THE APPLICATION OF MULTIBEAM SONARS IN ROUTE SURVEY

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Abstract

Route Survey is a Mine Counter Measure (MCM) technique that uses side scan sonars to determine optimal shipping route selection (in terms of ease of mine detection) through the pre-survey of all objects along these routes, and in times of conflict, the re-survey of these routes to find differences. This report looks at the EM 3000 multibeam sonar to assess its potential role in Route Survey. Software was developed to extract both backscatter and bathymetric information from the EM 3000 in order to perform the assessment. Algorithms, developed for the bathymetric data, produce "sun-illuminated" images for subjective visual object detection, and perform automated detection of objects of predefined dimensions. Algorithms were also developed for transforming backscatter data into side scan-like imagery as another means of target recognition. This report concludes that multibeam sonars are not yet capable of object detection to the degree required by the Navy, however regional multibeam surveys are of value in support of route selection and conventional side scan operation.

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Dedication

I dedicate this work to my wife Tamala. Her support of my work, her professional editing abilities, and her willingness to drop everything to follow me where ever the Navy has sent me has never gone unappreciated. None of this would have been possible without her.

CHAPTER 1 - INTRODUCTION

1.1 Introduction

Canada's Navy is presently taking delivery of the Maritime Coastal Defence Vessels (MCDV); there will be 12 in total. These vessels are designed to fulfill four primary roles, namely Coastal Patrol, Route Survey (RS), Mine Inspection and Mine Sweeping [Tecsult - Eduplus Management Group Inc.,1997]; the latter three roles are derivatives of Mine Warfare. This report examines if and how Route Survey could be aided through the use of commercial off-the-shelf Multibeam Sonars (MBS). As a point of clarification, the term *Multibeam Sonar* refers to multibeam echosounders or multibeam bathymetric sonars and should not be confused with *Multibeam Focussed Side Scan Sonars*.

Route Survey is the process of locating and classifying all objects along shipping routes through the collection of sea floor images using sonar. RS is intended to be performed prior to any situation where objects may be introduced onto the sea floor, such that before-and-after images (mosaics) may be compared. The Canadian Navy has purchased four Operational Route Survey payloads from MacDonald, Dettwiler and Associates (MDA) for use in Route Survey Operations [Department of National Defence, 1997]. These payloads include a towed body (tow fish) with a Multibeam Focussed Side Scan Sonar.

Side scan sonars rely on backscatter and shadows in order to detect an object lying on the sea floor [de Moustier, 1996a]. Without RS the Mine Inspection role cannot be performed effectively. That is, if the mine location is unknown, then there can be no mine inspection using a Remotely Operated Vehicle (ROV) which is attached to the MCDV. Furthermore, Mine Sweeping, which is a mechanical sweeping of a route in order to remove mines anchored to the sea floor, is blind if the mine location is unknown. Side scan sonars, such as the one purchased by the Canadian Navy, have their limitations. One limitation which this report emphasizes is a side scan sonar's inability to effectively identify objects in the near nadir regions, resulting in a 'gap' in coverage [de Moustier, 1996a]. Another limitation is the minimum water depth in which the tow fish may be deployed thus limiting route survey using an MCDV in very shallow water (<20 m).

The motivation behind, or the *raison d'être* of this research is the evaluation of multibeam sonars as the solution to the deficiencies of the tow fish as listed above. Specifically, the performance of these sonars in shallow water (<50 m) is examined, and their effectiveness as route survey sonars, as well as their integration into the MCDV tow fish as a gap-filling sonar is assessed. This report consists of five chapters: Introduction, Background, MBS Data Analysis, Multibeam Sonars in Route Survey, and Conclusion.

1.2 Report Contents

1.2.1 Chapter 2 - Background

Chapter 2 consists of three main subsections: Mine Warfare, Route Survey, and Multibeam Sonars. Mine Warfare originated in the American Revolutionary War and was initially quite ineffective [Hartmann and Truver, 1991]. Since that time however, technological advances have improved the mines such that modern mine warfare can paralyse an entire fleet. The goal of mine warfare however, is not always the destruction of a ship. In fact, a delay of supplies or of warships may provide the mine layer with the time required to gain victory in a distant battle. The Mine Warfare section discusses mine warfare history, modern mines, functions of mine warfare, and concludes with a brief discussion of Mine Counter Measures (MCM).

Canada's Navy has practised MCM for many years through the use of single beam side scan sonars and mechanical sweeping gear on board converted oil-rig tenders. As previously mentioned, the new MCDV's have four primary roles, three of which concentrate on MCM. This section focuses on the Route Survey portion of the MCDV's capabilities. The MDA tow fish uses a Multibeam Focussed Side Scan Sonar whose characteristics, capabilities and limitations are discussed. This discussion looks at the entire route survey package which includes the real-time and post-processing capabilities.

Multibeam Sonars are more recent in their development than are side scan sonars, and their Mine Like Object (MLO) detection qualities have not yet been fully researched. In the early part of this decade, MBSs were dismissed by Canada as MLO finding sonars primarily due to their resolution in a hull-mounted configuration [Poeckert, 1996].Since that time however multibeam sonars have improved in performance and resolution. Before the report looks at applications of MBS in route survey, the technology that makes up an MBS is described. This discussion examines the main components that make up an MBS as well as the ability of an MBS to accurately georeference its data. Finally, a summary of the differences between MBS's and Multibeam Focussed Side Scan Sonars is given.

1.2.2 Chapter 3 - MBS Data Analysis

Bottom Sediment Classification (BSC) through remote sensing (sonars) is an area which is actively being pursued by governments and industries due to the high cost of *in situ* testing. Many different types of sonars are employed for bottom sediment classification such as the Chirp sub-bottom profiler, as well as those which examine the first and second return echo pulses. These sonars are all normal-incident sonars in nature and are not as accurate as *in situ* testing [Mayer, 1996b]. The ability for an MBS to perform bottom sediment classification is still under development, however the need for bottom sediment classification data is discussed as well as the use of MBSs in bottom sediment classification.

Next, the discussion focuses on the amplitude backscatter and bathymetric imagery derived from MBS and how they can be applied to route survey. More specifically, Simrad EM 3000 MBS data products are examined. In order to carry out this task, two data sets were obtained for analysis. The first data set was collected in June of 1996, northeast of the Halifax harbour approaches, during the Maritime Command Operational Training exercise (MARCOT 96) where an area was surveyed with an EM 3000 before and after mine laying operations took place. A total of 18 Mk 62 Quickstrike mines (500 pound) were sown along two lines in 40 to 50 metres of water. The second data set consists of data collected during a January 1997 survey using the same EM 3000 sonar. In this survey, a 500 pound, MK 82 bomb was laid in 11 m and 22 m of water and a 1000 lb, Mk 83 bomb[1], was laid in 30 m of water. Both objects were laid over a relatively featureless sandy sea floor. The analysis of EM 3000 data collected during the surveys is the main part of this research project.

An MBS records data on a mass-storage device such as an optical disk or a magnetic tape. Each specific MBS model normally stores the data in telegrams which are in a unique proprietary format. Without some sort of key to decode the data telegram, byte by byte, it is virtually impossible to correctly extract the desired information from the telegrams themselves. The EM 3000 has its own unique telegram format (Appendix I). It is similar to previous telegrams from other Simrad sonars such as the EM 1000 with the exception that the telegrams are variable in length. Using UNIX C and the telegram key from Simrad [Hammerstad, 1996], a program was written (called *Interp*) to decode, or convert to plain text, the EM 3000 survey data.

A second program was written to examine the EM 3000 side scan data directly from the 'raw' telegrams. The UNIX C program (called *Raw_sidescan*) extracts the side scan data contained in a user specified file. This program was written in order to display, using *jview* [Hughes-Clarke, 1997a] (or any other application capable of importing 8 bit raw image files), the created images in order to determine if the Mk 82 and 83 bombs could be distinguished from the surrounding backscatter. Image enhancement filters and image classifiers were applied to the backscatter imagery in order to aid the detection process. These results are also discussed in this chapter.

The next portion of Chapter three examines the EM 3000 spatial resolution. Figures illustrating the EM 3000 footprint are generated using *synSwath* [Hughes-Clarke, 1997b] for various depths and vessel speeds. Through the use of the generated models, predictions are made as to the expected bathymetric detection of the mines in both data sets. The final task in this research was to write a C program (or filter) which could automatically detect and highlight the mines, or any mine like object. This program is called *MLO_Find* and attempts to identify the mine like objects (of a pre-defined size) from the raw EM 3000 telegrams. *MLO_Find* was applied to both data sets in an attempt to identify the mines. The results are discussed and compared with the modelled predictions.

[1] 1. Mk 62 and 63 mines are converted Mk 82 and 83 bombs through special detonators and the addition of retarding fins, and are essentially the same size as Mk 62 and 63 mines.

1.2.3 Chapter 4 -Multibeam Sonars in Route Survey

Chapter four takes the background information from Chapter two and the practical knowledge gained from Chapter three and suggests how an MBS might benefit Route Survey Operations. Specifically there are four areas within Route Survey which could benefit, <u>if a suitable sonar were to be found</u>, these being:

- bottom sediment classification;
- as a tow fish gap-filler;
- shallow water (<30 m) object detection; and
- the use of bottom topographic maps created from multibeam surveys.

These areas are discussed and conclusions are drawn as to the appropriateness of using multibeam sonars (the EM 3000 specifically) in each of these areas. This chapter concludes with the recommendation that multibeam sonars should not be purchased by the Canadian Navy for use in Route Survey Operations. Multibeam sonars cannot effectively identify mine like objects to the degree required by the Navy and are not considered appropriate as tow fish gap fillers. It is recommend however that multibeam data be obtained from agencies such as the Canadian Hydrographic Service, as the bathymetric information derived from the data may aid Route Survey in areas such as Q Route selection and tow fish safety.

CHAPTER 2 - BACKGROUND

2.1 Mine Warfare

2.1.1 History

The first naval mine ever to be made was the Bushnell Mine in 1776, named for its inventor David Bushnell.

> "Bushnell's mine was a simple watertight wooden keg, loaded with gunpowder, which hung from a float and, at that time, was called a torpedo. In 1777, under orders from General Washington, a number of the kegs were set adrift by Bushnell in an attempt to destroy a fleet of British warships anchored in the Delaware River off Philadelphia. The attempt failed." [United States of America, NAVSEA, 1985]

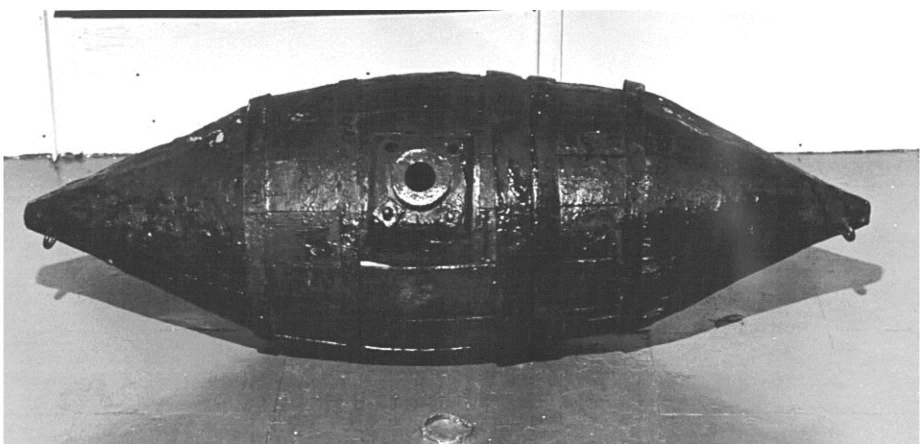


Figure 2.1 - The Bushnell Mine [from University of Texas 1996]

The Bushnell Mine failed for a number of reasons, one of which was the unreliable percussion type detonator. The most predominant reason for failure was how the mine were employed. Namely, they were launched upriver from their intended targets which were British ships at anchor [Hartmann and Truver, 1991]. The concept of having the ships come to the mine was not yet thought of at this, the earliest stage in mine warfare. During the American Civil War,

> "...the Tecumseh, an ironclad vessel...struck a mine...and she sank in a very few minutes...(Admiral) Farragut signalled to Brooklyn 'Damn the torpedoes (mines), Captain Drayton, go ahead.' No more mines fired. Later it was discovered that the mines were inert due to long immersion (corrosion) and wave action." [Hartmann and Truver, 1991 p. 35-36]

> The period between the Civil War and the First World War saw significant technological advances such as electricity and TNT which were immediately applied to mine warfare. It was the First World War however that caused a great leap in mine development and employment. New mines were developed and put in to use. Such mines include the 'M-sinker', which was the first magnetic influence mine and the famous Mk 6, a moored mine which had an automatic anchor. In 1914, the mining of the Dardanelles by Turkey ultimately led to the disaster at Gallipoli. This mining action by Turkey still serves as an excellent example of the effectiveness of mine warfare [Hartmann and Truver, 1991].

The Second World War saw the further development of detonators which had the ability to trigger mines by magnetic, acoustic and pressure means. As well, the effectiveness of ground mines (i.e., mines actually sitting on the sea floor no longer connected to an anchor) came into realization. In the closing months of the Second World War, the American mining of Japanese controlled ports, aptly named Operation Starvation, cut the once huge Japanese shipping empire down to zero in five months. In Korea, the mining of Wonsan using Russian mines from 1904, took the American weeks to clear which led to a delay in their operations. And finally, in Vietnam, the mining of Haipong Harbour in May 1972 resulted in supplies to North Vietnam by sea finally being cut off [Hartmann and Truver, 1991].

The history of mine warfare shows how mine technology and employment have progressed from primitive beginnings to today's much more advanced state. It should be noted that mines do not necessarily have to be the latest in advanced technology to create a delay to an opposing force. It was a World War I Era, Mk 6 type Russian mine that was used by the Iranian Revolutionary Guard in the Persian Gulf in 1988, which led to the near sinking of the American Frigate USS Roberts.

2.1.2 The Present-Day Mine Threat

Mines can be delivered in a variety of ways namely by air, by surface vessel or by submarine. The first method requires a degree of air superiority over the area of interest. The second can be carried out covertly, when in hostile waters, by *any* type of ship. For example, junks and sampans were used to mine Wonsan harbour during the Korean conflict [Hartmann and Truver, 1991]. The third type is best used when the area of mining is well controlled by the opponent or it is desired to keep the mining action covert. Today, many types of mines are in use or are stockpiled around the world. It is the intention of this paper to concentrate only on large mines specifically designed for anti shipping and anti submarine roles. Those smaller mines used to defend beaches from amphibious assault are beyond the scope of this paper and will not be discussed here.

> "One of the most cost effective forms of naval warfare is the mine. Mines are small, easily concealed, cheap to acquire, require virtually no maintenance are easy to store in considerable numbers, and can be laid easily and simply from almost any type of platform. They can be used strategically and tactically to deny

waters to hostile forces and to defend high value targets such as ports, anchorages and offshore structures from amphibious or seaborne attack and can very quickly wipe out or very seriously impair the effectiveness of surface forces. To counter and neutralise the mine requires an effort all out of proportion to its size. In short, the mine is probably one of the most deadly weapons that any navy can deploy in its armoury." [Janes Information Group Limited, 1995. p. 179]

2.1.2.1 Moored Mines

The M-sinker mine, developed during the First World War, is a moored mine. A moored mine is a mine that is anchored to the sea floor at a desired depth below the surface. The effective use of ground mines in the Second World War led to a concentration in mine development away from moored mines for many years. The moored mine however is once again considered important as it is effective in deep waters (greater than 200 feet) whereas the ground mine's shock wave is attenuated after a certain depth. The moored mine can be actuated by contact (older models), by magnetic, or by acoustic influence. These mines are most effectively countered by ships employing sweep wire systems or forward-looking high resolution sonar. The typical characteristics for a (deep sea) moored mine is a size from one to two cubic metres and a warhead of up to 1000 kg [Janes Information Group Limited, 1995].

2.1.2.2 Tethered Mines

The tethered mine is one which will lie in wait on or near the sea floor until it is unintentionally actuated by a target. Normally, these mines will detect a target passively and then use some type of active homing system to rise up and destroy the target. These mines are predominantly used off of the continental shelf in very deep water and play an important antisubmarine warfare (ASW) role. They can block a passage of an area of the sea where a moored mine could not be placed due to the length and weight of the long mooring cable required. Perhaps the type of mine most feared by submariners is the modified torpedo mine, typified by the American CAPTOR (Mk 60). This mine is a modified torpedo which sits on the sea floor waiting to be activated and home in on a target. The Captor has a sophisticated processor to detect, classify and prosecute a submarine (while ignoring surface vessels) and has a reported detection range of one thousand metres [Janes Information Group Limited, 1995].

2.1.2.3 Controllable Mines

Controllable mines are those which can be activated or detonated by remote methods. These would include hard wiring the activation switches to a shore-based facility, encoded acoustic signals or VLF transmissions [Janes Information Group Limited, 1991]. Friedman reported that in 1988, the Swiss company Tek Sea was developing the Telemine remotely controlled torpedo. The Telemine capabilities include a maximum two year dormancy period, activation by acoustic signal, and real time remote control by air, once activated [Friedman, 1992].

2.1.2.4 Ground Mines

Ground mines are normally laid in waters of less than two hundred feet. "If the water depth is doubled...say from 50 to 100 feet, then for the same target the charge weight should be four times as large...over a couple of hundred of feet their weight becomes excessive." [Hartmann and Truver, 1991, p. 103]. Ground mines can be triggered acoustically, magnetically, by a pressure signature or a combination of any or all of these. These mines can have extremely sophisticated sensing mechanisms that can allow them to wait for a *specific* ship. Ground mines come in numerous shapes and sizes from cylindrical to a nonstandard shape. Ground mines can be composed of materials from glass reinforced plastic (GRP) or steel. The composition and shape of the mine determine a mine's cost as well as its detectability-to-sonar characteristics [Janes Information Group Limited, 1991].

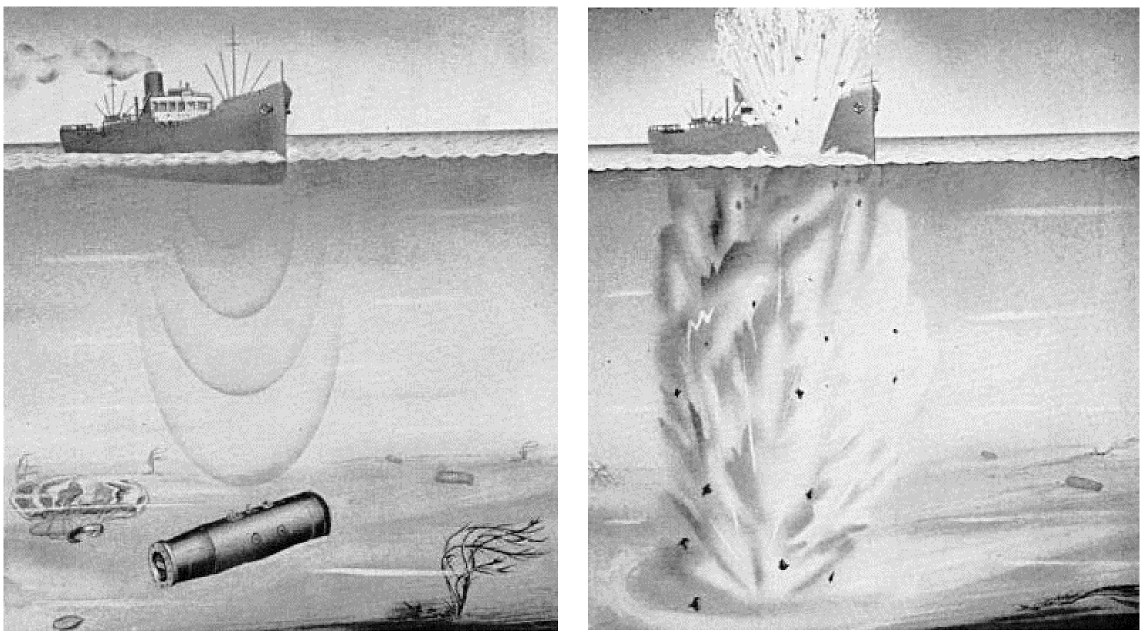


Figure 2.2 - Ground Mine in Action [from University of Texas, 1996]

Navies, such as the USN, have taken standard airdrop ordinance and modified them to act as mines. The USN Quickstrike mines are the Mks 82, 83 and 84 bombs, with 500, 1000 and 2000 lb warheads respectively, which have been modified as mines. Quite simply, these bombs are fitted with influence fuses (exploders) and their tails are adapted with a retarding device to become a mine. These mines are dropped in shallow water or on land and wait for a target. The great advantage to this type of mine is that stockpiles of mines do not need to be maintained as the standard bombs can always be converted so long as the exploders and retarding devices are available for a quick retrofit. Further, they remain as air deliverable, like their parent bombs, while the 2000-lb version is also submarine deliverable [Friedman, 1991].

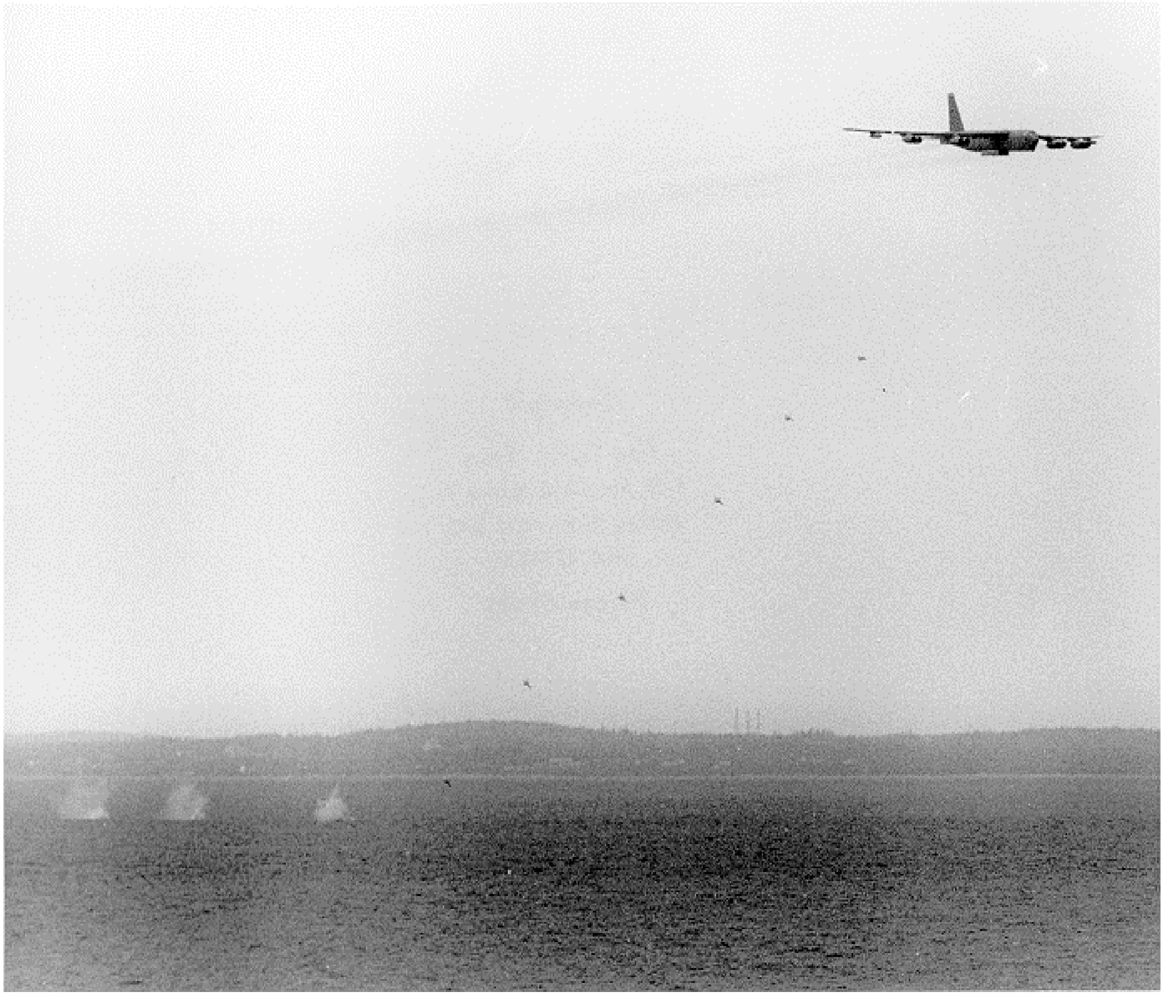


Figure 2.3 - B-52 Dropping Quickstrike Mines [from The Daily News, 1996]

Clearly, the advantage of the Quickstrike type mine is that relatively little time and effort needs to be exerted in order to have a large, deployable stockpile of effective mines. As well, the costs of dedicated mine manufacturing and storage requirements need not be incurred. The Quickstrike's predecessor, the Destructor, was the mine that shut off the sea going supplies to Vietnam in 1972 [Friedman, 1991]. In modern conflict, the Quickstrike could be a key to success. Against a poorer nation with little resources for Mine Counter Measures (MCM), a Quickstrike mine field could close the nation's ports for the remainder of the conflict. Against a nation with greater resources for MCM capabilities, the effect might not be as permanent, but could prove to be just as decisive regardless of the MCM resources available. The delay alone caused by the clearing of the minefield might allow the mine layers seagoing forces to reach their target while the opposition's forces are bottled up in harbour.

2.1.3 Advantages / Functions of Mine Warfare

Now that the history and threat have been reviewed, the advantages and functions of mine warfare can be reinforced. Hartmann and Turner, inspired by R.C. Duncan, write of the following on the functions of mine warfare:

> "Mines lie in wait without accepting a return threat.
>
> Mines may win battles passively -- that is, they may influence an enemy to retire without attacking.
>
> Mines may keep ships in constrained areas where they may be attacked by other means.
>
> Mines may cause ships to take longer alternative routes, thus reducing the number of effective ships available to the enemy.
>
> Mines are a continuous menace to enemy morale.
>
> Mines can attack targets that human controllers cannot see or hear.
>
> Mines not only sink and damage ships as other weapons can, but their effectiveness is also measurable in terms of the delay created in enemy operations.
>
> Mines can force the enemy to expend much effort and materiel on countermeasures that would otherwise not be necessary and, ceteris paribus, are otherwise not productive.
>
> Mines are individually very economical compared with many other weapons.
>
> The idea of an unsweepable mine is desirable but not necessary to achieve.
>
> If in the future all mines do become unsweepable, then there will be no need for antisweep devices such as ship counters.
>
> Defensive mining offers tremendous war-fighting leverage." [Hartmann and Truver, 1991, p. 233-238]

2.1.4 Mine Counter Measures (MCM)

Many MCMs are in existence today, each according to the specific type of mine they seek to nullify. Moored mines are best countered using ships with sweep wires or forward looking high resolution sonar. The sweep wires cut the mooring line which causes the mine to rise to the surface and the sonars simply locate the subsurface mine. Once on the surface, or at least located, the mine can be disposed of by other dedicated resources. Tethered mines may also be located and neutralised in the same manner. In order to counter ground mines (as well as another counter to tethered mines), two different approaches are used. The first is a towed wire or vehicle which attempts to simulate the acoustic, magnetic and sometimes pressure signatures of a large ship thus tricking the mine into detonation. The second, which is the focus of this report, is the use of high resolution sonar. If the mine can be 'seen' as well as geo-referenced then all that remains is to employ the mine disposal resources. The Canadian Navy uses Route Survey as its primary Mine Counter Measure. Through Route Survey operations, Q Routes are established.

2.2 Route Survey

The goal of Route Survey is to identify all objects on the sea floor so that an optimal (see § 2.2.2) shipping route may be identified. If a particular survey is conducted in peace time, then all objects may be mapped and classified as non-mines. Subsequent surveys may be compared with the first to determine if any new objects have been introduced onto the sea floor in or near the shipping route.

Canada's new Maritime Coastal Defence Vessels (Figure 2.4) are Route Survey capable. The Operational Route Survey Payload (ORS) is contained within a standard shipping container and can be mounted on the quarterdeck of any MCDV. Within twelve hours of the container being craned off of the jetty, the entire Route Survey Package is ready to be used in a survey. This section will discuss the four primary components of the ORS, namely the Towfish, the Tow Subsystem, the Towfish Handling Device Subsystem and the Towfish Processor Subsystem. The end result of a Route Survey, namely the creation of Q Routes, will follow. Finally, this section will conclude with a discussion of the mechanisms involved in mine burial.

Figure 2.4 - HMCS KINGSTON (from: Department of National Defence, 1997)

2.2.1 The Operational Route Survey Payload

2.2.1.1 The Tow Subsystem **[Tecsult - Eduplus, 1997]**

The Towfish itself is a hydrodynamic cylinder that measures 3.35 m in length by 0.35 m in diameter and is made of anodised aluminium. It has a fixed wing which is centred on the top of the body itself, and steering rudders aft. It is built to contain the Multibeam Focussed Side Scan Sonar (MBFSSS see § 2.2.1.6) and its ancillary equipment. This equipment includes a temperature, salinity and depth measurement device, an attitude measurement unit, an acoustic signal generator for underway towfish location (see § 2.2.1.5) and an emergency pinger in case the towfish becomes detached from the MCDV. The MDA tow fish is discussed in greater detail in § 2.2.1.7.

2.2.1.2 The Towfish Handling Device Subsystem (THD) [Tecsult - Eduplus, 1997]

The THD subsystem is used to launch, to recover, and to store the towfish, to compensate for the cable effects on the towfish due to ship's motion, and to act as the load termination point between the towfish and the ship. The THD may be controlled both manually and automatically. The manual functions include launching, recovering and paying out or heaving in of cable. In automatic mode, the Towfish Processor controls the paying out or heaving in of cable for motion compensation or terrain following functions.

2.2.1.3 Towfish Processor Subsystem (TFP) [Tecsult - Eduplus, 1997]

The TFP Subsystem performs all the computational functions for the ORS payload. The TFP consists of circuit card assemblies mounted in a 19-inch rack. The TFP provides two main functions, Interface Processing and Digital Signal Processing (DSP). The Interface processing provides a link between the sonar and the DSP. Optical signal data is encoded in the uplink signal (to DSP) and decoded in the downlink signal (to sonar). Furthermore, the interface processor provides the link between the Mine Warfare Control System (MWCS, see § 2.2.1.4) and the DSPs.

The main DSP consists of three sub-DSPs in total: a master, a port and a starboard processor. The port and starboard processors perform beam forming, beam steering, and processing of sonar data. The master processor performs the following functions:

- guidance and control processing for towfish attitude-control and terrain following;
- communication with the THD;
- receiving and execution of commands from the MWCS; and
- sending status, beam block and instrumentation data to the MWCS.

2.2.1.4 Mine Warfare Control System [Tecsult - Eduplus, 1997]

The MWCS is the command and control system onboard the MCDVs. It is a Local Area Network consisting of two data analysis consoles and a tactical display located in the operations room, a bridge display and a hull mounted Acoustic Positioning System

(APS). Using the APS (see §2.2.1.5), the MWCS interfaces with the ship's positioning sensors in order to determine ship position and track as well as the towfish position. In addition, surface contacts can be displayed because of an interface with the above water surveillance system (Figure 2.5).

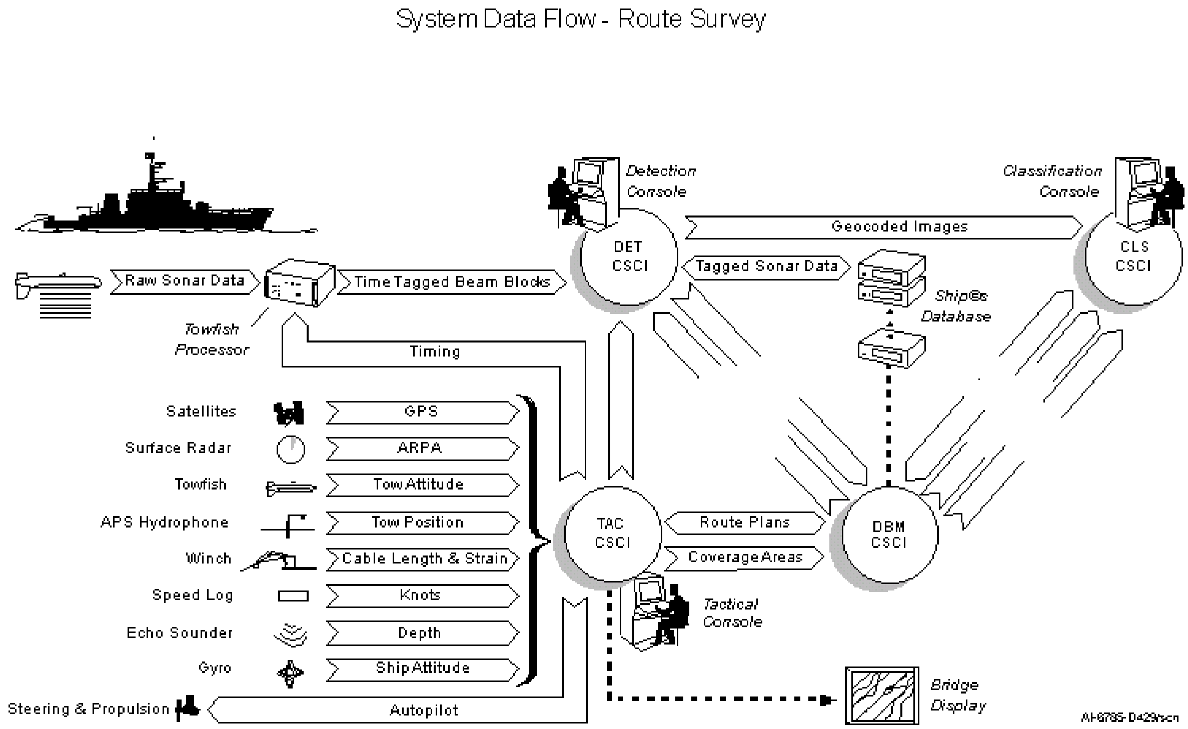


Figure 2.5 - Route Survey Data Flow (from Tecsult - Eduplus, 1997)

Mission Plans, Electronic Navigation Charts, and reference sonar data are downloaded into the MWCS via optical disk. The optical disks originate in the form of *Mission Plans* from the Coastal Operations Planning and Analysis Centre (COPAC). The tactical display displays a ship-centred overview of the local area of operations. As well, the tactical display provides towfish status and control functions. The tactical display also performs many other functions including the production of *Mission Download* optical disks which are returned to the COPAC.

The data analysis consoles are used for object detection and classification. The detection console has an automated detection algorithm available, but it is up to the console operator to determine if an auto-detected target is to be queued for classification by the classification console. The detection operator relies on experience to determine what is a mine-like-object and what is not.

The classification console receives the queued contacts from the detection console whereby the classification operator attempts to classify the contact as a mine-like-object, a non mine, or a mine. A series of tools is available to the classification operator to aid him/her with the job at hand. Most tools however, rely on the area in question having previously been surveyed.

The first tool which is available to the classification operator is the object database. Previously classified objects are marked with geocoded graphical symbols. The operator may use a correlation function which will analyse the new contact's position with respect to the classified object's position. A positional correlation figure is calculated and displayed to the operator. The next tool is a 'mug shot' database which consists of up to ten sonar snapshots of the previously classified object. If a previously classified object has not been marked, the operator may 'flip' the display between the original side scan data and the most recent data. By aligning the two flipping (or flickering) images, the operator may determine if the area has changed, an object has moved or a new object has been introduced. From these tools, the operator may make an informed decision as to the nature of the contact.

If the area in question has not been previously surveyed, then the operator has only his experience and image enhancement tools, such as filters, to aid in the decision making process. This limited alternative illustrates the importance of conducting Route Surveys in peace time. Objects can be detected without a *before* picture; however, if the survey is conducted after a suspected mine lay, every detected contact must be assumed to be a possible mine. In this scenario the mine layer has already achieved one of the functions of mine warfare: "Mines not only sink and damage ships as other weapons can, but their effectiveness is also determined in terms of the delay created in enemy operations" [Hartmann and Truver, 1991].

2.2.1.5 The Acoustic Positioning System [Tecsult - Eduplus, 1997]

The Mine Warfare Control System has an integrated Acoustic Positioning System (APS) which locates the tow fish relative to the vessel. The APS consists of three main components: The Command/Display Module, the Vertical Reference Unit (VRU) and a hydrophone. Tow fish positioning is accomplished in the following manner. The Tow Fish Processor, through the fibre-optic cable, initiates the positioning sequence by activating an acoustic responder on the tow fish. The APS hydrophone receives the triggered signal and passes the event to the APS microprocessor inside the Command/Display Module. The microprocessor calculates slant range and bearing, and this data is transmitted to the Tactical Console. This received data is combined with DGPS and inertial navigation (VRU) data, onboard the MCDV, to calculate an absolute position of the tow fish. The georeferenced position error of the tow fish is estimated to be +/- 20 m with 95 per cent confidence. [Sullivan, 1997].

2.2.1.6 Multibeam Focussed Side Scan Sonars

Single (transmit) beam side scan sonars such as conventional and bathymetric side scan sonars (see § 2.3.3.2) have one significant disadvantage which is the low maximum speed (~ 2 m/s) at which the tow fish must be operated [Huff, 1993]. This is due to two primary reasons, the first being that of tow fish stability. Some tow fish have no steering surfaces and become unstable at higher speeds and therefore, the speed must remain low. Furthermore, in order to reach deeper depths without steering surfaces the tow fish must sink and this can normally, only be achieved at slow tow speeds. [Hughes-Clarke, 1996a].

The second, and most significant reason, that side scan speeds are low is due to the sonar itself. Huff [1993] states that the speed limitation is due to the fact that the distance covered between pings must be less than the across track resolution. Because of the demand for faster data collection rates, multibeam focussed side scan sonars have been developed. Traditionally, in order to increase speed, the across track size of the image area had to be decreased or the along track resolution of the system had to be degraded in order to guarantee 100 per cent coverage. However, using a multiple element transducer array employing focussed array techniques, allows for maintenance of resolution and for increased tow speed.

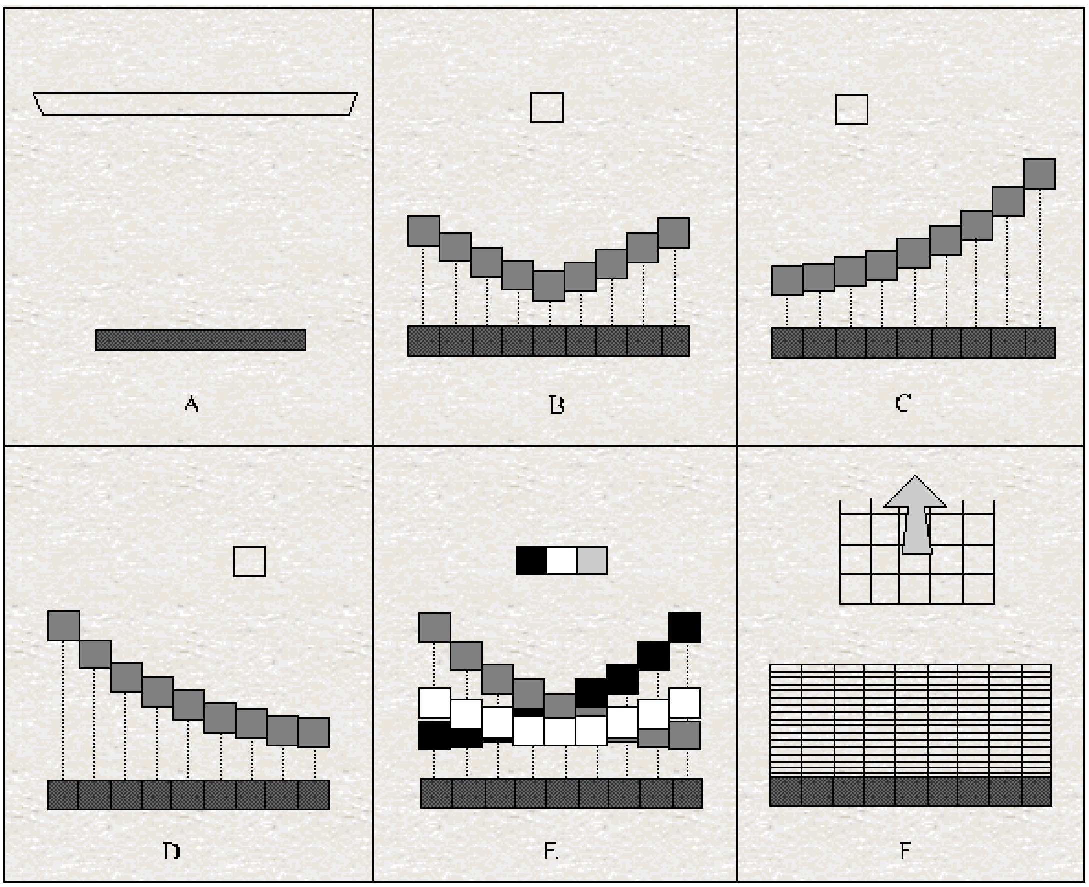


Figure 2.6 - Array Focussing (after Huff, 1993)

Figure 2.6 Part A, depicts a typical single beam, single-element transducer array (shaded) and its associated resolution cell (transparent) at an arbitrary distance from the transducer. The across track resolution cell size in each diagram of Figure 2.6 is determined by the sampling rate, pulse length and bandwidth of the sonar itself. The along track resolution cell size is never smaller than the single-element transducer array itself and grows in length with an increase in across track distance. The along track resolution cell size may be decreased by increasing the overall length of the transducer. However, the resolution in the near-field of a transducer array is approximately equal to the length of the single-element transducer array. For a (D =) 1 m transducer with a frequency of 320 kHz the near-field extends over 200 m (D/wavelength) [Fox and Denbigh, 1983]. Focussing is required in order remove the near-field constraints.

Focussing a transducer array can either be done physically i.e. mounting individual elements to resemble cup-shaped (focussed) array in B (mid-grey boxes) [Huff, 1993], or through a quadratic phase shift of the electrical signal over individual transducer elements within an array the same length as the single element array in A [Fox and Denbigh, 1983]. The latter alternative is preferred as the focussing can be made variable rather than permanently fixed at one particular point in space. Furthermore, the beams of the transducer may be steered with a linear electrical phase shift in addition to the quadratic shift. Different linear phase shifts superimposed over the quadratic phase shifts allow multiple beams to be formed resulting in an increased imaging rate (speed) [Fox and Denbigh, 1983].

Parts C and D are examples of quadratic phase shifting performed in order to achieve resolution cells in the off-centre regions. Part E shows how linear and quadratic phase shifting can be used to create multiple beams in order to focus on multiple resolution cells. Finally, Part F illustrates an array that has undergone quadratic and linear electrical phasing to allow simultaneous focussing on more than one resolution cell at any time, and on different resolution cells at different times. Specifically, Part F is an example of a five beam multibeam focussed side scan sonar.

2.2.1.7 MDA Tow Fish

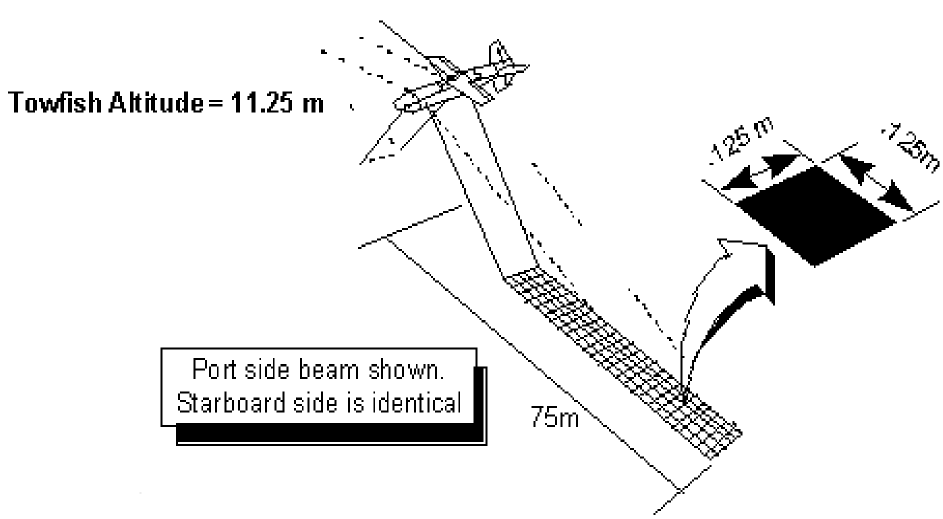


Figure 2.7 - MBFSSS Footprint Pattern (from Tecsult - Eduplus, 1997)

The side scan sonar in the MDA tow fish is a five beam multibeam focussed side scan sonar. The fact that the sonar has five individual beams results in a greater maximum tow speed equal to five times what could be achieved using a single beam side scan sonar of equivalent beam width to any one beam in the MBFSSS. The MDA tow fish transducer has 80 channels, the four centre channels being both transmit and receive capable. The tow fish has a maximum speed of 10 knots (ground speed) regardless of the tow fish altitude [Strong, 1997]. The greater tow fish speed that the MDA tow fish has, allows Route Survey operations to be effected in a much shorter time.

The MDA tow fish can operate in four primary depth modes. It can be towed at a fixed depth or it can be put into one of three Terrain Following Modes where its altitude above the sea floor remains fixed. The three Terrain Following Modes are known as Detection, Detection/Classification, and Classification modes which are at 30 m, 22.5 m, and 11.25 m respectively. Figure 2.7 shows the footprint pattern of the MBFSSS while Table 1.1 illustrates Cell Size, Gap, and Swath Width versus Altitude.

Mode	**Altitude (m)**	**Swath Width (m)**	**Gap (m)**	**Cell Resolution (m)**	
				Along Track	**Across Track**
Detection	30	400	60	0.325	0.125
Detection / Classification	22.5	300	45	0.250	0.125
Classification	11.25	150	22.5	0.125	0.125
Fixed Depth	A	13.3 * A	2 * A	0.011 * A	0.125

Table 1.1 - MDA Tow Fish Modes of Operation

As previously mentioned, all side scan sonars including the one onboard the MDA tow fish, cannot effectively identify objects in the near nadir regions, resulting in a 'gap' in coverage [de Moustier, 1996a]. The MDA towfish gap is 45 degrees either side of nadir. This equates to a gap twice the altitude of the tow fish and centred around nadir [Tecsult - Eduplus, 1997]. As a result of this gap (Figure 2.8), a 60 per cent overlap must occur in order to achieve 100 per cent coverage of the sea floor.

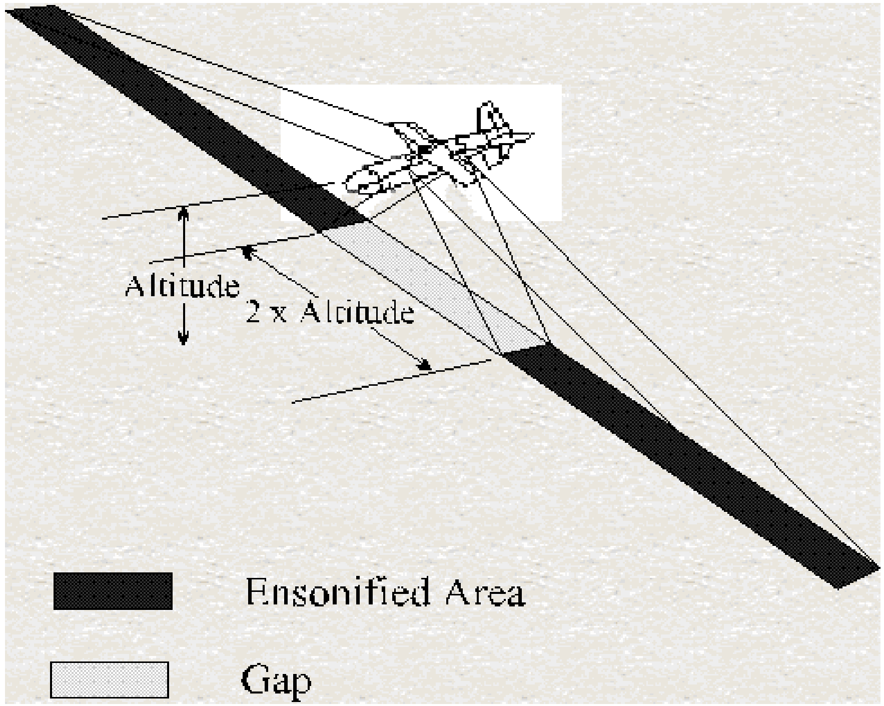


Figure 2.8 - Gap in MDA Towfish Coverage (after Tecsult - Eduplus, 1997)

2.2.2 Q Routes

Q Routes are predetermined shipping lanes which are used during any period of hostilities, where the threat of mines is great. These lanes, or corridors, are normally selected during peacetime according to criteria which will allow shipping the best chance of continuing during an opponent's mine laying operations. The criteria which comes into consideration are as follows. First, it is desired that the route can be defended by the transiting ship's forces i.e., convoys or battle groups, which can defend themselves and merchant shipping from an opponent's attack. This is more easily accomplished closer to the home waters of the transiting force [Deere, 1996]. Next, a Q route should be selected such that the mine layer has difficulty in evaluating the success of his efforts. If the mine layer is denied the intelligence that would allow him to improve his efforts in his next lay then the threat may be reduced [Deere, 1996]. This *can* be accomplished but normally requires superior force which is not always possible. The last and perhaps most important criterion is to select a route where the opponent's mines are easily detected i.e. over an *optimal* sea floor.

First, the sea floor should be topographically featureless with no clutter areas (i.e., boulder fields) so that objects stand out from the sea floor. Next, the sea floor should be one that is well known, i.e., previously surveyed and all objects detected and classified. Furthermore, the reverberation strength of the sea floor should be such that the backscatter intensity of foreign objects is much greater (or less) than the sea floor backscatter itself. The Canadian Navy's ORS Package has the ability to select Q Routes based on the above criteria.

An important sea floor characteristic, which has not yet been mentioned, is that of the sea floor make-up, or lithology. If the sea floor is conducive to mine burial, then the task of object detection becomes much more difficult. For example, a buried mine does not reflect more energy than the surrounding sea floor because it is *covered* by the surrounding sea floor. As well, a buried mine no longer stands proud of the sea floor, hence it is less likely to cast a shadow on a side scan sonar image.

The new ORS Package does not have BSC capabilities; however, the Esquimalt Defence Research Detachment (EDRD) has recognised the need for BSC capabilities and is presently conducting trials on various methods of BSC including remote sensing techniques [Poeckert, 1996]. Canada's Navy is not alone without an operational BSC capability; the United States Navy (USN) is also operationally deficient in this area. Like EDRD, the Naval Research Laboratory (NRL) has assessed the need for BSC and has drafted a Mission Needs Statement calling for, amongst other capabilities, "...a capability to make critical environmental measurements before actual MCM operations." and "...during an operation" [United States Navy, 1995]. Chapter 4 briefly discusses the research presently underway using multibeam sonars in a bottom sediment classification role.

2.3 Multibeam Sonars

> "In a multibeam echosounder the transducer is configured as one or more arrays of transducer elements. By controlling the phasing of the different elements, it is possible to form beams with different pointing angles. Usually only one beam is transmitted and multiple beams are formed simultaneously during reception. The transmit beam of a multibeam echosounder is quite narrow along ship and wide athwartships to insonify [sic] the sector to be mapped. Multiple receive beams span the athwartships transmit sector while the along ship receive beam width depends upon the pitch stabilization method implemented." [Pohner and Hammerstad, 1991, p. 17]

Given this brief introduction as to how a multibeam sonar works, its components and their theory of operation should next be examined. A typical multibeam system is made up of a transducer, transceiver (including a pre amplifier), computer processing system which integrates and controls all of the separate components, position and orientation sensor, and a data storage system [Glittum et al., 1986]. The main computer or a separate computer may be used to display the data for real time processing or editing. This paper will highlight some of the more important concepts in sonar design theory, but will not attempt to thoroughly explain all of the electrical engineering concepts employed.

2.3.1 The Transducer

A transducer is a device which is capable of converting electrical energy into acoustic energy and vice versa. Regardless of the type of sonar being used, a transducer, whether single or in an array, is required in order to ensonify the area of interest on the sea floor. The most simple echosounder is the single beam type; the transducer makes one transmission (ping) and receives the resultant echo for each depth measurement. The size of the transducer is designed according to the beamwidth desired. Beamwidth is defined as twice the angular distance from nadir to the point where the expanding wavefront has been reduced to half power. Half power is also expressed as the quantitative value of - 3 dB (re: 1 Pa).

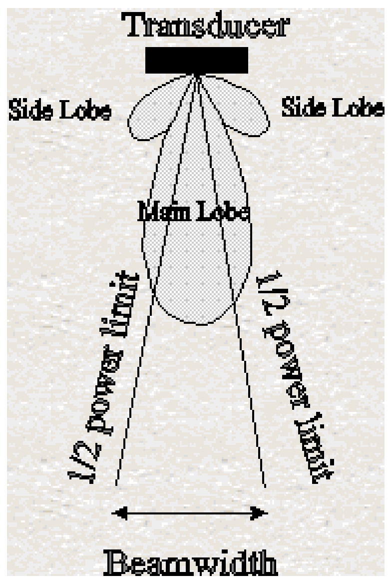


Figure 2.9 - Beamwidth (after Wells, 1996a)

In the above figure, the graphical representation of beamwidth is illustrated [Wells 1996a]. A multibeam system operates around a centre frequency, and the transducer is made up of an array of elements. In fact, it is the array of transducers whose overall size is determined according to the general rule that the beamwidth is inversely proportional to the number of wavelengths across the aperture. Inversely, if we have selected a desired beamwidth, the size of the aperture can be determined using the same rule [de Moustier, 1996b].

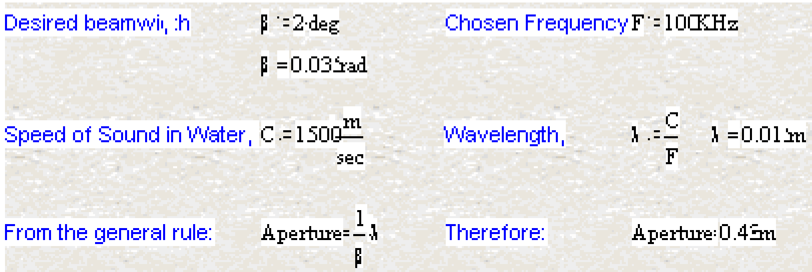


Figure 2.10 - Determination of Aperture (after de Moustier, 1996b)

It is apparent that the narrower the beamwidth, the longer the required aperture. The individual elements that comprise this aperture must be spaced in such a manner as to minimize the grating lobes created. This is accomplished by spacing the individual elements at a maximum distance of one half the wavelength. The smaller the separation between the elements the less likely it is that the grating lobes will be visible. The ideal transducer array would be made up of elements so small that the array would appear to be one continuous element. For higher frequencies, the required spacing between elements becomes smaller than the elements themselves; therefore the elements are staggered above and below each other in rows. Side lobe suppression is achieved through the weighting of individual element contributions across the array face [de Moustier, 1996b].

A (transmit) transducer array designed according to the brief discussion above will transmit a pulse which is very narrow along track and wide across track. The width across track is dependant upon the width of the transducer and the beam pattern of the transducer's elements. Typically, a multibeam system may have a transmit beamwidth of less than 3 degrees along track and up to 85 degrees either side of nadir. For systems without automatic pitch steering of the transmit beam, the receive beam length must be at least as long as the maximum anticipated change of pitch so that no data is lost (Figure 2.11). This requires a separate receive array orthogonal to the transmit array in a configuration known as a Mill's Cross (Figure 2.12).

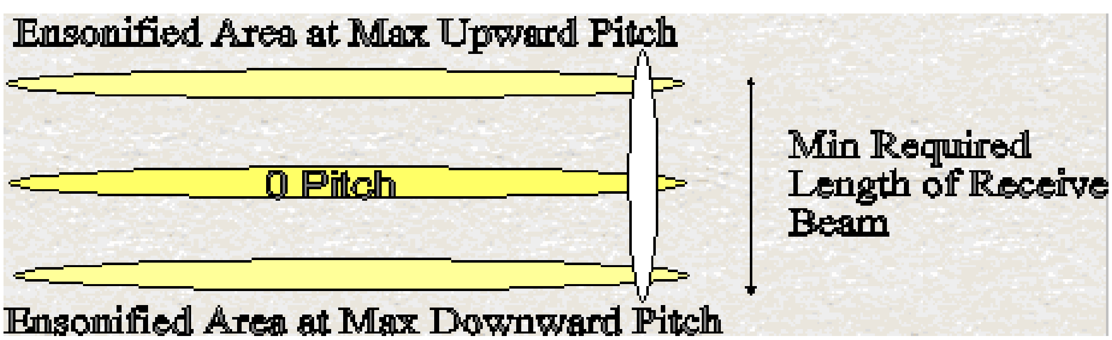


Figure 2.11 - Minimum Width of Receive Beam

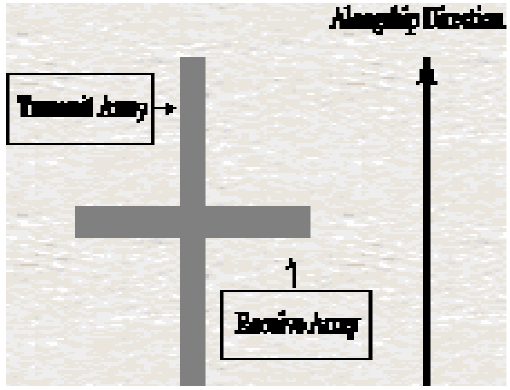


Figure 2.12 - Mill's Cross

2.3.2 The Transceiver

A transceiver is a unit that handles both the transmission and the reception of (electrical) signals. In a multibeam system, this is the place where beam steering and beam forming occur, which are the two defining operations of a multibeam system. Depending on the sophistication of the transceiver, it may perform pitch stabilization beam steering on the transmit pulse. These concepts are discussed below.

2.3.2.1 The Beams

As stated in the definition of a multibeam sonar at the beginning of § 2.3, only one beam is transmitted but many are formed simultaneously to receive the reflected energy from the subsets of the area ensonified by each transmitted pulse. The resulting pattern, which resembles that in Figure 2.13, shows the single transmit beam intersecting the receive beams in areas called footprints.

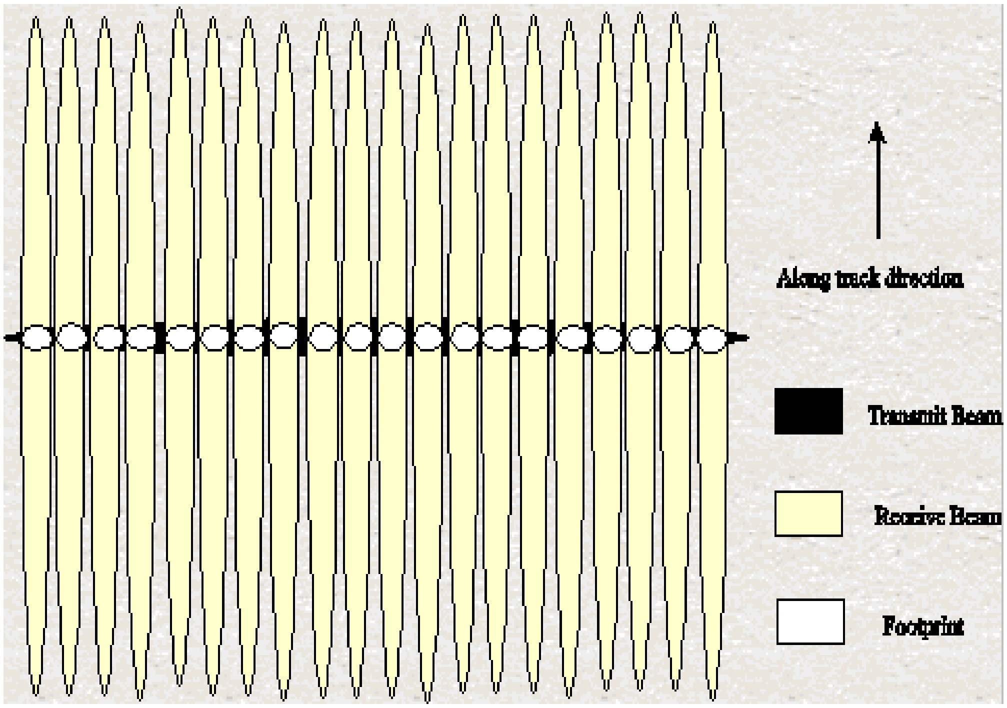


Figure 2.13 - Multibeam Transmit/Receive Pattern on Sea Floor (after Mayer, 1996a)

Otherwise defined, a footprint is equivalent to the intersection of the area ensonified and the projection of the receive beam pattern on the sea floor to a reference power level (normally -3 dB) [Hughes-Clarke, 1996a]. The energy returned from within each footprint is received and is passed on to the bottom detection unit. The combination of successive transmit and receive cycles forms a swath. The entire sea floor in an area of study may be mapped in the same manner as a push broom would clean a floor in successive adjacent, inverse direction sweeps.

It should be noted that the individual footprints illustrated in Figure 2.13 could overlap in a real scenario depending on the individual sonar characteristics versus the water depth, but are not shown as such for purposes of clarity. In successive along track transmit pulses, 100 per cent bottom coverage is generally desired. In order to achieve this, two dependent factors must be taken into consideration when setting the speed of the survey vessel, namely the transmit beamwidth versus the transmit pulse repetition rate at specific depths. The speed of the survey vessel must not exceed the point where successive transmit pulses no longer overlap, otherwise gaps will appear in the data.

The 'sweep' analogy as presented above should not be confused with a multi transducer or sweep system. A multi transducer (sweep) system is one where a ship has many transducers mounted athwartships extending onto booms on either side, each of these transducers being simple narrow beam echosounder. The sweep transducers can transmit in a staggered pattern to avoid mutual interference and to sample the bathymetry directly below.

Key differences exist between multi transducer and multibeam systems. The first difference is the width of each swath. Multibeam systems, through beam forming, can cover an area up to 12 times the water depth, i.e., six times on either side of the vessel [STN Atlas Elektronik 1996]. A multi transducer system's swath coverage is limited to the size of its booms in water where the depth multiple exceeds the boom width. Further, the booms themselves are subject to torque and hence speed limitations. These factors allow time and money to be saved by the larger swaths and greater survey speeds of a multibeam system. However, uncertainty in orientation, roll, refraction and bottom detection in the outer beams may reduce the useable swath width in a multibeam when meeting the International Hydrographic Organization's (IHO) standards for bathymetry. The acceptable depth error (0.3 m for depth < 30 m [Wells 1996c]) may require the reduction of the swath width to the point where the uncertainties no longer exceed IHO standards. The second difference is that a multi transducer system cannot give 100 per cent coverage in shoaller waters. This limitation *can* also be true for a MBS in very shallow water but normally only in the near nadir regions. Figure 2.14 illustrates how shoaller waters may cause gaps to occur between adjacent footprints. The last difference, is where multi transducer systems look in order to measure and analyse amplitude backscatter information. A sweep system only analyses vertical incident energy returns whereas a multibeam system looks at both vertical and oblique energy returns.

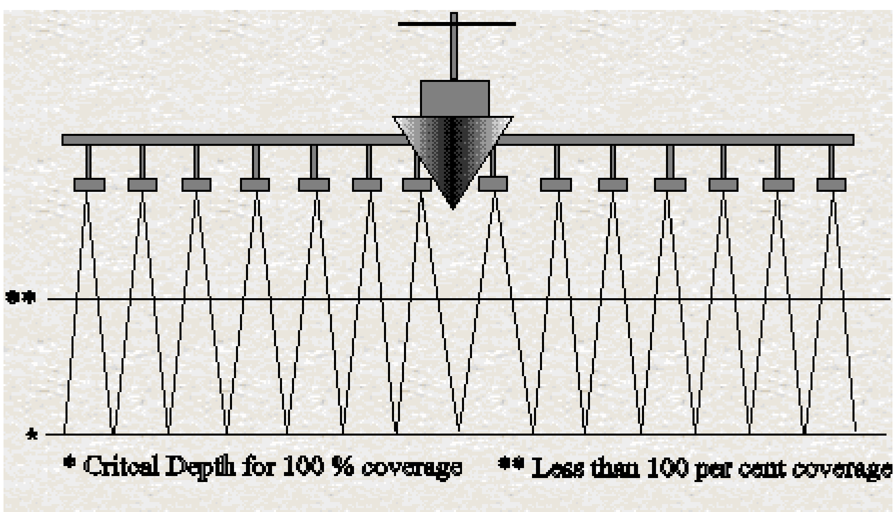


Figure 2.14 - Multi Transducer Configuration (after Mayer, 1996a)

2.3.2.2 Beam Steering and Beam Forming

Beam steering can occur in both the transmit and receive pulses. It consists of orienting a beam in a given direction; this orientation is achieved through steering. By inserting time delays in the elemental contributions in the transducer array, a virtual array is created whose face is perpendicular to the desired steering direction. As the beam is steered further away from broadside, the area of intersection between the beam and the sea floor becomes wider and takes on a parabolic shape. This is best described by imagining the intersection of a cone (receive beam) with a plane (sea floor). In fact, the width of the steered beam increases in inverse proportion to the cosine of the steering angle resulting in a loss of angular resolution for bottom detection [de Moustier, 1996c]. This statement is only true for conventional amplitude detection systems (see § 2.3.3.1). Increasing steering angle results in the receive beam looking in a broader angular sector and hence objects which would be detected in the smaller near nadir beams are lost in the outer beams. Other contributions to this loss in resolution are lengthening echos with decreasing grazing angle, lower backscatter , and the fact that the side lobes are looking in the near nadir direction when the centre of the beam is looking far from broadside. Referring to Figure 2.13, a more realistic diagram would show the footprints expanding in size toward the outer extremities and taking on a parabolic shape away from nadir. Furthermore, side lobes are not depicted but do exist parallel to each beam shown. The graph in Figure 2.15 depicts the expanding nature of a footprint (1.5 degree beamwidth) at various depths and increasing grazing angles. The loss in accuracy can be significant enough that the swath width must be narrowed in order to meet IHO accuracy standards.

Beam forming is the term commonly used to describe how the product of the transmit and receive beams combine to result in the equivalent of a narrow pencil-like beams, wherever they end up being steered. In a pitch steered system, the single transmit pulse is steered about the pitch axis of the survey vessel thereby maintaining bottom ensonification directly below the ship. Beam steering is usually achieved through the summation of time-delayed hydrophone contributions across the transducer array [de Moustier, 1996c]. Equivalently, the transceiver can accomplish (receive) beam steering through *FFT Beam forming* (Fast Fourier Transform). In *FFT Beam forming*, the spatial wavelengths in the across-track array direction of each instantaneously received echo are analysed in order to determine the direction of contribution. For the purposes of this paper the two methods will not be distinguished in further discussions.

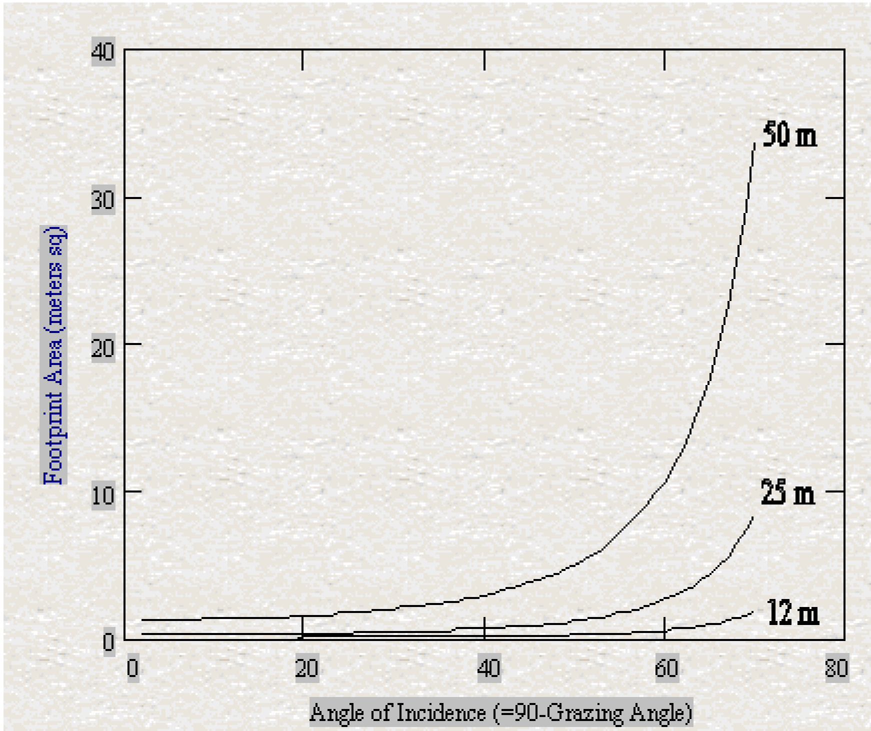


Figure 2.15 - Footprint Radius at Fixed Depths for Increasing Incidence Angles

(oblique intersection, 1.5 degree beamwidth)

2.3.3 The Processing System

The typical processors in a multibeam system are the bottom detection unit, integrator and operator unit. The bottom detection unit receives return data from the transceiver and calculates Two Way Travel Times (TWTT) for given beam angles. The TWTT's are then passed on to the integrator and are grouped with the position and orientation data captured at the time of transmission of each swath. Once grouped, the data is sent to the data storage unit to be retrieved by the operator unit during the survey or to a post processing unit after the survey. The operator unit is used for real time data cleaning and the application of parameters such as the water column. Some operator units can display real time data for cleaning and survey monitoring [Hughes-Clarke 1996a].

2.3.3.1 Bottom Detection Unit

The ideal multibeam sonar would have an infinite number of beams (footprints), each infinitesimally small, so that every nuance of the sea floor bathymetry could be captured. The reality however, has already been shown in Figure 2.15. Clearly, because the depth within a footprint is rarely ever discrete, then neither is the return. In fact, the return will be comprised of a time series of received acoustic pressures with peaks and valleys corresponding to the variations in depth, slope and seabed type within the footprint itself.

All this will be contained within the time segment for that particular depth at that particular distance from nadir for each beam. A method must be chosen which will determine the representative depth within each footprint. Three main bottom detection methods exist in multibeam bathymetry. They are Weighted Mean Time (WMT), Beam Deviation Indicator (BDI), and Split Aperture Correlator (SAC).

Weighted Mean Time is perhaps the simplest algorithm of the three. de Moustier describes the method as fixing the angular direction *a priori* and estimating the time of arrival for that direction [de Moustier 1996d]. Otherwise stated, each receiving beam's angle from nadir is fixed and the echo envelope received in that beam is analysed. The algorithm looks at the time distribution of the returns in each beam and calculates the weighted mean value. This method can be referred to as 'centre of mass' and uses a method similar to the formula below. In Figure 2.16, T is the mean of all the samples, N is the number samples, A is the weight of each sample and t is the time of each individual return.

$$T := \frac{\sum_{i=1}^{N} A_i \cdot t_i}{\sum_{i=1}^{N} A_i}$$

Figure 2.16 - Weighted Mean Time (after de Moustier 1996c)

The Beam Deviation Indicator can be applied to those systems using Fast Fourier Transforms (FFT). In these cases, BDI looks at individual time slices and estimates the angle of arrival. This is the opposite of WMT where the echos from predefined angles of arrival are examined in order to determine the time of arrival. A BDI processor transmits in the same manner as conventional systems but traces the direction of the return signal to the scattering point as a function of time. Discrete time slices are sampled and recorded for each transmit beam. These time slices are analysed and the angle of arrival (ie the beam direction) is then estimated [de Moustier 1996d]. The end result of BDI is a time series of angles which are then grouped into angular sectors equivalent to the beamwidth of the system [Hughes-Clarke, 1996a]. Phase ambiguities in the near nadir beams can make the use of BDI impractical; therefore, some systems have the ability to use BDI in the outer beams and WMT on the near nadir beams. BDI is similar to the bottom detection processing that is used in Bathymetric Side scan Sonars (BSS), which are sometimes referred to as Interferometric Sonars. BSS will be discussed briefly in § 2.3.3.2.

The accuracy problems associated with the larger footprints in the outer beams of a conventional multibeam sonar are significantly reduced by using a Split Aperture Correlator , as the resolution is not limited to the beamwidth. In a SAC the arrival time is computed at the zero crossing of phase for a pair of beams pointing in the same direction with the same time reference [Hughes-Clarke 1996c]. The differential phase is examined in order to determine the point where the phase crosses zero within the beam. Problems associated with two or more signals arriving at the same time are reduced considerably by measuring the angle of arrival inside very narrow receive beams [Pohner and Hammerstad 1991]. However, SAC is unreliable within 15 degrees on either side of nadir where the phase changes very rapidly [Hughes-Clarke 1996c]. If through a regression analysis the variance is too large, the weighted mean time method is then used [de Moustier 1996d].

2.3.3.2 Bathymetric Side Scan Sonars

Submetrix states the difference between the conventional multibeam system and BSS is that a BSS measures an angle at each of a large number of range intervals whereas the conventional multibeam uses WMT range on each of a number of fixed beams [Submetrix, 1996]. BSS systems use transducers which are located on a towed body (fish). The arrays are paired for a total of three or more arrays per side; they function as both transmit and receive arrays. These arrays are not installed orthogonal to each other as is the case with multibeam systems. In a BSS the arrays are mounted one above the other and slightly offset. The transducer arrays then measure the phase differential of the returning signals between the centres of the several pairs of arrays at different wavelengths. A result of the BSS transmit and receive arrays being parallel is that the receive array has an identical footprint to that of the transmit array and orientated in the same direction. The BSS has some limitations with respect to resolution. A BSS, using broad receive beams, has the inability to distinguish objects at the same range due to phase ambiguities [de Moustier, 1996a].

2.3.4 Position and Orientation Sensor

After each transmission, the main processor takes the sonar relative times and angles from the BDU and matches it with the positional information at the time of the ensonification. This positional information is the key factor in the difference between multibeam systems and side scan sonars. A side scan sonar's transducer is a towed body which is connected to the ship via a controllable winch. The exact position of the transducer is rarely known well enough for the side scan bathymetric information to meet IHO standards. A multibeam transducer is fixed to the ship and therefore, if the position of the ship is known, then the position of the transducer is known as well. This positional information is made up of horizontal position, elevation, orientation, and water column [Hughes-Clarke 1996b]. Each sensor will normally determine its required parameters at a position on the vessel different from that of the transducer, i.e., a GPS receiver determines the position of the GPS antenna. Keeping this in mind, lever arms and time delays must be calculated in order to determined the required orientation and position parameters at the transducer itself [Hughes-Clarke 1996b].

2.3.4.1 Horizontal Positioning

Positioning is defined as the determination of the coordinates of a point with respect to an implied coordinate system [Vanicek and Krakiwsky, 1986]. Many coordinate systems exist, however the WGS 84 system is quickly becoming the global standard. Positions are expressed either as latitude and longitude (f,l) or northings and eastings (x,y) for a two dimensional and hence a horizontal position. Position is easily and accurately determined using modern differential or Y-code (if available) GPS receivers. The horizontal accuracy required for multibeam surveys is at the metre level [Wells 1996b]. A GPS receiver meeting the National Marine Electronics Association (NMEA) standards will determine and transmit position in a specific format to the computer processor.

2.3.4.2 Elevation

The third variable which makes a position three dimensional, is the addition of the height vector z. The IHO vertical accuracy requirement is more stringent than that of the horizontal accuracy. IHO standards require a vertical accuracy of 30 cm for depths less than 30 m and 1% of depth for depths greater than 30 m [Wells 1996c]. Many factors influence the vertical position of a ship and they act independently of water depth. It is therefore more difficult to achieve shallow water accuracy than deep water accuracy. These factors are grouped into two categories, changes in water level and changes in draught [Wells 1996c].

Changes in water level are due to tidal variations, river levels, enclosed basins and heave. Tidal variations are periodic water height changes ranging from diurnal to semi-diurnal in frequency. River levels vary according to such factors as season, precipitation and dams. Enclosed basins are affected by the same factors as river levels but are also subject to seiches which are short period oscillations due to weather. Finally, heave is the change in water level due to sea, swell, and the piling up of wind-driven water along a shore line.[Wells 1996c]. All of these factors can be predicted, some accurately and some not. Due to the stringent shallow water requirements, a typical survey must have some method of determining the real time changes in water level.

Changes in draught are due to speed, attitude, manoeuvring and loading related factors [Wells 1996c]. Speed affects the dynamic draught and squat comes into effect in shallower waters. Squat is particularly noticeable in water where the depth is less than 1.5 times the vessel's draught, especially if the vessel enters such water at high speed [Ministry of Defence, 1987]. The last three factors need no explanation of how the draught is affected. What a survey requires is a single sensor that can give the real time three dimensional ship position within IHO specifications.

Although GPS is accurate enough for the horizontal position, the vertical component is not. The data rate from a typical GPS system is too slow to detect the higher frequency heave components [Wells 1996c]. The first three factors are best dealt with in a water level survey concurrent with the multibeam survey. The heave component is presently resolved by integrating the GPS receiver and an inertial motion sensor. The two components combined can meet the IHO specifications.

2.3.4.3 Orientation

The orientation (roll, pitch and heading) of a vessel, directly affects where the transducer is pointing and hence the position of the footprint. If the orientation of the vessel can be determined, two correction options exist. The first option is to note the real time orientation and then apply corrections to the collected data. The second option is to steer (electronically or mechanically) the transmit and/or receive beams in order to achieve a consistent nadir beam.[Hughes-Clarke 1996b].

2.3.4.4 Water Column

The last component which can have an effect on the quality of the bathymetry data is that of the water column. Unfortunately the water column is not a homogeneous mass with constant pressure, temperature and salinity properties throughout. These properties vary with depth as well as horizontal position and affect the velocity of sound and hence the bathymetry. Presently, the Sound Velocity Profile (SVP) is measured by the surveyor at non standard intervals. That is to say, the surveyor must decide how variable the water mass is or monitor the real time data to see when refraction errors are significant enough to call for another SVP. The SVP can be measured in a variety of ways. The most common is a SV profiler which is lowered into the water to the sea floor. The device measures the sound velocity along its descent and then the data can be down loaded to the processor. This is time consuming, as the ship must be dead in the water, but the lack of SVP data can lead to uncorrectable errors in the data. Newer innovations that would constantly feed real time SVP data into the processor are being trialed by industry, government, and academic institutions.

2.3.5 Data Storage

Now that all the sensors are feeding data into the central processor, data storage is required. Early hydrographic surveys involved the use of a lead line and the 20 or so soundings per hour were easily recorded manually. With the latest generation of multibeam sonars such as the Fansweep 20 as many as 1.9 million values are generated per hour [STN Atlas Elektronik, 1996]. This amount of data requires gigabytes of storage per day of survey. Modern day storage requirements are met through the use of mass data storage devices such as magnetic tapes and optical discs.

2.3.6 Multibeam Sonar Versus Multibeam Focussed Side Scan Sonar

The multibeam sonar's ability to accurately georeference bathymetric data has been discussed in § 2.3.4. The MDA tow fish (multibeam focussed) side scan sonar's data is georeferenced, but because it is not hull-mounted, the accuracy is much less (~20 m). The side scan system will transmit and receive on the same transducer array whereas a multibeam has separate receive arrays. The duality of the side scan array results in a narrower beamwidth and therefore, increased resolution. Traditional side scan beamwidths are typically 0.75 degrees or less, which is smaller than that of any multibeam system available. The MDA tow fish sonar has a fixed across track beamwidth of 0.125 m and an along track beamwidth dependant upon the tow fish altitude (Table 1.1). In a multibeam sonar the receive beam is very wide along ship and doesn't fit inside the ensonified area resulting in decreased resolution.

In their traditional configuration (hull-mounted multibeam sonar and side scan sonar on a tow fish), one significant difference between the two sonars is the relative positions of their transducer arrays in relation to the sea floor. The side scan array is close to the sea floor which results in smaller grazing angles which allows objects to cast larger shadows than that of a multibeam system resulting in easier identification of objects, such as mines, lying on the bottom. Furthermore, the narrower beamwidth of the side scan system means the shadows cast are more discrete than that of a multibeam system whose shadows are averaged with the topography inside the larger footprints. Figure 2.17 illustrates the effects of different grazing angles on side scan and multibeam systems as well as their comparable beamwidths. In view of the increased resolution and propensity for larger more discrete shadows, side scan sonar is well suited for object detection, thus making its reasons for use in mine detection clear.

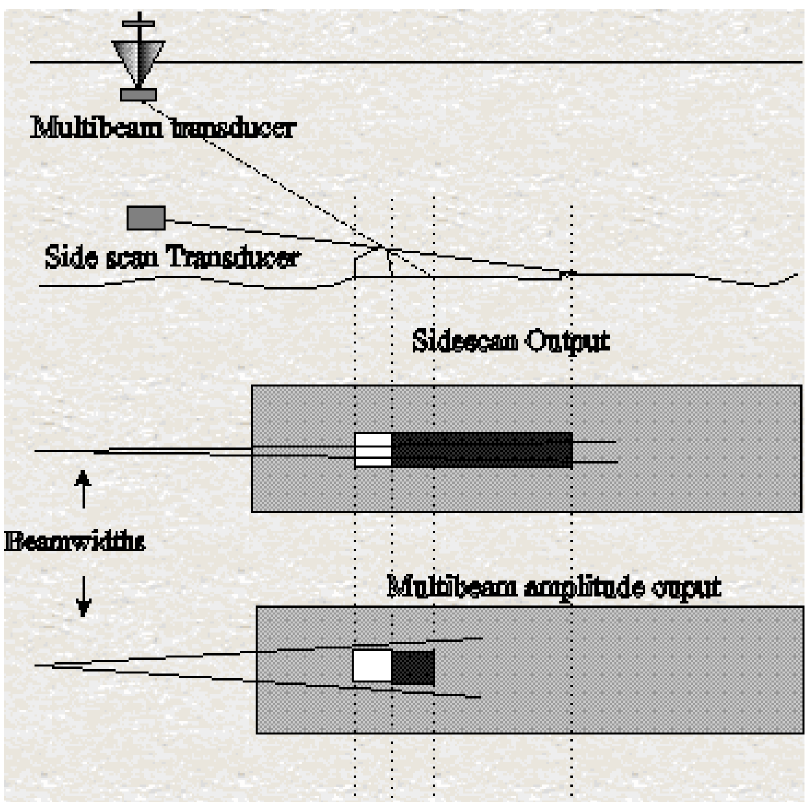


Figure 2.17 - Contrast in Side Scan and Multibeam Grazing Angles (after de Moustier, 1996a)

Although the MBFSSS is better suited for target identification, multibeam sonars offer their own distinct advantages. An MBS may be operated at a much higher speed than the sonar on the MDA tow fish, specifically, up to 15 kts versus 10 kts. As well, multibeam sonars have no associated gap as found in side scan sonars. These two advantages lead to faster surveys with no overlap. The next chapter assesses if an MBS's unique advantages make it suitable for use as a mine finding sonar.

CHAPTER 3 - MULTIBEAM SONAR DATA ANALYSIS

3.1 Overview

This chapter looks at the data products of an MBS in order to assess if they would be appropriate in a Route Survey application. This first part of this chapter looks at Bottom Sediment Classification through the use of a MBS backscatter data. This application of an MBS is still under development; therefore the discussion is more theoretical than absolute. There is no data analysis per say, however the possibility of using an MBS for Bottom Sediment Classification is an application very relevant to Route Survey.

The second (main) part of this chapter is a summary of the results of the main portion of the research undertaken for this project. Three Unix-C programs were written in order to decode and display the information contained within the raw telegrams of a Simrad EM 3000 multibeam sonar; they are *Interp*, *Raw_sidescan* and *MLO_Find*. Through the use of the programs that were written, as well as graphical models, a discussion of what data products could be used in Route Survey ensues. This discussion focusses on the capabilities and limitations of the MBS data which includes resolution and object placement within the swath.

3.2 Bottom Sediment Classification

The Operation Route Survey Payload does not have a Bottom Sediment Classification (BSC) capability (see § 2.2.2) however, the need does exist for one. Bottom Sediment Classification is important due to the possibility of mine burial in softer sediments. Mine burial occurs as a result of four primary burial mechanisms: impact burial, scouring, bed form migration, and liquification (see § 3.2.1). As an MCDV does not yet have the ability to detect a buried mine the threat to shipping is great. The best way to avoid this threat to avoid areas where mine burial is a possibility. Avoidance of areas conducive to mine burial may be accomplished by classifying the sea floor. Canada's territorial seas are vast and *in situ* testing is not a financial possibility; therefore, the best alternative is the use of a BSC sonar such as what an MBS can potentially offer.

3.2.1 Mine Burial **[Suhayda and Tumey, 1982]**

Suhayda and Tumey have identified that mine burial occurs as a result of four primary burial mechanisms: impact burial, scouring, bed form migration, and liquification. (Figure 3.1). The authors define a buried mine as one that has at least 25% to 50% of its volume below the sediment/water interface. This definition does not conform to any particular standard as it can be modified by the detection limits of a particular mine hunting sonar. The primary variables which determine the propensity of bottom sediment for mine burial are shear strength, grain size, bulk density and the presence of bed forms.

Impact burial occurs at the time of mine drop, and normally only for air dropped mines (except in very soft bottoms). The primary variable which can predict the propensity of the bottom to bury a mine on impact is the shear strength. Scouring occurs when a prevailing current creates a trough on the 'leeward' side of the mine. Eventually the mine will descend into the trough and be buried by further scouring mechanisms. Bed form migration occurs when the prevailing currents carry the bed form in the direction of the current flow thus burying the immobile mine. This is most often seen in the form of moving sand waves. Finally, liquification occurs through storm processes whereby the sediment volume is stirred enough that its shear strength is reduced to the point where the mine will sink.

The Canadian Navy does not have the means to detect buried mines. If a mine is buried in an area under Canadian MCM responsibility, it will most likely go undetected until it's too late. Installing bottom sediment classification sonars onboard the MCDVs would allow areas of high mine burial probability to be classified and subsequently avoided. If the MCDVs were fitted with BSC sonars, then both route survey and BSC could be performed at the same time, and ultimately Q Routes could be chosen based on *all* the criteria listed in § 2.2.2.

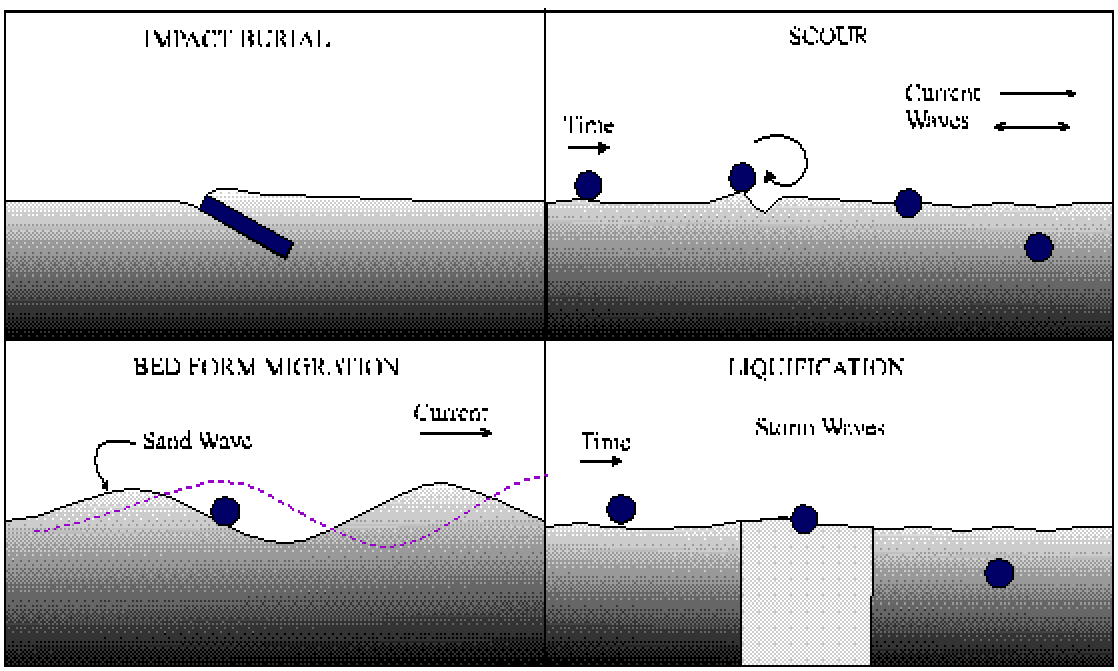


Figure 3.1 - Four Methods of Mine Burial (after Suhayda. and Tumey, 1982)

3.2.2 Normal Incidence Bottom Sediment Classification

Many different types of normal incidence Bottom Sediment Classification sonars are in use today. There are five primary methods used in normal incidence BSC processing [Mayer, 1996b]:

- Echo Character;
- Database;
- Statistical;
- Pattern Recognition; and
- Direct Property Measurement

The specifics to each individual approach above is beyond the scope of this report and will not be covered here. Mayer [1996b] gives a general overview of each of these approaches.

The key to each of the above mentioned approaches is the term *normal incidence*. That is, each of these methods uses acoustic pulses and returns with an incidence angle of 90 degrees. In fact, although the initial angle of incidence is 90 degrees, the waveform of the echo consists of true normal incidence and near normal incidence energy. The near normal returns result from the spherical spreading of the transmitted pulse. It is important to realize that for some sea beds (low impedance contrast), the near normal surface returns interfere with the sub-bottom returns and must be taken into account (Figure 3.2).

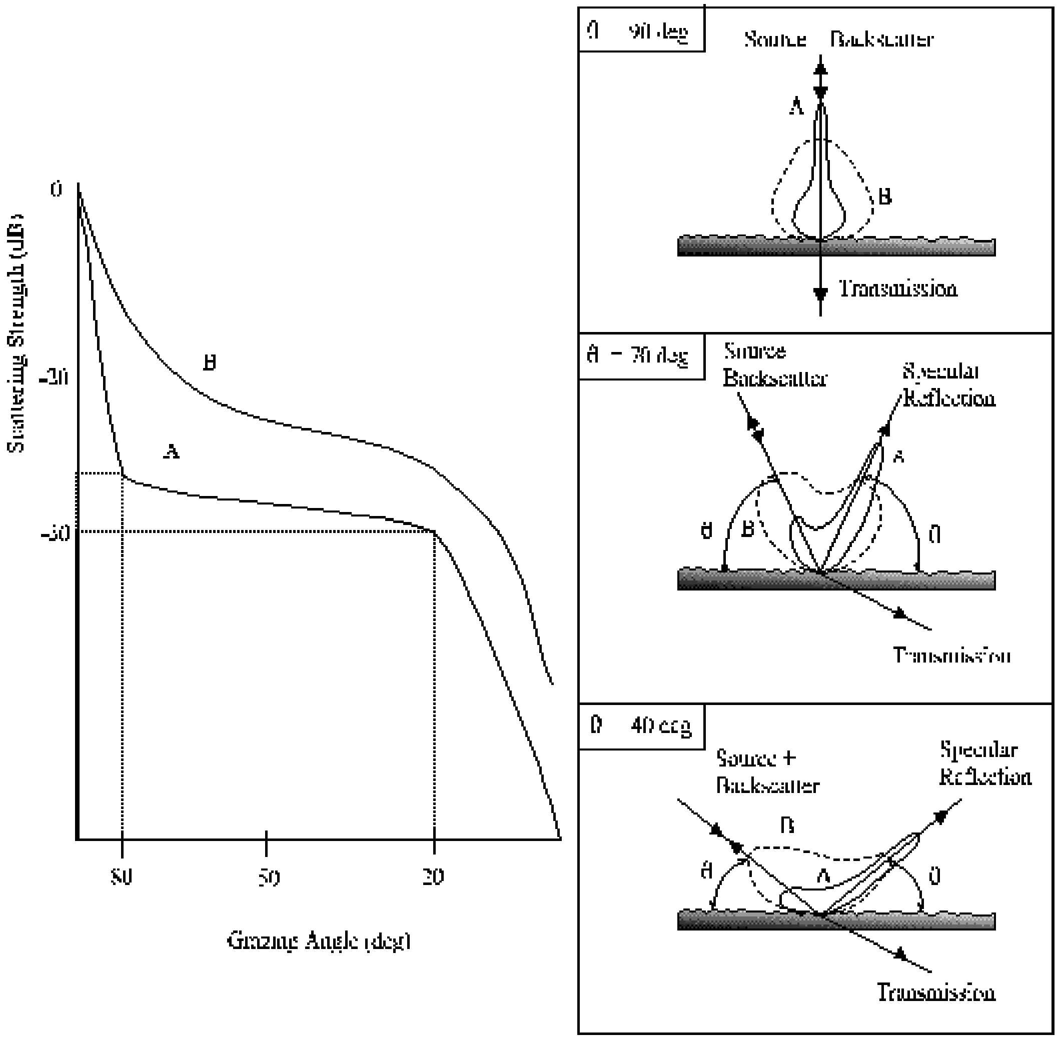


Figure 3.2 - Normal Incidence Interference

The (near) normal incidence approach to BSC limits itself to grazing angles within the beamwidth (generally within 10 degrees of nadir). This approach eliminates one area which is very difficult to model; that being the backscatter response (reverberation level) of a particular material type for varying grazing angles. The backscatter response depends upon the grazing angle, seabed surface and subsurface impedance, and roughness [Hughes-Clarke, 1993]. When considering seabed roughness, it must be specified relative to the wavelength of the incident pulse as compared to the scale of the bed form roughness elements. The reader is referred to Urick [1983] for a complete discussion of roughness.

3.2.3 Using an MBS for Bottom Sediment Classification

de Moustier and Hughes-Clarke [1996] discuss three non-incident BSC methods which can use acoustic echoes in order to infer the nature of the seabed. These methods include:

- Texture Mapping and Spectral Estimation;
- Echo Amplitude and Peak Probability Density Function (PDF); and
- Acoustic Backscatter Angular Dependance Functions.

These methods were originally developed for side scan sonar applications; however, they can be applied to MBSs. All three methods are described below as well as their application to MBSs.

3.2.3.1 Texture Mapping and Spectral Estimation

Texture is a very important characteristic used to identify objects or regions of interest in an image. Textural features contain information about the spatial (or temporal) distribution of tonal features within a band of information [PCI, 1993]. Acoustic Texture Mapping relies on observing the changes of ping characteristics both within a single ping, and over a number of pings. Through the extraction of statistics from grey-level co-occurrence matrices, boundaries may be identified [de Moustier and Hughes-Clarke, 1996]. Co-occurrence matrices derived from acoustic imagery show the relationship between a given pixel and a specified neighbour. Texture measures such as homogeneity, contrast, dissimilarity, mean, standard deviation and entropy are some of the statistics which may be derived from a co-occurrence matrix in order to aid in the texture mapping process [PCI, 1993].

In sea floor classification using texture, the amplitude backscatter information observed does not have to be absolute in nature, as relative changes are the key. These changes depend upon individual sonar characteristics such as pulse length and beam width, and upon the image transformations or registrations used in the sonar data processing. To date, no adequate physical models have been developed to predict the texture that can be attributed to specific physical properties; therefore, ground truthing is required in order to relate the relative data to absolute bottom types [de Moustier and Hughes-Clarke, 1996].

Spectral Estimation examines the shape of normalized spectra derived from acoustic returns in order attempt sea floor classification. Bottom types are identified by the specific shape of the normalized amplitude returns [Pace and Gao, 1988]. This method was originally developed for side scan sonars, and the models developed are platform specific i.e. normalized power spectra for the same sea floor vary with the specific sonar used due to unique beamwidths, pulse lengths, frequencies, etc. Furthermore, the spectra were derived from the mid to far range backscattered time-series from these low aspect ratio side scan sonars. As a result, this method does not apply very well to high aspect ratio, multibeam sonars in the near nadir (<60 degrees) regions due to the non-linearity of the time-sampling versus across-track distance in the near nadir regions [de Moustier and Hughes-Clarke, 1996].

3.2.3.2 Echo Peak PDF [de Moustier and Hughes-Clarke, 1996]

The echo envelope containing sea floor acoustic backscatter is comprised of both coherent and incoherent scattering. By examining the probability distribution function of the return echo amplitude, the coherence may be derived. The PDF may be Gaussian (coherent) or Raleigh-Rice (incoherent) in nature. By determining the ratio of coherent and incoherent components within the resultant PDF sea floor characteristics may be inferred [de Moustier and Hughes-Clarke, 1996]. Figure 3.3 illustrates Gaussian and Raleigh-Rice PDFs. The *Coefficient of Variance* [Stanic et al. ,1989] has been used as the ratio of /μ (standard deviation over the envelope mean) to indicate the scattering mechanism.

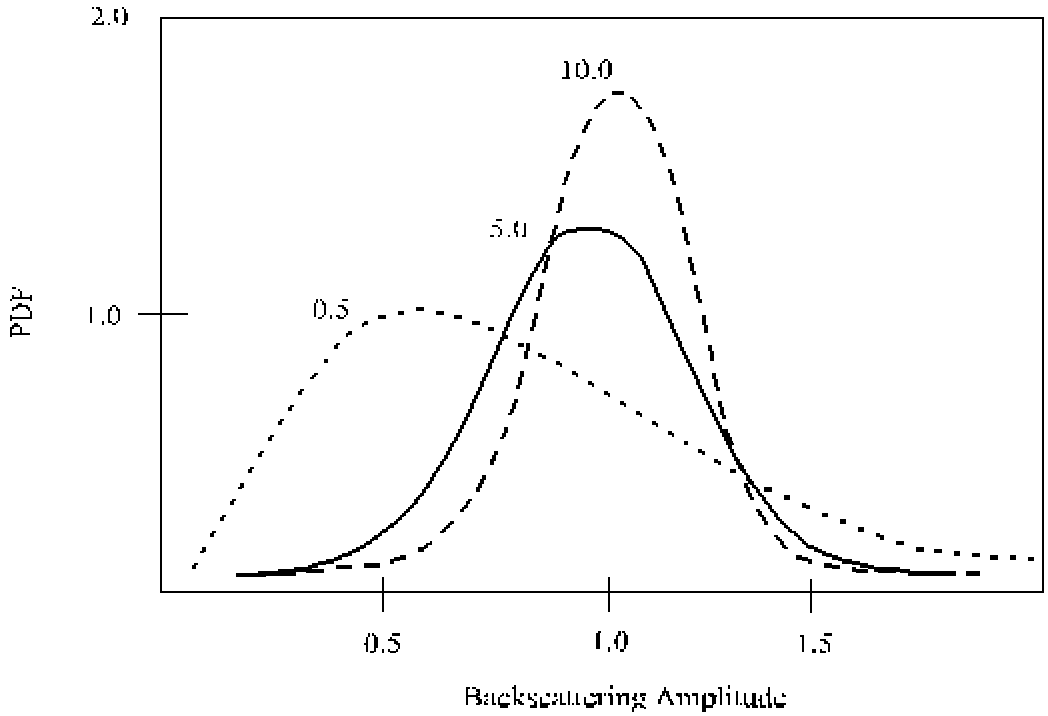


Figure 3.3 - PDF Distributions

This classification method is independent of both absolute amplitude and scattering cross section; therefore, it is relatively independent of individual sonar characteristics. This method, when applied to multibeam sonars, encounters some difficulties *outside* of the near nadir regions. That is, coherent (specular) reflections generally do not return to the transducer unless there are unusually large facets. This means only Raleigh-Rice scattering is observed while any Gaussian scattering is lost. The sea floor properties can no longer be so easily inferred.

3.2.3.3 Angular Response

The scattering strength from a particular sea bed type is dependent upon grazing angle as well as roughness and impedance contrast at a specific frequency. Figure 3.4 is divided into two major sections, on the left is a Scattering Strength versus Grazing Angle graph for ideal smooth (A) and rough (B) surfaces. On the right side of Figure 3.4 are three examples of how backscatter response varies with roughness and grazing angle (this figure assumes a constant discrete frequency throughout). Looking first at the graph, it can be seen that for a particular bottom type the scattering strength varies considerably with the grazing angle. Furthermore, the shape and the magnitude of the curves vary according to the specific seabed type. Examining the three diagrams on the right hand side, in each case Envelope A is the backscatter "beam-pattern" for a smooth sea floor where as Envelope B is for a rough sea floor. The beam patterns change for different grazing angles as does the shape of the envelope for different magnitudes of roughness.

All bottom types have their own particular response curves for a given frequency; therefore, if the response curve of a survey area can be accurately derived then all that remains is to compare the results with empirical curves. A properly calibrated sonar is required, but before the backscatter response may be compared to empirical response graphs the data must be corrected. First, the local slope of the point of ensonification must be determined, both along and across track [Hughes-Clarke, 1993]. Assuming a flat sea floor in an area where the sea floor is not flat can introduce large errors. Next, if the sonar in use is not pitch stabilised, then this factor must also be corrected [Hughes-Clarke, 1993]. Once the data is properly corrected, curve-fitting may be undertaken in order to attempt sea floor classification [de Moustier and Alexandrou, 1991]. This method has perhaps the best potential application to multibeam sonars due to the absolute nature of the calculations.

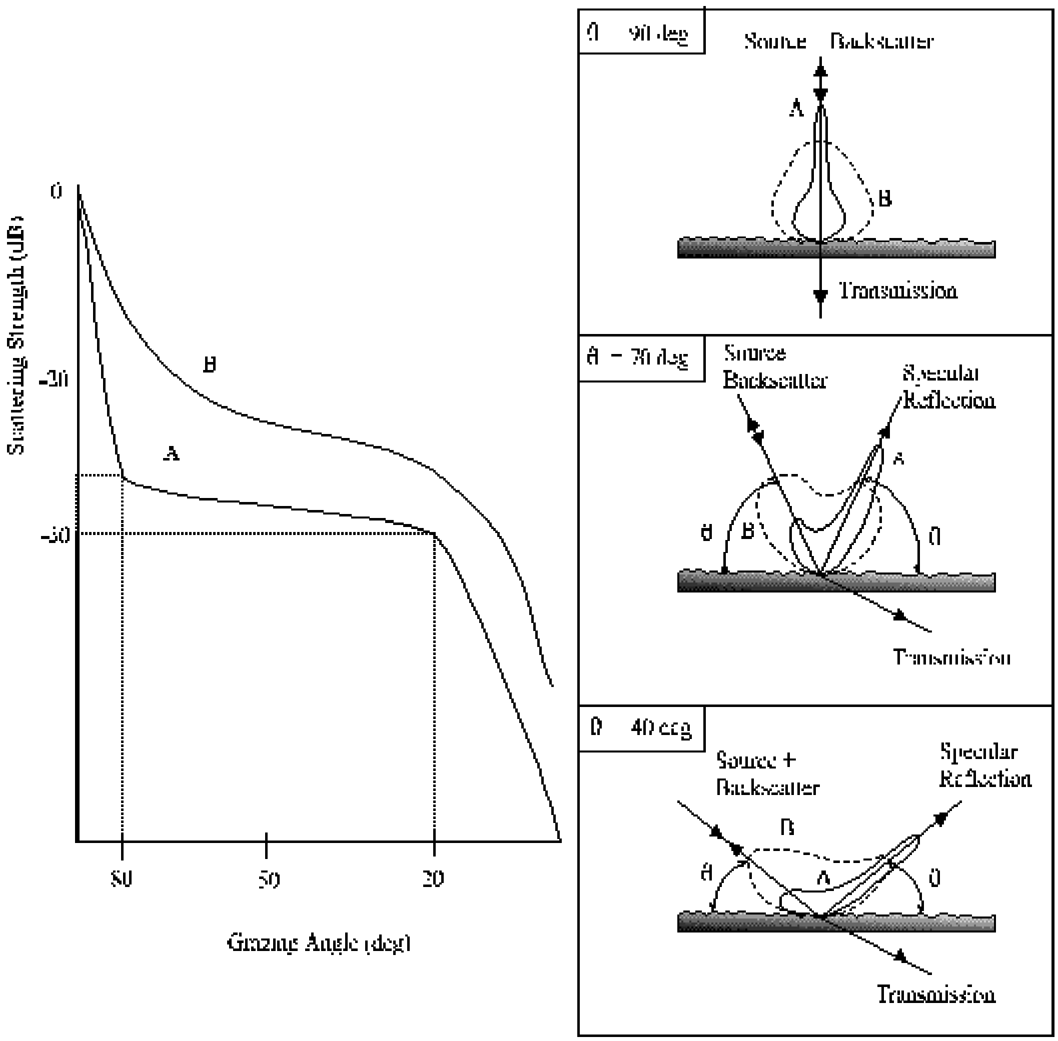


Figure 3.4 - Angular Response & Backscatter Beam Pattern (after Urick, 1983)

3.2.4 BSC Summary

Bottom sediment classification is a function currently beyond the Canadian Navy's capabilities. In light of the continuing bottom sediment classification research using multibeam sonars, it is reasonable to assume that one day MBSs *will* be used successfully for accurate, repeatable BSC. This (theoretical) capability is not justification for the Canadian Navy to equip its vessels with multibeam sonars. Clearly if the Navy is to use multibeam sonars they must provide some other significant benefit. The following sections will look at the amplitude backscatter and bathymetric data which are collected by a multibeam sonar in order to determine if these products can contribute to the mine-counter-measure roles of the MCDVs.

3.3 Data Analysis

3.3.1 The "*Interp*" Program

EM 3000 survey lines are stored on disk in the ".raw" format. Each of these ".raw" files are telegrams consisting of individual datagrams. There is a total of ten possible datagrams and they are listed in the next section [Hammerstad, 1996]. *Interp* was written so that a raw EM 3000 telegram could be converted into a text based output. Secondarily it served as a vehicle for a comprehensive understanding of the EM 3000 telegram structure.

3.3.1.1 Datagram Inconsistencies

In order to be able to read any information from a raw EM 3000 telegram, the manner in which it is written to disk must be known. The EM 3000 Technical Note [Hammerstad, 1996] contains the key to deciphering the telegram format and was required in order to write *Interp*. However during the creation of *Interp*, several inconsistencies between the supposed datagram format and the *actual* datagram format were found. Prior to analysing *Interp* itself, these inconsistencies will be examined. Appendix I contains the datagram formats which are listed below.

Depth Output:

> No inconsistencies.

Seabed Image Data Output:

> The sorting direction of the amplitude backscatter samples is listed as a signed short integer with a valid range of -1 or 1. The actual values are 1 or 255.
>
> The datagram is supposed to end with a 2 byte check sum. In fact the check sum is followed by one extra byte.

Position Output:

> The 'number of bytes in the input datagram' value (unsigned char) must be decreased by 2 (bytes) in order to reflect the actual length of the Position Input Datagram.

Attitude Output:

> No inconsistencies.

Heading Output:

> This datagram is not present in any telegrams.

Clock Output:

This datagram is not present in any telegrams.

Runtime Parameter Output:

Just prior to the end of datagram (ETX) variable there is supposed to be 10 (unsigned char) spare bytes. In fact there are 6 spare bytes followed by the ETX variable and the checksum, and then the last 4 (unsigned char) spare bytes appear.

Installation parameter Output:

No inconsistencies.

Sound Speed Profile Output:

The second set of 'Date' and 'Time' appear to be operator entered but this is not documented.

The 'N entries of' section appears to be fixed at 65 records instead of 'N' records.

NMEA 0183 Depth Output:

This datagram is not present in any telegrams.

3.3.1.2 *Interp* Discussed

Interp is a simple program both conceptually and in practice. The greatest challenge in creating this program was identifying the inconsistencies which were discussed in the previous section. The program listing for *Interp* is located in Appendix II and a sample output is located in Appendix III. The following sections discuss the algorithms used in *Interp*; the reader is directed to the comments in the program itself for more specific details on variables.

3.3.1.2.1 *main( )*

The *main()* section of this program first sets default values and calls the *get_file_info* function (see below) in order to open the files required during execution. Each datagram, regardless of type, has the same header which is comprised of the first 16 bytes. The first task which *main()* performs is to locate a valid header by using the second and fourth fields which are Start Identifier and EM Model Number. Once a valid header is identified the entire header is read and printed to the output file. Next, a *switch* statement determines what type of datagram follows the header, and calls the appropriate function to read and output the fields contained within that specific datagram. Upon return from the called function, *main()* will repeat header identification and function calling until the *end-of-file* is reached.

3.3.1.2.2 get_file_info( )

The *get_file_info()* function queries the user for the EM 3000 file which is to be *interpreted* as well as an output filename for the resultant output. If the user enters no output file name then ".interp" is appended to the input file name and used as the output file name. The user is then required to decide and enter whether or not they wish the following information to be included in the output:

- all the depth information (soundings for each beam);
- all the seabed (backscatter samples for each beam) information; and
- all the attitude information.

Flags are set according to the choices made by the user. The default (nil) entry is 'no'.

3.3.1.2.3 Specific Datagram Interpreting Functions

The remaining functions are those which are used to decipher each specific datagram type, apart from the initial common header. They are all alike in that they read each variable according to the datagram key in Appendix I. The last part of the *seabed*() and *install_param()* functions share a common algorithm which is required due to the variable length of these datagrams. This algorithm is used to find the last three fields in these datagrams and is illustrated by the flowchart in Figure 3.5. In *seabed*, prior to this algorithm being used the file pointer is advanced to the point where the extra byte or end-identifier is expected to appear.

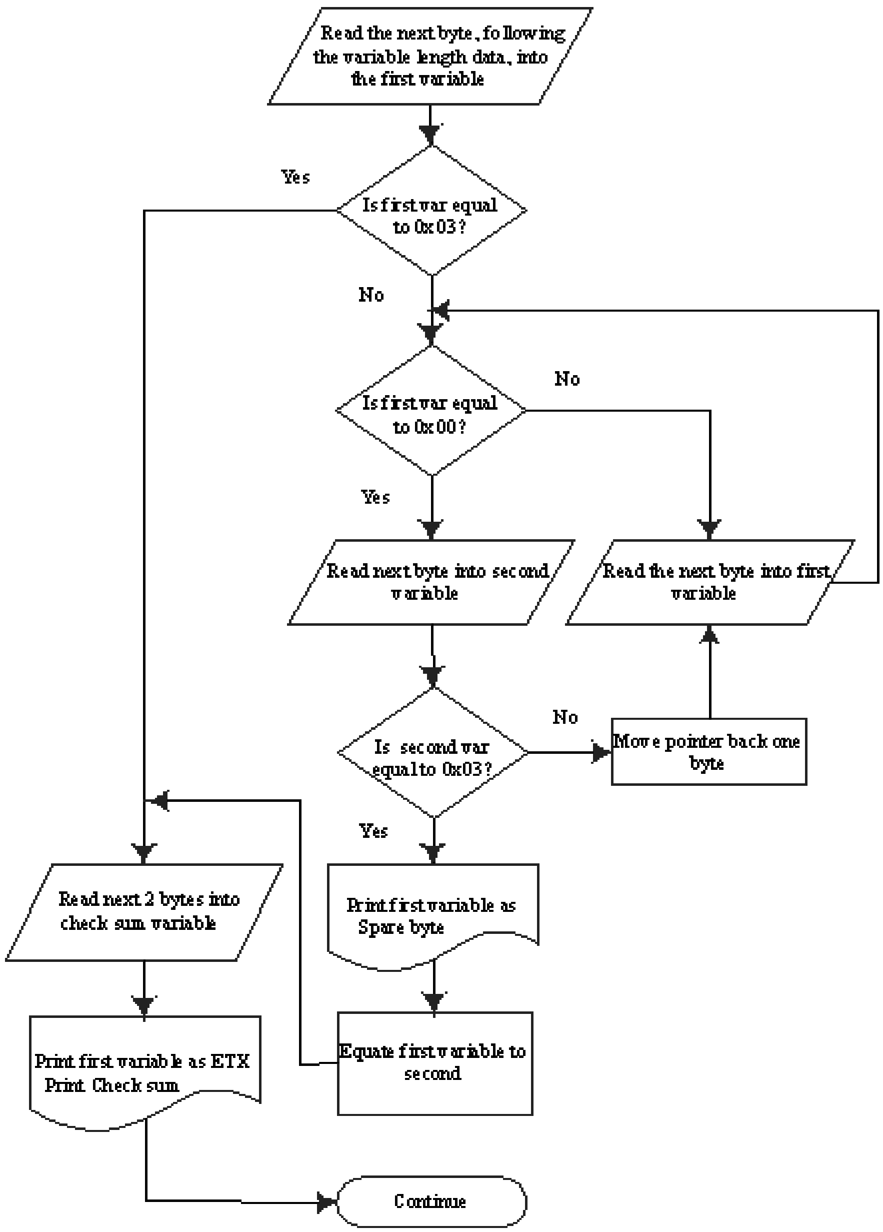


Figure 3.5 - Flowchart of End-datagram-finding Algorithm

Due to the ASCII embellishment of the raw data, the *Interp* program output can be very large, i.e. from a minimum of half of the size of the original telegram up to five times the original telegram depending on the flags set by the user. This program is particularly useful for reviewing the input parameters and sound speed profiles that were used during a survey. It can also be used to track any specific parameter used in the EM 3000's calculations.

3.3.2 The "*Raw_sidescan*" Program

This program creates a bitmap of the amplitude backscatter information which is extracted from EM 3000 telegrams. The bitmap can displayed by any application capable of importing raw (8 bit) bitmaps. Once the backscatter information is displayed, conclusions can be drawn as to the effectiveness (or appropriateness) of using EM 3000 amplitude backscatter information for the purpose of mine detection (see § 3.3.3). Before the conclusions are presented, the program itself is discussed. A listing of the program is located in Appendix IV.

3.3.2.1 *Raw_sidescan* Discussed

Raw_sidescan, like *Interp*, must identify datagrams within an EM 3000 telegram and read the data contain therein. Unlike *Interp* however, *Raw_sidescan* is only concerned with the depth and seabed image datagrams; therefore, any datagrams which are not of these two types are skipped. Although *Raw_sidescan* can display the extracted data in a textual format this is not its primary purpose. Rather, it is to create a bitmap (8 bit) of the amplitude backscatter intensities. The following sections discuss the algorithms used in *Raw_sidescan*; the reader is directed to the comments in the program listing itself for more specific information on variables.

3.3.2.1.1 *main( )*

The first call is the *get_files()* function (see §3.3.2.1.2) in order to set the input and output files as well as set the flag which can enable text output of the backscatter values. Following the *get_files()* call, the horizontal pixel width of the bitmap is set. This value is currently set at 1024, but may be modified and the program re-compiled if it is so desired. The *get_next_datagram()* (see § 3.3.2.1.3) function is then called in order to advance the input file pointer to the next valid datagram header. Next, the datagram type is read and the program acts on one of two choices: Depth datagram or Seabed Image Datagram. All other datagrams are ignored.

When the sonar unit transmits and receives a pulse, two types of information are collected, depth (bathymetry) and seabed image data (amplitude backscatter). The Depth datagram for a specific ping always precedes the Seabed image datagram for the same specific ping within the EM 3000 telegram. This order of precedence is important in the functioning of this program for two reasons. First, a maximum water depth of the ping area is calculated by *Raw_sidescan* (current depth + 20 percent) in order to scale the bitmap properly such that all the information is displayed within the chosen bitmap pixel width. The function is insensitive to depth outliers should they occur (see § 3.3.2.1.4). Should the depth of one ping be greater than the than current maximum depth, a new maximum depth is set (new depth + 20 per cent).

The second reason why the order of precedence is important is that the time (in milliseconds since midnight) of the current depth datagram is compared to the current seabed image datagram time. If the seabed datagram time does not match the depth datagram time then the entire ping is dropped. A ping may also be dropped if the number of valid beams exceeds the EM 3000 maximum (127). If any ping-drops occur their number is indicated in the file statistical summary screen output at the end of execution. One or two ping-drops per 500 pings is not uncommon.

Keeping the paragraph above in mind, the only other event that occurs while a depth datagram is being read is the call to *get_depth_data()* (see §3.3.2.1.4). This call is made in order to populate the *depth_attributes* data structure. The *depth_attributes* data structure contains more information than is required by the program. This has been done so that the program may be modified to provide positional information should it be desired in the future.

If the current datagram is a Seabed image datagram, the time and valid beam checks are performed and then the function *get_image_data()* (see § 3.3.2.1.4) is called in order to populate the *beam_attributes* data structure and the *beam_samples* array. Once the required data has been read, the Seabed image data may be written to text file if that option has previously been selected through the *write_to_file()* function. This function is similar to the datagram functions in *Interp* and will not be discussed. The final two functions which create the associated bitmap line for each Seabed Image data line are then called in turn, these being *create_raw_swath()* (see § 3.3.2.1.5) and *create_bit_map* (see § 3.3.2.1.6). The *main()* function continues reading subsequent depth and seabed datagrams until the end of the input file is reached.

3.3.2.1.2 get_files()

This function is used to open the input EM 3000 telegram, open the text output file (if required) and open the bitmap output file. The user may enter the file specifications on the command line in the format: *Raw_sidescan [input filename] [image output filename] [text output filename]* . If only one optional field is present the program assumes this field to be the *input filename* field. Furthermore, the *image output filename* field is assigned the input filename with ".ss_image" appended, and text output is automatically disabled. If a second optional field is present, then it is assigned as the *image output filename*, but again the text output is automatically disabled. If no command line arguments are entered the program will prompt the user for the required information. This function returns an integer value which is a flag for text file output.

3.3.2.1.3 get_next_datagram()

This function searches the EM 3000 file for the next valid datagram header. This is accomplished by looking for a unsigned char equal to 2 (hex) followed by an unsigned short integer of value 3000. If the *end-of-file* is reached, the function will terminate the program after printing the summary of accumulated statistics. If a valid header is found the input file pointer is moved to the datagram-type value of the header which will be read in the *main()* function.

3.3.2.1.4 Depth and Image Retrieval Functions

The *get_depth_data()* function and the *get_image_data()* functions are very much alike. They are based on the EM 3000 Technical Note [Hammerstad, 1996] located in Appendix I. Both of these functions read through the depth and seabed image datagrams in order to extract the data required to populate the *depth_attributes* and *beam_attributes* data structures respectively. The *get_image_data()* function also populates the array which contains the actual amplitude backscatter values for one transmit/receive cycle. The *get_depth_data()* function returns an integer value equal to the maximum depth sounding of all the valid beams. It is insensitive to depth outliers through a comparison of the maximum depth with the average depth for the entire swath. If the maximum depth is grater then 1.5 times the average, then the maximum depth is assumed to be an outlier and the average depth is returned in stead.

3.3.2.1.5 create_raw_swath()

This function is responsible for creating a variable length array containing the instantaneous amplitude backscatter information collected in one transmit/receive cycle. The array is variable in length due to its dependancy on the depth of water i.e. the greater the depth, the wider the coverage (in distance) and hence the more information which has been recorded. It is not until the *create_bit_map()* function has been called, that the array can be normalized into the selected bitmap pixel width.

The EM 3000 collects the (amplitude) backscatter samples as discrete 8 bit numbers, and sorts them from nearest to nadir to furthest, or vice versa, within each beam. Each footprint may have 1 to 2^{16} samples (~200 is the norm) of amplitude backscatter. The sorting direction is one of the values contained within the *beam_attributes* structure. Before the function creates the variable length array, the backscatter amplitude samples are sorted left to right, from beam 1 to beam 127 and the centre beam is identified. The centre beam is located by the point where the across track distance variable (in the *depth_attributes* structure) changes from negative to positive. Figure 3.6 illustrates the reference axes and sorting directions.

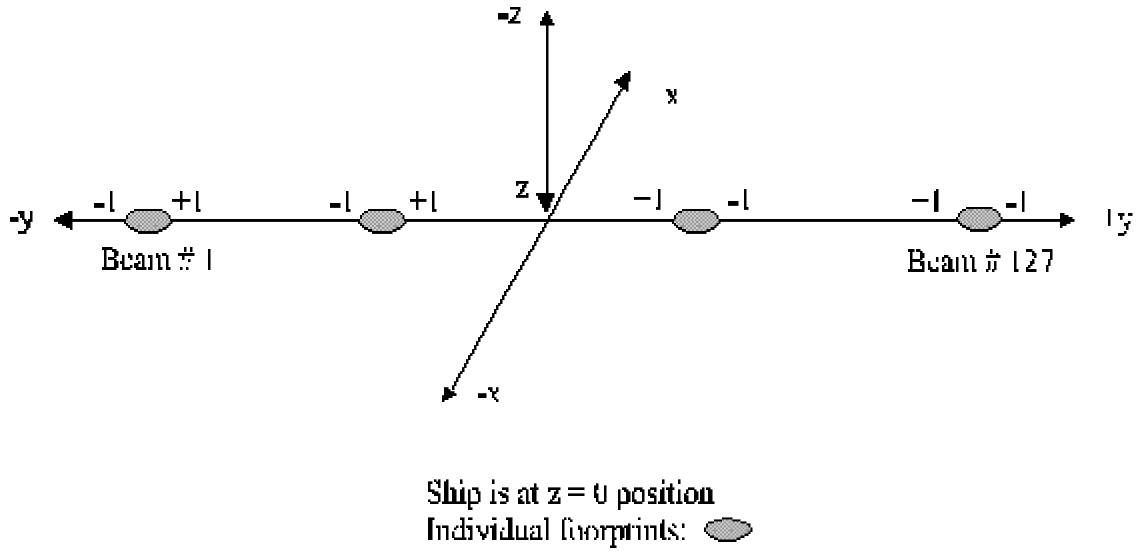


Figure 3.6 - Sonar Reference Axes and Backscatter Samples Sorting Directions

After all of the backscatter samples have been properly sorted, the next algorithm creates an array of backscatter values whose length is determined by the overall swath width of the particular transmit/receive data currently being processed. Therefore, the deeper the water, the greater the swath width (in distance units), and hence the larger the backscatter array. The array size is equal to the total swath width on the sea floor (in distance units) converted to pixels. The pixel width of each beam within each swath, is the horizontal across track dimension of each beam (m) divided by the spatial resolution (pixel/m) of the backscatter samples (Figure 3.7). The slant range resolution of the samples is derived from the Depth datagram and is equal to the Sound Speed (m/s) divided by the Receive Range Resolution (= 1/4 of the Sampling Rate (1/s) [Hammerstad, 1996]).

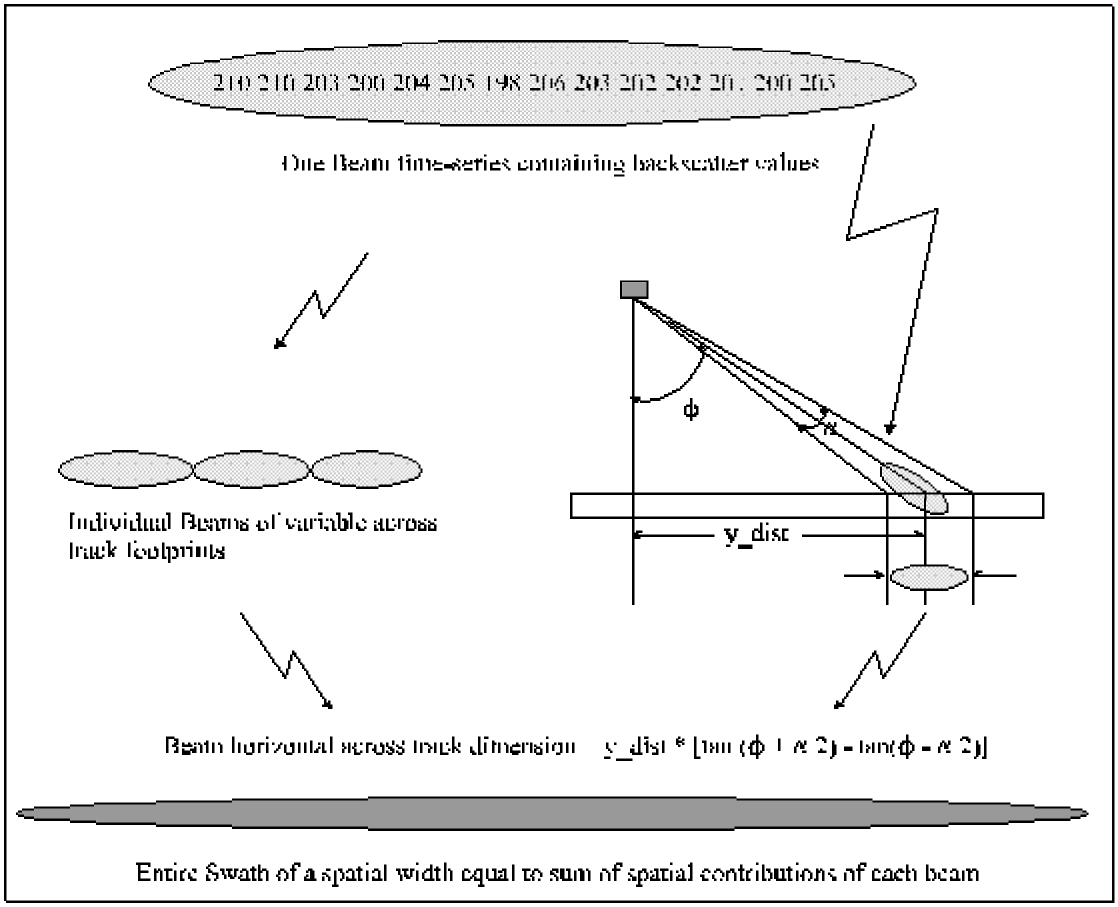
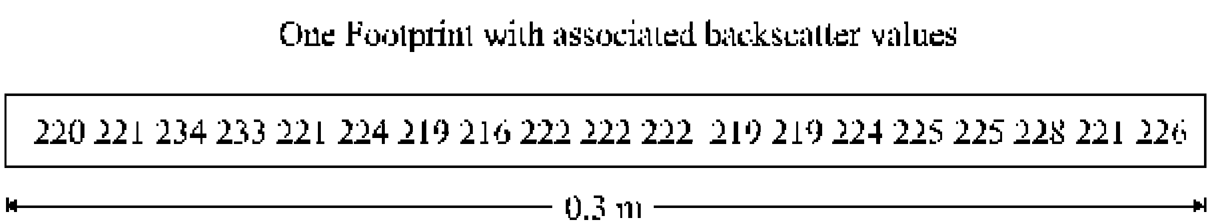


Figure 3.7 - Beam Horizontal Distance

One problem which was initially encountered during programming was that, in most cases, a non-integer amount of samples had to be averaged into a single discrete pixel value. Figure 3.8 shows the difficulty associated with this method. In this specific example, 2.7 backscatter values must be averaged into one pixel value. Using integer math, what really happens is only 2 values are used for each pixel. When the footprint is completely converted into pixels, only 14 of the original 19 backscatter values have been used which is a loss of almost 25 per cent of the original information.



Footprint size = 0.3 m

Resolution = 0.04 m/pixel

Total pixels = 0.3 / 0.04

= 7.5

Pixels allocated = 7

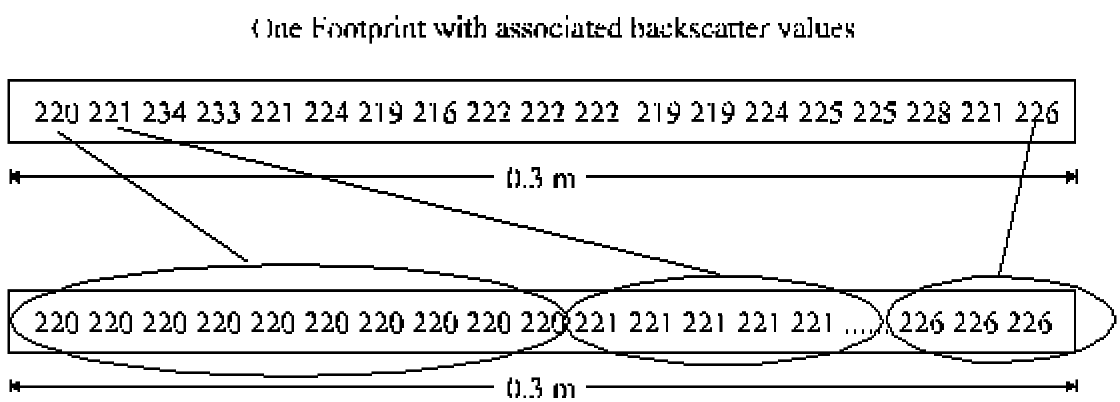
Total samples = 19

Samples per pixel = 19/7

= 2.71

Figure 3.8 - Footprint Samples

In order to alleviate the large loss of backscatter values due to integer math, the backscatter values are *stretched* (Figure 3.9) by a factor of 10 and the pixel calculations are performed once again. In this case 27.1 values are to be averaged in each pixel of which only 27 are used due to integer math. Once all 7 pixels are calculated only 1 backscatter value has been dropped which represents 1/2 of 1 per cent. There are some cases, especially in the near nadir regions, where there are more pixels than samples. In this case, the integer math does not drop any values. Upon completion, the function returns an integer value equal to the size (pixels) of the new array.



Footprint size = 0.3 m

Resolution = 0.04 m/pixel

Total pixels = 0.3 / 0.04

= 7.5

Pixels allocated = 7

Total samples = **190**

Samples per pixel = **190**/7

= **27.1**

Figure 3.9 - Stretching of Backscatter Values

3.3.2.1.6 create_bit_map()

This function takes the variable size array created in the previous function and fits it into the user specified bit map pixel width (set in *main()* see § 3.3.2.1.1). The method used to perform this formatting is the same type of stretch algorithm as used in *create_raw_swath()* except for the fact that the new array length (total pixels) is constant. Once the formatting has occurred, the fixed-width array is written to the image output file. Control is then returned to the *main()* function where the entire process is repeated until the end of the file is reached.

3.3.3 Using Amplitude Backscatter for Mine Detection

Using the *Raw_sidescan* program, the amplitude backscatter information may be displayed for any EM 3000 survey line (telegram). *Raw_sidescan* was used to display the backscatter imagery from the January 1997 survey data set. For this survey, a Mk 82 bomb(0.274 m x 1.67 m) was placed at 12 m and 22 m and was ensonified over multiple passes. As well, a Mk 83 bomb (0.38 m x 2.28 m) was laid at 30 m and was ensonified over multiple passes. The reader is referred to Hughes-Clarke et al. [1997] which gives an overview of the survey and the data obtained. It is important to note that the aim of this survey was to keep the mines in the near nadir regions. This section examines the results of the *Raw_sidescan* program used on this data set. Mine detection is performed visually and through the digital image analysis tool Xpace.

3.3.3.1 Visual Detection of Mines using Amplitude Backscatter

Figure 3.10 is the output from *Raw_sidescan* of line 0058. The mine is known to be in the location inside the superimposed box. Visual inspection of this area is inconclusive; there is no distinct object indicated by a contrast in backscatter values. Even when magnified, there is nothing unique which would identify the mine. Other examples of the January 1997 backscatter amplitude imagery and magnifications of the mine areas are located in Appendix V.

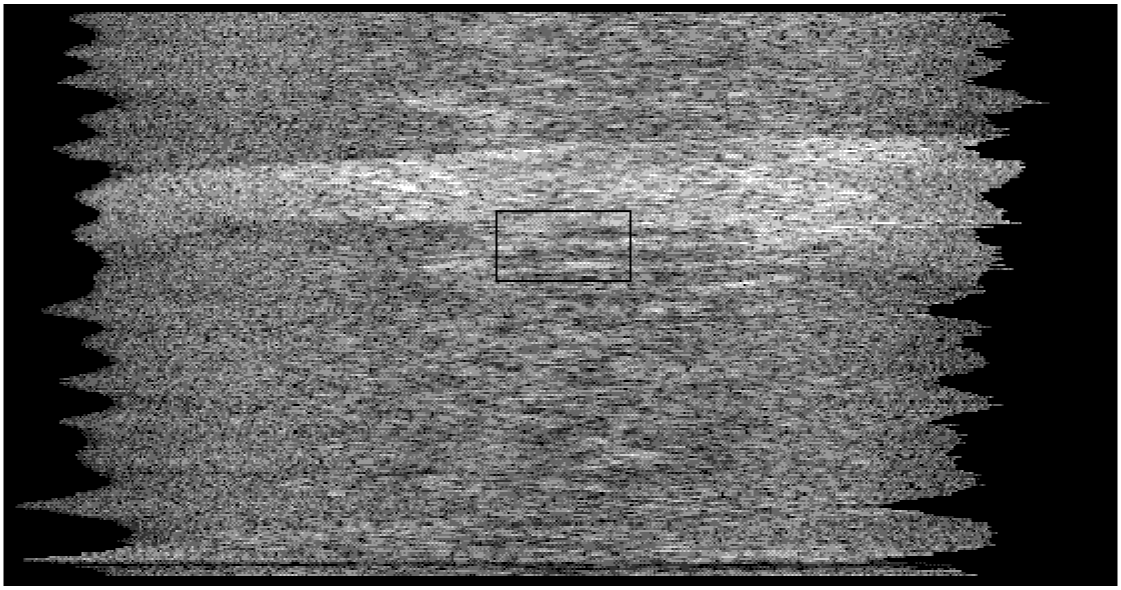


Figure 3.10 - Line 58 Backscatter Amplitude Image

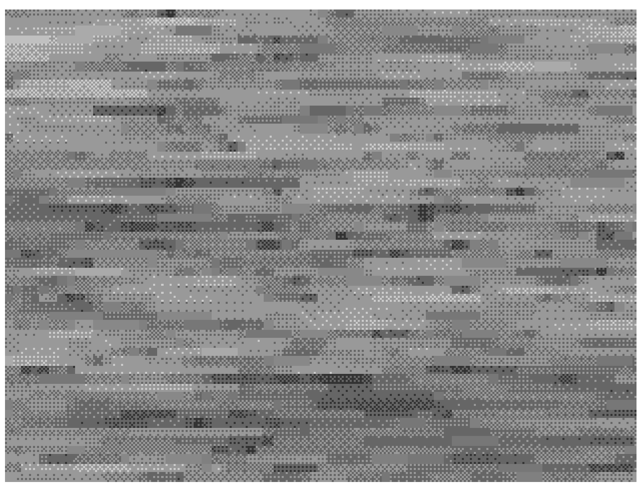


Figure 3.11 - Mine area Magnified

3.3.3.2 Xpace Analysis of Imagery

Xpace is a Digital Image Analysis tool made by PCI of Richmond Hill, On. [1995] It is primarily intended for use on digital images such as satellite multi-spectral and radar imagery. It does however have the capability to import raw images such as the backscatter amplitude imagery produced by *Raw_sidescan* in order to perform image enhancement and image classification. Xpace has several filters available for image analysis as well as the ability to perform image classification.

In view of the fact that a mine is a small object, only high pass filters were applied to the survey data in an attempt to identify the mine. Each high pass filter was applied to the image results of line 0058 from the January 1997 survey in an attempt to find the mine located in that data set. Listed below is a description of each filter that was applied to the image, a description of the results obtained and an image of those results. In each Figure the mine is in the centre of the box which is superimposed on the image.

Xpace allows for both supervised and unsupervised classification. As the lithology of the area surrounding the mine was unknown, training areas were not possible; therefore, the image was processed in the unsupervised classification mode. The classification method is described in § 3.3.3.2.5 and it is followed by the resultant images.

3.3.3.2.1 Laplacian Type I & II

The Laplacian edge detector generates sharp edge definition of an image. This filter can be used to highlight edges having both positive and negative brightness slopes [PCI, 1995]. The filter kernels used were 3 x 3 in size with their values shown below. The resultant images (Figure 3.12 and Figure 3.13) do not help identify the mine.

Type I

0	1	0
1	-4	1
0	1	0

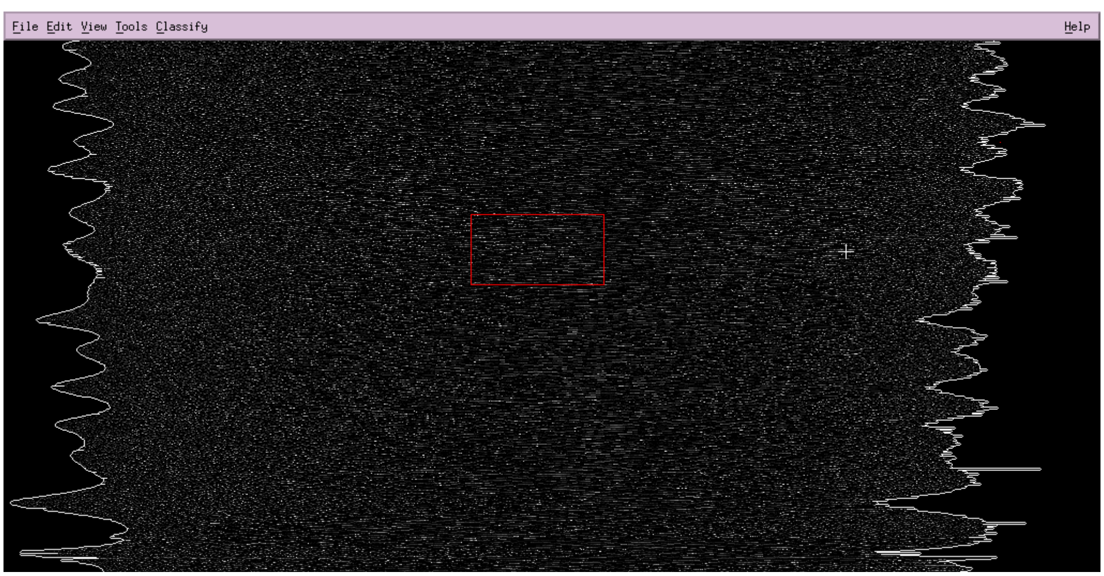


Figure 3.12 - Laplacian Type I Results

Type II

-1	-1	-1
-1	8	-1
-1	-1	-1

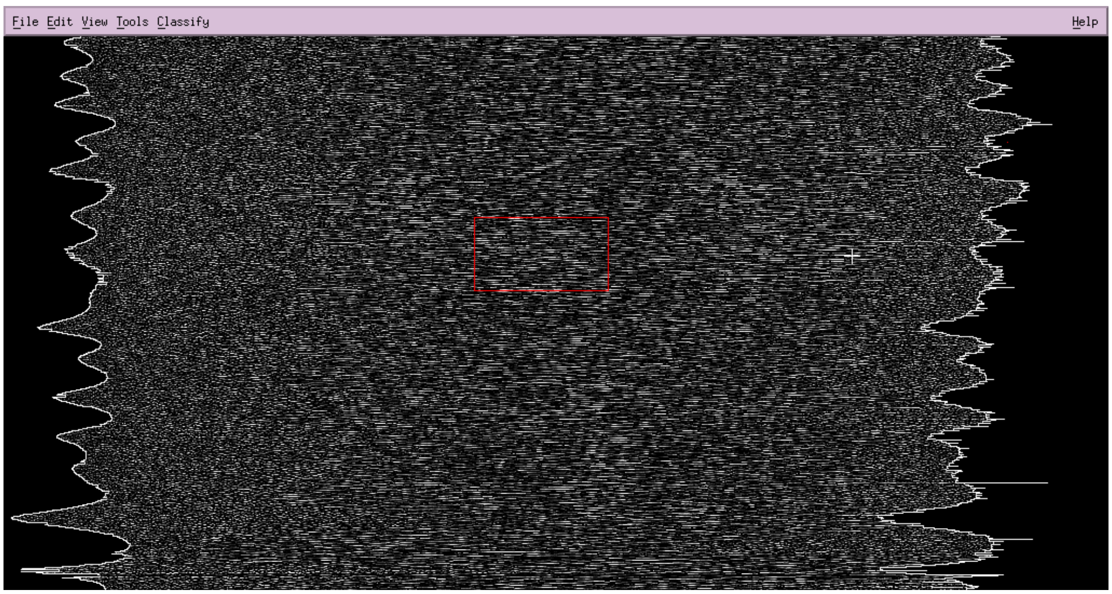


Figure 3.13 - Laplacian Type II Results

3.3.3.2.2 Sobel Edge Detector

This filter creates an image where edges (sharp changes in grey level values) are shown. This filter is only able to use a 3 x 3 kernel. This filter uses two 3 x 3 templates to calculate the Sobel gradient value as shown below [PCI, 1995]. The resultant image (Figure 3.14) does not help identify the mine.

Templates:

X

-1	0	1
1	2	1
-1	0	-1

Y

1	2	1
0	0	0
-1	-2	-1

Apply the templates to a 3 x 3 filter window.

a1 a2 a3

a4 a5 a6

a7 a8 a9

where a1 .. a9 are grey levels of each pixel in the filter window.

X = -1*a1 + 1*a3 - 2*a4 + 2*a6 - 1*a7 + 1*a9

Y = 1*a1 + 2*a2 + 1*a3 - 1*a7 - 2*a8 - 1*a9

Sobel Gradient = sqrt(X*X + Y*Y)

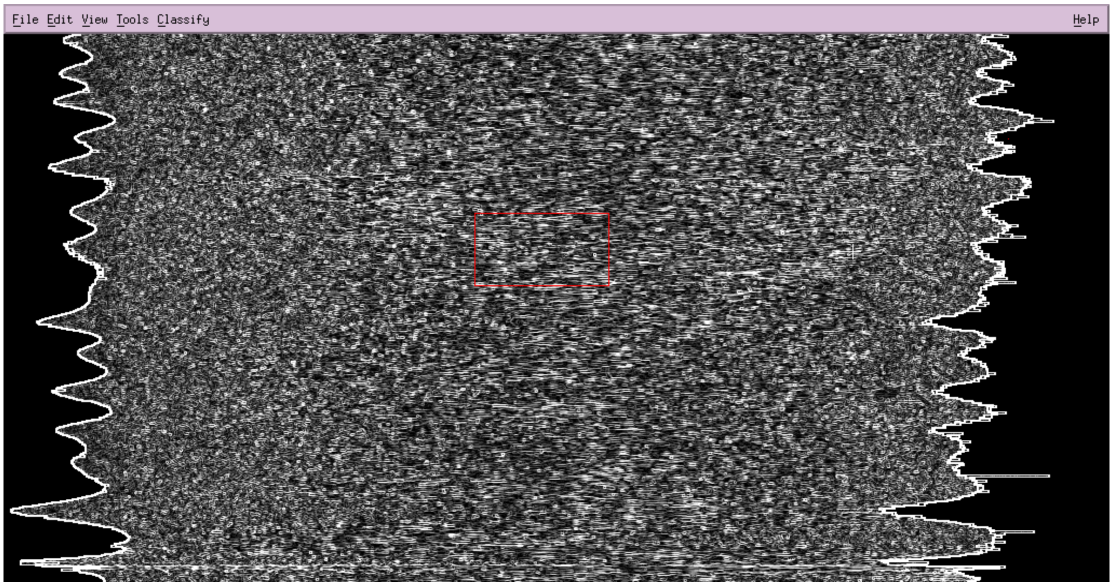


Figure 3.14 - Sobel Edge Detector Results

3.3.3.2.3 Prewitt Edge Detector

Like the Sobel Edge detector, this filter creates an image where edges are highlighted. This filter uses two 3 x 3 templates to calculate the Prewitt gradient value. The calculation method is the same as the Sobel Edge Detector with the specific values as listed below [PCI, 1995]. The resultant image (Figure 3.15) does not help identify the mine.

Templates:

X

-1	0	1
-1	0	1
-1	0	1

Y

1	1	1
0	0	0
-1	-1	-1

Apply the templates to a 3x3 filter window.

X = -1*a1 + 1*a3 - 1*a4 + 1*a6 - 1*a7 + 1*a9

Y = 1*a1 + 1*a2 + 1*a3 - 1*a7 - 1*a8 - 1*a9

Prewitt Gradient = sqrt(X*X + Y*Y)

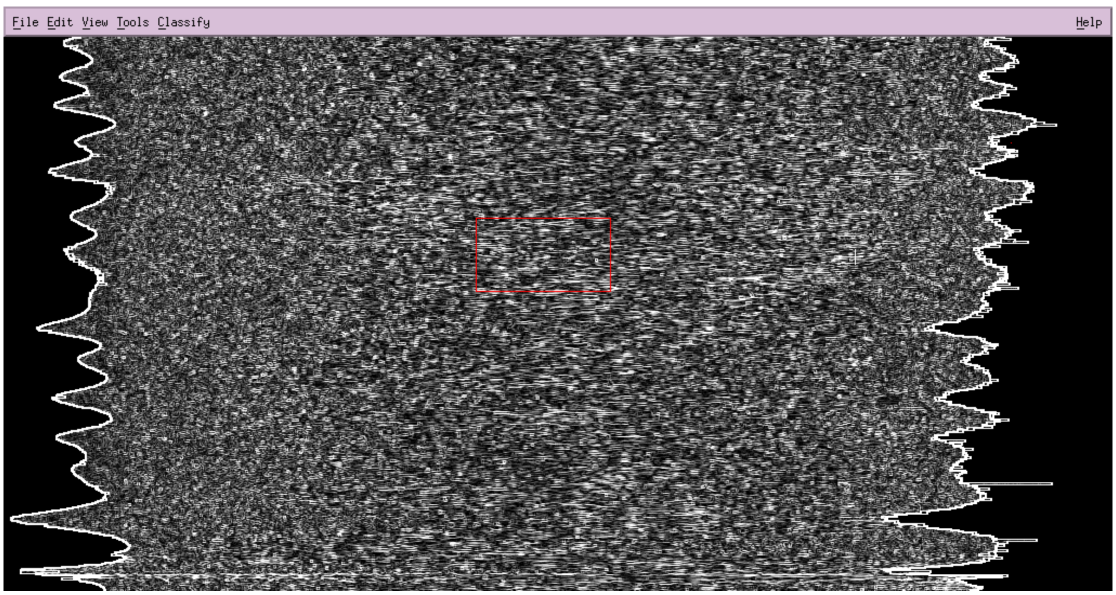


Figure 3.15 - Prewitt Edge Detector Results

3.3.3.2.4 Edge Sharpening Filter

This filter uses a subtractive smoothing method to sharpen an image and is applied in the following manner. First the image is smoothed using an averaging filter. The resultant image is then subtracted from the original image giving an image which highlights high frequency information. Finally this high frequency enhanced image is added to the original image to give an edge sharpened resultant image. The final image is noisier than the original [PCI, 1995]. The resultant image (Figure 3.16) does not help identify the mine.

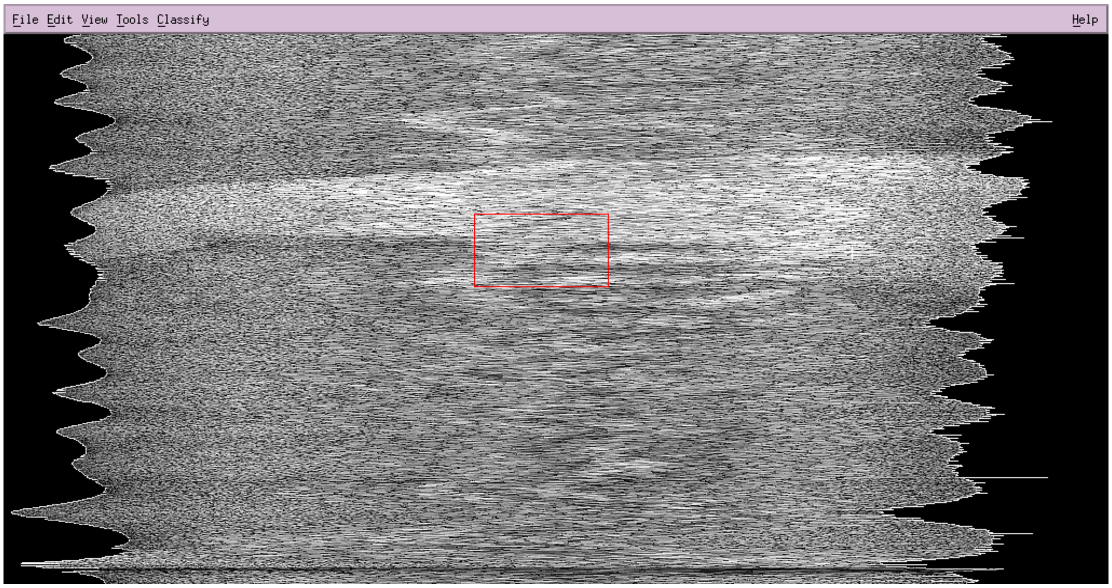


Figure 3.16 - Edge Sharpening Filter Results

3.3.3.2.5 Unsupervised Image Classification

Unsupervised classification was performed on line 0058 using a K-Means algorithm. The K-Means is a Minimum-distance-to-means classifier where K is the user specified number of classes. In this classification method, the algorithm attempts to cluster pixels of similar intensities together into the specified number of classes. Each class will have a mean pixel value, and through an iterative process, the mean value migrates to a final value [Lillesand and Kiefer, 1994]. In using this classifier on line 0058, two different K values were used, both with 20 iterations. Neither Figure 3.17 (K = 5) nor Figure 3.18 (K = 10) succeed in isolating the mine.

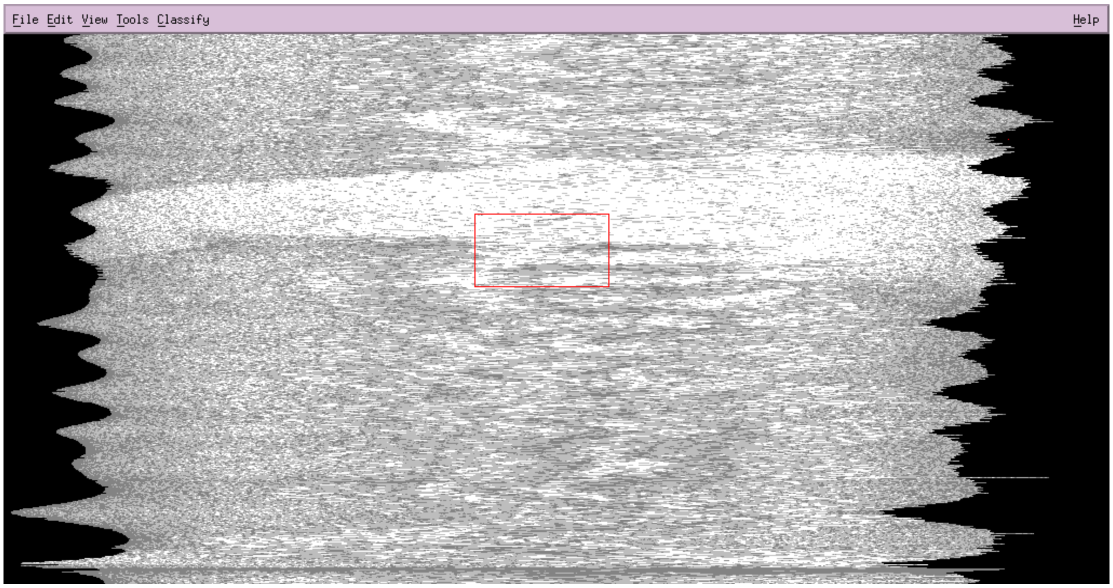


Figure 3.17 - K-Means Classification (K = 5)

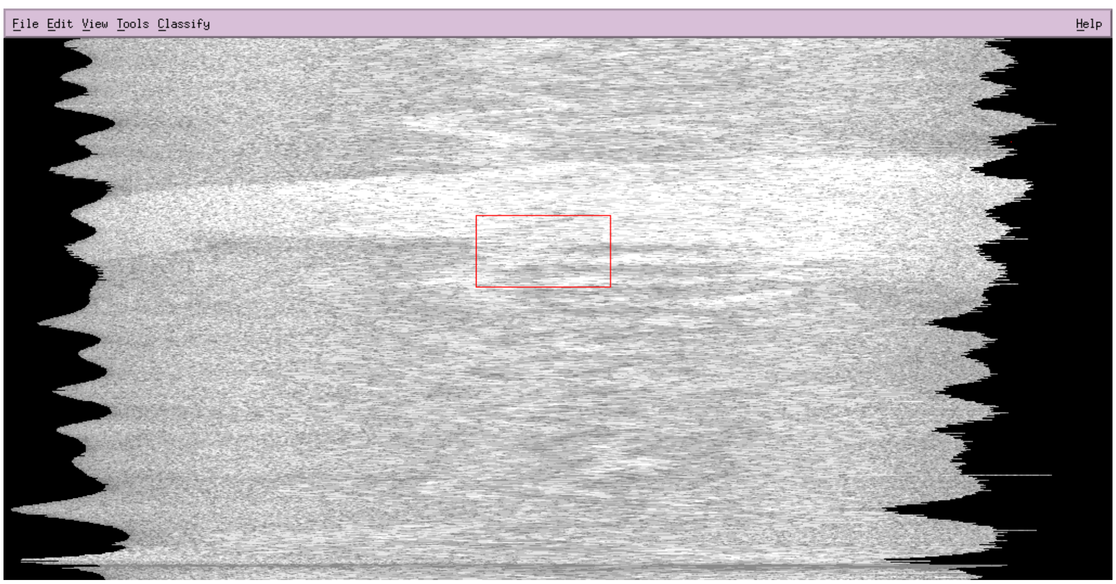


Figure 3.18 - K-Means Classification (K = 10)

3.3.3.3 Summary of Results

Side scan sonars are used for object detection for a number of reasons, however the most predominant is that of aspect ratio. Object finding side scan sonars are towed close to the sea floor in order to achieve small grazing angles with the sea floor. This results in high backscatter intensities on the transducer side of the object, and little or no return (shadows) on the far side of the object. This contrast in the side scan sonar imagery facilitates object detection.

The EM 3000 sonar used in the January 1997 survey was hull-mounted and the aim of the survey was to place the survey launch directly over the mine. The end result of this survey was very high grazing angles over the mine which resulted in little or no shadows being cast. This is the most probable reason why the mine was not located using amplitude backscatter information.

Some objects have reverberation levels which are very different than the sea floor on which they lay. The resultant amplitude backscatter contrast can be used for object identification. In the January 1997 survey, it appears as though the object and sea floor reverberation levels were similar. This factor also led to the mine not being detected in the side scan images.

3.3.4 MBS Spatial Resolution

From the previous section it was concluded that the amplitude backscatter information from the January 1997 survey was not helpful in object detection. The EM 3000's <u>other</u> data product, bathymetry, is examined in § 3.3.6 in order to determine if this is can be used for object detection. Prior to studying the survey results, this section uses models to predict if the EM 3000 can detect the mines used in the January 1997 and June 1996 surveys. The program *synSwath* [Hughes-Clarke, 1997b] was used to generate the beams.

The models used are EM 3000 beam images with the mine outlines superimposed. Each image (Figures 3.19 - 3.22) contains two sets of modelled beams, 45 degrees either side of nadir (indicated by the black dots). The first set of beams contains four or five consecutive pings calculated for:

- the depth of the sea floor,
- the vessel speed, and
- the ping rate of the sonar

for each particular survey line indicated. This grouping is designed to give a indication of the actual coverage of the survey lines. The second set of beams is a single ping at the depth of the particular survey line. The second set is used as a reference to the individual beam sizes. The size of the mines relative to each beam is modelled and displayed as the white rectangle to the right of each set of groupings. Outlines of the mine sizes are overlayed onto the beam groupings. It should be noted that the beam calculations were made for flat seas i.e. no induced roll, pitch or heave.

3.3.4.1 Model: 11 metres

Figures 3.19a and 3.19b illustrate that the ping rate of the sonar was sufficient for 100 per cent ensonification in the mine area at two different speeds. The size of the (Mk 82 - 500 lb) mine outline versus the size of the beams indicates that between 7 and 11 beams and 1 to 6 ping cycles are required in order to cover the mine. Given the size differential, the EM 3000 should be able to indicate a depth anomaly equal to the mine elevation in the beams covering the mine.

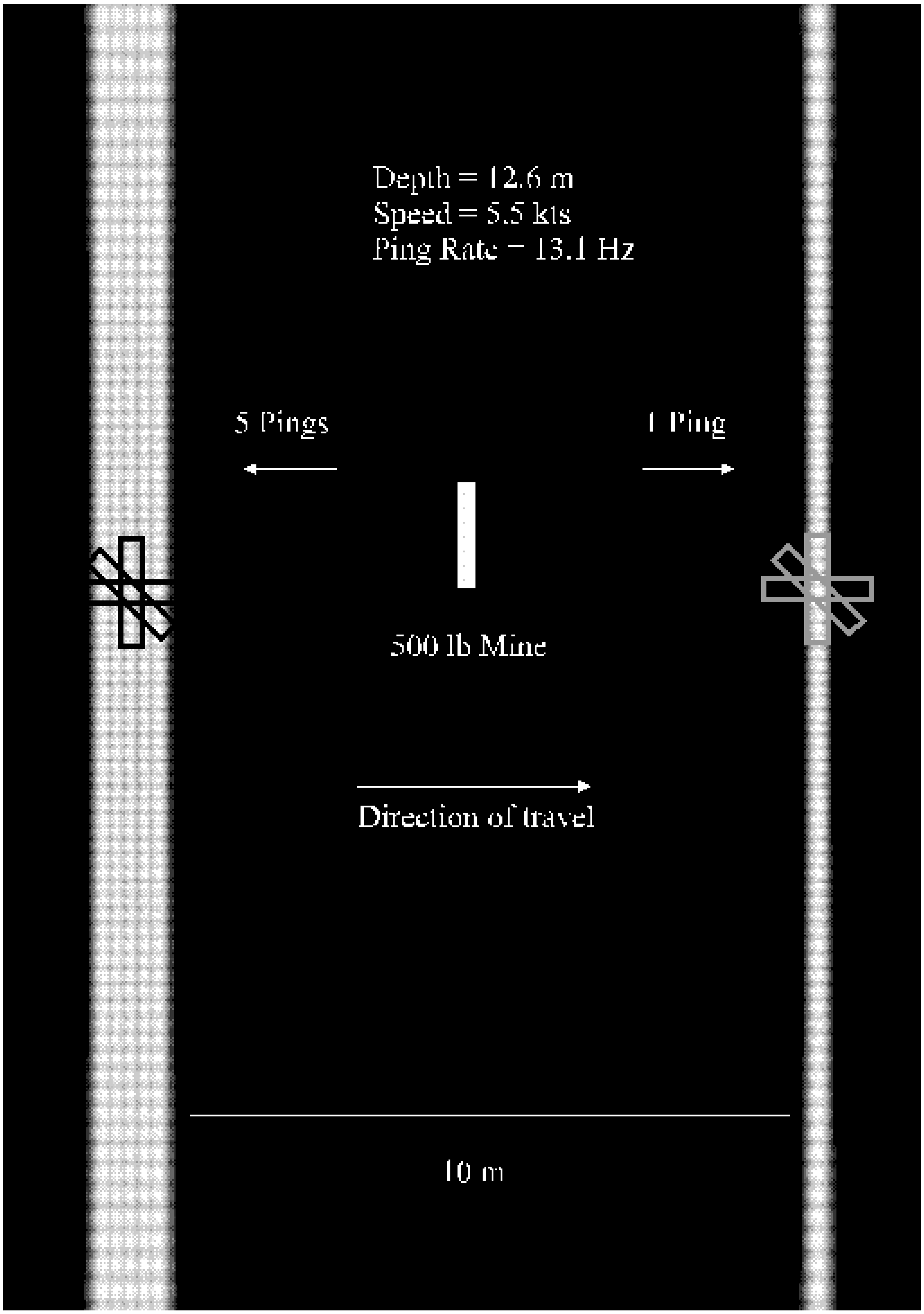


Figure 3.19a - Line 0058 Beam Model (no induced motion)

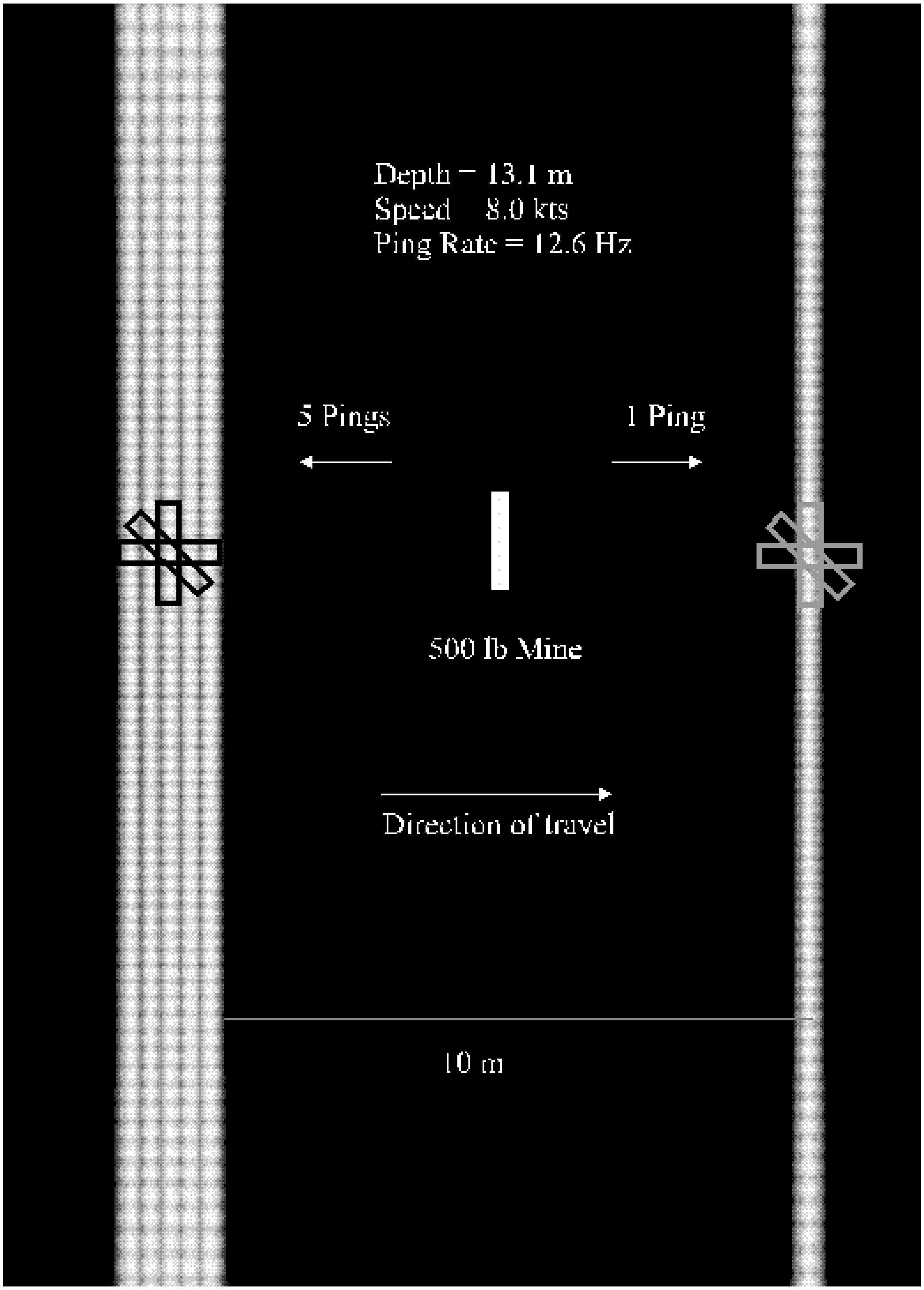


Figure 3.19b - Line 0066 Beam Model (no induced motion)

3.3.4.2 Model: 22 metres

Figures 3.20a and 3.20b illustrate that the ping rate of the sonar was sufficient for 100 per cent ensonification in the mine area at two different speeds. The size of the (Mk 82 - 500 lb) mine outline versus the size of the beams indicates that between 4 and 7 beams and 1 to 5 ping cycles are required in order to cover the mine. Given the size differential the EM 3000 should be able to indicate a depth anomaly equal to the mine elevation in the beams covering the mine.

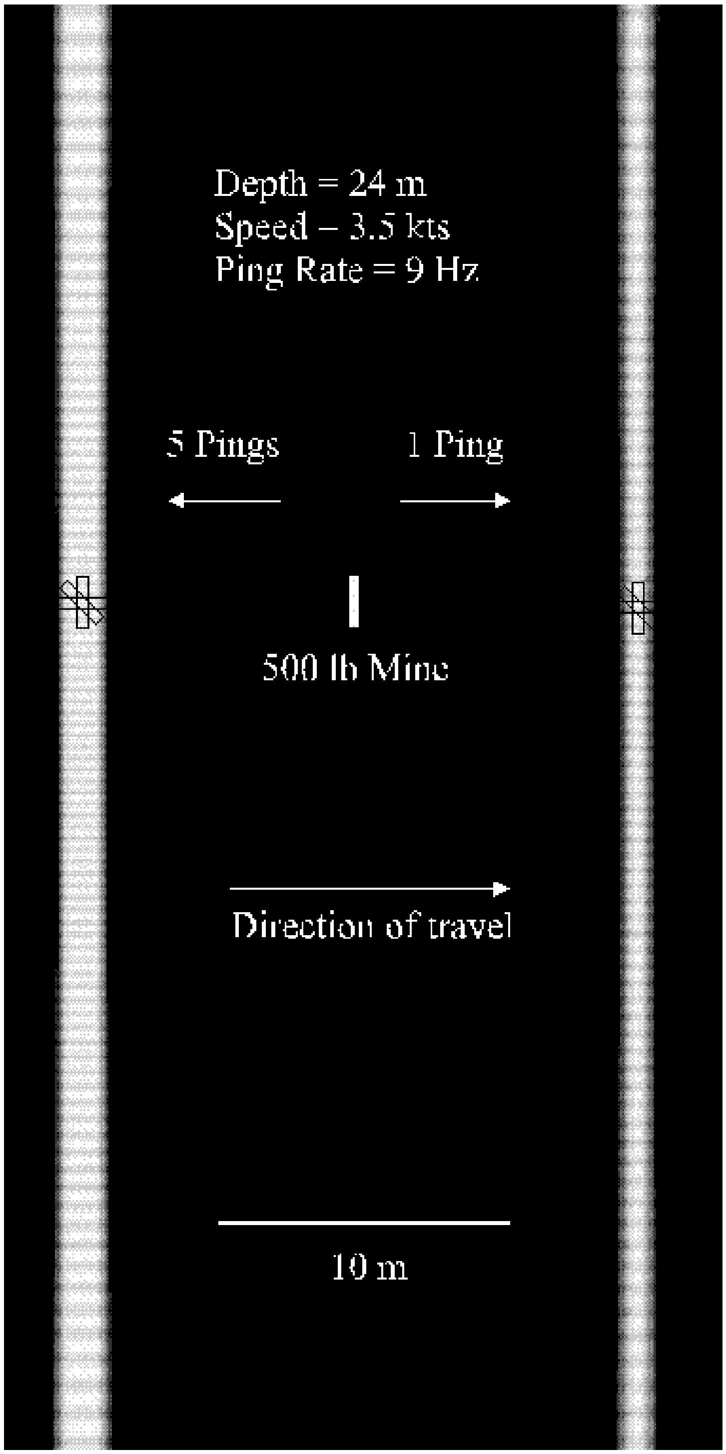


Figure 3.20a - Line 0005 Beam Model (no induced motion)

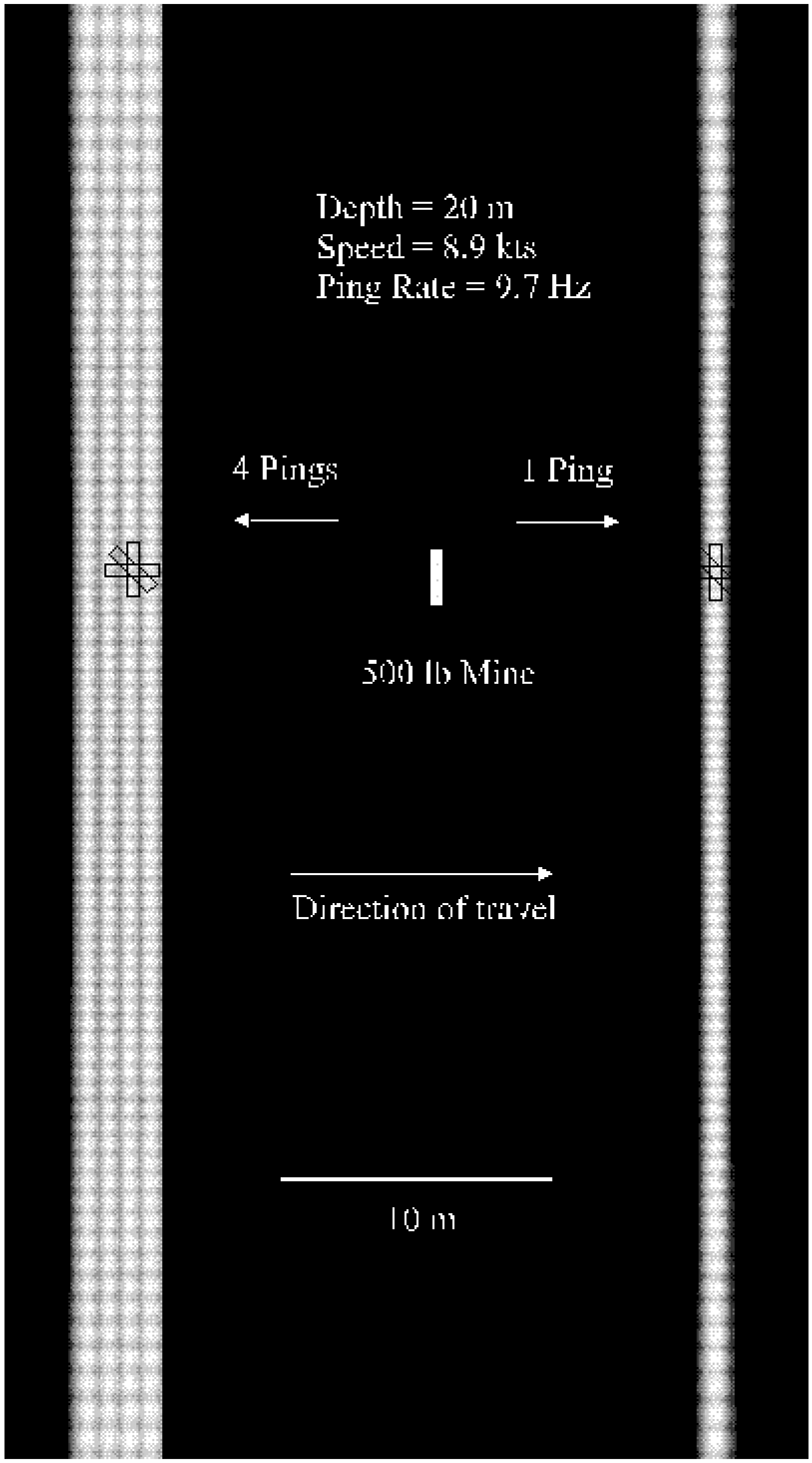


Figure 3.20b - Line 0023 Beam Model (no induced motion)

3.3.4.3 Model: 30 metres

Figures 3.21a and 3.21b illustrate that the ping rate of the sonar was sufficient for 100 per cent ensonification in the mine area. The size of the (Mk 83 - 1000 lb) mine outlines versus the size of the beams indicates that between 2 and 4 beams and 1 to 3 ping cycles are required in order to cover the mine. These survey lines are in deeper water than the previous models but the mine is larger (10 cm in height). Given the size differential the EM 3000 could indicate a depth anomaly equal to the mine elevation in the beams covering the mine.

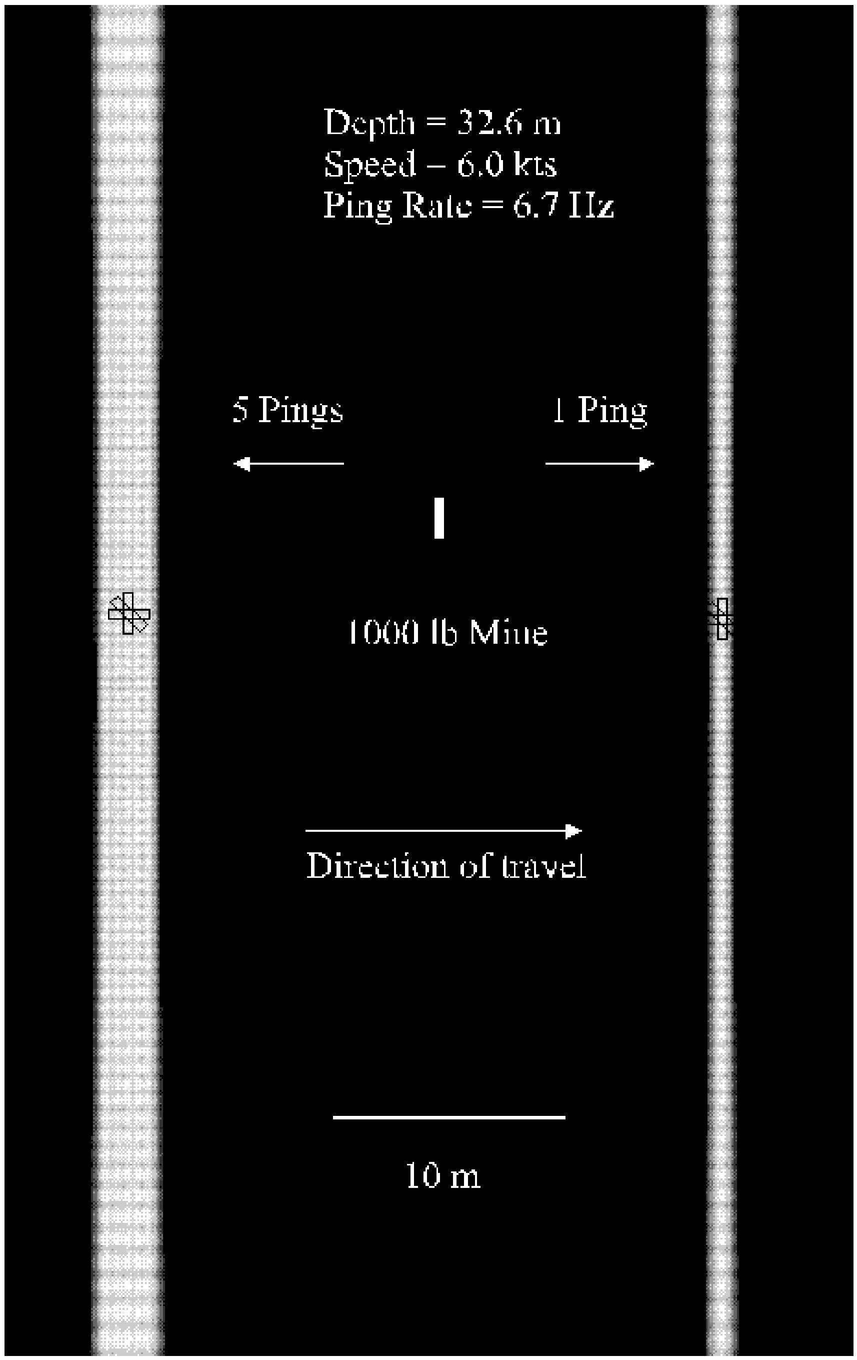


Figure 3.21a - Line 0047 Beam Model (no induced motion)

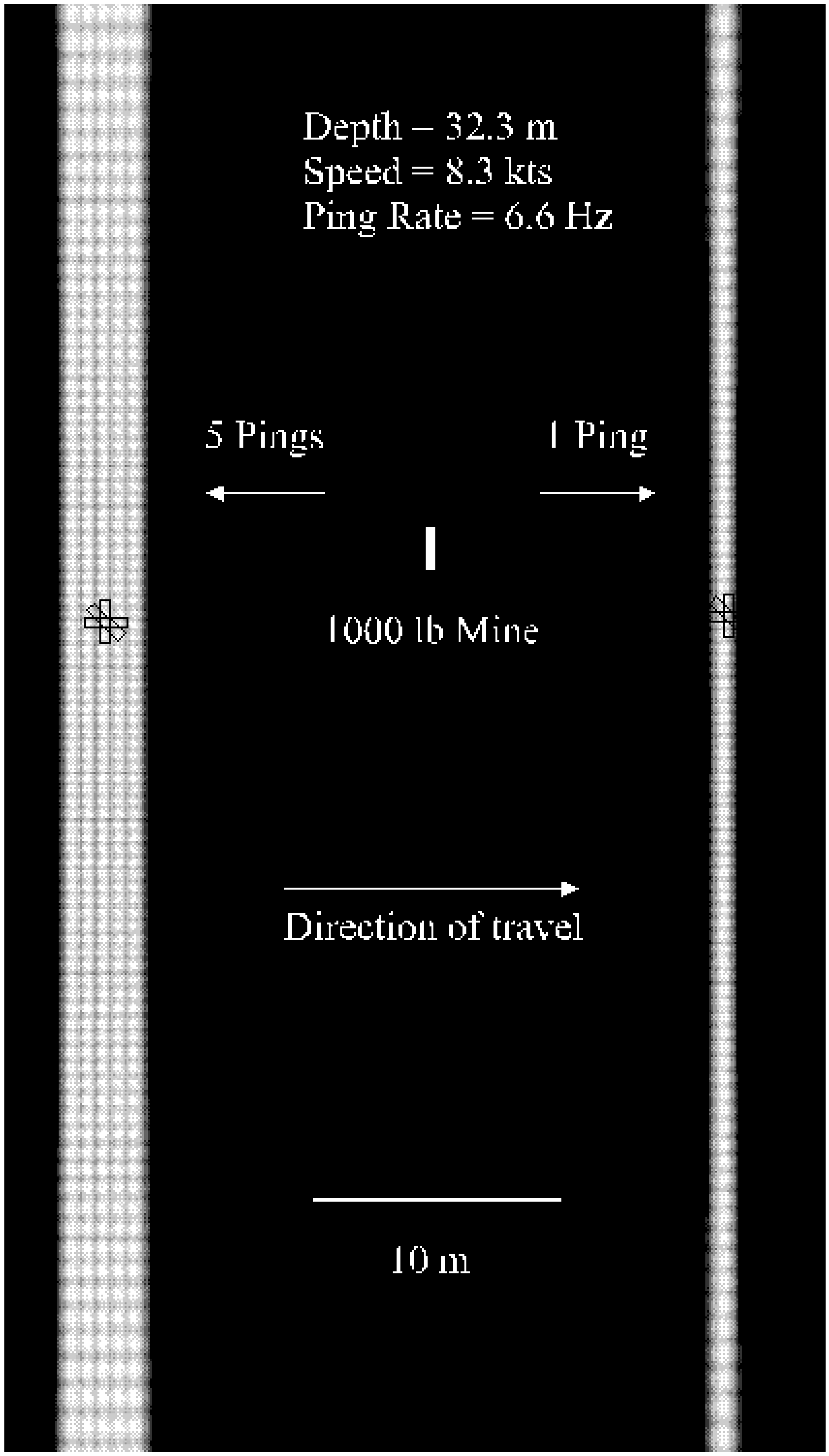


Figure 3.21b - Line 0049 Beam Model (no induced motion)

3.3.4.4 Model: 42 metres

Figures 3.22a and 3.22b illustrate that the ping rates of the sonar was not sufficient for 100 per cent ensonification in the mine area. The speed (11 kts) was too high for the ping rates automatically set by the operating software which has subsequently been updated. In this case the mine is the same size as a beam in the along track direction. However, only one third of the mine covers the same beam in the across track direction. The EM 3000 should indicate a depth anomaly equal to the mine elevation only if the mine lays in the across track direction (if the height discrimination is acute enough at this depth) and the mine does not fall into an area not ensonified by the sonar.

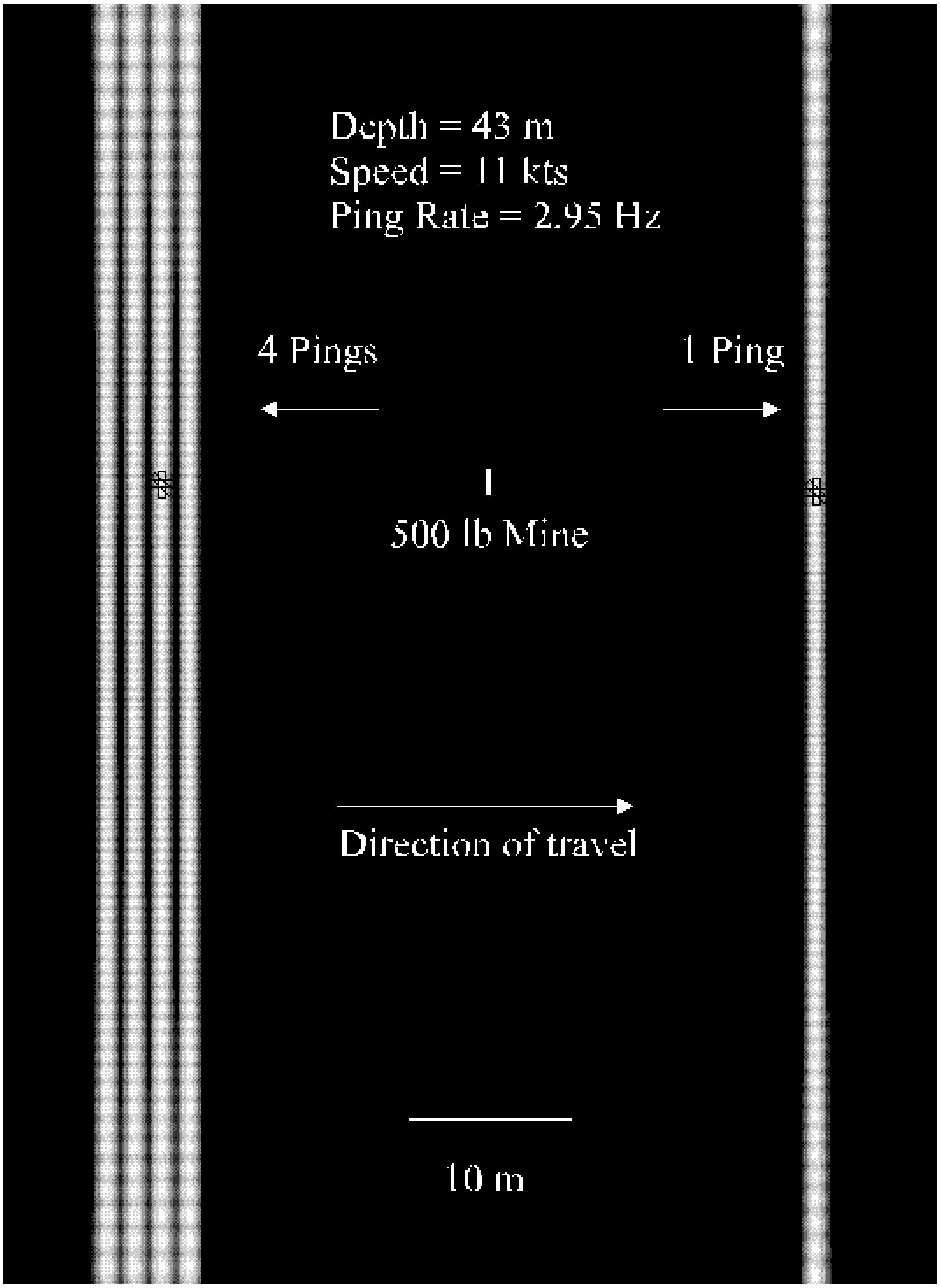


Figure 3.22a - Line 0002_211126 Beam Model (no induced motion)

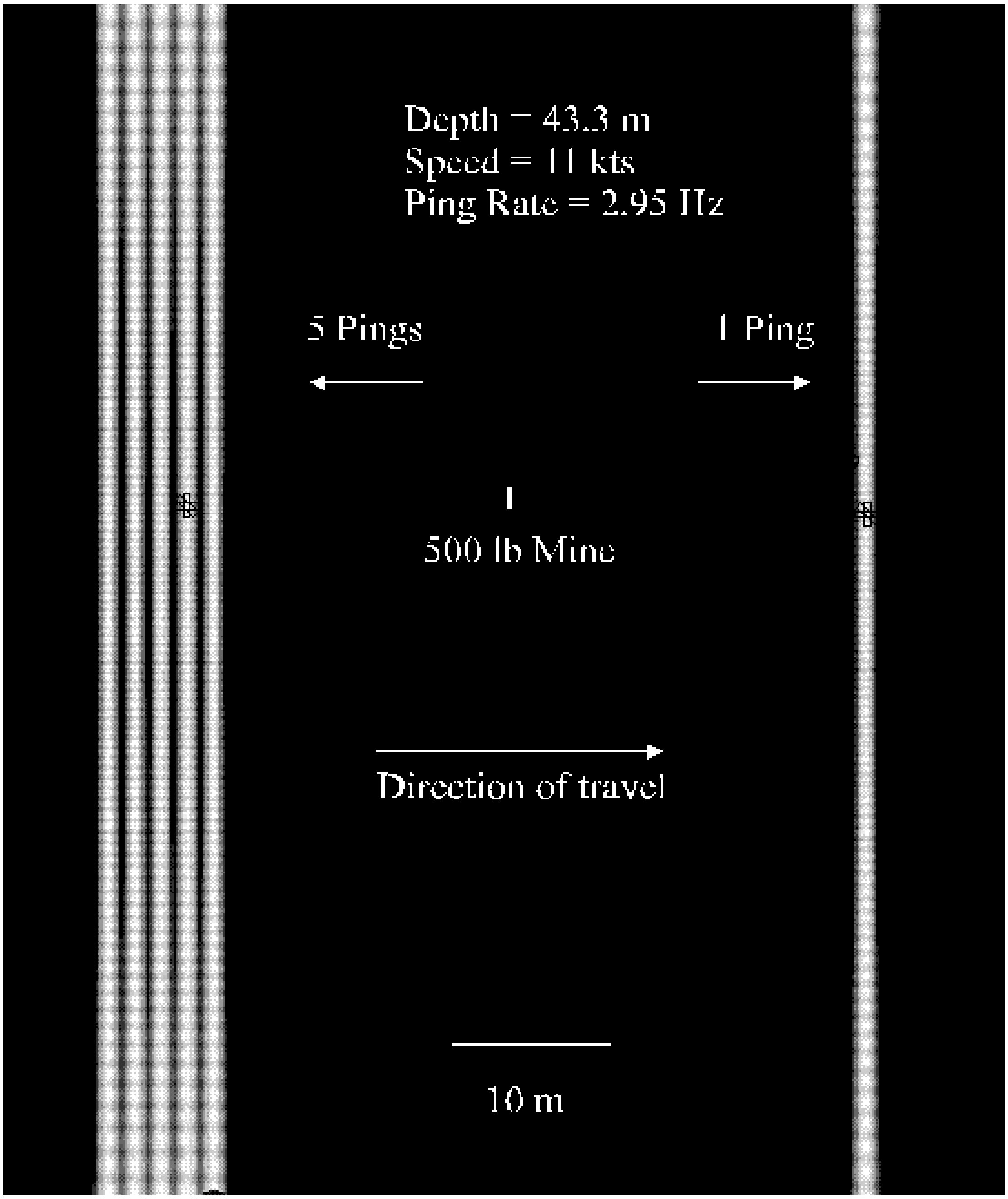


Figure 3.22b - Line 0003_180427 Beam Model (no induced motion)

3.3.5 The "*MLO_Find*" Program

Predictive modelling is performed in the previous section (§ 3.3.4), but before the actual results can be assessed the data must be extracted from the survey data sets and displayed. *MLO_Find* was written in order to generate an 8-bit bitmap which contains the bathymetric information derived from the EM 3000 telegrams in a sun-illuminated manner (see § 3.3.5.1.7). *MLO_Find* also performs an automated detection algorithm in order to flag any objects matching the dimensions of a user defined object. These results are also contained within the generated bitmap. The generated bitmap may be viewed on any application capable of importing raw bitmaps. Using *jview* [Hughes-Clarke, 1997a] with a predefined script, results in a cross being overlaid on the detected targets as a visual aid.

3.3.5.1 *MLO_Find* Discussed

MLO_Find is like the first two programs discussed in this chapter in that it must read raw EM 3000 telegrams to extract the data that it requires. *MLO_Find* only extracts the information contained in the depth output datagrams; all other datagrams are ignored. The image which is created is divided into three vertical windows, each 127 pixels wide. Windows One and Three are sun-illuminated bathymetry (see § 3.3.5.1.7) from the top of the screen and from the left-side of the screen respectively. Window Two shows the results of the automated detection algorithm.. In this section a pixel may have one of two values only, according to whether or not the pixel's corresponding beam contains an object (mine) whose dimensions are within the user defined values. The program is listed in Appendix VI and the *jview* script, as well as the output file which indicates the position of the mines within the bitmap are listed in Appendix VII. The algorithms used within the *MLO_Find* functions are discussed below. The reader is referred to the program listing for specific variable and structure information.

3.3.5.1.1 Global Variables

The *#define*'d global variables are set by the user prior to compiling the program and using it on the data set in question. MIN_HEIGHT, HEIGHT, and MAX_HEIGHT are the acceptable minimum, actual, and acceptable maximum heights (centimetres) of the object being sought. MAX_PIX_LENGTH is the maximum pixel length of an object that *mlo_find()* will 'detect". Any objects greater in length than MAX_PIX_LENGTH are assumed to be too large (i.e. a ridge) to be the object in question therefore, the user must have knowledge of the beam size at the particular depth of the current data set for particular grazing angles. A good rule-of-thumb (for a 1.5 degree beamwidth MBS) is 26 cm per pixel at nadir and 52 cm per pixel at 45 degrees for every 10 m of water. BACKGROUND and DISPLAY_VALUE are the 8 bit values for the pixels containing non-objects and objects respectively. The remaining *#define* 'd values are explained in § 3.3.5.1.6 and § 3.3.5.1.8.

3.3.5.1.2 *main()*

The first function to be called is the *get_files()* function which opens the input and output files which will be used in the program. Next, a while loop is used to find the next 20 depth datagrams and populate the depth[ ][ ] matrix. This matrix contains the depth values of each beam within 20 transmit/receive cycles. Once depth[ ] [ ] is fully populated, the result[ ][ ] matrix is cleared and the remaining functions are called in order to populate this matrix. Result[ ][ ] is the bitmap which is written to disk. The above sequence is repeated until the end of the input file is reached.

3.3.5.1.3 get_files()

This function is used to open the input EM 3000 telegram, to open the bitmap output file, and to open the (coordinate) file which will be used by *jview* to mark the object positions. The user may enter the file specifications on the command line in the format: *MLO_Find [input filename]*. If the command line option is used, the function automatically creates an image output file whose name begins with that of the input file name with ".mlo_image" concatenated onto it. As well, the function creates a coordinates output file whose name begins with that of the input file name with "coord_out" concatenated onto it. If no command line argument is entered the program will prompt the user for the required information.

3.3.5.1.4 get_next_datagram()

This function searches the EM 3000 file for the next valid datagram. This is accomplished by looking for a unsigned char equal to 2 (hex) followed by an unsigned short integer of value 3000. If the end-of-file is reached, the function will terminate the program after printing the summary of accumulated statistics and closing the input and output files. If a valid header is found the input file pointer is moved to the datagram type value of the header which will be read in the *main()* function.

3.3.5.1.5 get_depth_data()

For the current datagram, this function receives the number of valid beams, a pointer to depth matrix, and the current row (1 to 20) value *from main()*. The function first determines which is the first valid beam; all non-valid beams are given a depth value of zero. The function reads through the datagram and populates the depth matrix with the correct depth value. The function returns a flag which is an end-of-file indicator.

3.3.5.1.6 *mlo_find()*

This function is passed a pointer to the fully populated depth matrix and a pointer to the result matrix (output bitmap). Two searches are made within the depth matrix for an object who size is determined in the *#define* statements, from left to right and from top to bottom. A generic version of these searches is detailed in Figure 3.23. The specific searches are tailored according to the bounds of the depth matrix (search area). In the top to bottom search, the last row of depths from the previous depth matrix is added to the top of the current depth matrix such that no information is lost. If any pixels contain depths which appear to match the object in question's size, then the corresponding pixel in the result matrix is assigned the 8 bit value contained in DISPLAY_VALUE. When the algorithm identifies a depth decrease within the MAX_HEIGHT and MIN_HEIGHT bounds, subsequent pixels must be within the user specified TOLERANCE value from footprint to footprint or a depth increase within the MAX_HEIGHT and MIN_HEIGHT bounds in order for a pixel to be assigned DISPLAY_VALUE. The user should set TOLERANCE (in cm) according to the local slope where the object lies as well as the maximum desired deviation of the object height from footprint to footprint.

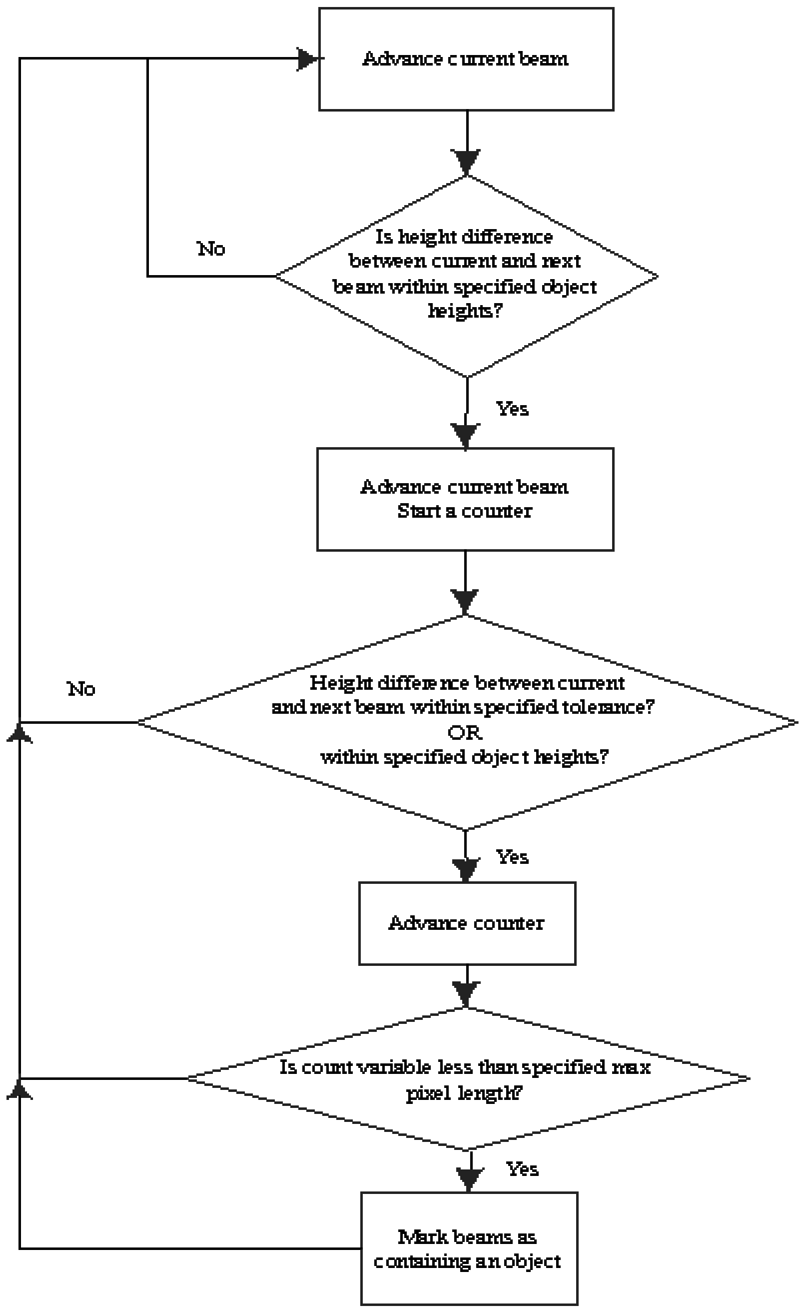


Figure 3.23 - Mine Height Search Algorithm

3.3.5.1.7 sun_illum()

This function is called immediately after *mlo_find()* has returned control to *main()*. As with *mlo_find()*, this function is passed pointers to the depth matrix and the result matrix. This function's purpose is to populate the first and third windows in the result matrix with sun illuminated values. The method is very simple in its implementation, the left-to-right algorithm is used as an example. A beam depth is compared with the previous beam depth of the same row. If the depths are the same, the 8 bit value 127 is assigned to the corresponding element of the second depth in the resultant matrix. If the depth is shoaller, then a lighter 8 bit value is assigned (>127), and vice versa if the depth is deeper a darker 8 bit value is assigned (<127).

The 8-bit values assigned to the result matrix are proportional to the predefined object's HEIGHT. If the predefined object's dimensions represent 100 per cent (127), any height difference less than HEIGHT is applied as a ratio of 127 to the neutral value 127. For example, if HEIGHT = 28 and the depth difference between two pixels is +/-14 then 50% of 127 (integer 63) is added or subtracted to the neutral value of 127. Therefore, if the second pixel was 14 cm shoaller than the preceding pixel, the element in the result matrix corresponding to the second element in the differencing operation would be assigned a value of 190. Depth differences exceeding HEIGHT are assigned the 100 per cent value. In the top to bottom illumination sequence, the last row of depths from the previous depth matrix is added to the top of the current depth matrix such that no information is lost.

3.3.5.1.8 target_file()

This function is used to create the ".mlo_coords" file which is later used by *jview* to highlight detected objects. A (low-pass 3 x 3) Mode filter is used on the centre window in the result matrix to detect any objects. In order to start the filter at the first element of the first row, the last row of the previous result matrix is inserted at the top of the current result matrix. The filter kernel assesses the number of result pixels which have been set to DISPLAY_VALUE. If this number is greater than or equal to HITS_REQUIRED then the pixel coordinates of the centre of the kernel are written to the coordinates file. To avoid overlapping markers in *jview* the NEIGHBOUR_LIMIT constant dictates the minimum pixel distance between successive coordinates written to file.

3.3.5.1.9 *overlap()*

overlap() is used to preserve the last row of the current result and depth matrices. The preserved rows are used in *mlo_find(), sun_illum(),* and *target_file()* above (see §3.3.5.1.8) in order to filter the newest result matrix with a Mode filter.

3.3.5 *MLO_Find* Results

As discussed above, *MLO_Find* extracts the depth information from an input datagram and looks for an object of predefined dimensions. In fact, two searches actually occur; one for height and length occurrences (§ 3.3.5.1.7) and one for occurrence groupings (§ 3.3.5.1.8). Table 3.1 shows a typical depth matrix with a Mk 82 mine in the centre (0.274 m x 1.67 m). The average depth in this example is approximately 13 metres, and the speed of the vessel is such that no overlap of successive pings occurs.

	Beam n	n+1	n+2	n+3	n+4	n+5	n+6
Ping x	1300	1298	1299	1298	1302	1300	1299
x+1	1300	1301	1304	1302	1299	1275	1298
x+2	1297	1302	1276	1275	1274	1265	1300
x+3	1298	1272	1274	1275	1274	1301	1300
x+4	1302	1273	1275	1273	1272	1301	1301
x+5	1300	1301	1300	1297	1299	1300	1300

Table 3.1 - Example Depth Matrix (depths in cm)

In the search performed in Table 3.1, HEIGHT = 28, MIN_HEIGHT = 24, MAX_HEIGHT = 32 and TOLERANCE = 4. Table 3.2 illustrates the content of the resultant matrix formed after the search for height and length anomalies where BACKGROUND = 100 and DISPLAY_VALUE = 254. This matrix represents the pixel values of this particular sub-section of Window Two in the output bitmap. The shading applied to this example is a visual indicator of the beams containing the mine. Notice element (x+2, n+5) is not nominated as a pixel containing the object as its value is outside the TOLERANCE limits.

	Beam n	n+1	n+2	n+3	n+4	n+5	n+6
Ping x	100	100	100	100	100	100	100
x+1	100	100	100	100	100	254	100
x+2	100	100	254	254	254	100	100
x+3	100	254	254	254	254	100	100
x+4	100	254	254	254	254	100	100
x+5	100	100	100	100	100	100	100

Table 3.2 - Resultant Matrix from Height and Length Search

The mode filter is applied to the resultant matrix from Table 3.2 in order to generate the ".mlo_coords" file. The filter runs from left to right, row-by-row. With HITS_REQUIRED = 4 the filter skips element (x+1, n+5) as the number of hits is only two. The filter continues without "finding" an object until element (x+2, n+2) where the number of hits is five. The coordinates of this element are then written to file. Given that NEIGHBOUR_LIMIT = 3, (in both dimensions) no other coordinates are written to file for this specific object; the filter then continues until the next object or end-of-file.

Table 3.3 is the matrix which would be formed by the left-to-right sun-illumination (Window Three) of the bathymetry in Table 3.1. Because no data exists to the left of column *n*, the elements in this column are assigned the neutral value (127). When the calculated values are displayed as pixels, the illusion of sun-illumination occurs (Figure 3.24). A sample calculation at element (x+2, n+2) follows:

(MAX_HEIGHT = 28)

element (x+2, n+2) value: 1276

preceding (x+1, n+2) value: 1302

difference: 26

resultant value: 127 + (difference ÷MAX_HEIGHT)*127

= 244

	Beam n	n+1	n+2	n+3	n+4	n+5	n+6
Ping x	127	136	123	131	109	136	131
x+1	127	123	114	136	140	215	13
x+2	127	105	244	131	131	167	0
x+3	127	244	118	123	131	10	123
x+4	127	254	118	136	131	0	127
x+5	127	123	131	140	118	123	127

Table 3.3 - Left-to-Right Sun-illumination Numerical Results

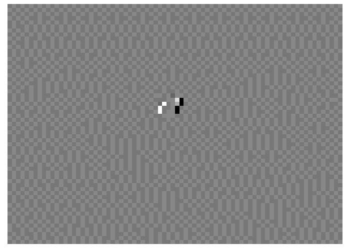


Figure 3.24 - Sun-illumination Example of Values in Table 3.3

MLO_Find will detect an object even on a sloping terrain so long as the MAX_HEIGHT, MIN_HEIGHT, and TOLERANCE variables are correctly set. Since the *mlo_detect()* function looks at relative changes between adjacent elements (beams), these variables must be increased from flat sea floor values to the maximum slope change between adjacent beams plus the desired tolerance. A side effect of accounting for slope that a wider window detection has been opened, and on flat sea floors more height detections will occur.

3.3.5.1 *MLO_Find* Limitations

The two principal factors determining the output performance of *MLO_Find* are depth (resolution) and the data quality of the survey lines read by the program. First, the survey depth must be such that the spatial resolution of the multibeam sonar can discriminate the object being sought. As the multibeam, transducer increases in altitude above the sea floor, so does the beam size (2*altitude * tan(1/2 beamwidth) at nadir). A discrete object whose size, with respect to an individual beam, contributes to a shoaller beam being calculated and logged in sufficiently shallow water, will eventually no longer contribute sufficiently to the average depth calculations in deeper water and larger beams. Actual results are illustrated in the following sections.

Ideally, a multibeam sonar pings, ensonifies the sea floor, and records the correct discrete depth value for each individual beam. In the real world this does not always happen, but *MLO_Find* relies on bathymetry exclusively in order to find a object. Looking at the January 1997 survey data used in this report, the bathymetric data is not always correct. In fact, two problem areas arise:

- in the amplitude/phase detect crossover area; and
- anomalous errors throughout.

In the amplitude/phase detect crossover regions the bathymetry is very erratic. Observing the image in the Figure 3.25a, there is a large amount of "hit" pixels in Window Two resulting in many target detects. In this particular case, it is believed that the mine lay in the crossover region. Due to the amount of noise here, the mine is not identified. Modifying the *MLO_Find* program to ignore any single differential depth changes (Figure 3.25b) falling within the mine HEIGHT window, does not produce any better results; this area is too noisy compared to the size of the object being sought.

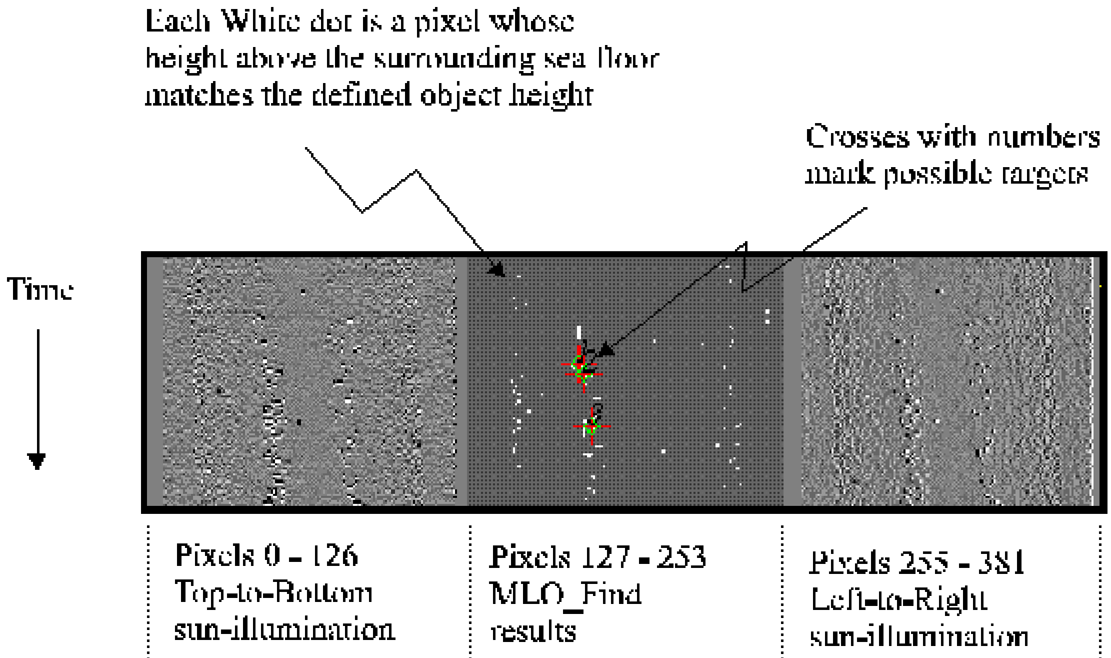


Figure 3.25a - Line 0070 Noise in Crossover Regions

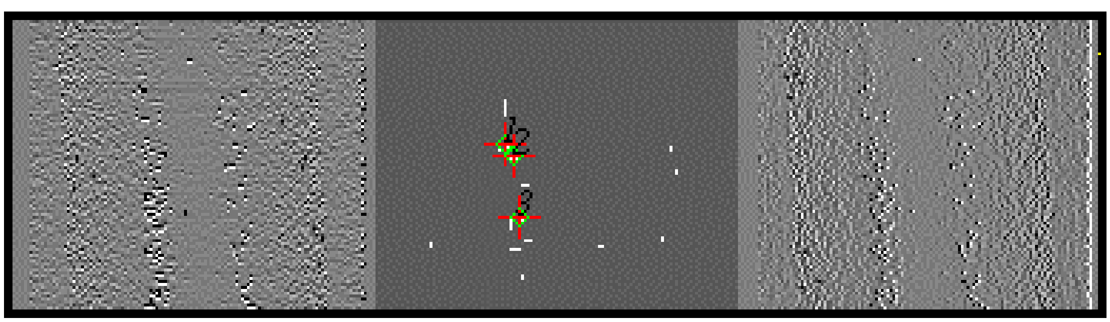


Figure 3.25b - Line 0070 Noise in Crossover Regions Reduced

If the bathymetric values calculated and logged by the system were always correct *MLO_Find* would locate any mine given that the size of the object was sufficiently large with respect to the beam size. In reality, multibeam sonars do record erroneous bathymetric values due to any number of possibilities which will not be discussed here. Regardless, Tables 3.4 and 3.5 show how one bad bathymetric value can result in an object not being detected. The resultant bitmap will show a total of five "hit" pixels in Window Two and the incorrect sun-illuminated bathymetry in Windows one and three. However, with NEIGHBOURS = 4, the object is not found by the mode filter and hence it is not highlighted with a cross in *jview*.

	Beam n	n+1	n+2	n+3	n+4	n+5
Ping x	1650	1652	1648	1649	1650	1649
x+1	1650	1651	1651	1649	1652	1648
x+2	1650	1620	1622	1622	1650	1649
x+3	1650	1621	*0*	1622	1647	1649
x+4	1653	1652	1653	1652	1652	1652
x+5	1650	1652	1648	1649	1650	1649

Table 3.4 - Bathymetry of a Mk 82 at 16.5 m - One Bad Value

	Beam n	n+1	n+2	n+3	n+4	n+5
Ping x	100	100	100	100	100	100
x+1	100	100	100	100	100	100
x+2	100	254	254	254	100	100
x+3	100	254	100	254	100	100
x+4	100	100	100	100	100	100
x+5	100	100	100	100	100	100

Table 3.5 - Resultant Matrix - No Detect

3.3.5.2 12 metre Results

A total of 17 survey lines from the January 1997 survey were processed by *MLO_Find* at the 22 m depth level; the results are listed in Table 3.6:

Event	Results
Number of lines processed	13
Number of lines with bubble noise	1
Total Good lines processed	12
Number of Lines with Target in Nadir	9
Average number of pixel "hits" (modelled)	10.55 (9-11)
Sample standard deviation	2.24
Number of good lines and no mine(i.e. in crossover)	3

Table 3.6 - 12 m Results

At 12 metres depth, when the mine was detected an average of approximately 10 beams reflected a depth change equal to that of the mine. From § 3.3.4.1 the model suggest that between 9 and 11 beams should indicate the mine. The actual results (10.55) indicate that the sonar performed as expected. This depth does not present any difficulties to the EM 3000 for this particular object size at nadir (0.26 m x 1.67 m).

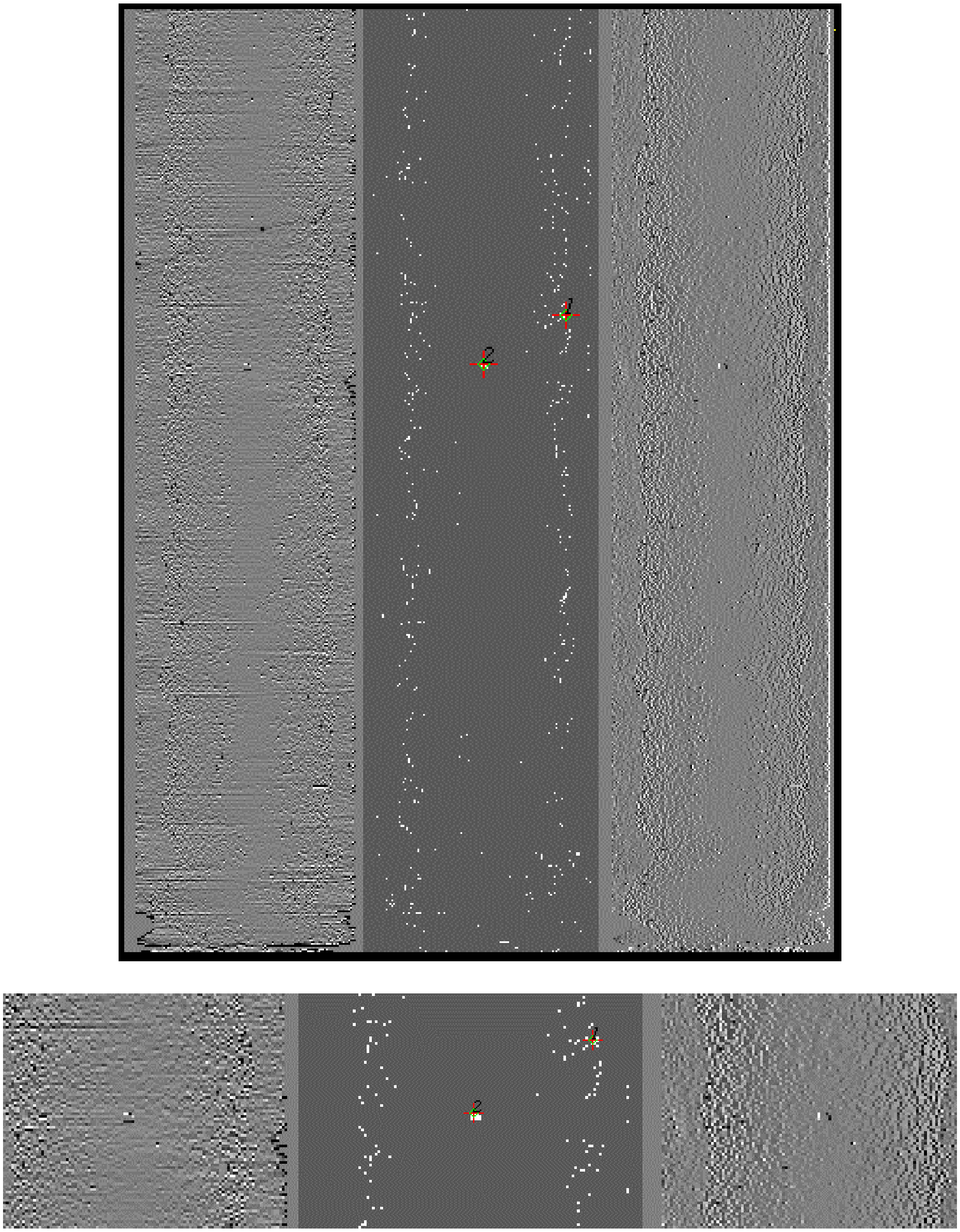


Figure 3.26 - Line 0058 with Blowup

Four possibilities are suggested as to why the mine was not detected in some of the survey lines. First, some beams may have contained erroneous data (see § 3.3.5.1) however, there were very few isolated pixels in the nadir regions to indicate this explanation. Second, external noise such as air bubbles in the water from repeated passes interfered with the proper functioning of the sonar. After examining the data, it appears that external noise was involved in three lines however the mine was detected in two of those. Third, the pitch compensation may have not been functioning properly while the vessel was pitching directly over the mine. This may have caused areas on either side of the mine (along track) to be ensonified while the mine itself never "heard" a ping [Hughes-Clarke, 1997c]. Finally, the remaining three lines (of the usable 13) appear to have had no problems with their data. The mine may have been in the crossover regions and its signature was masked by the internal crossover noise. This last hypothesis is supported by the visual sun-illuminated images (see Hughes-Clarke et al. [1997]).

3.3.5.3 22 metre Results

A total of 22 survey lines from the January 1997 survey were processed by *MLO_Find* at the 22 m depth level and the results are listed in Table 3.7:

Event	Results
Number of lines processed	22
Number of lines with bubble noise	4
Total Good lines processed	18
Number of Lines with Target in Nadir	9
Average number of pixel "hits" (modelled)	7 (4-7)
Sample standard deviation	2.9
Number of good lines and no mine(i.e. in crossover)	8
Remaining line appears to have the mine in the extreme outer beams (5 hits)	***

Table 3.7 - 22 m Results

When the mine was detected at 22 metres depth, an average of 7 beams reflected a depth change equal to that of the mine. From § 3.3.4.2, the model suggests, that between 4 and 7 beams should indicate a mine. The actual results (7) indicate that the sonar performed slightly better than expected. The unexpected performance may have been due to the pitch compensation transmitting more than once on the mine's position. This depth does not appear to represent any difficulties to the EM 3000 for this particular object size (0.26 m x 1.67 m). It is interesting to note that almost half of the "good" lines did not produce any results. One possible suggestion is that the mine may have been in one of the crossover regions and its signature masked by the internal crossover noise. This hypothesis is supported visually in four lines (see Hughes-Clarke et al. [1997]). By visual inspection, in three lines, the mine appears to be amongst processing noise caused by air bubbles. *MLO_Find* could not distinguish the mine.

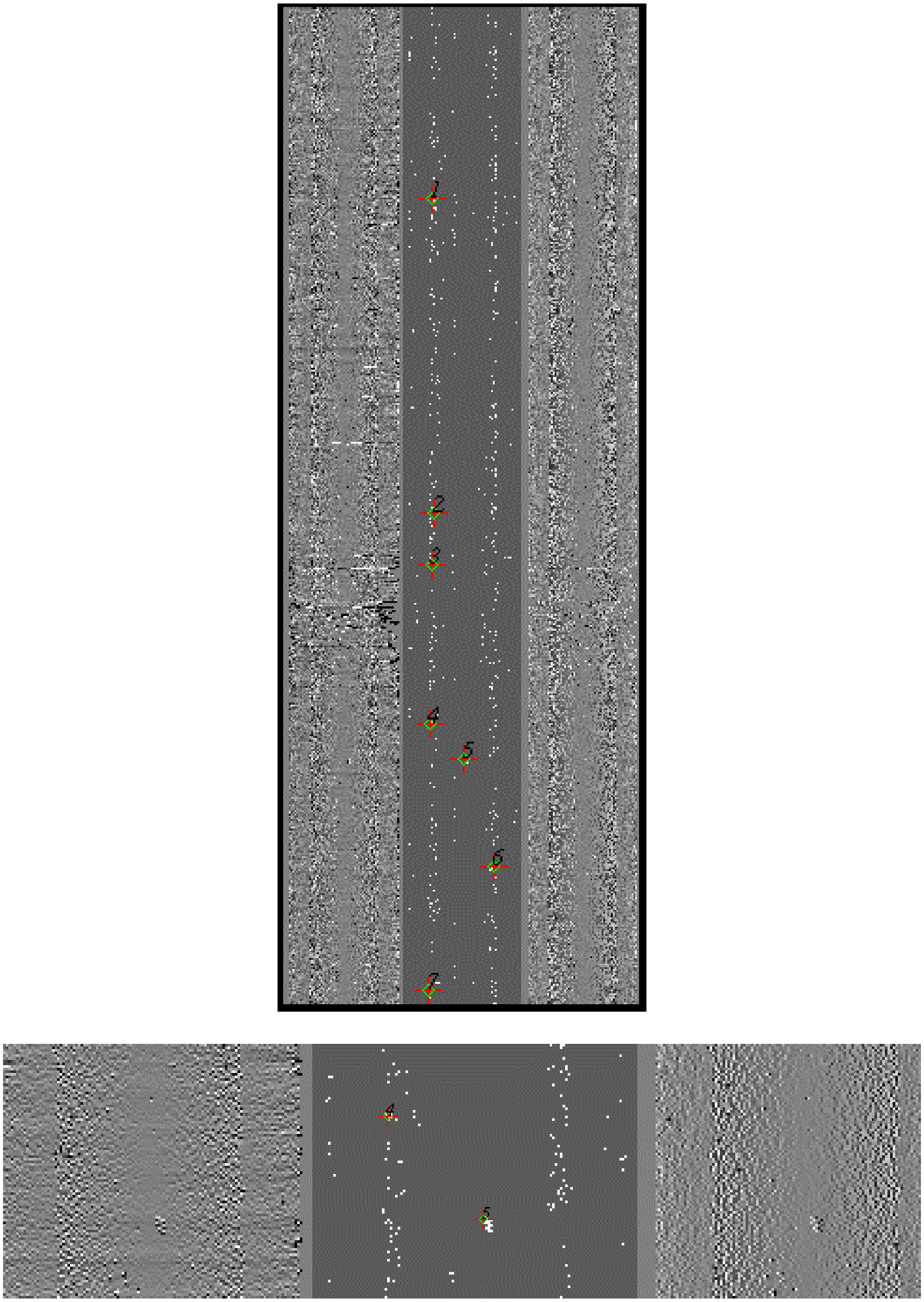


Figure 3.27 - Line 0005 with Blowup

3.3.5.4 30 metre Results

A total of 22 survey lines from the January 1997 survey were processed by *MLO_Find* at the 30 m depth level; the results are listed in Table 3.8:

Event	Results
Number of lines processed	13
Number of lines with bubble noise	1
Total Good lines processed	12
Number of Lines with Target in Nadir	2
Average number of pixel "hits" (modelled)	6.5 (2-4)
Sample standard deviation	0.71
Number of good lines and no mine(i.e. in crossover)	10

Table 3.8 - 30 m Results

At a depth of 30 metres, when the mine was detected, an average of 6.5 beams reflected a depth change equal to that of the mine. From § 3.3.4.3, the model suggests that between 2 and 4 beams should indicate the mine. The actual results (6.5) indicate that the sonar performed much better than expected *when it did actually detect the mine*; however, the sonar did not detect the mine very often. The unexpected performance may have been due to the pitch compensation transmitting more than once on the mine's position. This depth appears to present significant difficulties to the EM 3000 for this particular object size (0.38 m x 1.8 m). Through visual inspection of the imagery it appears that in four lines the mine was in the crossover region and in three lines the bubble noise interfered with *MLO_Find* detecting the mine.

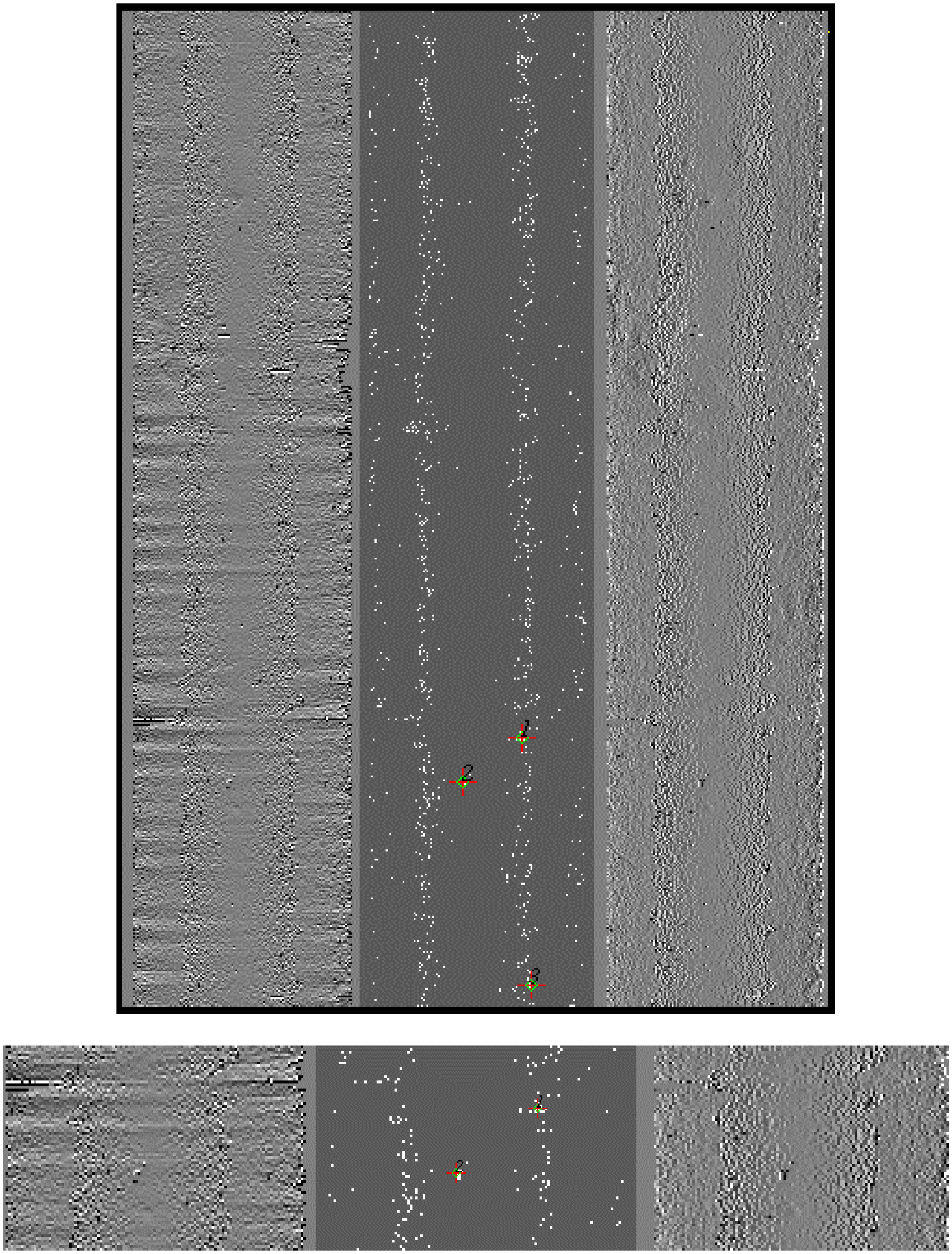


Figure 3.28 - Line 0042 with Blowup

3.3.5.5 42 metre Results

The June 1996 survey was conducted over a region of bedrock outcrop and boulder fields. Furthermore, the ping rate of the sonar was too low for the vessel speed resulting in less than 100 per cent ensonification of the sea floor (see § 3.3.4.4). When *MLO_Find* processed this survey data, the amount of pixel "hits" was numerous as was the number of targets found (NEIGHBOURS = 4). If NEIGHBOURS had been set to a value less than four, hundreds of objects would have been detected.

Referring to the model in § 3.3.4.4 only one pixel hit should have occurred for the MK 82 mine if it was laying in the along track direction. However, many targets were detected with 4 or more hits (Figure 3.29). It is believed that these target were boulders and small ridges whose heights fell within the mine HEIGHT parameters. This assumes that the EM 3000 vertical resolution at 42 m is accurate enough to discriminate between 22 and 34 cm. Objects the size of a Mk 82 mine (0.26 m x 1.67 m) at this depth require a resolution greater than that of the EM 3000's capabilities.

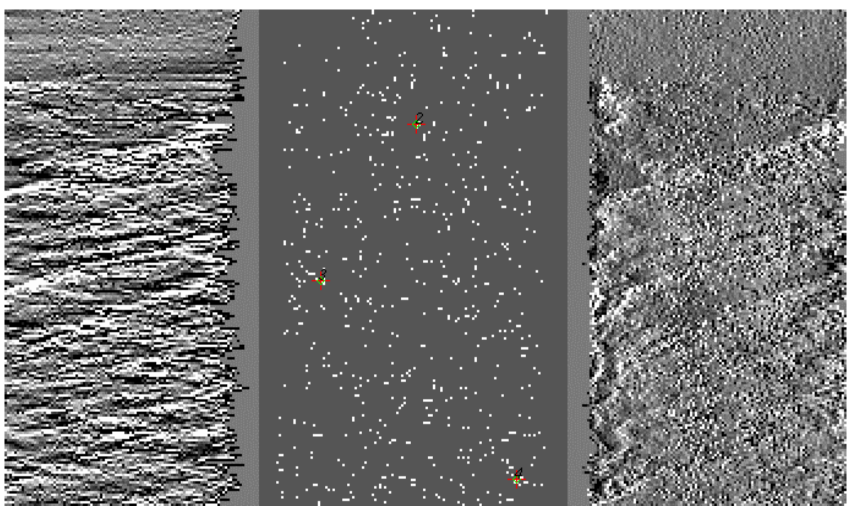


Figure 3.29 - Line 0002_211126 Blowup

3.3.6 Using Bathymetry for Mine Detection

From the January 1997 survey it appears that the EM 3000 is able to detect an object the size of a Mk 82 mine in water depth less than 20 metres, in the nadir and near-nadir beams with little difficulty. Depths beyond 22 m appear to demand too much of the EM 3000's resolution. An examination of the *MLO_Find* images at 11 and 22 m, suggest that the amplitude/phase detect crossover begins at approximately 20 beams on either side of nadir. These beams (numbers 43 and 83) are at approximately 20 degrees from the nadir beam.

In the depths and regions where the EM 3000 could detect the mines the results were very good. The beams ensonifying the mines clearly indicated the bathymetry associated with the mines' height. Bathymetry could be used effectively in depths less than 22 m for mine detection. However, further studies are required to identify how the amplitude/phase detect crossover point affects the results.

3.4 Summary

Normal Incidence Classifiers can reliably and repeatedly classify the sea floor. Multibeam sonars however, do not yet have this ability due to their unrefined processing methods which were originally developed for side scan sonars. Further research and development is required before multibeam sonars may be used as BSC sonars.

From the analysis of the EM 3000 multibeam backscatter data, the near nadir mines in the January 1997 survey, were not detected amongst the surrounding sea floor backscatter. Even when image enhancement filters and unsupervised classifiers were applied to the backscatter imagery, the mines remained undetected. The most probable cause for the non-detection was the high grazing angle between the multibeam transducer and the near nadir mines resulting in no shadows being cast behind the mines.

Beam modelling using *synSwath* was performed in order to predict how the EM 3000 should have ensonified the mines used in the two survey data sets. Through the *MLO_Find* program, the actual detection results were noted and compared to the predictions. The EM 3000 appeared to be able to detect 500 lb mines in less than 20 metres of water within 20 degrees (either side) of nadir. Beyond 20 metres the resolution was unreliable and beyond 20 degrees the amplitude/phase detect crossover region was too noisy to detect the mines at all.

The EM 3000 is a sonar with few equals in resolution and performance. Sonars such as the Atlas Fansweep 20 and Submetrix ISIS 100, however must be considered as close competitors. I believe that more surveys should be conducted using multibeam sonars of equal or higher resolution to the EM 3000 in order to determine if <u>any</u> multibeam sonar has the capability to detect mines using backscatter imagery, as well as bathymetry.

CHAPTER 4 - MULTIBEAM SONARS IN ROUTE SURVEY

4.1 Bottom Sediment Classification

As discussed in the previous chapter (see §3.2), multibeam sonars have the potential for accurate, repeatable Bottom Sediment Classification. Today however, the technology is still unproven, unreliable and subsequently commercially scarce. Given the cost of a multibeam sonar such as the Simrad EM 3000, which is approximately $300,000 (uninstalled with no positioning sensor), it is hard to justify investing such a large amount of capital into a speculative application. Each processing method discussed in § 3.2 is usable (sometimes almost exclusively) by side scan sonars. Given the fact that the MCDVs already have side scan sonars, there would be little logic in purchasing multibeam sonars to perform (less effectively) the analysis methods developed for side scan sonars.

Until the multibeam BSC methods become more, a more reliable alternative is readily available: Normal Incidence Classification (see §3.2.2). This alternative cannot offer 100 per cent ensonification, however, it does offer a BSC capability presently non-existent within the Canadian Navy. Furthermore, it is an inexpensive approach to a BSC capability on board the Maritime Coastal Defence Vessels. Two examples of Normal Incidence Classifiers using existing echosounder transducers are the RoxAnn Seabed Classification System [NORDSEA, 1997] which retails for approximately CDN$ 35,000 [Egan, 1997]. QTC View [Quester Tangent Corporation, 1997] retails for approximately CDN$ 19,000 [Lacroix, 1997]. These prices do not include taxes, installation, or services of a technician for calibration and sea trials. The RoxAnn price does not include the price of the 486 (minimum) computer which is required to run the processing software.

Collins and Lacroix [1997] have proposed a *fleet* approach to seabed classification. This new system would entail one BSC sonar (QTC View) on each hull of a fleet of minesweepers. A central processing facility would have a dedicated mobile data collection unit (ISAH-S) [Quester Tangent Corporation ,1997] which would have its data analysed by a post processing workstation with extended seabed classification capabilities. The post processed results would then be downloaded to the individual units to collect data in a supervised classification mode. This master unit concept would ensure that classification consistency was maintained on all the separate platforms throughout the fleet. Furthermore, the master unit could be used for more extensive post processing than would be available on the QTC View units themselves. Outfitting the entire MCDV fleet (12) would cost approximately CDN$ 743,000 [Collins, 1997].

4.2 Tow Fish Gap Filler

The ensonification gap inherent within any side scan sonar (see § 2.2), and specifically the MDA tow fish (see § 2.2.1.7), requires a 60 per cent overlap by the MCDV. Incorporating a gap-filling sonar into the MDA tow fish would reduce the amount of survey time required for a particular area and thus reduce the overall cost of survey operations. Of course, issues such as the following would have to be taken into account, if an effectual gap-filling sonar could be found:

- the cost of installation;
- hydrodynamic considerations of the protruding transducer;
- hardware requirements (ie positioning sensor / space required);
- postprocessing hardware/software; and
- the compatibility with the existing setup/systems.

The conclusions drawn in Chapter 3 (see § 3.4) state that the EM 3000 could best be used for object detection (500 lb mine-like in size) in less than 20 metres altitude and within 20 degrees of nadir. The MDA tow fish is designed to operate in terrain following modes at 11, 22, and 30 metres with the 30 metre option used for detection (see § 2.2.1.1). In fact, it is intended that the 30 metre detection mode will be used most often in Route Survey operations [Bradford, 1997]. Clearly, the EM 3000 would not be the sonar of choice at this depth. Furthermore, the EM 3000's swath limitations (20 degrees) would not fill the entire gap regardless of the terrain following depth chosen; a survey overlap would still be required. Finally, backscatter imagery would be largely ineffectual due to the small shadows cast from nadir to 45 degrees.

The EM 3000 multibeam sonar is, in my opinion, one of the premier multibeam sonars available with respect to resolution and performance, however, it is not suitable as a gap-filling sonar onboard the MDA tow fish. Other multibeam models [Hughes-Clarke, 1997c] show that the EM 3000 appears to have one of the better resolution and ensonification capabilities of those sonars listed. Further surveys, similar to the January 1997 survey are required using other high resolution multibeam sonars in order to assess their suitability as gap-filling sonars. Until these surveys are conducted, I believe that no multibeam sonar can be used as a gap-filler until their beam widths are reduced and their crossover noise is suppressed.

4.3 Shallow Water Object Detection

The MCDV, with the MDA tow fish, is designed to operate in water depths between approximately 30 m [Bradford, 1997] and 200 m [Sullivan, 1997] regardless of the tow fish altitude. These parameters make the MCDV ideal for continental shelf surveys, however, harbours and harbour approaches may be too shallow for the MCDV to conduct Route Surveys. For example, Canada's two primary naval ports, Halifax and Esquimalt, and its two primary shipping ports, Montreal and Vancouver, are inaccessible to the Operational Route Survey (ORS) package.

In areas too shallow for the ORS, single beam side scan sonars are used in Route Survey. The Canadian Navy currently uses the Simrad 972 single beam dual frequency (non-simultaneous) sonar. This sonar has a range of 50 m to 300 m (100 m to 600 m swath width) which is dependent on the tow speed and operating frequency selected. Normally, the sonar is towed from small naval vessels (11 m to 22 m) at approximately 3 to 4 knots, at the 100 metre range setting, in adjacent lines at 75 metre spacing (which allows for with a 25 metre overlap) [Bradford, 1997]. A 1000 m^2 area can be surveyed in approximately two hours with the above operating parameters. Post processing software includes Triton's Vista Mosaic Package and Geological Survey Canada's Mosaicking Software [Bradford, 1997].

The EM 3000 proved to be successful in object detection (500 lb mine) in less than 20 m of water and within approximately 20 degrees of nadir. These constraints result in swath width of 14 m. Assuming a 5 m overlap and a speed of 12 knots it would take approximately five hours (2.5 times the Simrad 972 survey time) to survey the same 1000 m^2 area mentioned above. In depths between 20 and 30 m, the EM 3000 sonar cannot reliably detect (500 lb) mine like objects.

In view of the limitations of the EM 3000 sonar, it would not be an effective mine detection sonar in water too shallow for the ORS. Once again, other multibeam sonars with comparable or better resolution and performance must be tested. However, I believe that a multibeam sonar cannot currently replace the side scan technology already in use for object detection.

4.4 Bottom Topographic Mapping

The Canadian Hydrographic Service (CHS) uses multibeam echosounders for charting purposes, specifically the Simrad EM 3000 and EM 1000 multibeam sonars for shallow and deep water charting respectively. CHS is able to provide accurate bathymetric data consisting of 100 per cent bottom coverage in any area they survey. The Route Survey Office can use this data depending on the specific operational requirements. Of course, this data would have to be converted into Digital Elevation Models (DEM) in order to be of any use. Two specific cases where the data can be used are in "Coarse" Route Survey and Tow Fish Terrain Following.

4.4.1 Coarse Route Survey

Chapter 2 mentioned that the ultimate goal of Route Survey Operations is the creation of Q routes (see § 2.2.2), and that Q Routes have a number of ideal qualities which Route Survey endeavours to meet. One of these qualities is that of an *optimal* sea floor, namely:

- topographically featureless;
- well known (all objects surveyed);
- contrasting reverberation levels with foreign objects; and
- non-conducive to mine burial.

The multibeam data provided by CHS, can be used as a pre-side scan survey tool in order to identify sea floor areas that may be suitable for Q Routes. This pre-side scan survey process is defined here as <u>Coarse Route Survey</u>. Coarse Route Survey using multibeam data offers three advantages to Route Survey Operations: time savings, regional topographic data, and backscatter data. First, if the area of interest has been previously surveyed, then the data may be examined to find a topographically featureless area. If the area of interest has not been surveyed, using CHS multibeam equipped vessels may be less expensive than using an MCDV due to the higher areal coverage rate that a multibeam equipped vessel has over the MCDV. Furthermore, CHS only charges incremental costs (i.e. overtime) to Route Survey Operations if a survey is required specifically for the Navy.

The second advantage results from the fact that the MDA tow fish is a non-bathymetric side scan sonar, which means topography cannot be extracted from the side scan data [Westwell-Roper, 1997]. Multibeam data however, does provide topographic data which can be used to help identify an optimal sea floor. Finally, the backscatter data derived from a multibeam sonar a qualitative assessment of sea floor lithology to be made.

4.4.2 Terrain Following Danger Avoidance

The ORS uses sounding data from the MCDV echo sounder 35 metres ahead of the tow fish, in the terrain following mode of operation [Sullivan, 1997]. The tow fish has been designed to follow terrain up to a maximum five per cent grade [Strong, 1997]. If a pinnacle is detected, a manual over-ride is required to make the tow fish rise at its maximum rate (1.5 m/s). Obviously, some pinnacles can cause the tow fish to be damaged as can be seen in Figure 4.1.

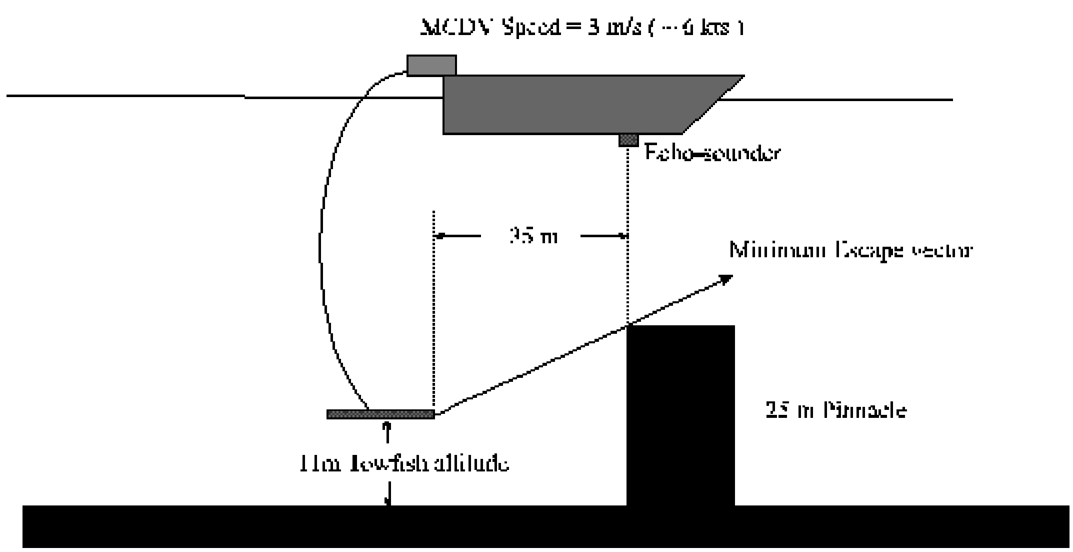


Figure 4.1 - Pinnacle Danger to the Tow Fish

A relationship exists between the maximum pinnacle height, ship speed, tow fish rise speed, and the ship echo sounder to tow fish distance. The formula below defines the maximum pinnacle height for a given vessel speed in which the tow fish can avoid hitting the pinnacle. This formula assumes:

- 0.25 second detection delay for the two way travel time to a pinnacle at 200 m;
- the ship echo sounder to tow fish distance of 35 m;
- a maximum tow fish rise speed of 1.5 m/s;
- a 2 second delay from pinnacle detection to operator over-ride for commencement of towfish rise; and
- an instantaneous achievement of pinnacle height (i.e ledge or cliff face).

Table 4.1 defines the maximum pinnacle heights for selected speeds and towfish altitudes.

$$MaximumHeight = \left(\frac{35m}{ShipSpeed} - 2.25\sec\right) * 1.5m/s + TowFishAlt$$

Speed vs Altitude	2 m/s	3 m/s	4 m/s	5 m/s
11 m	33.88 m	25.13 m	20.75 m	18.13 m
22 m	44.88 m	36.13 m	31.75 m	29.13 m
30 m	52.88 m	44.13 m	39.75 m	37.13 m
1 m/s = 1.94 knots				

Table 4.1 - Maximum Pinnacle Heights

Unfortunately, the ORS cannot use DEMs in conjunction with the a ship's positioning sensors and echosounder for an enhanced terrain following capability [Strong, 1997]. Looking beyond the ship's echo sounder's bore sight would allow the tow fish more time to rise above pinnacles thus increasing the maximum pinnacle height required to present a danger to the tow fish. Although this bathymetric chart look-ahead capability has not yet been incorporated into the current ORS, it is an area of improvement being researched by MDA [Sullivan, 1997].

Clearly, Route Survey operations can benefit from the bathymetric and regional backscatter data collected by CHS in their multibeam surveys. During the *Mission Planning* phase of a survey, the multibeam data may be examined to ensure that no dangerous pinnacles or ledges lie on the proposed ship's survey lines. If the look-ahead capability is incorporated into the ORS, then through the use of DEMs the MCDVs may proceed with high speed, low altitude route survey with greater confidence that the tow fish will not be lost or damaged on a steeply rising pinnacle without detailed Mission Plans. As a side note, DEMs must be used, as the S-57 standard Electronic Charts do not have an adequate sounding density for use in this Route Survey application [Strong, 1997].

A lost or damaged tow fish is not only very expensive but during times of conflict could result in the unnecessary delay of shipping. This, of course, is one of the primary goals of a would-be opponent mining Canadian controlled waters. Therefore, multibeam data obtained from the CHS (or any other source) is very important to Route Survey Operations.

4.5 Summary

Multibeam sonars do not yet offer a reliable, repeatable Bottom Sediment Classification capability. In fact, the BSC processing methods being studied were originally developed for side scan sonars which the Canadian Navy already possesses. Multibeam sonars do not yet offer the resolution which would justify their use onboard the MDA tow fish as a gap filling sonar. Nor do they provide the resolution or coverage rate required in waters too shallow for the MCDV Operational Route Survey package. The Canadian Navy would not benefit by purchasing a multibeam sonar(s) for use in Route Survey Operations.

The multibeam sonars which CHS uses onboard its vessels for bathymetric surveying offer Route Survey Operations valuable data. This data can be used for Coarse Route Survey and for safer tow fish terrain following; both functions can save the Canadian Navy time and money. CHS and Route Survey Operations have a close working relationship, including financial agreements, which should be maintained. In fact, I believe the Canadian Navy should dedicate more funds to the CHS for survey operations as it would benefit both organizations in achieving their goals.

CHAPTER 5 - CONCLUSION

5.1 Concluding Remarks

From the ineffective Bushnell mine to the most modern ground mine capable of waiting for a *particular* ship, the primary aim of mine warfare has remained constant: *to cause undue delay to, damage to, or to destroy an opponents' shipping in order to expedite a military victory.* The most rudimentary mines are inexpensive, easily mass produced and easily delivered. They can also be as effective as the most expensive technologically advanced mines if they are properly used. To this end Mine Counter Measures, specifically Route Survey, must effectively identify shipping routes where mines may be easily detected.

The Canadian Navy's new Maritime Coastal Defence Vessels offer a mine detection capability through Route Survey Operations. The Operation Route Survey Payload onboard the MCDV, uses a tow fish containing a Multibeam Focussed Side Scan Sonar which, with the processing software, is ideal for use as a mine detection system. The Payload however, has two distinct disadvantages which are discussed below.

First, there is an ensonification gap of 45 degrees on either side of nadir, which is an inherent property of any side scan sonar. This gap results in a 60 per cent overlap required by the survey vessel during survey operations. This overlap represents an increased survey time and subsequently an increased cost for each survey undertaken. Time and money could be saved if a gap filling sonar could be integrated into the tow fish.

The second disadvantage of the Operation Route Survey Payload is a minimum operating depth of approximately 30 metres. Because of this minimum depth constraint, other survey systems (sonars) are required for shallow waters in order for Route Survey to be able to effectively cover all of Canada's major harbours. Presently, smaller side scan sonars (Simrad 972), towed by small naval vessels are used in shallow water. However, a sonar with a wider swath and faster survey speed than the Simrad 972 could represent time and cost savings to Route Survey Operations.

The multibeam sonar was originally developed, and continues to be used, as a very effective bottom mapping sonar which offers 100 per cent ensonification. The multibeam sonar offers two specific data products, these being bathymetry and amplitude backscatter data. From the bathymetry, accurate and densely populated Digital Elevation Models may be produced which illustrate the true regional topography of the sea floor. Furthermore, multibeam sonars are being developed as bottom sediment classification sonars using the backscatter data. To date, multibeam sonars have not been tested as object finding sonars.

Using data from two EM 3000 surveys, this report assessed the ability of the multibeam sonar to identify mine like objects at varying depths. The assessment was based on the output of two programs written during the course of this research. The first program, *Raw_sidescan*, extracted the backscatter information from the EM 3000 data telegrams and created an output file in the form of an (8-bit) bitmap. Using the program's output, the backscatter data was examined to see if the mine was distinguishable from the surrounding sea floor backscatter information; it was not.

A second program was written to extract bathymetric data from the EM 3000 telegrams and display this information in a bitmap (8-bit), divided into three windows. These windows were: sun-illuminated bathymetry from the right, sun-illuminated bathymetry form the top, and the results of a mine like object detection search within the data. The sun-illuminated imagery in concert with the automated detection process proved to be an effective tool, in specific circumstances, in finding the mines used in the surveys. The mines were easily detected by the sonar in depths less than 20 metres and within 20 degrees of nadir. Beyond these parameters, the resolution and internal noise of the sonar resulted in very few detections of the mines. One potential problem which was also noticed was that of the pitch compensation beam-steering process. In seas where the vessel pitched heavily, the sonar appeared not to ensonify the sea floor evenly. In fact the sonar seemed to cluster its transmissions on one point rather than evenly spacing them. This resulted in the mine either being ensonified a lot or not at all.

Through analysis of the output of the programs written for this research, it was determined that multibeam sonars do not yet have the resolution required to be used as mine detection sonars. This determination includes consideration of multibeam sonars as gap filling sonars and as a shallow water route survey sonars. It was therefore recommended that the Canadian Navy not purchase multibeam sonars for use in Route Survey Operations.

Regardless of the lack of recommendation above, multibeam sonar data, collected by organizations such as the Canadian Hydrographic Service, does offer Route Survey Operations very useful information. The multibeam data can be used for Coarse Route Survey and for safer tow fish terrain following Mission Planning. Digital Elevation Maps created from multibeam bathymetry can be used to identify topographically featureless sea floors which are ideal for the creation of shipping routes. Furthermore, the amplitude backscatter information allows for a qualitative assessment of the sea floor lithology. In the Mission Planning aspect, survey routes may be chosen such that pinnacles or ledges, dangerous to the terrain following tow fish, may be avoided.

In summary, although multibeam sonars have been determined as unsuitable mine like object detection sonars, this does not preclude their data from being useful to Route Survey Operations. As discussed above, the bathymetry and backscatter information derived from multibeam surveys can be very useful. As multibeam sonars increase in resolution and decrease their internal noise, they may yet prove to be useful mine like object detectors. The evaluation that was carried out in this research should be revisited, in the future, as multibeam sonar technology improves.

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Appendices

Appendix I - Telegram Key (**Not Included**)

Appendix II - Source Code Listing of *Interp.c* (**Not Included**)

Appendix II - Sample *Interp* Output (**Not Included**)

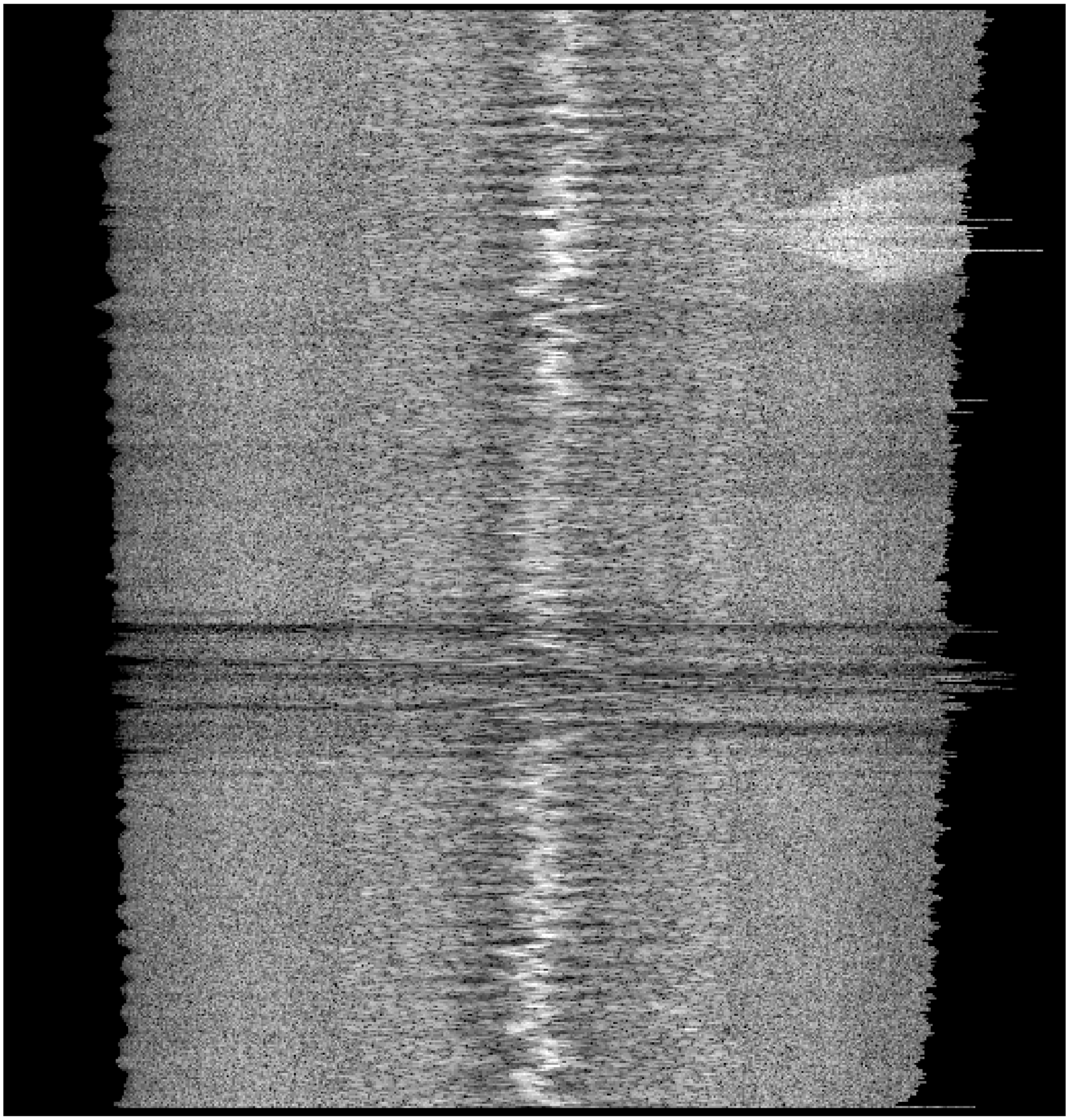
Appendix IV - Source Code Listing of *Raw_sidescan.c* (**Not Included**)

Appendix V - *Raw_sidescan* Output Samples

Appendix VI - Source Code Listing of *MLO_Find.c* (**Not Included**)

Appendix VII - Ancillary Parts to *MLO_Find.c* (**Not Included**)

Appendix V - *Raw_sidescan* Output Samples



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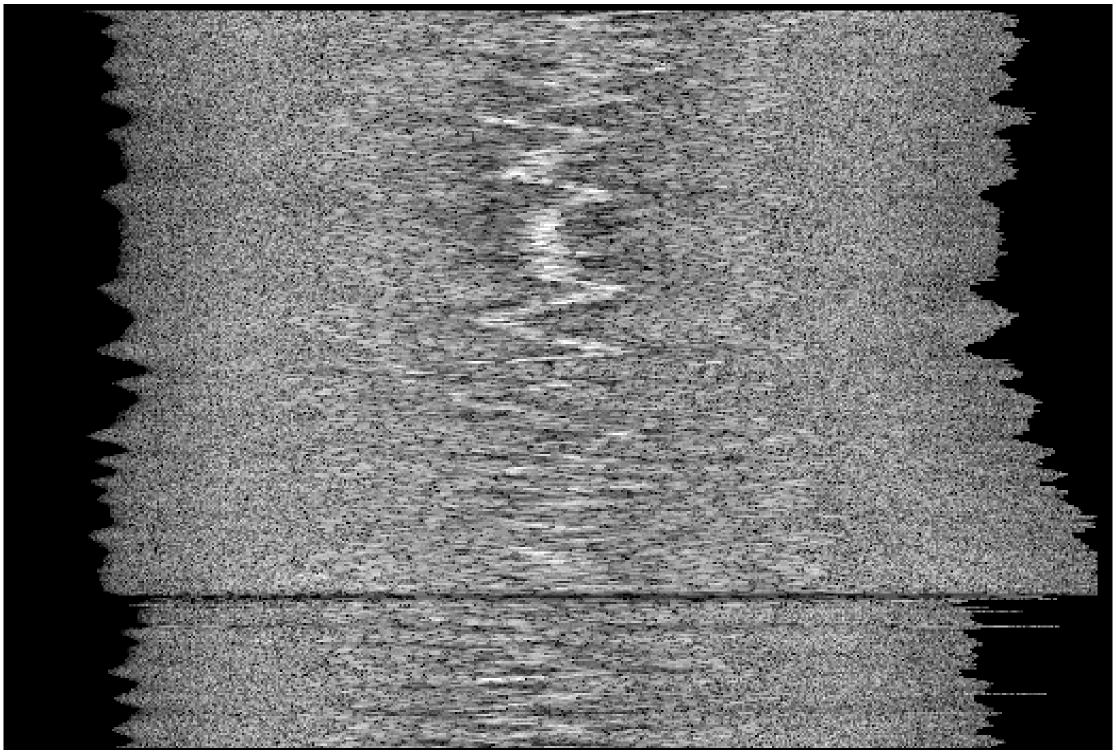

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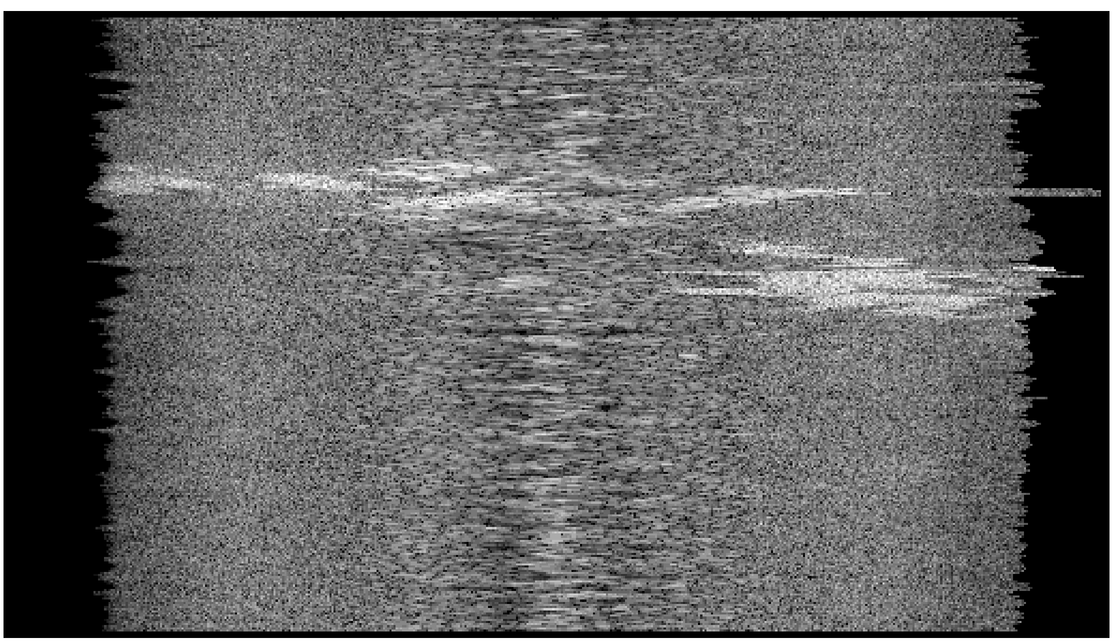

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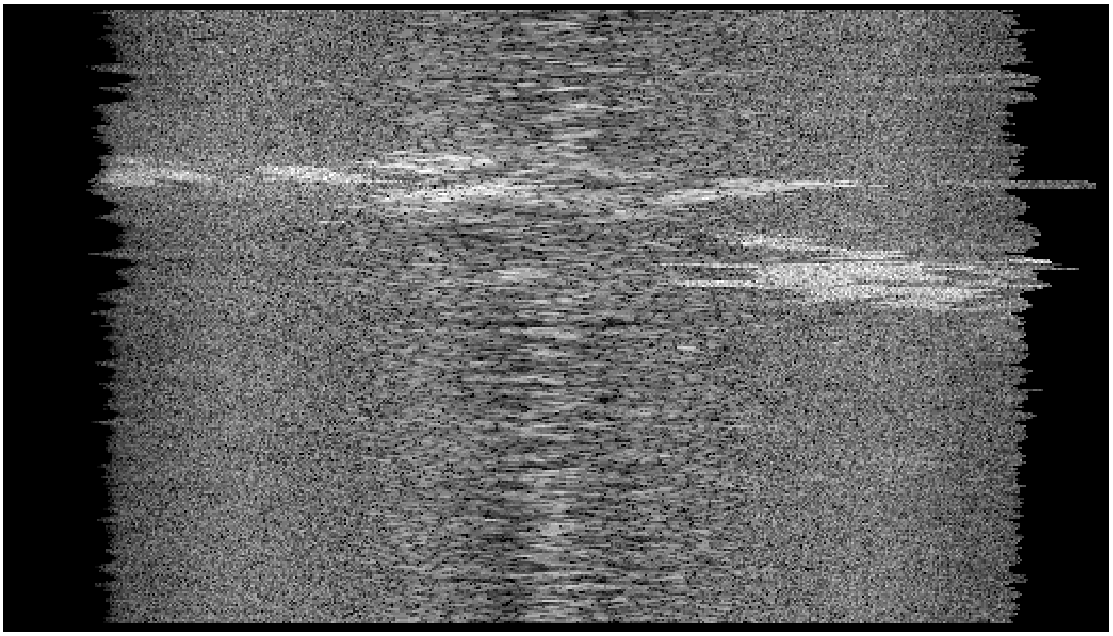

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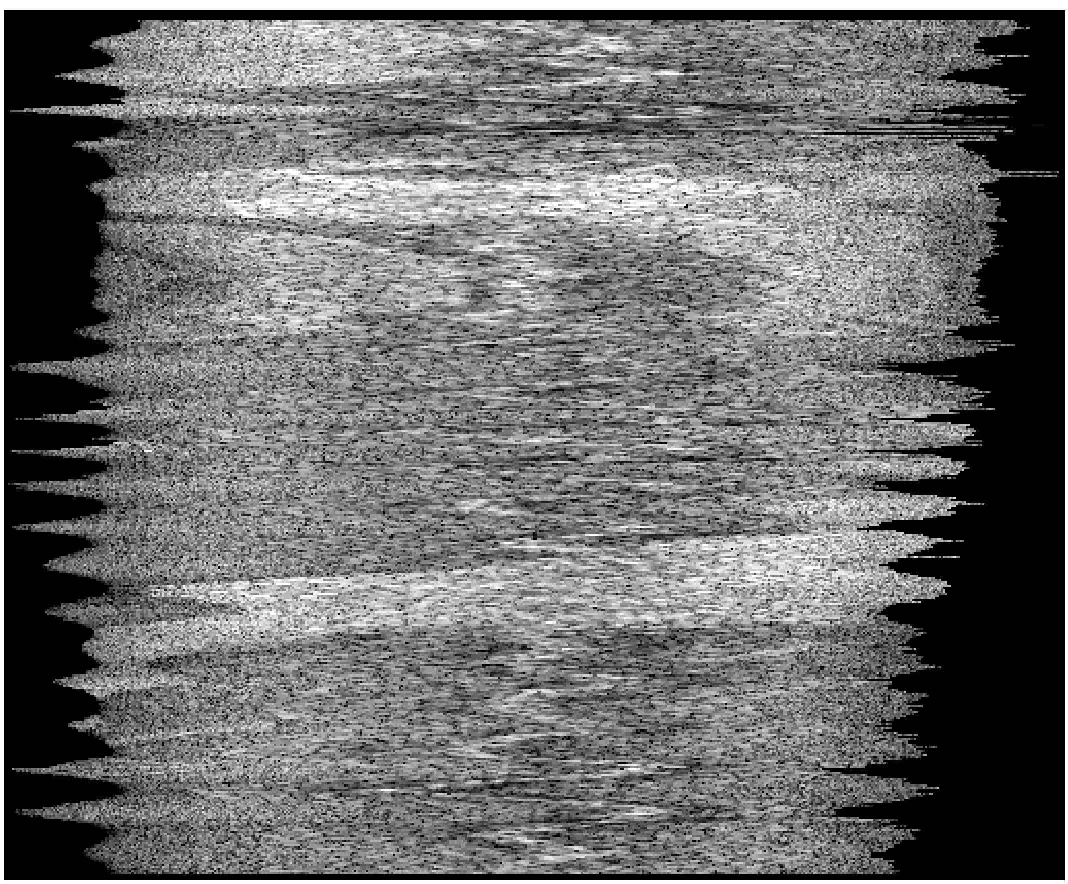

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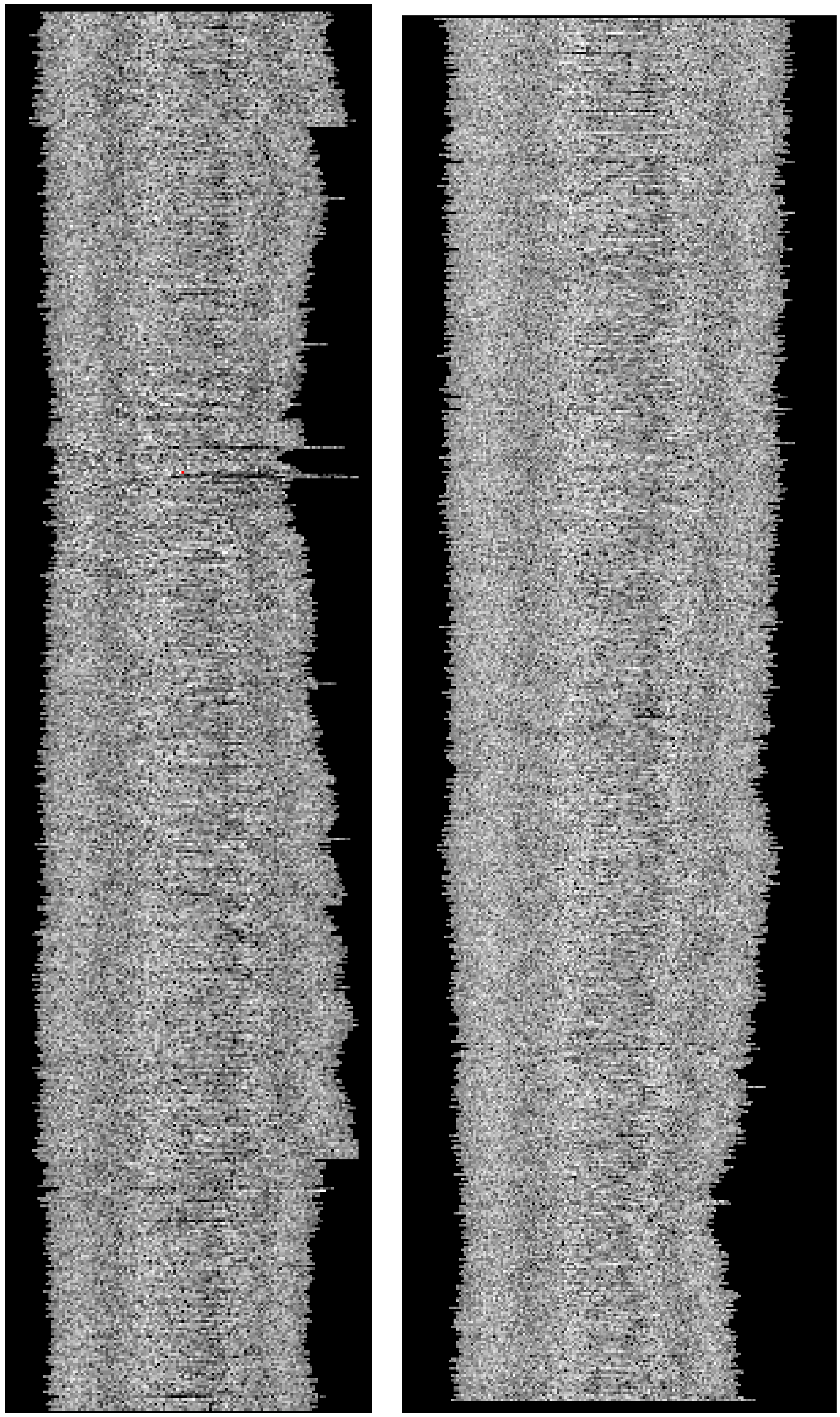

Figure V.6 - Line 0002_211126 & Figure V.7 - Line 0003_180427