimensions for varying water depths assuming a flat seafloor.

Chapter 4: Sounding Density and Target Delineation

Section 4.1: Vessel Parameters that Affect Sounding Density

Determining the location of a potential target on the seafloor is the first step in target detection, however, more importantly is establishing the vertical and horizontal extent of the target. The knowledge of both vertical and horizontal dimensions, allows for the proper assessment of risk potential that the targets may pose to navigation. The ability to determine the extent of a target is controlled by the sounding density, and more specifically, how many individual discrete beams actual interrogated a target (number of hits), allowing it's shape to be delineated. Sounding density is in essence, the number of discrete data points that interrogate the seafloor. Because a multibeam sonar is physically mounted to the hull of a vessel, any parameter that alters the vessel position, and hence the location of the swath, can vary the sounding density.

Section 4.2: Effects of Vessel Motion on Transmit and Receive Beam

For MBSS systems, we derive a measure of the TWTT for nadir and oblique beams that are narrowly constrained. Each of these narrowly constrained beams are formed by the product of two planar like beams, the outgoing-transmit beam, and one of the receives beams. Therefore, in making our TWTT measurement of nadir or obliques beams, any vessel motion that influences the position of either the transmit or receive beams, can affect the sounding density.

This is because the multibeam sensor, since it is physically attached to the vessel, experiences all motions that vessel experiences. Some multibeam systems utilize sophisticated beam steering configurations to modify the orientation of the transmit and receives beams in real time, in order to minimize this effect. This is performed through active roll, pitch and yaw compensation, which attempts to maintain a vertically oriented swath, that is nearly perpendicular to the direction of travel. However, neither multibeam sonars evaluated in this paper utilize roll, pitch or yaw compensation, and thus the orientation and position of their respective swaths is sensitive to all motions experience by the vessel.

In taking sounding measurements along a swath, there are two component; first, the area must be ensonified by the transmit beam, and secondly, energy from the seafloor must be reradiated back towards the source and detected by several narrow receive beams. Thus, we can discuss how vessel motion effects the orientation of the transmit and receive beams, seperately.

4.2.1 Effects of Vessel Motion on the Transmit Beam

The most important factor to remember with regards to transmit beam, is that the region of seafloor from which a target can be detected is limited to those portions of the seafloor ensonified by transmit beam. Since the MBSS sonar is physical mounted to the survey vessel, and in our case, no active roll, pitch and yaw compensation is applied, any changes in vessel orientation will affect the transmit beam.

Vessel orientation is monitored by measuring the roll, pitch, yaw as well as heave of the vessel, and each parameter will have a different affect on transmit beam footprint. Although these effects are discussed individually, one must keep in mind that at any given time, it is their cumulative effects that alter the swath geometry, and hence influence data sounding density.

- Change in Roll at Transmit:
(Assuming the use of mbss that do not have roll nor pitch stabilization)

Changes in roll with affect the across-track position of the transmit beam. Should the vessel roll sharply to starboard, the transmit beam beneath the vessel will extend further to port in the across track dimension than to starboard. The transmit beam is unaffected in the foreaft direction by changes in roll.

- Changes in Pitch at Transmit

Any pitching motion of the vessel will translate the transmit beam footprint in the along track direction. For example, should the vessel pitch bow down, the transmit beam beneath the vessel will shift further towards the stern. In severe pitching conditions, this can create bands of tightly spaced transmit beams followed by regions where very few transmit beams have interrogated the seafloor, generating inter-ping gaps.

- Changes in Yaw at Transmit

Yaw is a measurement of the pointing direction of the vessel. Changes in yaw will rotate the position of the transmit beam around the vertical axis of the transducer. If the heading changes dramatically enough between pings, it is possible that the oblique beams in the outer portion of the swath will contain inter-ping gaps.

- Heave

Changes in heave will alter the altitude of the sensor above the seafloor. As the beam footprint on the seafloor is dependent on the water depth, changes in heave will either enlarge or shrink the size of the transmit beam footprint on the seafloor depending on the heave experienced. This will have the effect of increasing or decreasing the total swath width as the vessel moves up and down.

4.2.2 Receive Beam Issues

- **Effects of Roll**

It is the geometry of the receive beams that allow for numerous soundings across a swath to be determined. While for the case of the transmit beam there is only one beam, the receive beams differ in that there are numerous beams equal to the total number of soundings per swath. When a vessel rolls, the number of receives beams oriented towards port and starboard changes. This effect is particularly noticeable in the outer beams where the swath coverage oscillates from side to side. If a vessel rolls to starboard, more soudings will be detect to port at greater slant ranges than if the vessel experienced no roll. This pattern will then swing to the port side as the vessel returns to an upright position and then rolls to starboard.

- **Effects of Pitch and Yaw**

The receives beams themselves are commonly quite large in the fore-aft direction to allow for changes in pitch and yaw between the transmit and receive intervals, but are very narrow in the across-track direction. Any changes in pitch or yaw of the vessel, will have very limited impact on the orientation of the receive beams since they are broad in the along track direction to accommodate changes in vessel orientation, and the position of soundings on the seafloor have already been determined at the time of transmit. As mentioned previous, changes in pitch will alter the fore-aft displacement of beam footprints, whereas changes in yaw can alter the positions of sounding solutions in the outer portions of the swath.

- **Effects of Heave**

As heave will change the altitude of the sonar wrt to seafloor, there is a noticeable affect on the receive beams. As the footprint size varies as a function of depth, for fixed angular sectors, the swath width will increase or decrease in the sonar rises or falls. This phenomena can be easily demonstrated by the scenario where a sonar (using a fixed angular swath) passes over an incised canyon on the seafloor. That system will experience an increase in the swath width as it passes over this morphological feature, and a subsequent increase in the beam footprint dimensions. This is similar to what would occurred if the vessel where to experience heave that increased the depth of water beneath the sonar transducer.

4.2.3 Other Factors that Influence Sounding Density

In the along track direction, the amount of distance travelled between pings, is of great importance to the overall data density. The two key factors that control this distance are the shot repetition rate (ping period) and the vessel speed.

4.2.3.1 Effects of ping period.

This is refered to as the amount of time taken in between successives measurements of depths across the swath. The ping period must be greater than or equal to the amount of time taken for sound to propagate to and from those targets that are the furthest away from the sonar. This distance, and hence travel time, will depend on the water depth and the obliquity of measure of outer most beam. Processing CPU considerations apply an addition constraint on the ping period for multibeam sonars operating in shallow waters (Miller et. al., 1997). Since soundings from across the entire length of the swath cannot be determined instantaneously, there is a finite amount of compute time required by the sonar processing unit to calculate all these values. Typical, this compute time, rather than the TWTT limits the ping period to between 0.5 and 0.1 seconds. Most modern day sonars have a compute time of 0.1 s, hence can ping at 10 Hz in shallow waters. (Miller et. al., 1997)

4.2.3.2 Vessel Speed, and influences of local tidal and current conditions.

The vessel speed can also influence the along track data density, insofar that faster speeds will generate larger gaps between successive swaths than slower speeds. This affect is compounded by the position/heading of the vessel with respect to any local tidal/current phenomena. For example, moving with the current will increase the vessel's relative speed over ground and generate a greater gap between succesive pings than when the vessel is steaming into the current.

Chapter 5: Evaluation of Reson Multibeam Systems

Section 5.1: Actual Dimensions of Concrete Blocks

From the dive conducted over the pipeline, we know the physical dimensions of the concrete blocks. Each block is about 1m (height) x 1m (length) x 0.2 m (width). Each block is seperated from the next block by about 3 m, but their spacing does vary.

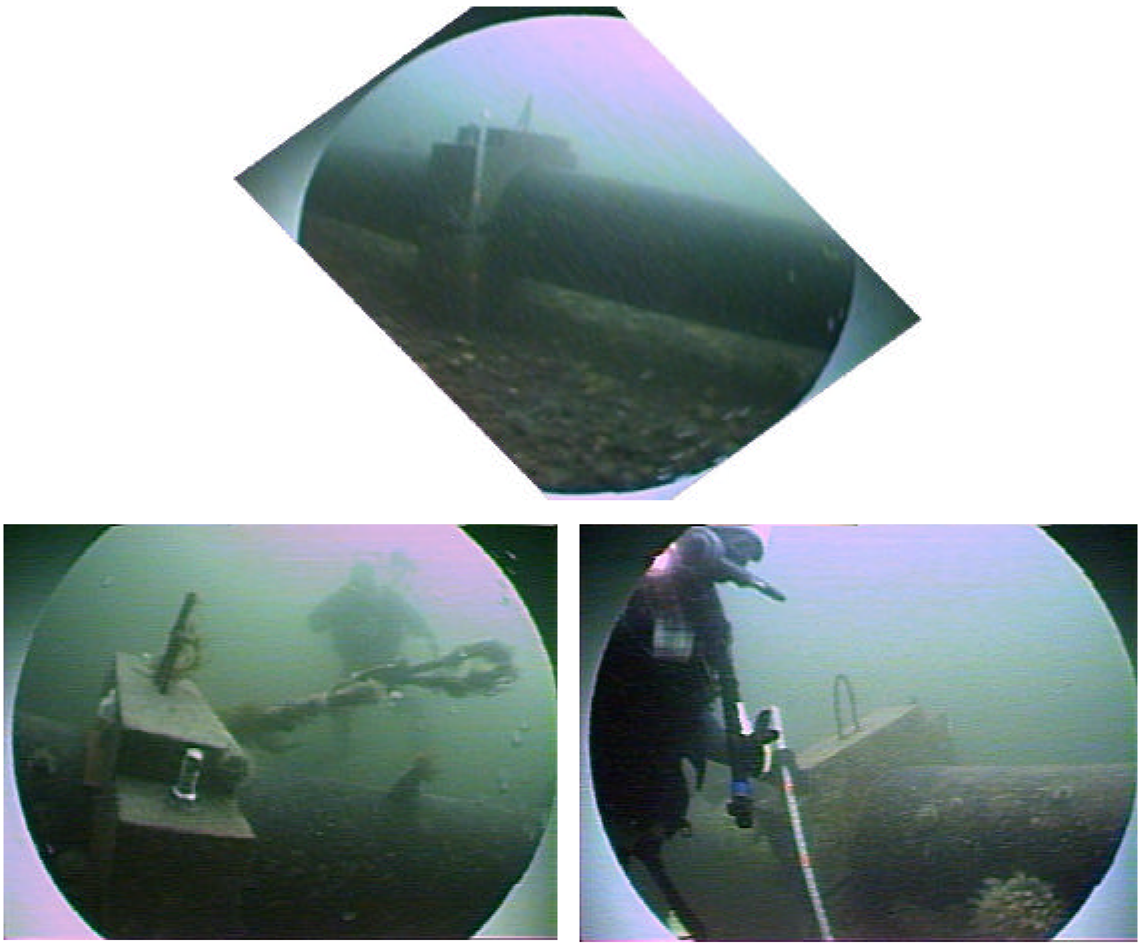

Figure 13: Various underwater perspectives of concrete collars being sought.

The following section explores the ability of the two sonars to detect these concrete blocks. In order to compare the abilities of the two sonars, only a single line for each sonar, collected in a North – South orientation over the pipeline was used. This allowed targets detected in both nadir and outer beams from both sonars to be examined .

Section 5.2: Evaluating the data from the Reson 8101 Multibeam

5.2.1 Vertical and Across Track Extent of Anomalies from Target Strikes

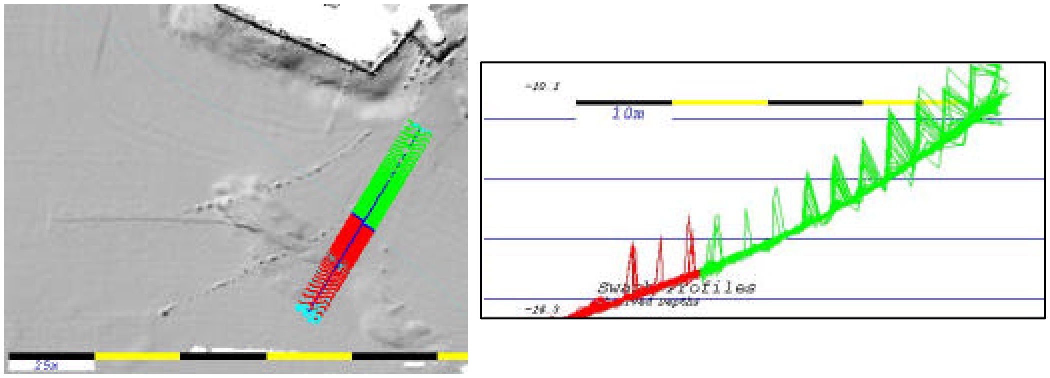

Figure 14: Geoswath editing display of a series of pings collected over the pipeline, illustrating the vertical relief of the concrete collars.

Figure 14 display the geographic location of 80 swath profiles, stacked one upon the other, and depicts the vertical extent of the concrete collars on the seafloor. The blue horizontal lines in the right hand window, are seperated by 1 m, and the concrete collars in the MBSS dataset appear to be 1m high and approzimately 3m meters apart. In this view it is difficult to determine the horizontal extent of the targets, particularly in the along track dimension. The image on the left illustrates where the soundings displayed are located, and are superimposed ontop of the sun-illuminated bathymetry for that area.

In the nadir region, there are fewer hits per target in comparison to the outer beams. This may be a function of the shape and size of the targets, the orientation of the ensonification swath, and the interaction of the individual beams with the targets. Recall from the footprint dimensions table that for 15 m water, the nadir beams had a dimension of ~0.4 m along track x ~ 0.4 m across. Since in the nadir regions, the beams are literally ensonifying the targets from directly above, the width of the targets is very small (~ 0.2 m) with respect to the beamwidth in the across track dimension, and fewer beams actually interrogate the target (Figure 15).

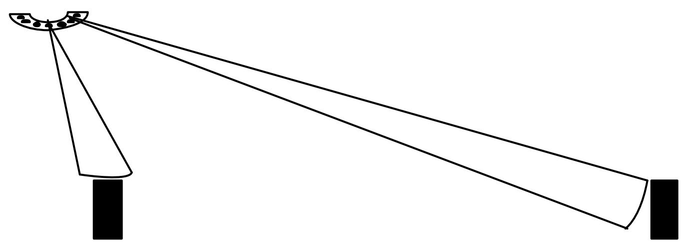

Figure 15: The orientation of concrete targets being interrogated by nadir and oblique beams, illustrating the relatively larger target size of a concrete block in the outer region.

Since the orientation of the swath is perpendicular to the face of the targets, the outer beams have an easier target to detect. This is because the faces of the concrete collars presents a larger surface for incident energy to be reflected from and more beams will interact with a target in the outer range, generating more hits per target then for the nadir region. The low grazing angle of these outer beams will also generate shadow zones on the lee side of the targets, from which little information about the seafloor will be acquired (Figure 16).

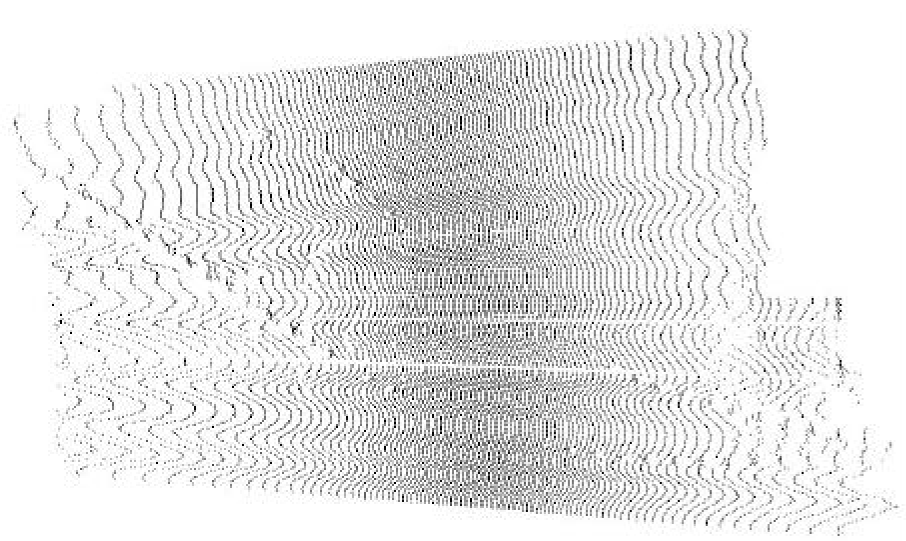

Figure 16: Diagram depicting the latitude, longitude positions of soundings from Reson 8101, demonstrating the shadow zone created on the lee side of the concrete targets, as well as the limited number of discernible targets in the nadir region.

Figure 17 displays the target strike positions and heights viewed from the south (right window), as well as the location of soundings displayed (left window) . The target strike window (right) indicates that the vertical extent of the targets is on the order of 1 m, and that the horizontal extent in the across track dimension is less than 0.5 m. However, this across track dimension and spacing is misleading because of the orientation of the swath with respect to the target. Since they are perpendicular to each other, the lee side of the target is actually in a shadow zone of the concrete collar, and a return from the seafloor on the lee side of the collars won't occur until a beam is able to pass overtop of the concrete collar and interrogate the seafloor beyond the shadow zone. This will distort the size of the targets in the across track direction, making them appear larger than they actually are, depending on the grazing angle.

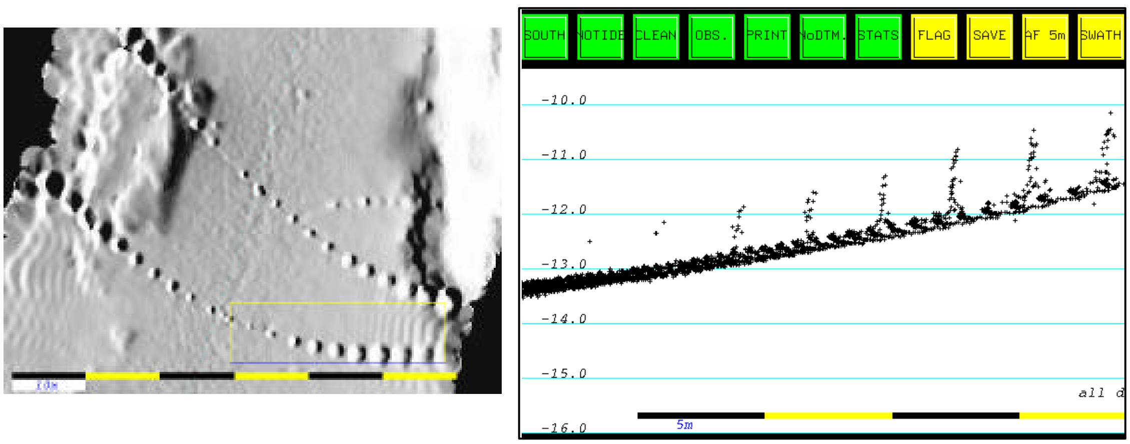

Figure 17: Location and distribution of target strikes from Reson 8101 data over pipeline.

Figure 17 better illustrates the uneven distribution of target strikes between nadir and outer regions. Furthermore, the vertical extent of anomalies in the outer region appear greater than the nadir target stikes. As all concrete blocks are of the same dimension, this variation in height is an artifact of the multibeam data, and could potentially be the result of refraction due to the use of an imperfect sound velocity profile, or it could be representative of a change in the bottom detection algorithm used by the multibeam processor, from amplitude to phase detection. In this view, we cannot determine the along track dimensions of the targets.

5.2.2 Along Track Extent of Anomalies from Target Strikes

Figure 18 displays the location and distribution of the targets strikes of an inner beam viewed from west. This orientation depicts the horizontal extent of the target in the along track direction. This dimension appears to be on the order of 0.5 m to 1m, and the target has a vertical extent of over 1 m. The square shape of the target is well defined by the soundings that interrogated the it.

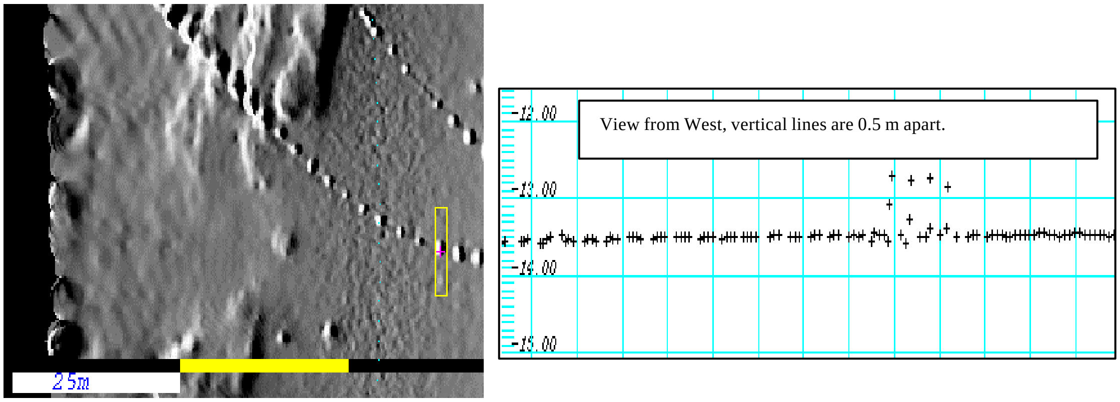

Figure 18: Distribution of soundings in the along track direction, viewed from the west.

5.2.3 Summary of Target Dimensions as Determined from Reson 8101 Data

Overall, the number of target strikes in the nadir region is much lower than for the outer beams. Furthermore, the outer beam target strikes appear greater in height than target strikes for concrete targets located in nadir region. As these blocks are the same size, either the sounding solutions from nadir or the soundings from outer beams are not representative of the true target geometry. Still, one must point out that the detection of targets less than 1 m^3 across the entire width of the swath is quite impressive. The bathymetric data suggests that the targets are between 1 – 2 m in height, and have a length of 0.5 – 0.75 m in the along track domain. Because of the perpendicular orientation of the faces of the concrete blocks with respect to the ensonification swath, the horizontal extent of the targets in the across track direction is difficult to accurately determine. The target widths as they appear in the digital elevation model, are much larger than their actual width of 0.2 m.Evaluating the data from the Reson 9001 Multibeam

5.2.4 Vertical and Across Track Extent of Anomalies from Target Strikes

Figure 19 below consist of 80 consective pings from the Reson 9001 MBSS over a portion of the pipeline. The narrower swath width of the Reson 9001 is immediately apparent. Furthermore, this diagram highlights the sensitivity of the swath to vessel motion. The effects of pitching, as well as the vessel roll are visible in the geoswath editing window (left side). Extreme pitching motion between pings can create inter ping gaps in the data in the along track dimensio, as the vessel rolling from side to side causes the swath to oscillate from side to side. The target strikes in the right hand window indicate that the vertical extent of the anomaly detected by the Reson 9001 is on the order of 0.5 to 1 meter. Figure 20 and Figure 21 better illustrate the horizontal and vertical extent of the anomaly in both the across track and along track dimensions

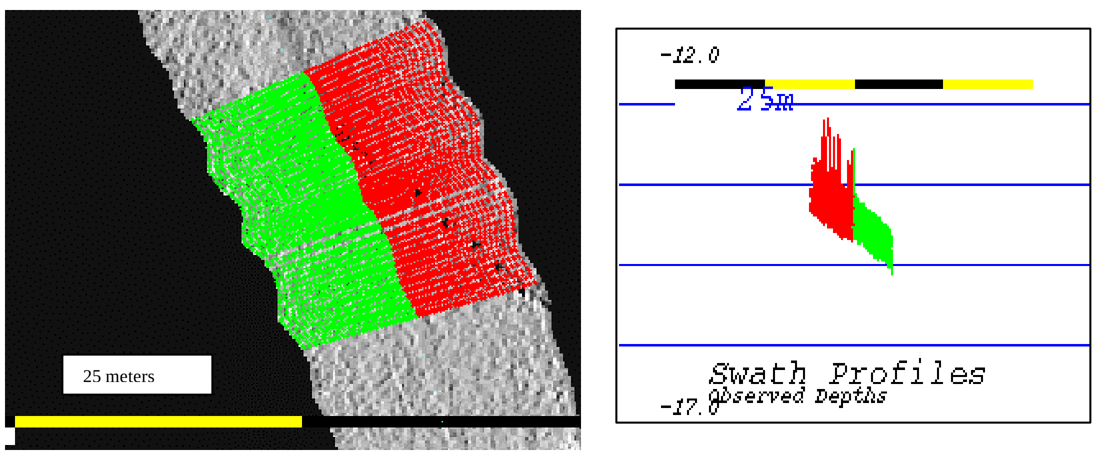

Figure 19: Geoswath editing window of swath ping locations and the sounding solutions from a Reson 9001 dataset.

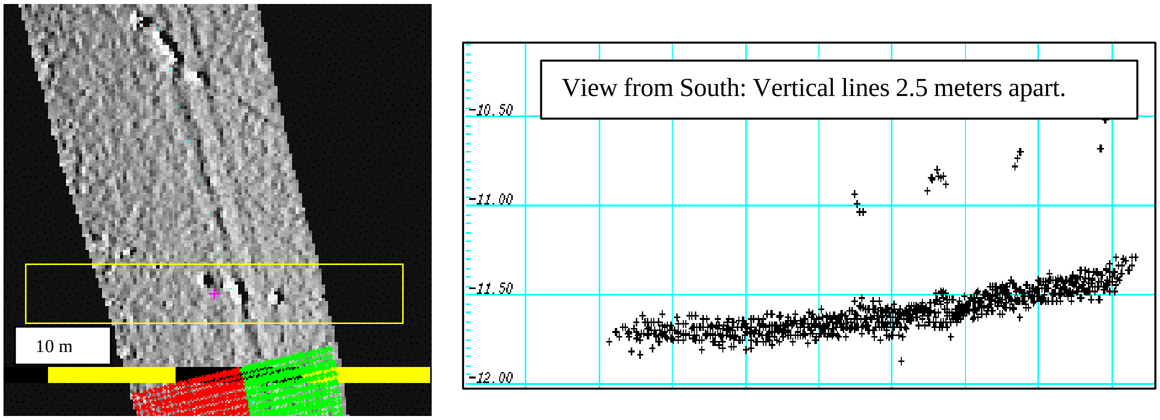

Figure 20: Across track distribution and vertical extent of target strikes of Reson 9001.

Visible in the target strike window of Figure 20, are the concrete targets on the seafloor seperated by ~ 3m. The vertical extent of the targetes remains relatively consistent between solutions from inner beams and solutions from outer beams. In this close up view of target strikes, the height of the concrete collars is between 0.5 – 1 m. In the nadir region of the swath, fewer sounding hits on the target occured in comparison to number of hits per target in the outer region of the swath. The was also observed in the sounding solutions for the Reson 8101, but is not as pronounced in the Reson 9001 data because of its' narrower swath width.

Figure 21 is a different illustration of the vertical extent and horizontal extent of targets across the entire width of the swath.

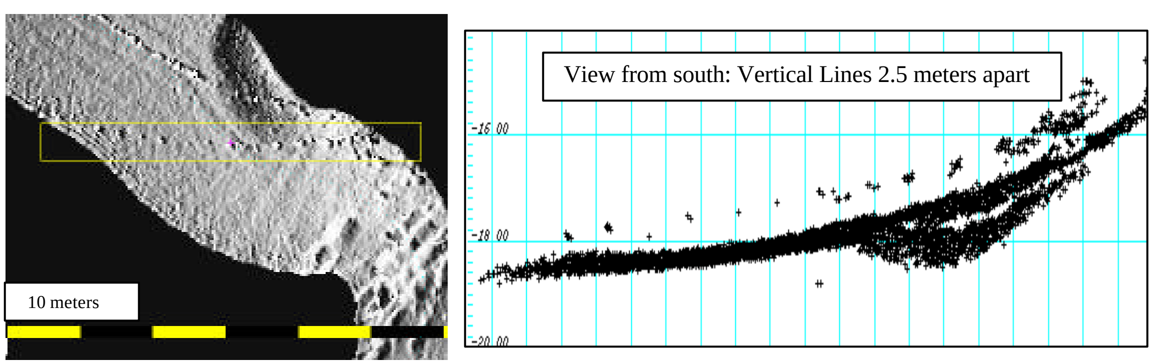

Figure 21: Distribution of targets strikes across entire width of swath.

5.2.5 Along Track Extent of Anomalies from Target Strikes

Figure 22 displays the soundings solutions viewed from the west of the Reson 9001 as it passes by one of the concrete collars, highlighting the along track dimensions of the target. The target appears to have an along track dimension of 0.75 – 1 m, and rises almost 1 m above the surrounding seafloor.

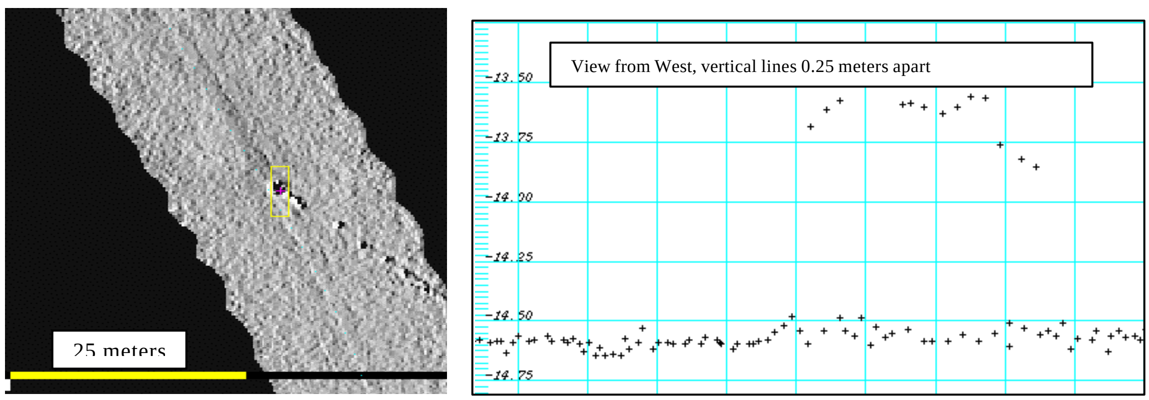

Figure 22: The along track extent of concrete target as determined by Reson 9001.

5.2.6 Summary of Target Dimensions as Determined from Reson 8101 Data

Like the Reson 8101, the Reson 9001 had very few target strikes on the concrete blocks in the nadir region of the swath. As previously illustrated in Figure 15, this is likely the result of the relatively small target width with respect to nadir beam footprints, as compared to the relatively large target face that is visible to low grazing outer beams. However, unlike the Reson 8101, the vertical extent of the strikes across the width of the swath appear to be consistent (much narrower swath). The sounding solutions indicate that the targets are between 0.75 - 1 m in height, and have a length of 0.75 – 1.0 m in the along track domain. Like with the Reson 8101, the perpendicular orientation of the faces of the concrete blocks with respect to the ensonification swath makes the determination of the horizontal extent of the targets in the across track direction difficult.

Chapter 6: Data Presentation

6.1.1 Gridding Bathymetric Data

Given the large volume of data collected by a multibeam sonar, it is not feasible to graphically display all soundings solutions in the final digital product. Instead, bathymetric data is gridded at an appropriate resolution depending on the water depth, to create a digital terrain model of the surveyed region. This grid size (resolution) is based on the average water depth and typically is about 10 % of this depth. The basic principle of gridding bathymetric data, is to take a dataset that has an uneven distribution in the density of sounding data points, and generate an orthogonal, regularly spaced series of nodes (Hughes-Clarke, 1998b). These node values are determined by an averaging procedure that takes into account the different influences of inner and outer beam soundings that fall within a certain radius corresponding to the grid size. Once the data is gridded, the digital terrain model can be sun-illuminated to the display the seafloor geomorphology. Gridding is carried out by the UNB – SwathEd multibeam post-processing software

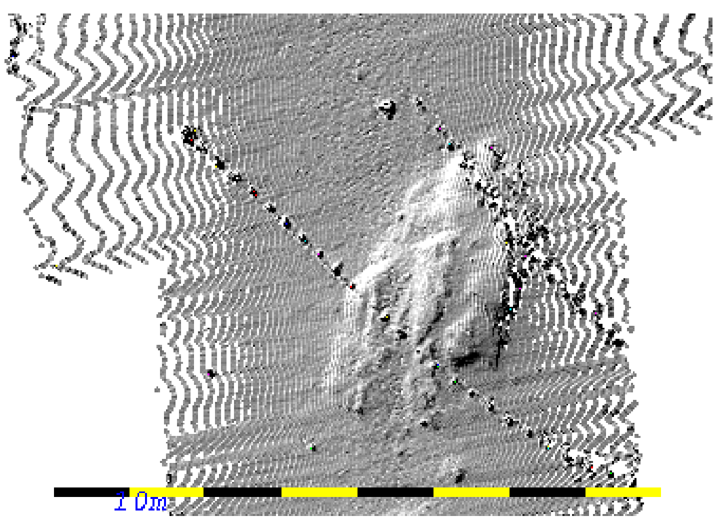

Figure 23: Sun-Illumination of digital terrain model over pipeline, gridded at 0.5 m

Figure 23 illustrates the varying footprint sizes, and boresite locations of nadir and outer beams. In the outer beam region, because of their low grazing angle, the distance between the boresite of neighbouring beams increases. In this representation, the grid size is 0.5 m, and depth data is only assigned to those grid nodes that are intersected by the boresite of a beam, and the area of influence corresponds to the grid size. Thus, if the grid node size is smaller than the beam footprint, the seperation between beams becomes visible in the outer portions of the swath. The effect is more apparent for systems that utilize a wide angular sector, like the Reson 8101. The sinuous nature of the outer beam data points reflects the influence of vessel motion on the orientation of the swath.

Ideally, the design of a survey will provide a certain amount of swath overlap between parallel lines. In most cases, this overlap will provide adequate cover in the outer regions of the swath, preventing this phenomena. However, should it be necessary to produce a final product using data similar to that displayed in Figure 23, there are some gridding options available to us in the OMG swathed suite of tools to minimize such effects.

6.1.2 Effects of Anomalous Sounding Solutions on a Regular Digital Terrain Model

Although reducing multibeam data into a regularly spaced grid is a common method used for building digital terrain models, there are some disadvantages to this approach. Some of these disadvantages are particularly apparent when using such a digital terrain model to visually display the distribution and extent of small scale features. A regularly gridded digital terrain model, is a smoothed surface representation of the true sounding distribution, which in itself, may not necessarily represents the true seafloor because of sounding noise (Hughes-Clarke et. al., 1997). Because building a regular grid is a process by which several neighbouring data points become represented by a single node within the regular grid, elevations whose values differ greatly from their nearest neighbours are suppressed by the more dominant elevation values. Solitary values, like those representative of single strikes off a concrete target, may not be adequately represented in a regular digital terrain model. Even if such data points do influence a grid node value, the resulting geometry in a regular grid can differ greatly from the real world.

This problem is apparent in both Reson datasets as there are very few sounding solutions that result from inner beams intersecting the concrete collars. Because these individual strikes are similar to outliers, their influence on the digital terrain model is suppressed, and subquent targets in the nadir region are poorly represented in the resulting sun-illuminated image. Below are a series of images that illustrate this effect, the first image depicts the location of all strikes across the width of the swath, and the second window displays the digital terrain surface derived from the sounding solutions.

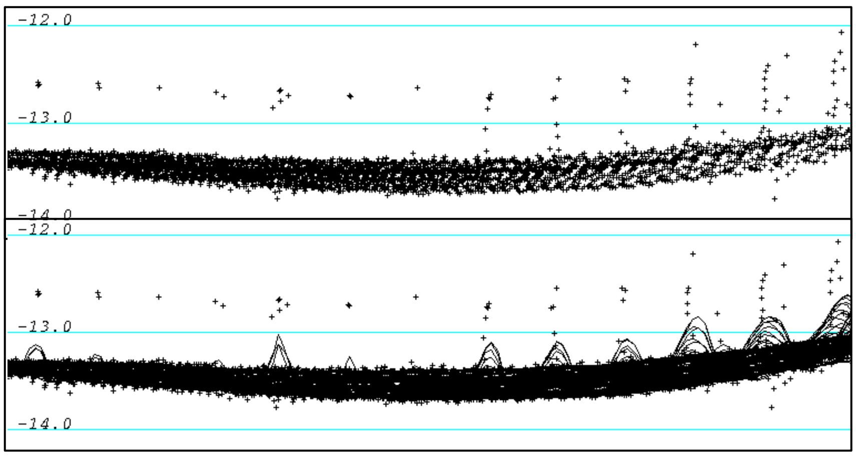

Figure 24: Soundings and resulting DTM illustrating the smoothing effect of gridding.

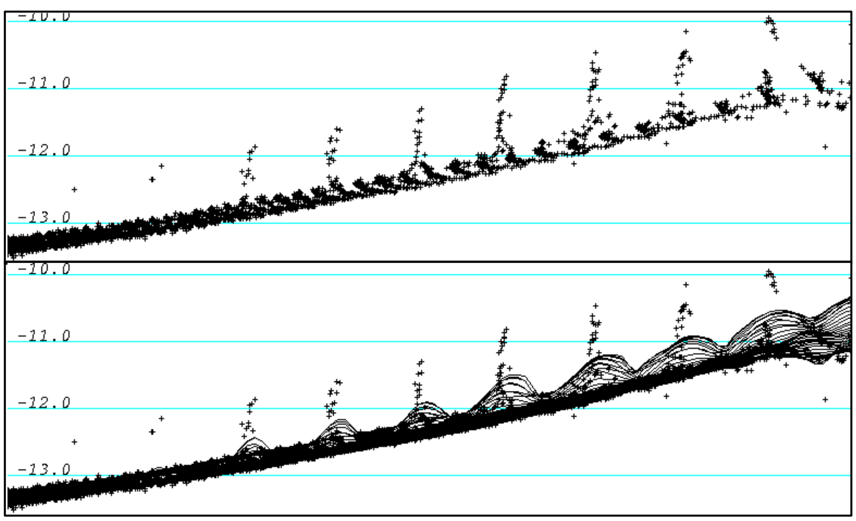

Figure 25: Soundings and resulting DTM illustrating the suppression of elevation points that differ from the dominant values.

Obviously, this smoothing of the data will distort the vertical and horizontal extent of the target geometries in the digital terrain model. This makes the accurate determination of the size of small scale targets from a regular DTM, very difficult.

Another option is to generate a digital terrain model that honours as many elevation data points as possible. Instead of generating a three dimensional surface from a regularly spaced series of nodes, an approximation of the surface for a region of unevenly distributed data can be built using a triangular irregular network. In this manner every elevation point will be represented in the digital terrain model, whether it be a single strike from a concrete collars, or an elevation value derived from an outlier. While building a TIN model may make it easier to discern small scale targets in a DTM, it does have the disadvantage of being more memory intensive. Furthermore, it is a much noisier representation of a three dimensional surface, since all elevation points are honoured, including sounding noise and outliers, which a regular DTM would suppress

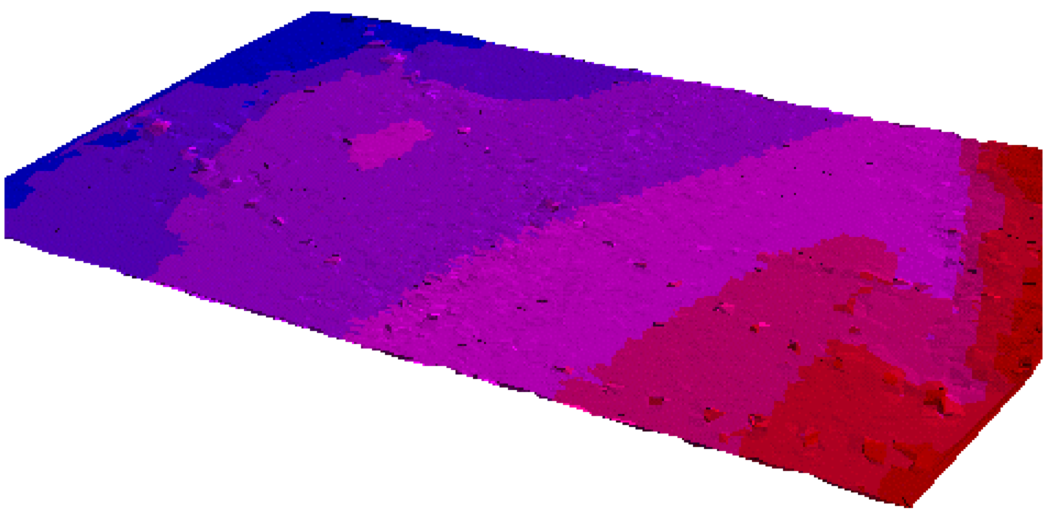

Figure 26: A TIN model of the pipeline, highlighting the locations of the concrete collars.

Chapter 7: Conclusion

The purpose of this paper was to explore the capabilities of two multibeam sonars in detecting concrete blocks on the seafloor whose dimensions approached that of beam footprint.. The reason to conduct such a study is that multibeam sonars have been described as being capable of providing 100% coverage. However, there is a finite dimension to their multiple narrow beams, and therefore targets may have to be larger than a minimum spatial dimension before they can be adequately resolved. Since multibeams are being deployed more frequently is shallow waters specifically for the detection of short wavelength features, it behooves us as end users to have better understanding of the practical limitations with respect to their ability to resolve small scale targets.

There are a number of factors that influences a MBSS ability to resolve a target. Two of the most important factors are the physical beam footprint dimensions and the overall sounding density. Because a multibeam sonar is physically mounted to the hull of a vessel, any motion experienced by the vessel, will alter the swath orientation and subsequently influence sounding density.

Overall, the number of target strikes in the nadir region was much lower than for the outer beams for both mulitbeam sonars. This is likely the result of the relatively small width of the concrete collars with respect to nadir beam footprints, as compared to the relatively large targets (faces of the concrete blocks) that are very visible to the outer beams.

The targets dimensions as determined from the sounding solutions of the two different sonars were not dramatically different. The Reson 8101 sonar performed such that the targets could be reasonably described as being 1 – 2 m in height, and had a length of 0.5 – 0.75 m in the along track domain. The Reson 9001 provided sounding solutions that indicated that the targets were between 0.75 - 1 m in height, and had a length of 0.75 – 1.0 m in the along track domain. Because the perpendicular orientation of the concrete blocks created shadow zones from which no depth data could be gathered, it was difficult to accurately determine the target dimensions in the across direction.

While complete delineation of the actual shapes of the concrete targets was not achieved by either sonar, one must point out that the detection of targets less than 1 m^3 across the entire width of the swath by both sonars, is quite impressive. In terms of quantifying the minimum spatial dimensions of these multibeam systems, the unique irregular shapes of the targets makes it difficult to indicate any values for a minimum spatial dimension. One would expect that small scale targets would be more difficult to detect in the outer regions of the swath, where beam footprints are larger, then targets that were located in the nadir regions. In this study, the opposite is true. It can be stated that in the nadir regions, the small target width is approaching the minimum width of what can be successfully detected, given the few number of target strikes in the nadir region. Should these blocks have been any narrower, it is possible that they would have gone undetected.

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