Sector-specific Beam Pattern Compensation for Multi-sector and Multi-swath Multibeam Sonars

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DEDICATION

I dedicate this thesis to my wife, Hsiao-lan.

ABSTRACT

Increasingly, multibeam sonar systems are using multi-sector and multi-swath to improve the ensonification coverage of seabed survey. These systems provide not only bathymetry but also seafloor backscatter products. The proper calibration of seafloor backscatter is very important and the use of multiple sectors complicates the approaches and applications to achieve sediment classification.

With the addition of sectors and multiple swaths, the apparent seafloor backscatter is overprinted with artefacts generated by variations in the power and beam pattern of each sector, the frequency dependent propagation in the ocean (absorption attenuation), and frequency dependent reflection of the seafloor (angular response). Current backscatter output from these systems is not properly reduced to correct for these artefacts.

Since the difference of the source level and beam pattern residuals in different sectors will limit the ability to distinguish seafloor types, the goal of this thesis is mainly to illustrate the problems and solutions of source level and beam pattern residual artefacts in backscatter images. Specific applications are presented using Kongsberg Maritime EM2040, EM710, EM302 and EM122 systems all of which are both multi-sector and multi-swath. The benefits of the algorithm can be used to minimize the source level and beam pattern residuals. This algorithm, developed as parts of this research, is illustrated through examples of data improvement that utilize the new OMG beam pattern correction software developed herein.

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List of Symbols, Nomenclature or Abbreviations

BS	Backscatter Strength
BW_P	Pulse Bandwidth
BW_T	Transducer Bandwidth
CA	Crossover Angle
CCGS	Canadian Coast Guard Ship
CSL	Canadian Survey Launch
CW	Continuous Wave
FM	Frequency-modulated
GA	Grazing Angle
GGE	Geodesy and Geomatics Engineering
KM	Kongsberg Maritime
MBES	Multibeam Echo Sounder
OMG	Ocean Mapping Group
OWTT	One Way Travel Time
Rc or RX	Receiver
SIS	Seafloor Information System
SS	Sector Separation
TVG	Time-varying Gain
TWTT	Two Way Travel Time
Tx or TX	Transmitter
UNB	University of New Brunswick
USNS	United States Navy Ship

VRIA	Vertically Referenced Incidence Angle
WD	Water Depth

Chapter 1 Introduction

This thesis is a summary of the research and subsequent software developments undertaken to improve backscatter products derived from the Kongsberg new generation multibeam echo sounders (MBES) which have multi-sector and multi-swath. The conventional multibeam echo sounder normally has only a single sector and single swath. In order to enhance the confidence of the 100% coverage of seafloor ensonification, however, the new generation MBES increase sectors and swaths.

The products of MBES mainly can be separated into two parts: bathymetry and backscatter strength. For the case of backscatter strength, the controls on the received seafloor backscatter include the absolute level and angular variation in the power of the transmitted acoustic energy and the receiver sensitivity (beam pattern), the propagation in the ocean (absorption attenuation), and reflection and scattering of the seafloor (angular response). Unambiguously separating the contributions of each of these controls is a challenge.

If properly reduced for sonar parameters and grazing angle (GA), the backscatter products can be useful as a significant part of marine geology and geo-technical engineering programs. Previously, hydrographers and oceanographers would gather the rock core sample of the seafloor to identify the sediment distribution. By comparing multibeam backscatter with selected samples at the same location of interest, the properly reduced backscatter strength can be used as a proxy for sediment type. However, before one builds a dependable classification of the sediment by backscatter strength, a first priority is to correct the beam pattern, absorption attenuation, and angular response. This thesis will not address absorption attenuation and angular response but just focus on how to remove the beam pattern residual using a modified version of the Ocean Mapping Group (OMG) software developed by the author.

The apparent seabed backscatter angular response curve derived from the backscatter products generated by conventional multibeam systems typically includes uncompensated sonar beam pattern residuals. To minimize the appearance of this, the OMG of UNB has previously developed a series of software algorithms to compensate for the beam pattern residuals of the backscatter products. For a single sector multibeam, the beam pattern residual can be monitored as a single function across the entire swath. However, with the multi-sector and multi-swath developed in the new generation multibeam system, there is a requirement to separate the beam patterns for each sector of each swath. The existing OMG software cannot correct the sector-specific beam pattern residuals as well. Of course, the multi-sector and multi-swath multibeam systems face different issues in the operating design. These issues include the active motion compensation, sequential transmission timing and the order of sectors, survey mode (pulse length and type) change, individual frequency for each sector, etc.

This thesis uses data from EM2040, EM710, EM302 and EM122 sonars to cover the full range of ocean depth. These 4 types of the Kongsberg multibeam echo sounders are all designed as multi-sector and multi-swath systems. However, there is another more immediately pressing issue that is the EM302 which is installed in the Canadian Coast Guard Ship (CCGS) Amundsen which has a strongly different response signal problem in one of the sectors. This problem causes the backscatter mosaics to have a very noticeable strip of erroneous backscatter strength estimates. This problem may be probably caused by the specific hardware of the EM302 system. Therefore, to figure out and solve this more immediate problem is also the one of the short-term aims of this thesis.

Figure1. 1The installation of EM710 (CSL Heron), EM302 (CCGS Amundsen), EM122 (USNS Heezen) and EM2040 (CCGS Otter Bay). [Hughes Clarke, 2011 GGE3353 Notes]

Figure 1.2 is the backscatter mosaic image of EM302 which is using 16 sectors (dual swath). To distinguish sediment types using this mosaic image is a problem because there are too many fluctuations in the backscatter response signals that do not relate just to the seabed response. The darkest strip of the mosaic image shows the transmitter source level problem. In other zones, the bright and dark areas are affected by the beam pattern residuals and angular response. Because EM302 has 16 sectors (dual swath), the beam pattern in the different sectors will present slight differences and these differences will affect the beam pattern residuals at the sector boundaries. In addition, due to the seafloor's geometry changes, the angular response will also affect the backscatter strength of seabed sediment types.

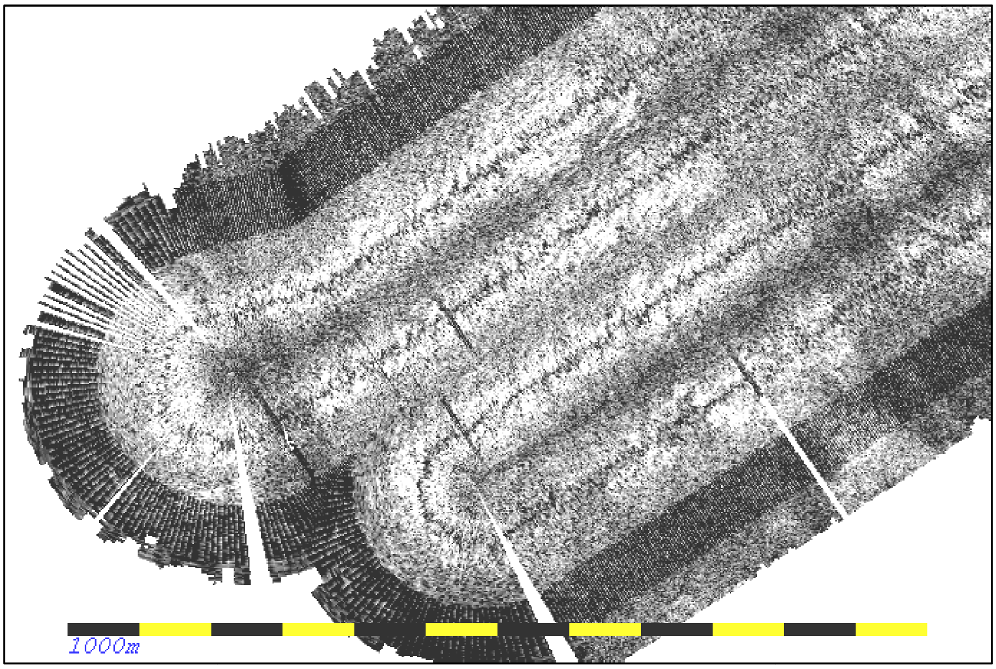


Figure1. 2 The EM302 backscatter mosaic image without any compensation.

Before the current modifications to the conventional OMG beam pattern correction software, Llewellyn (2006) had previously attempted to identify sector boundaries to fix the beam pattern residuals in an older EM300 which was a multi-sector but single swath multibeam. However, his algorithm still had some limitations which was that the exact angle of each sector boundary was not always precisely predicted and the algorithm was not designed to deal with multi-swath.

Therefore, the motivation of this work is to minimize the beam pattern residuals between the different sectors and different survey modes. The end result is to ensure that the backscatter mosaics can actually present a minimally artefact-affected indication of the seafloor sediments. The approach of this project requires computer programming to modify the current OMG software. This thesis will discuss the technical details of above mentioned issues, as well as outline the modified OMG software development in solving the beam pattern residuals of new generation multibeam system. Finally specific results for the four systems are presented to illustrate the effectiveness of the research.

Chapter 2: The multi-sector and multi-swath of Kongsberg Maritime multibeam echo sounder

As far as known, the conventional multibeam system has single sector and single frequency. Single sector multibeam systems may not achieve 100% ensonification coverage if the ship's orientation (yaw and pitch) changes too quickly. Nowadays, as the requirements of survey standards become stricter, the technologies utilized by multibeam system also have to improve. For example, if there is a commercial case that has a requirement for 100% ensonification coverage, sometimes the single sector and single swath multibeam systems may not achieve that requirement. Therefore, the new generation multibeam system has been designed to use multi-sector and multi-swath to provide more confidence in the 100% coverage of the ensonification.

2.1 System Parameters

To cover the full range of ocean depths, there are 4 general types of the Kongsberg Maritime multibeam echo sounder which have multi-sector and multi-swath capabilities: EM2040, EM710, EM302, and EM122. All of these sounders can use dual swath and have characteristics which are summarized in Table 2.1

EM2040

The EM2040 multibeam echo sounder is the latest generation of multibeam models and it is designed to be a flexible and high resolution system for surveys in shallow depths and which require very high resolution inspection. Although performance in excess of 400m depth is possible, the usual operational depth is commonly between 1m and 100m depth as the system angular sector becomes attenuation limited at greater depths. The system has an operating frequency region from 200-400 kHz. The system has 3 modes which use pulses centered at 200kHz, 300kHz, and 400kHz. The 200kHz mode has 4 sectors (maximum 2 sectors in each swath) and the 300kHz, and 400kHz have 6 sectors (maximum 3 sectors in each swath). Depending on the depth, all of them automatically vary the pulse length and type (Continuous Wave(CW) & Frequency Modulated (FM)). Each mode and pulse length combination potentially provides unique beam pattern residual for each of the up to 6 sectors.

EM710

The EM710 is a multibeam echo sounder for high resolution surveys from shallow to medium water depths. The system has an operating frequency from 70-100 kHz and the maximum survey range is from 2-2000m. Optimal depth ranges are from about 10m to 500m as the system angular sector becomes attenuation limited at greater depths. EM710 can be offered with different range and resolution performances by choosing different transmitter and receiver beam widths. For all depth ranges 3 sectors per swath are used. The EM710 can also provide 6 sectors in dual swath mode. The dual swath mode has 4 survey depth modes which are Very shallow, Shallow, Medium, and Deep mode. Normally, they are using CW pulses of varying lengths. In order to increase the detection range, the Deep mode switches the outer sector to FM pulse.

EM302

The EM302 is a multibeam echo sounder that is designed to survey continental slope and rise depth ranges. The system has an operating frequency of 26-32 kHz and the maximum survey range is from 10-7000m. It is optimal for the range of about 100-2000m. Like the EM710, the EM302 can be provided with different transmitter and receiver array sizes and resulting beam widths. The maximum angular swath that can be reached is +/- 70°. The EM302 has either 4 or 8 sectors per swath and can do dual swath that depend on the survey depth mode. Although the EM302 has 7 survey depth modes, the dual swath option is available for just 4 survey depth modes which are Shallow, Medium, Deep, and Deep' mode. When the system uses Deep' mode, the outer sectors will be switched from CW pulse to the FM pulse. The extra long pulses used in FM mode mean that the duty-cycle limitation prohibits dual swath.

EM 122

The EM122 multibeam echo sounder is designed for full ocean depth surveys and suited for detailed seafloor mapping from 50-11000m in the ocean. The system has an operating frequency of 10-14 kHz and is capable dual swath. The EM122 can provide either 4 or 8 sectors per swath and provides dual swath for the CW modes that depend on the survey depth mode. The survey depth modes of the dual swath have 4 configurations which are Shallow, Medium, Deep, and Deep’ mode. To increase the detection range, the EM122 switch the outer sectors from CW pulse to FM pulse.

Technical specifications for multibeam systems				
System	EM 2040	EM 710	EM 302	EM 122
Operating frequency (kHz)	200-400	70-100	26-33	10-14
Range (m)	0.5-500	3-2000	10-7000	50-11000
Maximum coverage (Cold sea, gravel)	>800m 200 deg 10x water depth	2500m 140 deg 5.5x water depth	>8km 150 deg 5.5x water depth	>30km 150 deg 6x water depth
Beamwidths (degrees)	TX: 0.5, 1 RX:1 (at 300 kHz)	TX: 0.5, 1, 2 RX:1, 2 (at 100 kHz)	TX: 0.5, 1, 2, 4 RX:1, 2, 4	TX: 0.5, 1, 2 RX:1, 2, 4
System accuracy	>2 cm	0.2% × water depth	0.2% × water depth	0.2% × water depth
Maximum number of sounderings per ping	Up to 1600	Up to 800	Up to 864	Up to 864
Pulse form	CW&FM	CW&FM	CW&FM	CW&FM
Pulse length	25μs-12ms	150μs-120ms	0.7ms-200ms	2ms-100ms
Max ping rate (Hz)	50	>30	>10	>5
Transducer depth rating	6000 m	250 m	NA surface	NA surface

Table2. 1 The technical specifications for Kongsberg Maritime multibeam systems with multi-sector and multi-swath.[Kongsberg]

All these systems use individual transmissions for each sector. Those transmissions vary in centre frequency, pulse length, bandwidth and type, source level and beam pattern. It is essential to remove any sector-specific beam pattern before the backscatter is useful for seafloor characterization.

An empirical set of coefficients can be modified in the transceiver to try and minimize these residuals. The default values for these are often, however, not adequately adjusted in new installations resulting in noticeable sector and swath residual beam pattern.

2.2 Motion compensation of multi-sector and multi-swath sonars

In order to get the best detail of the bathymetry and target detection, one of the most important issues is to guarantee to get 100% coverage of seafloor ensonification. For the case of single-sector and single-swath multibeam data, the density of the multibeam data is affected by the ship’s attitude. Because roll affects lateral displacement of the whole swaths, this effect can be compensated by roll stabilization. Roll stabilization is achieved on receive and can be varied continuously with time so that a unique value is applied for each beam. Multiple sectors are not, therefore, necessary. Pitch stabilization, however, has to happen at time of transmit and for the case of a single sector can only use one transmitter steering angle. Effective yaw stabilization requires that one side of the swath be steered forward when the other is steered back. No amount of single sector steering can achieve both of these simultaneously and thus yaw stabilization is not possible with a single sector. When the ship has pitch effect, using only single sector steering, the density of data becomes different in the same survey line. Some parts of the swath corridor are denser and some parts are less dense. Thus, imperfect compensation for pitching and yawing is the key point that multi-sector systems are designed for. The new types of multibeam echo sounder, EM710, EM302, EM2040, and EM122 were designed to use multi-sector to better solve the effect of the ship's attitude. In addition they were also designed with a dual-swath mode to improve the along track density of the data. All these benefits come at the cost of complexity. This thesis addresses the problem of inter-sector backscatter radiation pattern differences.

If the swath coverage is disturbed by rapid changes in orientation of the ship, the confidence in complete coverage will be decreased. The orientation of the ship includes roll, pitch, and yaw. Each of them affects the data density in different ways.

Roll stabilization

The roll rotation will cause lateral displacement of the whole swath. The effect of the roll rotation results in irregular outer beam edges of the whole survey line and this effect will narrow down the guaranteed surveyed area as shown in Fig. 2.1. The amount of swath corridor reduction increases as one goes to wider angular sectors. To compensate for the roll effect, there needs to be continuous updating of the time delays used during receive beam steering to ensure that the beam maintains a constant angle w.r.t. the local level.

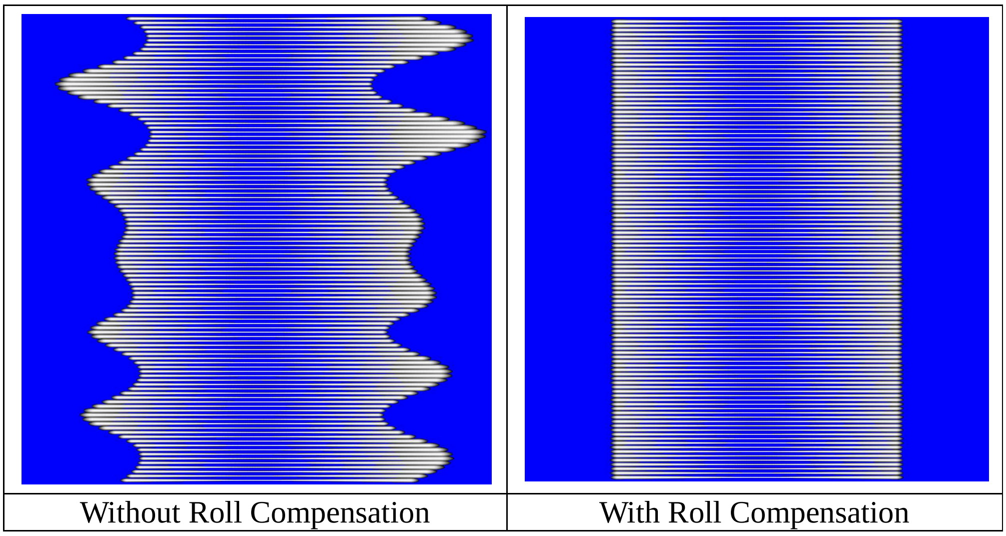


Figure2. 1The effect comparison of the data with roll compensation or without roll compensation. The data is 200×200m, 20m depth, 12 knots, 6X WD 1.2 degree bandwidth, and 0.3 second rep. rate. [Hughes Clarke, 2011 GGE3353 Notes]

Pitch stabilization

Most of the sonar receivers are installed with a port-starboard orientation which causes little effect on the beam position due to pitch. In contrast, the pitching of the transmission shifts the resulting transmit beam footprint fore-aft. Without compensation, the angles of pitch cause the along track profile spacing to become variable, resulting in either gaps or overlap. When active motion compensation of pitch is used, the transmit steering angle is relative to the long axis of the array so that the subtended angle with reference to the horizontal plane varies with the transmit steered angle. Although the active motion compensation of pitch can keep the along track spacing equidistant at nadir, this compensation when using only a single sector will also overcompensate at outer sectors. Alternately two points on either side can be optimally stabilized, the inner portion of the swath is then undercompensated as in Fig. 2.2.

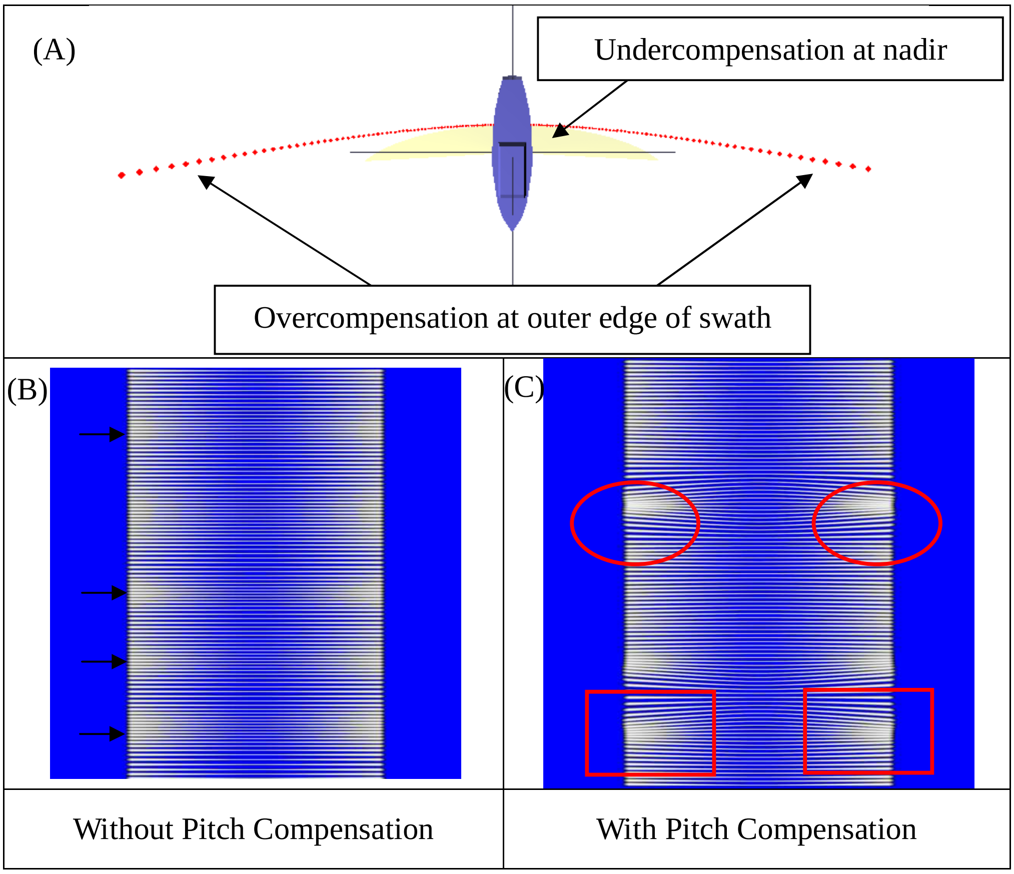


Figure2. 2 The pitch effect and the pitch active compensation. The data is 200×200m, 20m depth, 12 knots, 6X WD 1.2 degree beamwidth, and 0.3 second rep. rate. (A) shows how the pitch active performs. (B) shows the data without pitch compensation; the black arrows present the looser swaths and black arrows present the closer swaths. (C) show the data with pitch compensation; the red circles and squares present the overcompensation at outer sector. [Hughes Clarke, 2011 GGE3353 Notes]

The conventional multibeam sonar has one single fore-aft transmit line array and it generates a single transmit beam pattern which covers the full angular sector from the starboard side to the port side. As a result multibeam manufacturers apply conventional active pitch steering by choosing an incidence angle away from nadir at which the pitch compensation will be exact (Hughes Clarke, 2011 GGE3353 Notes). While the pitch active compensation performs, the beams which are inboard will be undercompensated and the beams which are in the outboard will be overcompensated. Therefore, to solve the effect of pitch, the new generation multibeam systems are designed to use the multi-sector capability. Each sector has an individual steering angle which is designed to optimize the combined effect of pitch and yaw stabilization for that particular sector alone. (See Figure 2.3).

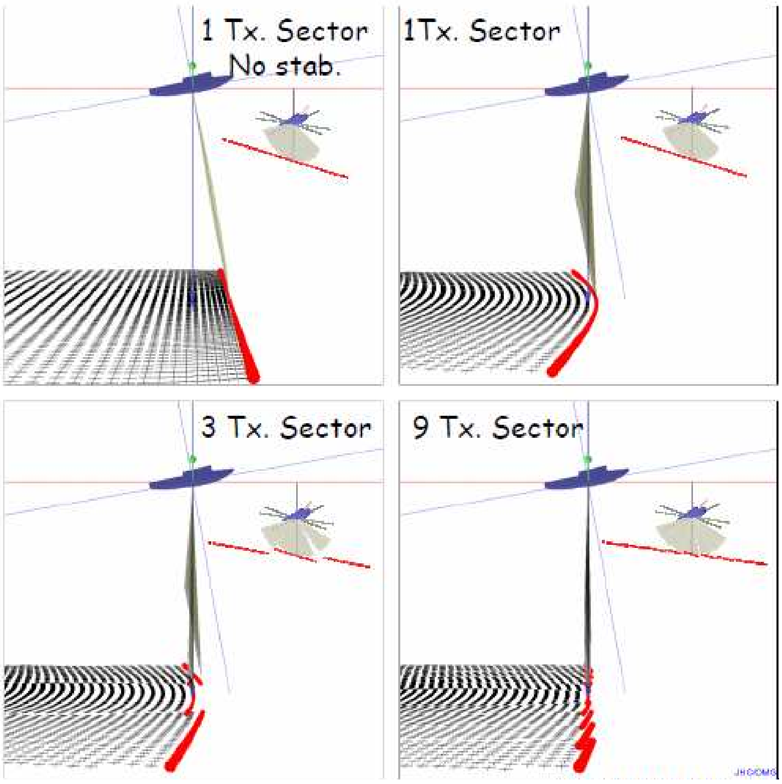


Figure2. 3 The pitch stabilization of single-sector and multi-sector echo sounder. The top two figures are the beam coverage of the single-sector echo sounder without or with pitch stabilization. The bottom two figures are the beam coverage of the multi-sector echo sounder with pitch stabilization. [Hughes Clarke, 2011 GGE3353 Notes]

While pitch stabilized is now significantly improved over single sector, this comes at the price of sector-specific beam pattern problems.

Yaw stabilization

In yaw effect, the data density is changed by the heading and it affects the beams coverage in the outer part of the swath. When the ship changes heading direction or is crabbing due to current or wind, the single line array multibeam system will gather denser or overlap ping coverage in the outer swaths on the side it is turning towards and sparser coverage on the other side. However, it was found that by using a single line array the yaw can only compensate one side at a time. To solve this problem the only way is to separate the beams in two or more discrete sectors and compensate for the effect by using different transmit steering angles.

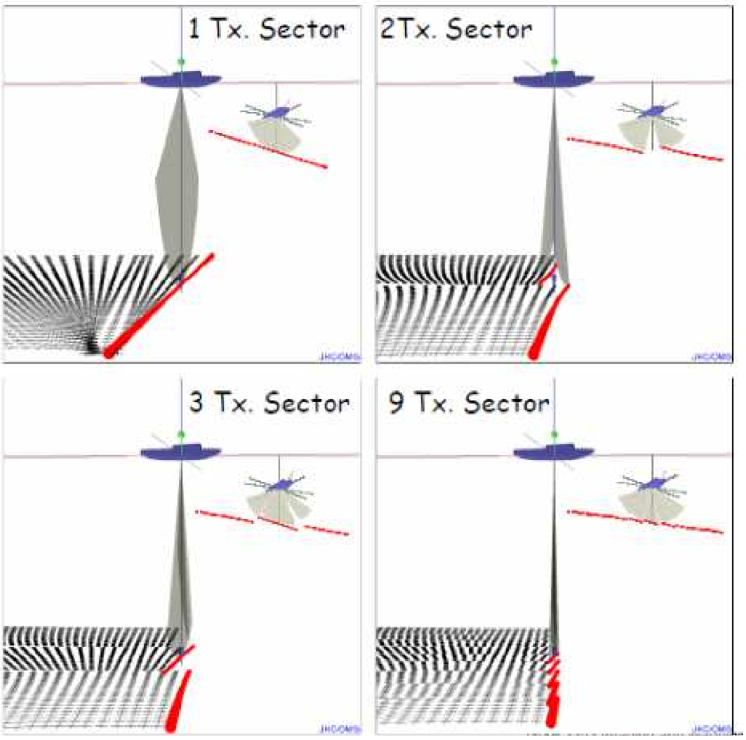


Figure2. 4 The yaw stabilization of single-sector and multi-sector echo sounder. The top left figure is the beam coverage of the single-sector echo sounder without yaw stabilization. The other figures are the beam coverage of the multi-sector echo sounder with yaw stabilization. [Hughes Clarke, 2011 GGE3353 Notes]

Again this requires multiple sectors and adds the complication of sector specific beam patterns which this thesis addresses.

2.3 Along-track resolution of the multibeam sonar systems

In a typical multibeam survey, the density of the ensonification is defined in two dimensions, across track and along track. The along track is controlled both by the transmitter's beam width and the inter-ping propagation distance. The across track is controlled by the receiver's beam width and beam spacing.

In addition to the problem of the rotation of pitch and yaw described previously, the ping rate can also affect the along-track density of the ensonification. The conventional multibeam has one swath per ping cycle. The ping rate is controlled by the ship speed and the water depth and the angular sector. Therefore, once the ship speed is too fast or the water depth is too deep or the swath angle too wide, the density of the ensonification in the along-track becomes insufficient.. In order to increase the confidence of the 100% ensonification coverage in the along-track, multibeam manufacturers have designed a new generation of multibeam systems with dual swath mode. The main idea of the dual swath is to generate two (or more in the future) times the along track density of ensonified footprints in a ping cycle. Figure 2.5 shows the difference between single swath and dual-swath. In the same ship speed, depth, angular sector, and ship attitude situation, the dual swath can double the coverage of ensonified footprints in the along-track. Achieving dual swath requires a second set of transmissions using discrete bandwidths. This only makes the problem of backscatter residual beam patterns even more difficult as these extra sector transmissions might again have different source levels and beam patterns.

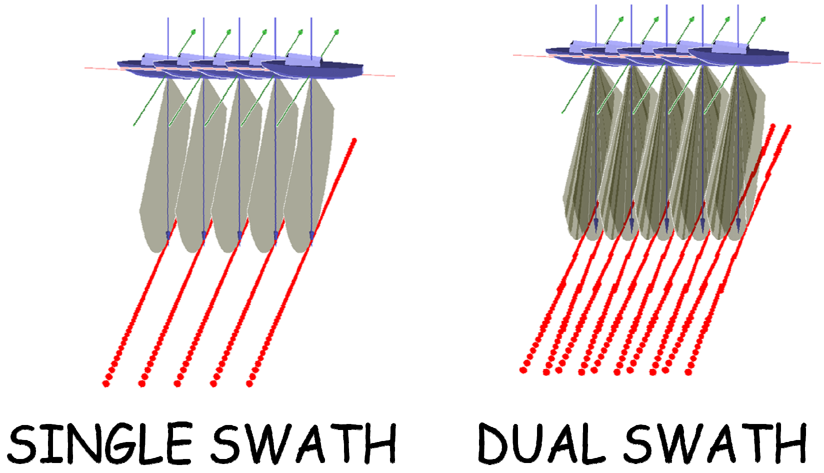


Figure2. 5 The different of the single swath and dual swath. [Hughes Clarke, 2010, GGE 5043 Notes]

2.4 Review of multi-sector and multi-swath multibeam sonar systems

Normally, the way the conventional multibeam system works is using single-sector and single centre frequency. However, as the multi-sector and multi-swath multibeam systems have become available, the single frequency may not be suitable. The new generation multibeam system has to transmit a sequence of pulses with non-overlapping bandwidths. Furthermore, since the transducers cannot generate two pings simultaneously, the individual transmission time of each sector may be separated by a few milliseconds. Having varying centre frequencies means that the seabed physical scatter process will be slightly different due to the differing wavelengths. This further complicates the apparent beam pattern residuals as it also includes the seabed angular response.

Figure 2.6 and 2.7 shows that to keep discrete frequencies of the multi-sector and multi-swath in the available bandwidth, one has to consider the bandwidth of each sector. If the multibeam sonar uses shorter pulses (broader bandwidth) to achieve range resolution, it must have fewer sectors (fit within available transducer bandwidth) and sidelobes in frequency must be controlled through pulse shaping.

Figure 2.6 and 2.7 shows the dual swath mode of the EM710 or EM 302. The number of sectors, transducer pulse length and type (CW & FM), and frequencies of the dual swath mode are changed by depth. Each sector has its unique frequency and pulse length. In some cases, as the depth increases, the multibeam echo sounder systems may keep the same frequencies in different survey depth modes. However, they change the pulse length to offset range resolution against signal to noise. To control the usage of a specific depth mode, users can also switch from automatic mode changing to a manually selected mode in the SIS system. These mode changes which affect the beam pattern residuals have to be distinguished by identifying all of the utilized centre frequency, sector number, pulse type, and pulse length parameters.

In order to get the optimal range resolution using a certain frequency, the multi-sector and multi-swath multibeam systems were designed to utilize different pulse lengths in different depth modes. The more sectors that a multi-sector and multi-swath multibeam system has, the better it can compensate for pitch and yaw to maintain the evenness of the ensonification. However, the maximum number of sectors within a multibeam system will be limited by the ratio of the pulse bandwidth (BW_P) and the available transducer bandwidth (BW_T).

The range resolution is limited by the bandwidth of the pulse. Higher bandwidth, achieved either through short pulse lengths (CW) or swept pulses (FM) can get better range resolution. For example, the range of operational frequencies of an EM 710 is between 70-100kHz and the available transducer bandwidth (BW_T) is thus 30kHz. If this system is using 0.2ms pulse length, the pulse bandwidth (BW_P) is 5kHz. Thus, the required separation of each sector in centre frequency has to larger the pulse bandwidth (BW_P). The maximum number of the sectors can be up to 6. In practise, the sector separation (SS) should be spaced ~1.5x BW_P to ensure no crosstalk between sectors. For example, a maximum of 4 district centre frequencies are used for EM710.

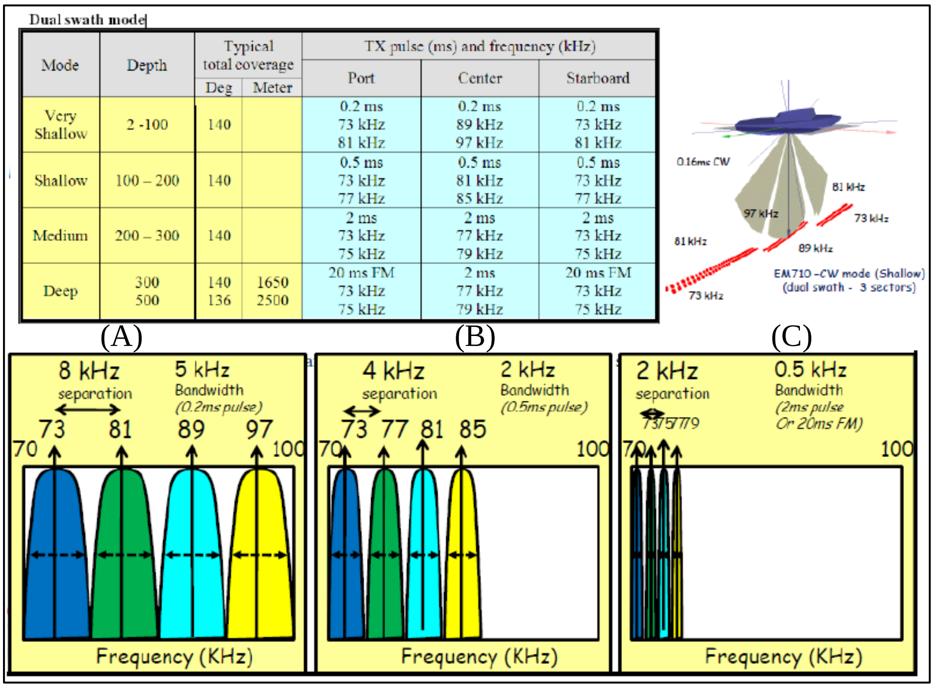
$BW_T \approx$ 10-40% of centre frequency

$BW_P = 1/\tau$ (τ : pulse length, for CW pulse) or $f_2 - f_1$ (for FM pulse)

$SS = (BW_T / n) \times 1.5$ (n : sector number)

$SS \geqq BW_P$

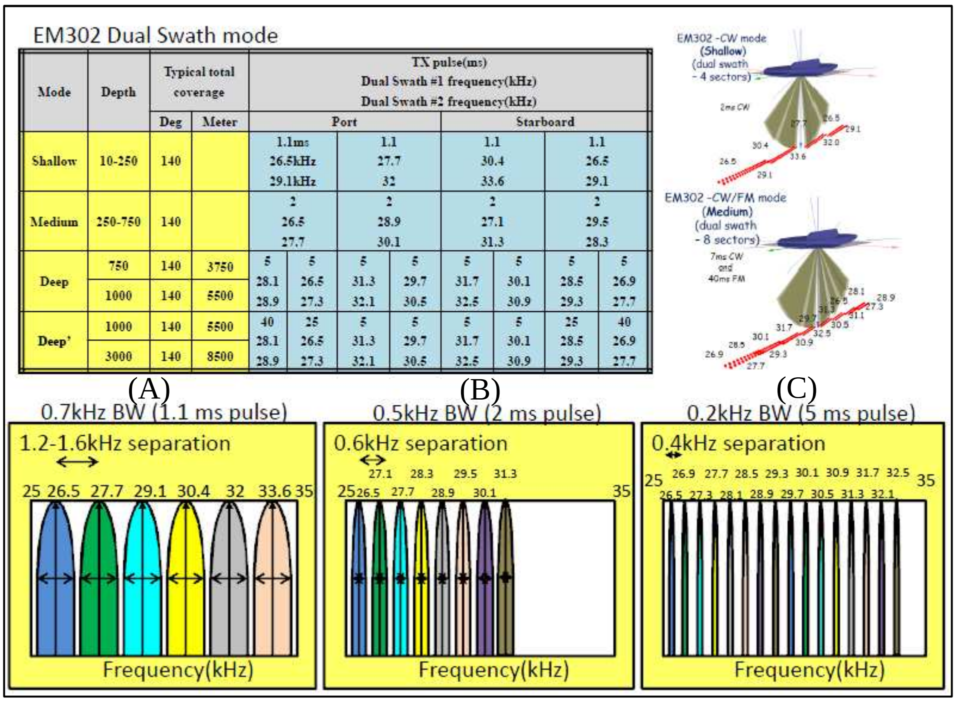
When the survey depth is getting deeper, the pulse length will increase to enlarge the ensonifed area to get better signal to noise ratio. As a result, the reduced pulse bandwidth (CW case) for the EM302 and EM122, thus allows the opportunity to have more sectors (switching from 4 to 8). For the EM2040 and EM710, however, as the attenuation changes so strongly over the range of the transducer bandwidth, the same number of sector are manufactured, using only the lower end of the transducer bandwidth. In Figure2.6 (C), in order to decrease the absorption coefficient (100kHz is 33 dB/km and 70kHz is 23 kHz), the higher end of the bandwidth will not be used (See Table3.1).



Dual swath mode

Mode	Depth	Typical total coverage		TX pulse (ms) and frequency (kHz)		
		Deg	Meter	Port	Center	Starboard
Very Shallow	2 -100	140		0.2 ms 73 kHz 81 kHz	0.2 ms 89 kHz 97 kHz	0.2 ms 73 kHz 81 kHz
Shallow	100 – 200	140		0.5 ms 73 kHz 77 kHz	0.5 ms 81 kHz 85 kHz	0.5 ms 73 kHz 77 kHz
Medium	200 – 300	140		2 ms 73 kHz 75 kHz	2 ms 77 kHz 79 kHz	2 ms 73 kHz 75 kHz
Deep	300 500	140 136	1650 2500	20 ms FM 73 kHz 75 kHz	2 ms 77 kHz 79 kHz	20 ms FM 73 kHz 75 kHz

Figure2. 6 The EM710 dual swath with three sectors options. (A), (B), and (C) show with the pulse length increased, the bandwidth will be decreased. [Hughes Clarke, 2010, GGE 3353 Notes].



Mode	Depth	Typical total coverage		TX pulse(ms) Dual Swath #1 frequency(kHz) Dual Swath #2 frequency(kHz)							
		Deg	Meter	Port				Starboard			
Shallow	10-250	140		1.1ms 26.5kHz 29.1kHz		1.1 27.7 32		1.1 30.4 33.6		1.1 26.5 29.1	
Medium	250-750	140		2 26.5 27.7		2 28.9 30.1		2 27.1 31.3		2 29.5 28.3	
Deep	750	140	3750	5 28.1 28.9	5 26.5 27.3	5 31.3 32.1	5 29.7 30.5	5 31.7 32.5	5 30.1 30.9	5 28.5 29.3	5 26.9 27.7
	1000	140	5500								
Deep'	1000	140	5500	40 28.1 28.9	25 26.5 27.3	5 31.3 32.1	5 29.7 30.5	5 31.7 32.5	5 30.1 30.9	25 28.5 29.3	40 26.9 27.7
	3000	140	8500								

Figure2. 7 The EM320 dual swath with three sectors options. (A), (B), and (C) show with the pulse length increased, the bandwidth will be decreased. [Hughes Clarke, 2010, GGE 3353 Notes].

Chapter 3: Multibeam backscatter overview

3.1 Sonar equation

As the above chapter mentioned, the Kongsberg Maritime EM multibeam systems can generate two main products, bathymetry and estimated backscatter strength. The bathymetry is the water depth which is computed by using two way travel time (TWTT), depression angle and azimuth of the each beam through the water column. The beam backscatter strength is also as part of the multibeam system data output. The backscatter strength is a property of the seabed that can potentially be derived from the intensity of the returned signal from the seabed which is used for bottom classification. Although, the type of the seabed bottom is one of the major controls of the received backscatter intensity, the return signal intensity is still affected by 4 other potential factors that modulate the across-track backscatter variations:

(1) Transmitter and Receiver beam patterns (per sector, per swath) including both source level and shape

(2) Attenuation of the water column (frequency and range dependent)

(3) Seabed grazing angle (GA)

(4) Ensonified area (pulse length dependent)

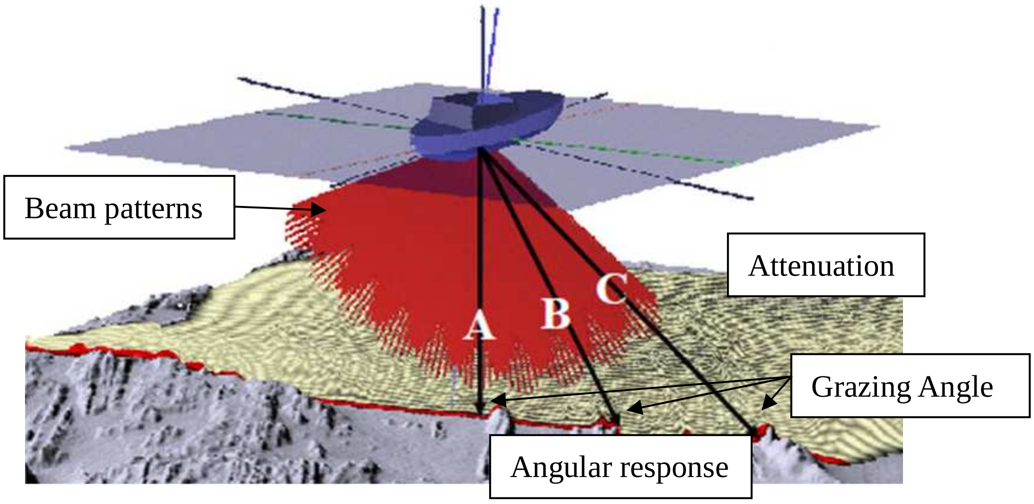


Figure3. 1 The 4 potential signals that modulate the across-track backscatter variations. [Hughes Clarke 2011, GGE5043 Notes]

Any correction applied to a sector is trying to compensate for all 4 factors. The following description explains the contribution of these factors.

The resulting signal to noise level in the ocean can be derived using the sonar equation (Urick, 1983):

$$SN = SL - 2TL - NL + BTS + DI \quad (1)$$

where,

SN = Signal to noise ratio

SL = Source level (include transmit power and angular variations) (factor 1)

2TL = Two way transmission loss (factor 2)

NL = Noise level

BTS = Bottom target strength (backscatter strength) (factor 3 & 4)

DI = Directivity index (an amplification due to narrowness of beams) (factor 1)

The echo level, EL, of the signal backscattered from the bottom, may be derived from the sonar equation,

$$\mathrm{EL} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{BTS} + \mathrm{DI} \tag{2}$$

3.1.1 Source Level

Because the transducer and receiver beam pattern is defined relative to specific angles (depression angle and azimuth angle), the source level term (SL) is directional (Figure 3.2). As most of the energy is constrained within a narrow azimuth range corresponding to the width of the transmitter main lobe, the major variation that needs to be accounted for is depression angle variations. Some transmit and receive patterns are stabilized with roll, others are not. Thus, when trying to remove these signatures, the data must be referenced either by vertically referenced or sonar-referenced depression angle, depending on whether the patterns are stabilized or not. For the case of KM sounders, most of the beam patterns are believed to be roll stabilized. Superimposed on the depression angle variations (the “shape of the pattern”) are the absolute source level and receiver sensitivity variations which are essentially static offsets between the sectors.

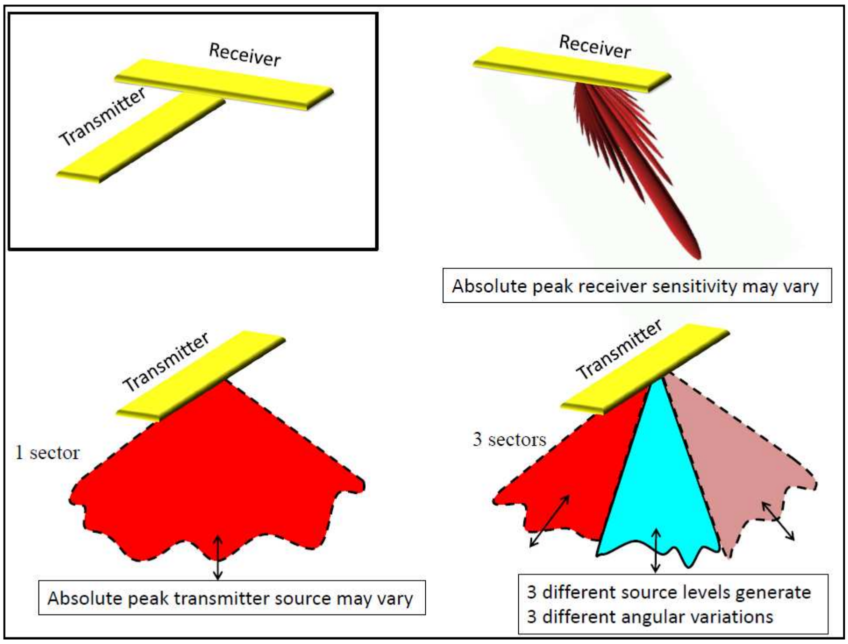


Figure3. 2 The angular variations of transmitter and receiver beam pattern.

3.1.2 Transmission Loss

The two way transmission loss is related to both the spherical spreading and the absorption losses in the water column:

$$2TL = 40\log R + 2\alpha R \tag{3}$$

Where R is the range to target and α is the absorption coefficient of the water column in dB/km which is strongly frequency dependent (Fig. 3.3).

The sound travelled in the ocean is attenuated by the absorption coefficient α (dB/km) of water column. The absorption coefficient is composed of two main structures: viscous absorption and chemical relaxation effects. By using empirical relation based on observations knowing Frequency, Temperature, Salinity, Depth, pH value, the absorption coefficient can be estimated (Francois & Garrison 1982) (Figure3.3). The equation of the seawater absorption coefficient at frequency f (kHz) is written as the sum of chemical relaxation processes and absorption from pure water:

Total absorption	=	Boric Acid Contribution	+	Magnesium Sulfate Contribution	+	Pure Water Contribution

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \tag{14}$$

Where the pressure dependencies are given by P_1, P_2 and P_3, and the relaxation frequencies are f_1 and f_2. The absorption equation in pure water affects all frequencies and the chemical relaxation is due primarily to Boric Acid smaller than 10 kHz and $MgSO_4$ smaller than 1 MHz. For the case of multi-sector sonars as each sector utilizes a discrete frequency, the change in α from sector to sector needs to be accounted for properly.

Kongsberg utilize an estimate of absorption in their multibeam system which does account for sector-specific centre frequencies. However, it is only as good as the input temperature and salinity values. If the default estimate value is wrong, it will have a range varying error in backscatter. This will distort the angular response curve, which is overprinted on the apparent beam pattern. This thesis does not address this issue and, meanwhile, a parallel MScEng thesis by Rodrigo Carvalho is examining both environmental variations (Temperature, Salinity, and Depth) and sonar variable variation (Frequency) and looking at approaches to correct for false input values.

MBES type	Frequency 1 (kHz)	Attenuation 1 (dB/km)	Frequency 2 (kHz)	Attenuation 2 (dB/km)
EM2040	400	95	200	53
EM710	100	33	70	23
EM302	34	8.4	26	5.3
EM122	13	1.5	11	1.12

Table3. 1 Seawater absorption range of 4 types MBES at the temperature=10°C, the salinity=35 ‰, the depth=100m, and the pH=8.

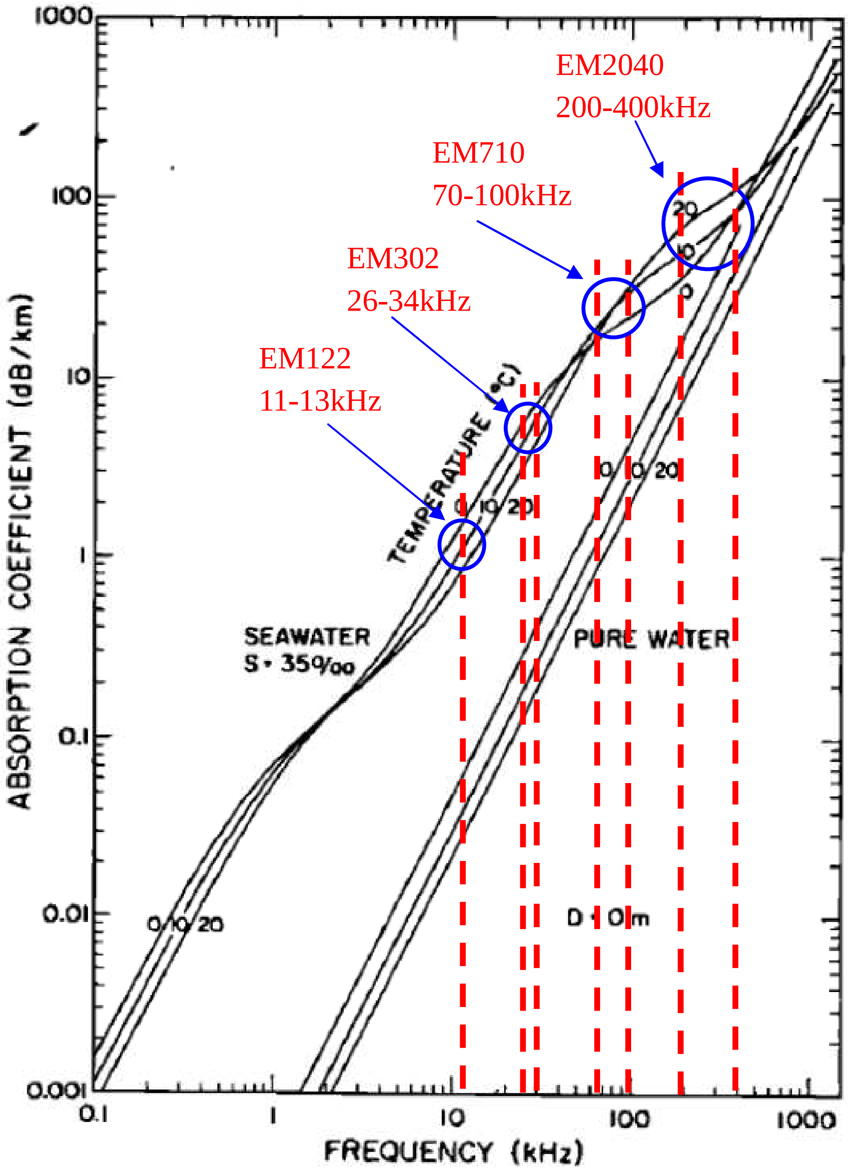


Figure3. 3 Seawater absorption at three temperatures (0, 10, and 20°C) for frequencies of 1000 kHz to 0.1

kHz as given by if the salinity=35 ‰ and the pH=8. The range of operating frequencies for the Kongsberg multi-sector sonars is overprinted. [Francois *et al.* 1982]

3.1.3 Bottom Target Strength

The bottom target stength will be affected both by the reflective property of the seabed, and by the area of the bottom that contributes to the backscattered signal at any time. It is normal to define the characterizing quantity for the bottom reflectivity as a bottom backscattering coefficient, BS(dB) and the backscattering area, BA, as the ensonified area.(Urick, 1954)

$$\mathrm{BTS} = \mathrm{BS} + 10\log(\mathrm{BA}) \tag{4}$$

The backscattering area will be controlled by the beam geometry that is defined as θ_x and θ_y(Figure 3.4), at normal incidence (0° incidence angle or 90° grazing angle (GA)) while in other directions it will be controlled by the alongtrack beamwidth θ_x, and the transmit pulse length, τ(Urick, 1954, Hammerstad, 2000)

$$\mathrm{BTS} = \mathrm{BS} + 10\log\theta_x\theta_y R^2 \quad \text{for } \varphi=0° \text{ (normal incidence angle)} \tag{5}$$

$$\mathrm{BTS} = \mathrm{BS} + 10\log\theta_x \frac{c\tau}{2\sin\varphi} R\ , \quad \theta_y = \frac{c\tau}{2R\sin\varphi} \quad \text{for } \varphi>0° \text{ (oblique incidence angle)} \tag{6}$$

Where

θ_x=Along track beamwidth

θ_y=Across track beamwidth

R=Range to target

c=Sound speed

φ= Incidence angle

τ=Pulse length

Notably, the ensonified area is affected by changes in pulse length, implemented by mode and by sector, which can show up in the data if not reduced properly. If the pulse lengths are not exactly as intended, or if the real time corrections are inadequate, then apparent shifts in the backscatter strength values will result at mode and/or sector boundaries.

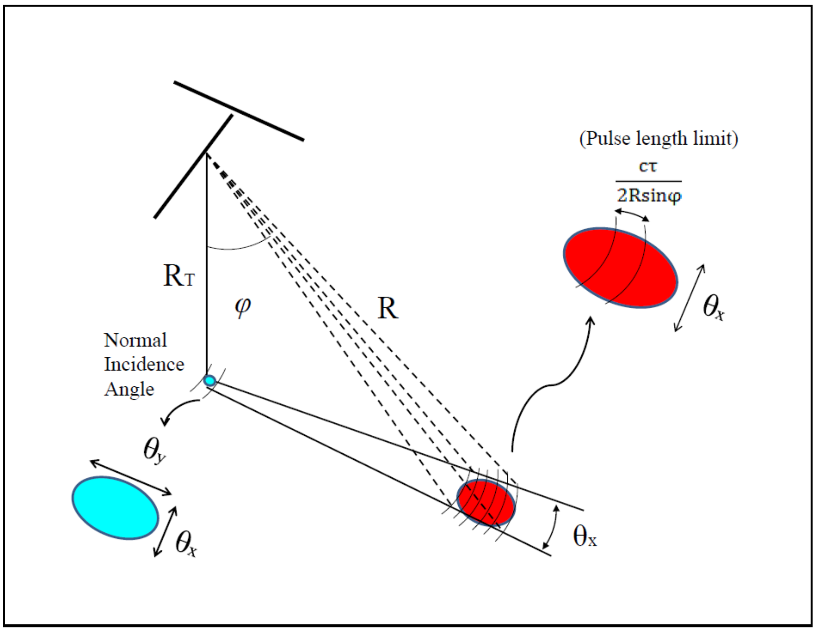


Figure3. 4 The ensonified area enlarged if the incident angle is increased.

3.2 Signal normalization and TVG

The receivers of most of the Kongsberg Maritime multibeam systems have a limited dynamic range and thus, a time-varying gain (TVG) is applied (note this is no longer the case for the newest EM2040). The TVG is used to avoid signal overload or amplify the returning target signal which is hidden in noise. The TVG for most commercial systems compensates for TL only. The KM TVG additionally attempts to compensate for changes in BTS with grazing angle. To extract variations in seabed reflectivity, the required normalizing TVG run in Kongsberg Maritime multibeam systems is predicted before reception, and is designed so that the average signal level in the receiver is at an optimum level.

The Kongsberg Maritime EM multibeam echo sounders all have beam backscattering strengths and optionally seabed image reflectivity as part of their data output. These data may be used for bottom classification, provided that how the data is collected and processed is clearly defined. Hammerstad (2000) described the assumptions inherent in the KM TVG. One of the main factors is the model of the shape of the seabed angular response (AR). Three terms are defined : BSo, BSn, CA, described below.

From the Backscatter Strength and Grazing Angle curve chart, if a uniform flat bottom is characterized by a mean backscattering coefficient, BS_O, and that the angular variation is given by Lambert's law, i.e. :

$$BS = BS_O + 20\log(\cos\varphi) \tag{7}$$

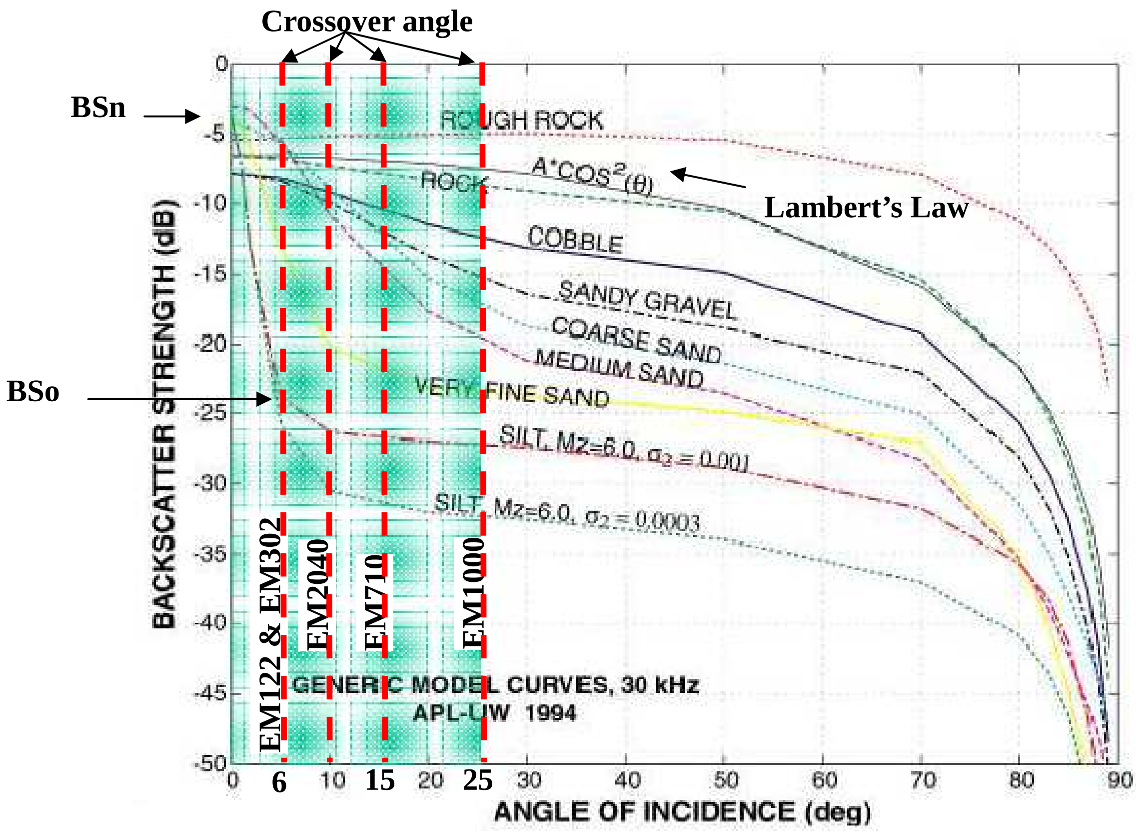


Figure3. 5 The relationship of backscatter strength and the angle of incidence. [deMoustier, 2010 multibeam course Notes]

Hammerstad(2000) explained that if the incidence angles are small (grazing angles are large), the Kongsberg TVG has assumed the backscattering coefficient is a linear line decreased from BS_N at 0° to BS_O at an angle which the backscattering coefficient curve starts to become flatter (See Figure3.5). The angle is the crossover angle (CA). For each of the main frequencies used by Kongsberg systems, a default crossover angle CA is used reflecting typical sediment AR curves at that frequency. If the incidence angle is larger than CA, the AR is assumed to become Lambertian. The range R at the CA and the range to normal incidence R_I is defined as:

$$R = R_I \sec(CA) \qquad (8)$$

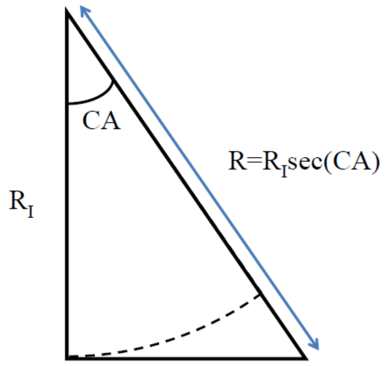


Figure3. 6 The relationship of the range to the normal incidence crossover angle (CA).

Thus, Hammerstad (2000) replaced the equation by the R and R_I to present the full model for the backscatter coefficient in Kongsberg TVG. When the incidence angle is located in 0°, R $\leqq$ R_I, the equation (9) will be applied. When the incidence angle is located between 0° to CA, R_I <R<sec(CA)R_I, the equation (11) will be applied. When the incidence angle is larger or equal to CA, R$\geqq$1.1R_I, the equation (10) will be applied.

$$BTS = BS_N + 10\log\theta_x\theta_y R^2\,, \quad \text{for } R \leqq R_I \qquad (9)$$

$$BTS = BS_O + 5\log\left(\frac{R}{R_I}\right)^2\left[\left(\frac{R}{R_I}\right)^2 - 1\right] + 10\log\frac{c\tau}{2}\theta_x R\,, \quad \text{for } R \geqq \sec(CA)R_I \qquad (10)$$

$$BTS = BS_N + 3.162\sqrt{\frac{R}{R_I} - 1}(BS_O - BS_N) - 5\log\left(\frac{R}{R_I}\right)^2\left[\left(\frac{R}{R_I}\right)^2 - 1\right] + 10\log\frac{c\tau}{2}\theta_x R\,,$$

$$\text{for } R_I < R < \sec(CA)R_I \qquad (11)$$

The Kongsberg multibeam system backscatter normalization for angular response is based upon the equation (9), (10), and (11) to run the TVG law. The crossover angle was fixed at 25° for the old EM1000. Other default values of the crossover angle are used for

EM2040 (at 10°), EM710 (at 15°), EM302 (at 6°), and EM122 (at 6°). Thus, when using different types of MBES to survey, the crossover angle default setting will change. The BS_O which is relative to crossover angle will also change the TVG law (see Figure3.5).

The R_I, BS_N and BS_O are estimated based on previous pings. However, the crossover angle is different for different sediments and frequencies. For example, in Figure 3.5, the crossover angle of the silt is about 10° and the crossover angle of the gravel is about 30°. The crossover angle of different sediments is frequency dependent as it also depends on the wavelength λ. The default setting of the crossover angle in the Kongsberg multibeam system will influence the TVG law to adjust the backscatter strength.

Kongsberg Maritime EM Multibeam echo sounders try to flatten the Backscatter Strength by using Kongsberg Maritime EM Sidescan Flattening Algorithm (Hammerstad, 2000). Assuming the seafloor is flat, if the grazing angle (GA), θ, is between 90° to (90° −CA), the Backscatter strength will be decreased with range (equation (12)). If the grazing angle (GA) is between (90°-CA) and 0°, the Backscatter strength will be increased with range (equation (13)). (See Figure 3.7)

$$\Delta BS = (BS_N - BS_O)((\theta - GA - CA)/CA) \quad \text{for } 90° > \theta > CA \tag{12}$$

$$\Delta BS = 10\log(\sin^2(\theta)) \quad \text{for } GA > \theta > 0° \tag{13}$$

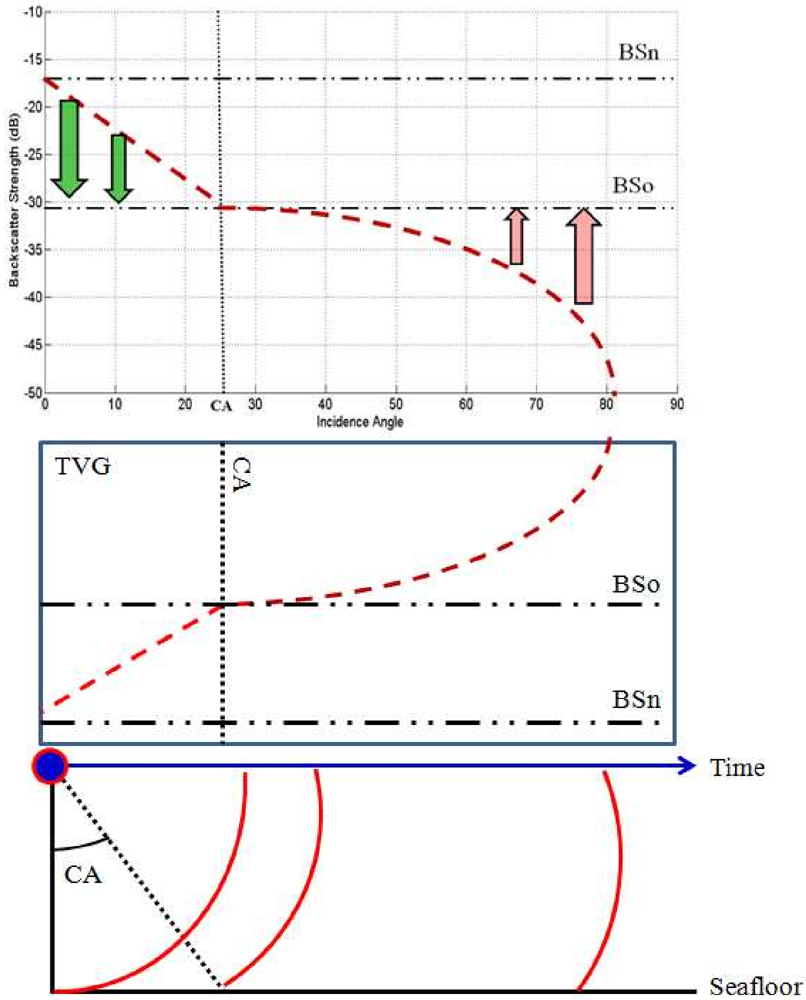


Figure3. 7 The relationship of backscatter strength, TVG, and incidence angle.

Because of the sediment interface roughness and the sediment volume inhomogeneities, the varying model of angular response curves is different in different types of the seabed. From above algorithm, the Kongsberg Maritime system, based on the results of preceding pings, computes the best approximate response curve and the values of BS_O and BS_N. However, the value of CA is fixed and not altered based on the preceding pings. This limitation can cause artifacts in seabed imagery data.

Another limitation of the grazing angle term (GA) in this algorithm is that it assumes the seabed is flat. If it is not, the TVG will be applied erroneously as the true grazing angle (GA) and ensonified areas are not as modeled. The limitation of not having exactly the correct grazing angle and the crossover angle not mimicking the real shape of the angular response (AR) on the TVG is most critical close to normal incidence. The changes in AR and ensonified area at that geometry are very sensitive to grazing angle. Away from normal incidence unless there is strong topography, this issue is not so critical. This limitation is recognized but is not addressed by this thesis. The OMG code "***deTVG***" (Beaudoin, 2006 unpublished) does attempt to address this factor.

3.3 Importance to this work

While the stated aim of this research is to compensate for inter-sector beam pattern residuals (both shape and absolute level), in reality, the signature of both the AR and KM TVG will also influence the resulting appearance of the backscatter strength. In practise, the compensation involves an attempt to flatten the combined BS response.

To illustrate the impact of the AR and the KM TVG, an explaination of the effect is described below.

Angular response

For the simplest case of a flat seafloor, a given seabed type will exhibit a variation in BS with grazing angle that will appear to be constant also in vertically referenced incidence angle (VRIA). Without prior knowledge of the shape of the AR, it will be practically impossible to separate the beam pattern and AR contributions to the observed VRIA variations. As a result the old OMG beam pattern correction flattened the product of both signals without trying to separate them.

This combined correction is fine as long as two criteria are met:

(1) the shape of the AR doesn't change (i.e. the seabed sediment type is smiliar).

(2) the seafloor is flat enough that VRIA and (90－grazing angle) are reasonably equivalent.

If the seabed AR changes along a survey line, then the combined beam pattern and AR product will be altered. If one tries to reduce the combined effect from one seafloor AR type, when the product has been estimated using another seafloor AR type, the flattening effect will have residual artefacts (See Figure 3.8). This effect will be most distinct at those grazing angles where the AR is steepest and most variable between typical sediment types. In practise, this is close to normal incidence.

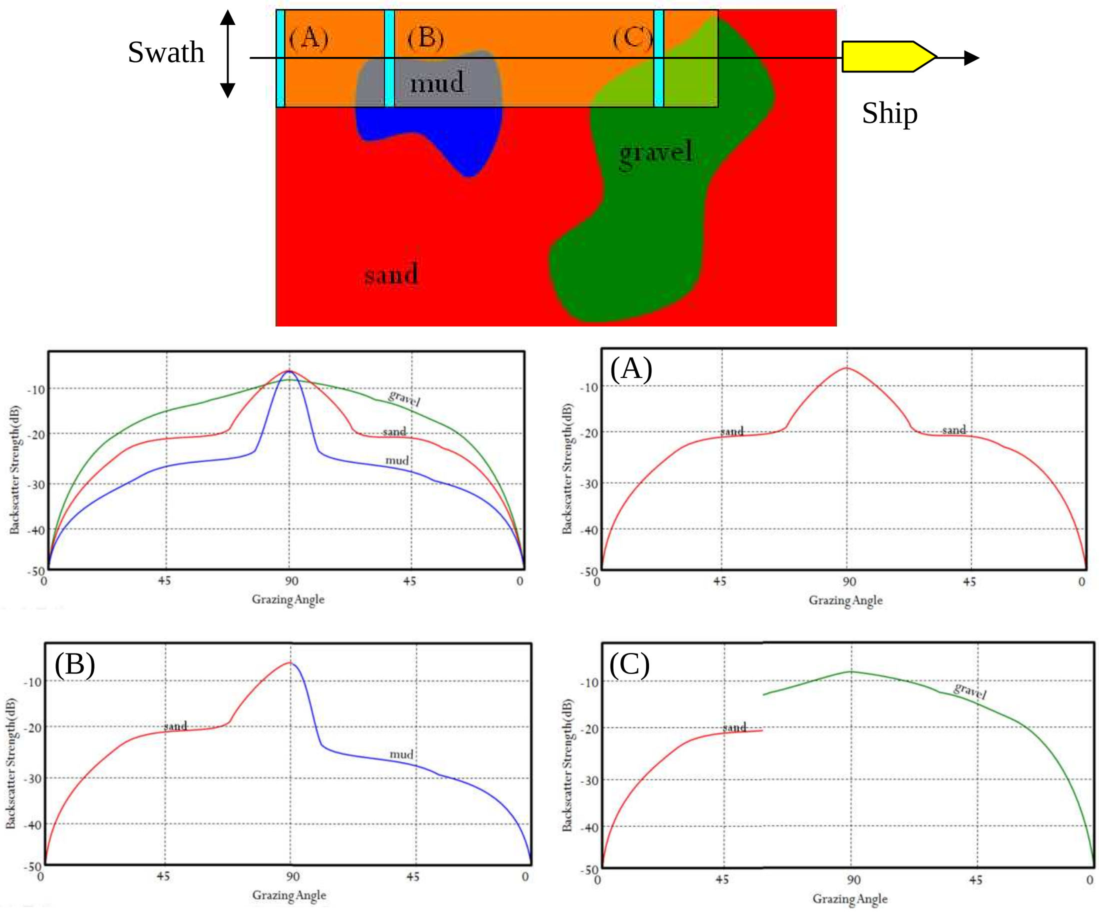


Figure3. 8 The Angular response in a survey area with mixed regions of mud, sand, and gravel sediment. The top left chart is the angular response curves for mud, sand, and gravel. (A) is the sand angular response curve when surveyed in the sand seabed; (B) is the sand and mud angular response curve when surveyed in the half sand and half mud seabed; (C) is the sand and gravel angular response curve when surveyed in the sand and gravel seabed.

For a flat seafloor, normal incidence occurs at nadir and thus the combined response would expect a peak at 0° VRIA. As soon as the seafloor is sloping the peak will be more off to the side. Along a typical swath corridor, the seafloor slope will vary and thus this peak BS will migrate back and forth in VRIA. If an average VRIA response is acquired through stacking data as the seafloor slope varies, the real peak in the AR (fixed in grazing angle) will be smeared out in VRIA. This effect is also true at oblique VRIA if one has steeply inward facing slopes, or cast shadows.

Because one normally has no a priori knowledge of the shape of the AR, even though the grazing angle is known, the effect of the unknown AR overprint on the VRIA-reference beam pattern cannot be separated.

In the ideal case where the seabed type is known, and the grazing angle is also known, the unambiguous inter-sector beam pattern variation can be extracted with more confidence. In the general case, however, where the seabed response is unknown, the AR and the beam pattern have to treated together. This approach is built into the code develop as part of this thesis.

KM TVG

All of the Kongsberg Maritime multibeam systems reduce the BS by assuming the seafloor is locally flat. As a result, the actual non-flat topography of the seabed corrupts the apparent backscatter response by virtue of having slightly different grazing angles and instantaneously ensonified area than modeled. Figure 3.9 illustrates an example of surveying on a sloping seafloor. The grazing model of the KM TVG will assume the minimum range to the sloping seafloor as the nadir range Ro. Then, the systems assume this nadir range Ro as the depth of the flat seafloor model. At the range of the seafloor Rn, the position of the model grazing angle (θ_{model}) will be located farther away and shallower than the position of the true grazing angle (θ_{true}). Moreover, the ensonified area is also changed due to the actual grazing angle.

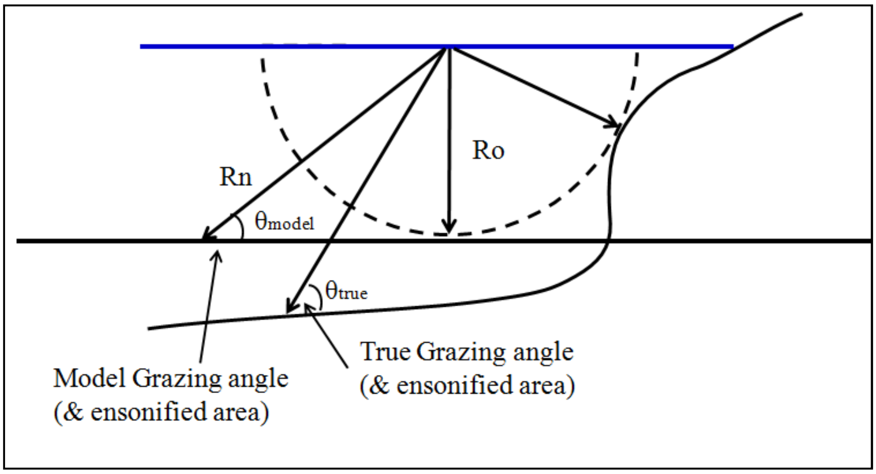


Figure3. 9 The comparison of the model grazing angle and true grazing angle.

This can now fully be compensated for using the OMG ***deTVG*** algorithm (Beaudoin 2006 unpublished, examples in Brucker *et al.* 2007).

Beam pattern

The actual beam pattern of KM multibeam systems is not something that can practically be measured in isolation. The only way to estimate the beam pattern is by using the apparent backscatter strength of the seabed to exhibit the VRIA variations and use this as a proxy for the relative beam pattern of MBES. However, the estimate of backscatter strength from the KM multibeam systems contains all of:

- the seabed angular response (what is actually desired)
- residual artefacts due to imperfect assumptions in the KM TVG, and
- uncompensated residuals due to the sector-specific beam pattern.

Practically, it is very difficult to unambiguously extract the beam pattern from the angular response and KM TVG in the backscatter strength.

If one uses a multi-sector MBES to survey a seabed of known sediment type and slope (known AR and known GA), the beam pattern residuals of multi-sector MBES between ideal backscatter and real backscatter can be unambiguously observed (Figure 3.10). In practise, however, most of the survey seabed types are unknown and the distributions of the sediments are unpredictable (Figure 3.8). As described in the KM TVG section, to get an ideal backscatter strength in an unknown seabed is very hard. Therefore, when compensating the beam pattern residuals in a survey line by using an average of the BS, this beam pattern residual compensation will be minimizing the residual AR and KM TVG as well.

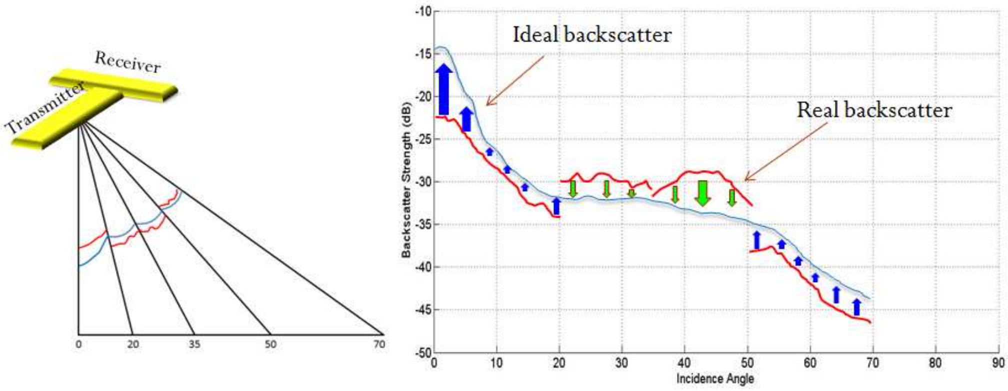


Figure3. 10 The Compensation of the beam pattern for multi-sector multibeam systems.

Chapter 4 Problems of Backscatter Beam Pattern Residuals and Previous OMG Solutions

One of the most important aims of the multibeam survey is seabed sediment classification. The properly reduced backscatter strength of the seabed is depended on to classify sediment types. A measure of the bottom backscatter strength (a dimensionless number) is desired. However, there are some effects that affected the signal return strength of the seabed. These effects generally can be separated into two parts: seabed geological change and transducer beam pattern effect.

4.1 Geology effects (Type and grazing angle dependence)

Although the Kongsberg Maritime multibeam system has the incidence angle normalization algorithm (Hammerstad, 2000, described in Chapter 3), the estimate of the backscatter strength of seabed is still not completely correct. The incidence angle normalization algorithm of the Kongsberg Maritime multibeam system assumed the seabed is flat. Therefore, the main angular response is provided, but a deviation in the slope will move the angular response curve up or down and this is not modeled. That means when you survey in an area which has the same sediment on the seabed, the seafloor slope angle is overprinted on top of the angular response.

The seabed angular response is considered a significant factor which affects the variations in received backscatter strength of the seabed across the swath. To consider the angular response, one has to be aware of the changing morphology of the seafloor. Due to the changing of the seabed slope, the grazing angles are not the same as the incidence angle (Figure 4.1). This is a recognized but separated problem. The problem addressed here is the angular variability in sonar transmission level and receiver sensitivity (beam pattern). Both the beam pattern and the angular response generate across-swath backscatter strength fluctuations. As described in Chapter 3, without a priori knowledge of the AR, in practice (and in this thesis) only the combined AR and beam pattern effect is removed. The AR is combined with the beam pattern effects and the product is then measured using vertically or sonar-relative angles.

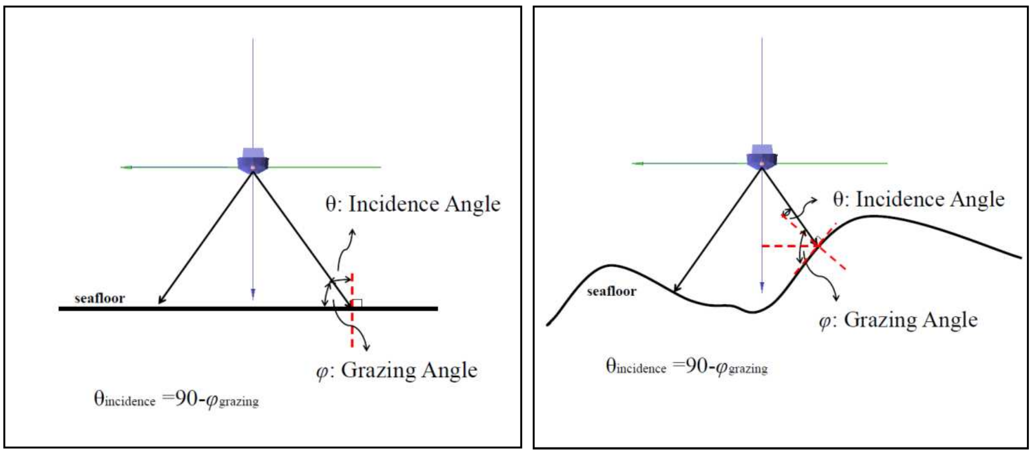


Figure4. 1The relationship of the incidence angle and grazing angle in flat and slope seafloor.

4.2 Backscatter beam pattern problems of multi-sector and multi-swath multibeam

As multi-sector multibeam echo sounder systems have been designed to increase the number of sectors and swaths, the transducer beam pattern of each sector became another factor to influence the backscatter strength of seabed. Variations in the power amplification and frequencies of multi-sector and multi-swath transducer make the receive backscatter strength of the same sediment appear different.

Since the transmitter and receiver and the associated electronics of each multibeam hardware are manufactured with slight differences, there are some factors which will cause the same seabed to exhibit apparent backscatter strength differently even when the same model of multibeam sonar is used (Hughes Clarke *et al.* 2008). The factors can be summarized as:

(1) Transmitter source level *w.r.t.* frequency

(2) Receiver sensitivity *w.r.t.* frequency

(3) Transmitter and receiver across track beam width and shape

(4) Scaling of the acoustic wavelength with respect to seafloor roughness elements

(5) Actual pulse length achieved with designed specifications

(6) Method of reduction of FM pulse through match filtering

Although designed identically, the sensitivities of transducers and receivers are slightly different in each multibeam hardware. While Kongsberg models those sensitivities, based on design criteria, the actual resulting patterns differ slightly from unit to unit, and do not provide exactly the design values. Sometimes, the same type of model of multibeam system surveys in the same area on the identical seabed structures using the same frequencies but because of the variability in actual sensitivities of the transmitter and receiver, the backscatter strength will present different (Hughes Clarke *et al.* 2008). Moreover, it is noteworthy when the multi-sector and multi-swath multibeam systems survey an area by using discrete frequencies, each sector's sensitivity presents the seabed image slightly differently. For example, if a surveyed seabed type contains sandy gravel, because the sensitivities of the sectors are slightly differently, the other sectors may present the backscatter strength as medium sand or coarse sand. (See Figure 3.5)

In addition, the transducer across track beam width and shape is another factor that causes the beam pattern residuals. Each sector of a multi-sector multibeam system has its own beam pattern. Because of the curved shape of the sector beam pattern, the backscatter strength of the beams on the edge of the sector will be weaker while this sector ensonifies the seabed (See Figure 4.2 (A)). The Kongsberg Maritime multibeam system will auto compensated for the across track beam pattern (See Figure 4.2 (B)). The actual across track beam patterns (blue dash line) may deviate from the design model (black line) (See Figure 4.2 (C)). As a result, a residual will be left in the data which is the difference between actual and designed (See Figure 4.2(D)).

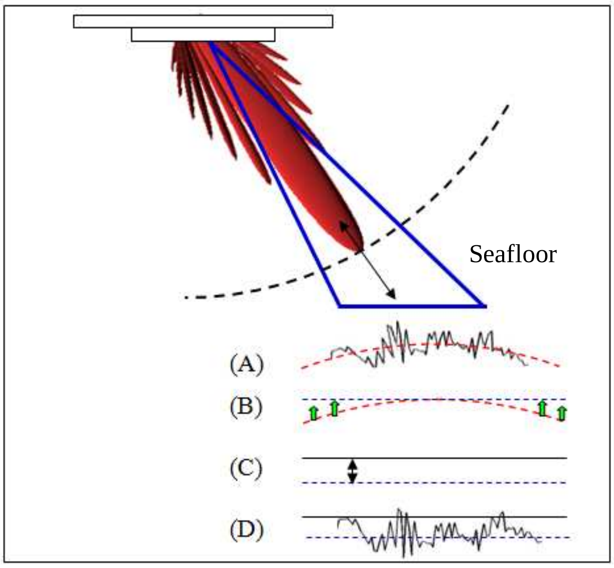


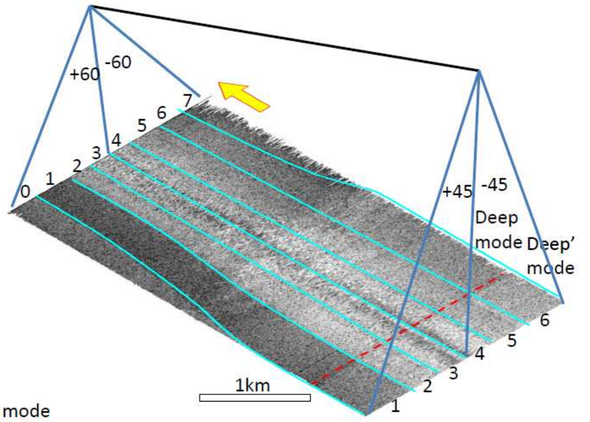
Figure4. 2 The auto stabilization of the sector beam pattern.

Scattering theory (Jackson *et al*, 1986) explains the physical controls on the level of the seabed backscatter strength (BS) as a function of seabed roughness with respect to the wavelength. Thus from sector to sector as the centre frequency is changed, one might expect a slight shift in the BS. According to APL-UW High Frequency Ocean Environmental Acoustic Model Handbook (1994), the average differential of different generic bottom types scattering strengths over the frequency range from 80kHz to 100kHz (~20%) is between -0.27dB to 0.42dB. Across multi-sector systems, the typical wavelength (λ) changes only 10-20% so this is a small effect.

The new generation of multibeam systems not only use separated frequencies in the multi-sector and multi-swath but also use different pulse lengths in different sectors of different depth survey modes. Even a single mode has multiple pulse lengths from sector to sector. When the pulse length changes in different sectors, while the beam pattern is not affected by the pulse length, the change affects the ensonified area and thus the signal level will be amplified or reduced by un-modeled pulse length variations. Such a shift in the signal level will appear to be a change in the beam pattern level.

Figure 4.4 shows a backscatter image of a survey line of EM302 that was collected by Canadian Coast Guard Ship (CCGS) Amundsen. The depth survey modes of this survey line are switched from Deep’ mode to Deep mode. When the EM302 multibeam system used Deep’ mode to survey, it has dual-swath and includes 8 sectors per swath. However, the data just shows 6 sectors in the survey coverage because the transmitter uses 8 sectors over +/- 70° but in order to keep the same swath width, uses a receiving angle only from +/- 60°. Thus, the data that used Deep’ mode doesn’t exhibit the outer sector. Figure 4.3 shows that when the survey goes from shallow to deep, due to an operator selection of fixed swath width in metres, the system will automatically reduce the angle of receiving. As the survey depth goes deeper, the outer sector will not be used.

Therefore, the EM302 outer sectors with FM pulse which are revealed in the Deep’ mode are sector 1 and sector 6 (of total range 0-7) and the nadir sectors which are sector 2 to 5 are CW pulse. As the seafloor got shallower the EM302 multibeam system changed to Deep mode, the receiver angle gets wider and the data now displays 8 sectors which are sector 0 to 7 and all sectors are CW pulse.



EM302 Dual Swath mode

Mode	Depth	Typical total coverage		TX pulse(ms) Dual Swath #1 frequency(kHz) Dual Swath #2 frequency(kHz)							
		Deg	Meter	Port				Starboard			
Deep	750	140	3750	5 28.1 28.9	5 26.5 27.3	5 31.3 32.1	5 29.7 30.5	5 31.7 32.5	5 30.1 30.9	5 28.5 29.3	5 26.9 27.7
	1000	140	5500								
Deep'	1000	140	5500	40 28.1 28.9	25 26.5 27.3	5 31.3 32.1	5 29.7 30.5	5 31.7 32.5	5 30.1 30.9	25 28.5 29.3	40 26.9 27.7
	3000	140	8500								

Figure4. 3 The multi-sector changed the receiving angle to keep the same swath width.

From Figure 4.4, one can see that there are beam pattern residuals that are caused by both sector boundaries and pulse-changes. However, the EM302 that is installed in CCGS Amundsen has another additional hardware problem with one of sectors. This sector of the EM302 multibeam is either a different power level or different receiver sensitivity so that the backscatter image has strongly different response signals. The backscatter strength of this sector shows as the black arrows in Figure 4.4. It is from just one sector in the 1st swath. Thus, the artifact appears and disappears every other swath.

As mentioned, the EM302 multibeam system which is installed in CCGS Amundsen has a strongly different response signals problem in one of its sectors. From Figure 4.4 (A), it is hard to recognize which sector and which swath causes this problem. To classify this sector, however, the only possible way is to separate each sector. If the dual swath data are separated into 2 separate swath images, one can see that the problem sector is just happening in the 1st swath (Figure 4.5(B)) and there is no problem sector in the 2nd swath (Figure 4.5 (C)). This method just distinguished the swath but we need to identify the specific sector. By using new extensions of ***getBeamPattern*** as a part of this thesis, each sector's beam pattern can now be separated by sector and by swath. By plotting the beam pattern of each of the multiple sectors from each of the two swaths, the sector which has strongly different response signals is seem to be located in sector 1 of the 1st swath.

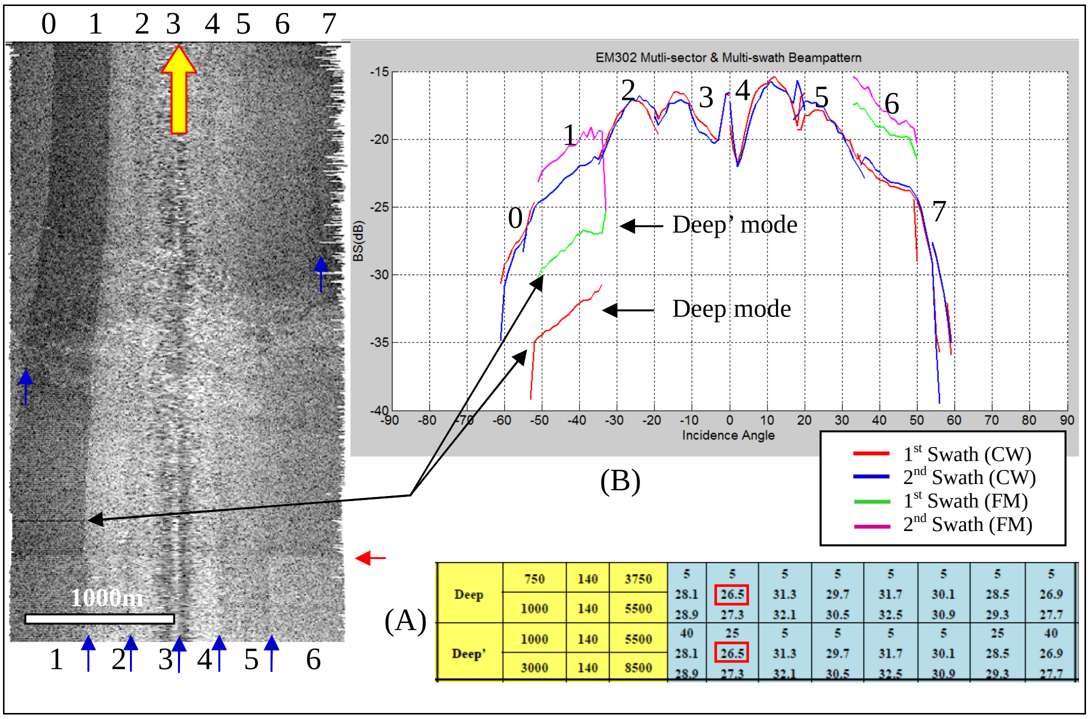


Figure4. 4 The backscatter mosaic images of EM302 that is installed in CCGS Amundsen. (A) is the backscatter mosaic image that is just automatically calibrated by Kongsberg Maritime echo sounder system. (B) is the beam pattern of the survey line. The yellow arrow is the survey direction; the black arrows show the problem sector; the red arrow is the pulse-changed beam pattern residuals; the blue arrows are the multi-sector beam pattern residuals.

Comparing Figure 4.5 (B) & (C), the 1st swath image shows the backscatter strength problem in sector 1 that is caused by either transmitter source level or receiver sensitivity. The absolute level of sector and swath changes slightly when the pulse length goes from CW to FM in the outer sectors (0, 1, 6, and 7) as the mode changes from Deep to Deep'.

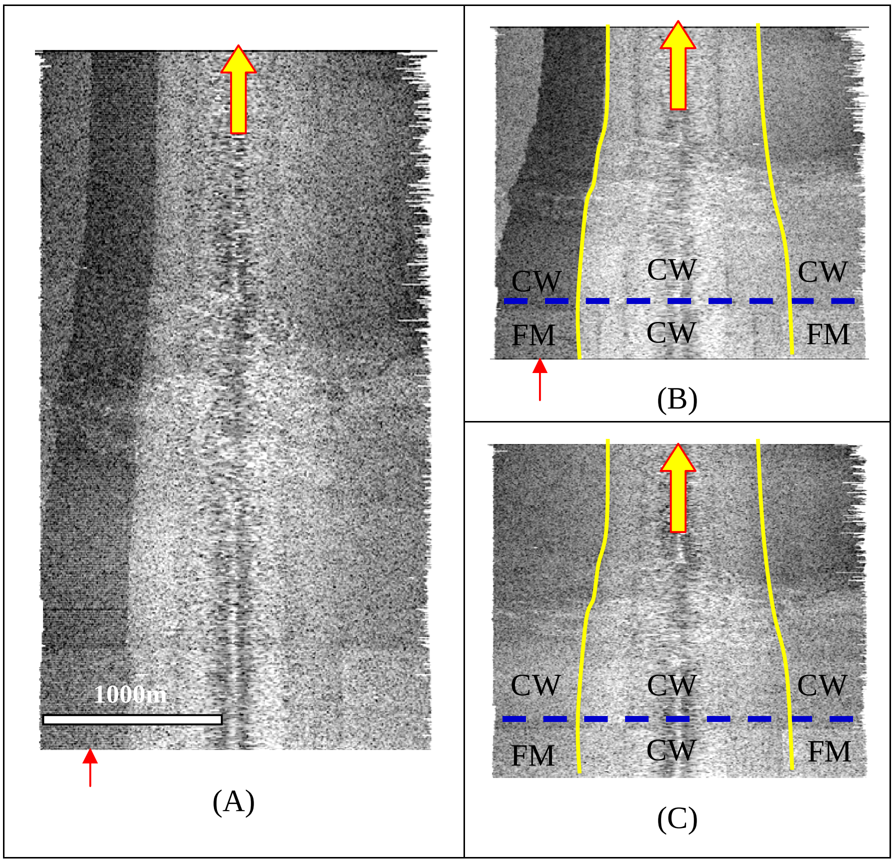


Figure4. 5 The dual swath of the backscatter mosaic images of the EM302 multibeam system. (A) is combined with 1st swath and 2nd swath; (B) the backscatter mosaic images of the 1st swath; (C) the backscatter mosaic images of the 2nd swath. The yellow arrows are the survey direction; the red arrows present the problem sector of the transducer.

4. 3 The solution and limitations of the original OMG software

To solve the above problems which are related to multi-sector and multi-swath EM302 multibeam system, modifications to the OMG software were developed as part of this research. The original OMG software provides two packages, ***getBeamPattern*** and ***makess***. They can be separated into 2 parts:

(1) ***getBeamPattern***: It is a beam pattern calculation software and is used to determine the backscatter strength fluctuation for the single sector Sidescan or multibeam. The pattern is derived with respect to the vertically referenced incidence angle (VRIA).

(2) ***makess***: It is backscatter registration software to combine the individual beam trace data into a horizontal range image. It also can be combined with a beam pattern correction file (from ***getBeamPattern***) to adjust the backscatter strength as a function of VRIA.

While it has previously been applied to minimize the beam pattern residuals in the multi-sector and single swath data (EM300, Llewellyn, 2006), it assumed that the sector boundaries were fixed in VRIA However, these two software packages are really just suited for single sector and single swath. In order to properly solve multi-sector and multi-swath multibeam, the algorithm of old OMG software has been changed to:

(1) Use ***getBeamPattern*** to pick, in turn, one of the sector center frequency (and associated pulse length and type) to normalize only the frequency, pulse length,

and pulse type of interest of whole survey line. Repeat in turn for all center frequencies, pulse length, and pulse type found. (Figure 4.6 (C))

(2) Stack and re-calculate the combined backscatter strength of beams with this frequency pulse combination and calculate the backscatter strength by VRIA.

(3) Calculate the average backscatter strength of the sector-specific backscatter strength patterns. (Note: this is the average of all sectors, not just individual sectors.)

(4) Then, use the average backscatter strength to compute each launch angle's backscatter strength differential for each sector that occurred at that angle.

(5) Finally, ***makess*** can use the new format output sector-specific backscatter strength differential to adjust the backscatter strength for each beam. The ***makess*** will take the new output of ***getBeamPattern*** and applies the new modification uniquely by sector.(See Table 4.1)

Beam Launch Angle(deg)	Average Beam Intensity by Stacking(dB)	Intensity Differential	Number of Beam Samples
0.000000	0.000000	0.000000	0
……	……	……	……
29.000000	-32.657410	8.637936	1902
30.000000	-29.939967	5.920493	68086
31.000000	-29.336249	5.316775	95610
……	……	……	……
179.000000	0.000000	0.000000	0

Table4. 1 The typical beam pattern format that generated by the original ***getBeamPattern*** software package. Note the pattern is binned into one degree segments.

By using the above old algorithm procedures, the result, Figure 4.6 (B), attempts at removing the multi-sector beam pattern residuals. Notably a problem exists with estimating the beam pattern residual at the sector edge. The sector edges (the blue arrows in Figure 4.6 (B)) still have offsets due to the multi-sector beam pattern residuals. The beam pattern residuals due to pulse changes (the red arrows) are even not improved in the survey line as they are no longer distinguished by a mode flag which only existed in pre EM710 format of Kongsberg Maritime telegram. Moreover, this algorithm is averaging 1^{st} and 2^{nd} swath so the backscatter response problem that are caused by the source level problem sector 1 in the 1^{st} swaths cannot be solved.

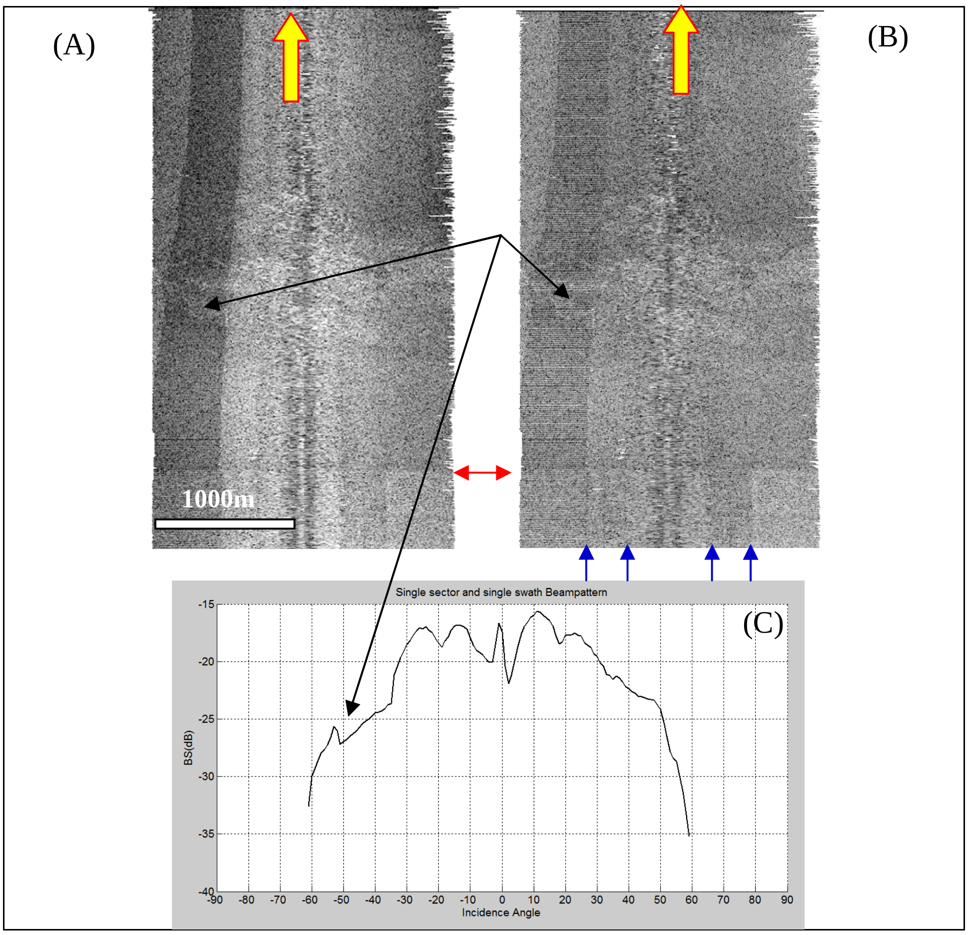


Figure4. 6 The comparison of backscatter mosaic images with and without the old OMG beam pattern correction. (A) is the backscatter mosaic image without the beam pattern correction. (B) is the backscatter mosaic image with the beam pattern correction. (C) is the normalization of the backscatter beam pattern ignoring sectors and swaths.

However, the old ***getBeamPattern*** would isolate beam patterns for specific "mode" (Llewellyn, 2006). This recognized that an entire swath might use a different pulse length and sector boundary (eg. EM300 Llewellyn, 2006). But it could not separate multiple "modes" within a single survey swath which was needed as a way to break up a swath consisting of multiple pulse lengths. As long as only one swath is present, and the sector boundaries don't move the old method worked. It coped with mode changes adequately as they used to be recorded in the telegram. The following sections review the method of Llewellyn (2006) as a precursor to describe the new algorithm developed in this thesis

4.4 The other solution for the beam pattern residuals (Llewellyn, 2006)

This section reviews the previous approach implemented by Llewellyn (2006). The old telegram formats of multi-sector multibeam systems did not record the information of the sector number, Llewellyn (2006) tried to use a multi-step solution in OMG software to correct for the multi-sector beam pattern residuals of the EM300 multibeam system, which are:

(1) Determine the angular location of each sector boundary

(2) Redefine the angular beam launch vectors which are used in both the beam pattern correction and backscatter production software

(3) Auto-processing for the mode-intelligent features of the beam pattern correction software which produces residual beam pattern models for different pings modes of the system

(4) Inter-beam interpolation on the produced beam models to account for any beams to which a statistically low amount of data was attributed.

4.4.1 Determination of the angular location of each sector boundary (Llewellyn, 2006)

From observing the original OMG software procedures, the operational mode is stored in the “Runtime Parameters” telegram and the beam angle for each given beam of a ping, which is depression angle, is stored in the “Depth” telegram. The sector angle is calculated as:

$$\theta_{beam} = 90° - \theta_{depression} \tag{14}$$

Since there was no sector information stored in the EM300 raw data, and the official designation of EM300 sector boundaries that was provided by Kongsberg Maritime were not correct, the only way to determine whether two adjacent beams belong to two different transmitter sectors is by examining the pitch steering angles. Therefore, there is no guarantee to determine an actual sector boundary location along the entire line of the multibeam data. What can be done, however, is to converge all swaths of the entire multibeam data and re-calculate the apparent new sector boundary angle based on: 1) the steering angle of the receive beam; 2) the roll of the ship at the moment of receive; 3) the roll installation angle of the transducer. See Figure 4.7.

$$\theta_{beam} = \theta_{steer} + \theta_{roll} + \theta_{installation} \quad (15)$$

Where:

θ_{steer} = Transducer-relative receive steering angle

θ_{roll} = Horizon-relative vessel roll angle at moment of receive (equal to the angle between the gravity vertical and the transducer boresite)

$\theta_{intallation}$ = Vessel-relative transducer installation angle

The θ_{beam} is used to define which sector. To get the θ_{roll} from "attitude" telegram in the raw data, it can be used to calculate the receive time and using the receive time to interpolate the receive beam angle. The equation is shown as:

$$T_{receive} = T_{initial\ ping\ time} + T_{sector} + TWTT \quad (16)$$

Where:

$T_{initial\ ping\ time}$ = Time of first sector firing (logged in raw Kongsberg Maritime telegram)

T_{sector} = Time delay caused by the interval between sector firing

TWTT = Two Way Travel Time

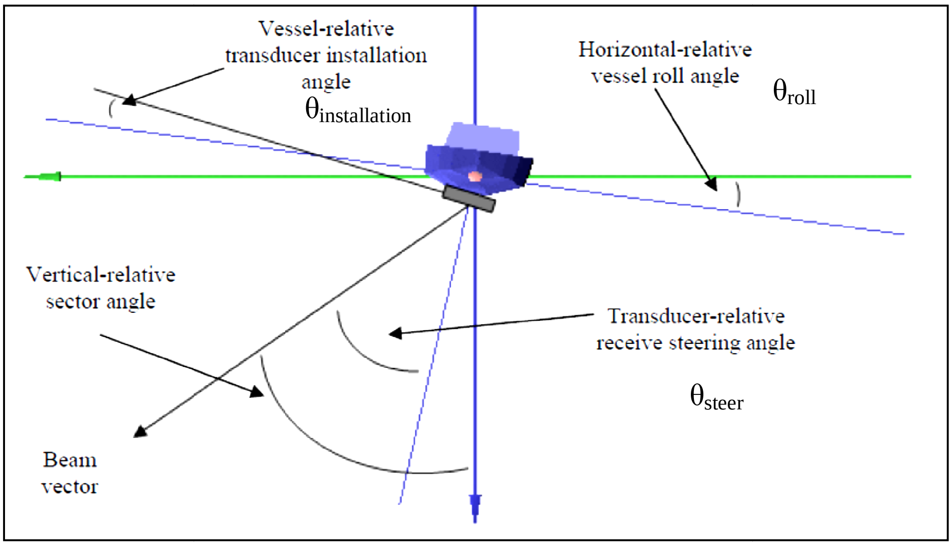


Figure4. 7 Individual angular components used to calculate the sector angle. [Llewellyn 2006]

After running the converging algorithm, the sector boundaries (angles) can be estimated and the sector boundaries described as Table 4.2.

Mode	Number of Sectors	Sector Boundaries (degrees) *positive=port, negative=starboard*
Extra Deep	3	5.0, -5.0
Very Deep	9	36.5, 23.0, 18.0, 5.0 -4.3, -16.2, -24.0, -34.0
Deep	9	53.0, 35.0, 27.0, 9.0 -8.0, -29.0, -36.0, -51.0
Medium	3	47.0, -44.0
Shallow	3	47.0, -44.0
Very-Shallow	3	47.0, -44.0

Table4. 2 The EM300 Sector Boundaries in Use by the System on CCGS Amundsen as Calculated Using Raw Angular Measurements. [Llewellyn 2006]

4.4.2 Redefinition of Launch Angles Using Raw Angle Determination (Llewellyn, 2006)

The launch angle of each beam is the fundamental information used in OMG software (***getBeamPattern*** & ***makess***). Conventionally, the OMG software calculated the launch angles by using the arc tangent of the beam's across-track distance divided by the beam's depth under the draft. The equation as shown below:

$$\theta_{launch} = \tan^{-1}\left(\frac{D_{across}}{D_{depth} - D_{draft}}\right) \tag{17}$$

Where:

D_{across} = The beam's across-track distance

D_{depth} = The depth of beam

D_{draft} = The draft of transducer

However, this equation does not achieve a perfect calculation to determine the launch angle. This equation approximates the entire beam ray trace as a single linear vector which means the launch angle is a gross simplification that is neither exactly the angle at which the sound arrives at the array, nor the grazing angle at which the sound impinges on the seafloor. In addition, there are some artifacts that are generated by the calculation of the equation (17). Therefore, instead of equation (17), Llewellyn redefined the definition of each beam launch angle by using the receive steering angle, roll of the ship at receive, and transducer installation angle in equation (15) and (16).

As these launch angle are redefined, the statistics of the beam samples of intensities are also re-sampled in angle. The residual boundary (See Figure 4.8) artifacts that are generated by equation (17) will be removed.

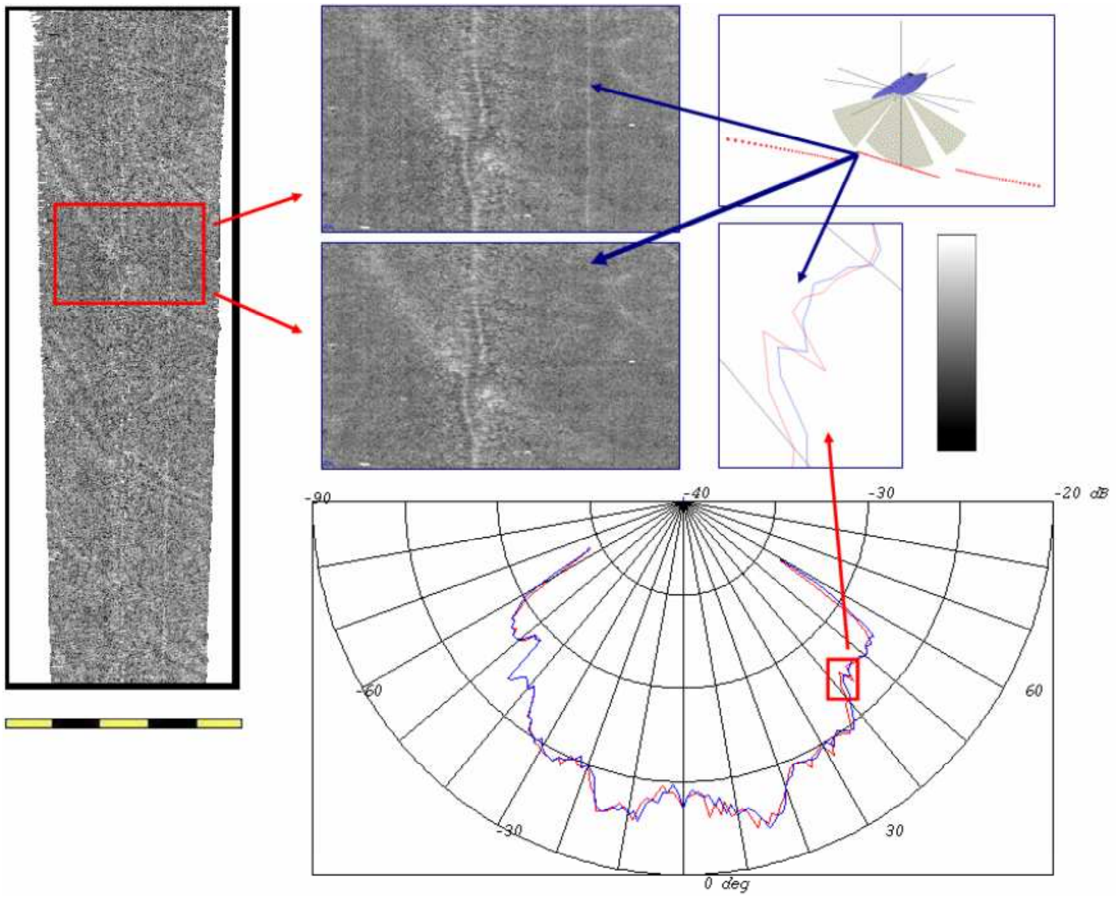


Figure4. 8 The EM300 multibeam system backscatter mosaic image using raw angle determination. (A) and (B) show the mosaics before and after the sector boundaries residuals are removed. (C) contains the residual beam patterns showing the difference between the beam patterns at the sector boundaries using the two types of angular determination. Here the red pattern shows the method of using the depth and across-track distance transformation, while the blue pattern shows the method of raw angle determination. One can see small yet frequent 1-2 dB shifts in beam pattern backscatter strength between the two plots. Water depth is 180m, with a backscatter range of -15dB to -40dB. [Llewellyn 2006]

4.4.3 Multi-mode solution

As well as the multi-sector beam pattern residuals problem, there is another problem that is affected by changed in the depth survey mode in a survey line. The change of multibeam depth survey mode depends on the seafloor depth. When the depth changes dramatically, there may be two or more depth survey modes in a single survey line. As Figure 2.7 shows, when the multibeam depth survey modes automatically change by depth, the pulse length, frequency and number of sectors are also changed.

The original or pre Llewellyn OMG beam pattern correction software, ***getBeamPattern***, allowed one only to stack all swaths and average as one beam pattern for an entire survey line. If a mode flag exists they could be separated by mode. For the new systems addressed in this thesis, mode changes are only implied by sector number, center frequency, pulse length, and pulse type. According to the result in Figure 4.6, however, if this one beam pattern is applied to a multi-mode and multi-sector data, the beam pattern residuals are still not removed.

The method that Llewellyn uses to solve the artificial problem of multi-mode is to use the software to extract modes that the system used during the course of the survey. That means the software will automatically generate unique beam pattern models for matching each mode.

4.4.4 Inter-beam interpolation within beam pattern models

The beam pattern models of the backscatter strength are stacked from the entire survey line. The entire beam launch angles are estimated as the nearest angle rounded to the outer degree within one degree bins; the OMG software processes the beam backscatter strength average. However, this method sometimes may cause one degree beams intensities of the beam pattern which are getting little or no data.

When the multibeam system is set in Equidistant mode, all beams are spaced at fixed across track intervals to keep inter-beam distance of the swath equal. The receive channels also have to spread out at a fairly large angular distance at nadir and closer at outer edges. Therefore, most of the problematic situations occur close to nadir where the resulting beam spacing can be more than a degree (See Figure 4.9). This beam pattern for the file shown in Table 4.3 indicating beam pattern effects due to a statistically low number of samples contributing to the average which is used to compute an overall beam backscatter strength.

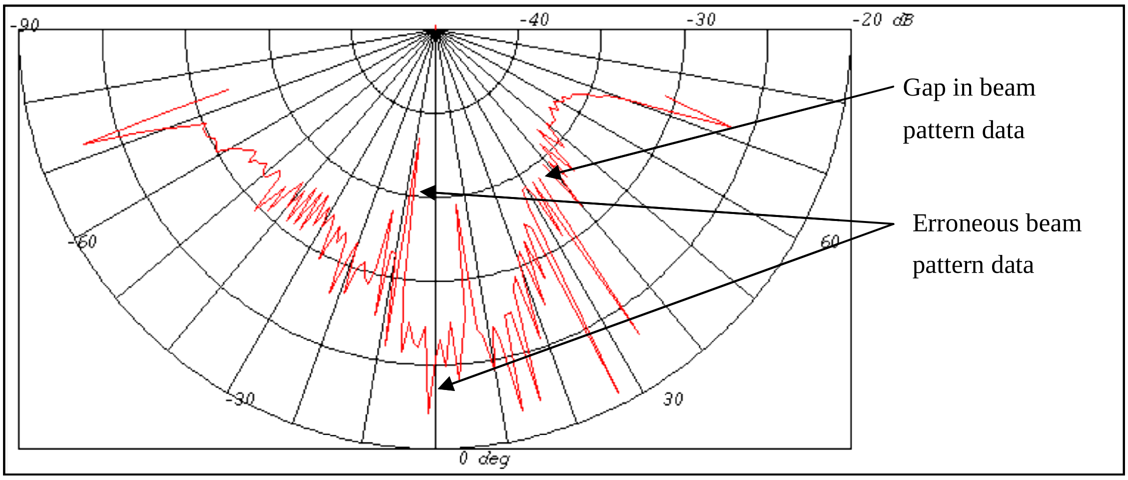


Figure4. 9 The EM300 beam pattern with missing and erroneous beam pattern data. This is the pattern for the file shown in Table 4.3, indicating erroneous beam pattern effects due to a statistically low number of contributing to the averages used to compute an overall beam intensity. [Llewellyn 2006]

To account for this problem, Llewellyn uses an additional function to run on the beam pattern model data structure created by the old ***getbeampattern***. The concept of this additional function is set 15% of the average number of samples per angular entry to be a minimum threshold value. Comparing each of the entries, if any entry is zero or less than the threshold value, the entry's backscatter strength information (beam backscatter strength, backscatter strength differential, and number of beam sample) will be interpolated by replacing or averaging the previous or/and next entry.

As will be discussed later, this approach with significant modification will be used to handle statistics with a low number of observations on the sector edges.

Chapter 5: Solution of the Backscatter Beam Pattern Residuals

Both the original OMG beam pattern correction software and Llewellyn's improved method can improve the beam pattern residuals in some certain situations, however, for dealing with multi-sector and multi-swath multibeam system, they have some limitations.

The original OMG beam pattern correction software was designed to process single frequency, single sector with only a single mode. Therefore, once it is used to process the multi-sector, multi-swath and variety mode, the resulting mosaic image will exhibit artifacts.

Because the pre 710 telegram of the Kongsberg Maritime multibeam echo sounder did not contain the sectors information before 2005, the algorithm of Llewellyn is designed to identify sector boundaries. The algorithm did minimize the beam pattern residuals but had limitations. The limitations are as follow:

(1) The exact angle of each sector boundary was not always precisely predicted.

(2) The algorithm of Llewellyn was not designed to deal with multi-swath because contrasting sectors from alternate swaths share the same angle.

Before a new "Raw range and beam angle (f)" datagram was added in the Kongsberg Maritime datagram format (Table 5.1), the only way to remove the beam pattern residuals was to determine which beam belongs to which sector by using Llewellyn's algorithm. This way is not only inefficient but also not accurate because the beams close to the sector boundary may still be assigned to an incorrect sector. After Kongsberg company provided a new Kongsberg Maritime multibeam output datagram in January 2009, the “Raw range and angle 78” datagram (Table 5.2) now contain the sector’s centre frequency, pulse length, pulse type (CW and FM), and transmitter sector number etc.. These information are important that they can be used to now exactly identify each beam’s attributes.

Data Description	Format	Valid range	Note
Number of bytes in datagram	4U	—	—
Start identifier = STX (Always 02h)	1U	—	—
Type of datagram = F (Always 46h)	1U	—	—
EM model number (Example: EM 3000 = 3000)	2U	—	—
Date = year*10000 + month*100 + day (Example: Feb 26, 1995 = 19950226)	4U	—	—
Time since midnight in milliseconds (Example: 08:12:51.234 = 29570234)	4U	0 to 86399999	—
Ping counter (sequential counter)	2U	0 to 65535	—
System serial number	2U	100 –	—
Maximum number of beams possible	1U	48 –	—
Number of valid receive beams = N	1U	1 to 254	—
Sound speed at transducer in dm/s	2U	14000 to 16000	—
Repeat cycle – N entries of :	8*N	—	—
– Beam pointing angle in 0.01°	2S	-11000 to 11000	1
– Transmit tilt angle in 0.01°	2U	-2999 to 2999	1
– Range (two-way travel time)	2U	0 to 65534	1
– Reflectivity (BS) in 0.5 dB resolution	1S	-128 to 126	—
– Beam number	1U	1 to 254	—
End of repeat cycle			
Spare (Always 0)	1U	—	—
End identifier = ETX (Always 03h)	1U	—	—
Check sum of data between STX and ETX	21U	—	—

Table5. 1 The old raw range and beam angle (F) datagram. The red square is the information that contain in each beam. [Kongsberg]

Repeat cycle 1 - Ntx entries of:	24*Ntx	—	—
Tilt angle re TX array in 0.01°	2S	-2900 to 2900	6
Focus range in 0.1 m (0 = No focusing applied)	2U	0 to 65534	—
Signal length in s	4F	—	—
Sector transmit delay re first TX pulse, in s	4F	—	—
Centre frequency in Hz	4F	—	—
Mean absorption coeff. in 0.01 dB/km	2U	—	—
Signal waveform identifier	1U	0 to 99	1
Transmit sector number	1U	0 –	—
Signal bandwidth in Hz	4F	—	—
End of Repeat cycle 1			

Table5. 2 The sector's information of each beam in new raw range and angle datagram. [Kongsberg]

5.1 Methods to Modify the OMG Beam Pattern Correction Software

As chapter 4 mentioned, the OMG beam pattern correction software package contains two softwares: ***getBeamPattern*** and ***makess*** (and functions contained in ***Echo_calib.c*** and ***Echo_calib.h***). For these two softwares, the previous methods are to utilize a single common beam pattern for the entire swath to minimize the beam pattern residuals. No account was taken of the multi-sector, multi-swath nor the information that is now available in the "raw range and angle" datagram of each beam. The new algorithm developed here to solve the beam pattern residuals proceeds as follows:

(1) Identify the information that can separate the multi-sector, multi-swath, and multi-mode.

(2) Re-calculate a modified beam pattern correction file by ***getBeamPattern*** software that separates sectors, swaths and modes into separate vertically referenced patterns

(3) Apply the modified beam pattern correction file to ***makess*** software

The resulting correction file no longer applies a single beam pattern for an entire swath. Rather, multiple patterns, unique for each identified sector are used. The algorithm will be described in the following sections.

5.2 Identify the information that can separate the multi-sector, multi-swath, and multi-mode

There are 9 new information items in the modified “raw range and angle” datagram (Table 5.2). However, not all of them can be used to identify the multi-sector, multi-swath, and multi-mode. Therefore, the first step was to determine which information is useful. Table 5.3 shows the specifics of the dual swath mode of the EM 302. There are 4 dual swath modes which are Shallow, Medium, Deep and Deep’ mode that utilize dual swath. From these 4 modes, sectors can be distinguished in the same mode or other mode that share the same center frequency. Furthermore, the Deep and Deep’ mode have 8 sectors and they all utilize the same frequencies of each sector and each swath. The only difference that can be used to separate the two modes identify is the outer sectors which have different pulse length and pulse type. Therefore, the algorithm to identify beams’ attributes is using a unique combination of four parameters as follow:

(1) Pulse length

(2) Center frequency

(3) Pulse type (CW or FM)

(4) Transmit sector number (as some outer sectors share all of 1, 2, and 3)

Mode	Depth	Typical total coverage		TX pulse(ms) Dual Swath #1 frequency(kHz) Dual Swath #2 frequency(kHz)							
		Deg	Meter	Port				Starboard			
Shallow	10- 250	140		1.1ms 26.5kHz 29.1kHz		1.1 27.7 32		1.1 30.4 33.6		1.1 26.5 29.1	
Medium	250- 750	140		2 26.5 27.7		2 28.9 30.1		2 27.1 31.3		2 29.5 28.3	
Deep	750	140	3750	5 28.1 28.9	5 26.5 27.3	5 31.3 32.1	5 29.7 30.5	5 31.7 32.5	5 30.1 30.9	5 28.5 29.3	5 26.9 27.7
	1000	140	5500								
Deep'	1000	140	5500	40 28.1 28.9	25 26.5 27.3	5 31.3 32.1	5 29.7 30.5	5 31.7 32.5	5 30.1 30.9	25 28.5 29.3	40 26.9 27.7
	3000	140	8500								

Table5. 3 The dual swath mode of the EM 302 multibeam system. [Kongsberg]

These 4 beam attributes are the most important identified information of the sector beam pattern. Depending on these 4 beam attributes, the algorithm can be designed a procedure flow as two steps as Figure 5.1.

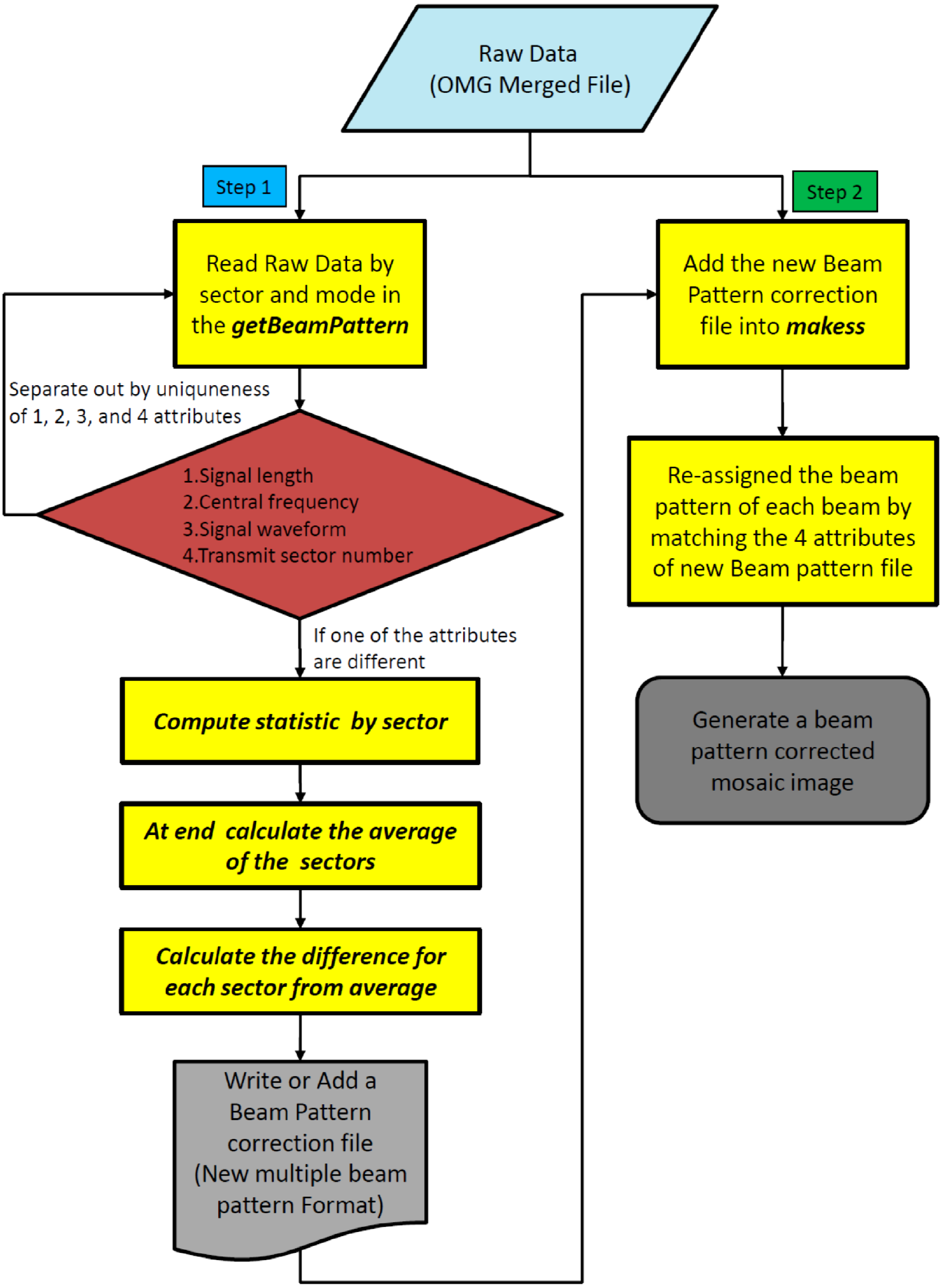


Figure5. 1The procedure flow of the beam pattern correction software. Step1 is the procedure of the ***getBeamPattern***; Step 2 is the procedure of the ***makess***.

5.3 Re-calculate a new beam pattern correction file by getBeamPattern software

As each beam has its pulse length, centre frequency, pulse type and sector number defined, the next step is to calculate the beam pattern correction file by ***getBeamPattern*** software. However, there is a problem with the format of the conventional beam pattern correction file. The conventional beam pattern correction file has mixed different sectors and frequencies into one common beam pattern correction. One option could be to run though the file and only work on one beam pattern for one sector at a time. Then repeat as many times as the unique sectors are presented until no new sector exists. After finishing finding all new sectors, stack each sector and average the backscatter strength of all sectors simultaneously.

For example, if the survey data of the EM302 multibeam echo sounder contains dual swath and uses the Deep mode, the frequencies and sectors have 16 unique sector combinations. As the depth is getting deeper, the survey mode will automatically switch to Deep’ mode. The center frequencies and sector ID of Deep’ mode are the same as the Deep mode. However, the transducer pulses of outer sectors 4 of the 16 modes are changed from CW to FM pulse. The transducer pulse is a significant controller of the absolute level of the apparent beam pattern. Therefore, the new beam pattern correction file should not just contain one beam pattern for these outer sectors as well.

For a file that contains Deep and Deep', there are 16 for deep, of which 8 are identical for Deep' (the centre 4 of each). But there are 8 new sector combinations. Thus, 20 discrete sector combinations need to be identified.

According to the situation of multi-sector, multi-swath and multi-mode, the new beam pattern correction file is designed as Table 5.4. The concept of the new beam pattern correction file is to use 4 beam attributes to uniquely identify which sector combination each beam's attributes and creates a unique beam pattern correction for that combination. If there are beams for which one of the 4 beam attributes is different in the survey data, a new beam pattern will be generated that addresses these new beams in the same beam pattern correction file. If beams have the same 4 attributes, the ***getBeamPattern*** will stack and calculate the average angular backscatter strength for that sector. Once all the sector angular patterns have been computed, an average backscatter strength for all the sectors is calculated, and a differential from that average is calculated for each valid angle and for each sector pattern.

Total beam pattern correction mode number				
20				
Mode number	Center frequency(Hz)	Sector number	Tx pulse length	Pulse type
0	26500.000000	1	0.025000	1
Beam Launch Angle(deg)	Average Beam Intensity by Stacking(dB)	Intensity Differential	Number of Beam Samples	
0.000000	0.000000	0.000000	0	
……	……	……	……	
39.000000	-30.124335	7.197288	4085	
40.000000	-29.472499	6.545452	3893	
……	……	……	……	
179.000000	0.000000	0.000000	0	
Mode number	Center frequency(Hz)	Sector number	Tx pulse length	Pulse type
1	31300.000000	2	0.007500	0
Beam Launch Angle(deg)	Average Beam Intensity by Stacking(dB)	Intensity Differential	Number of Beam Samples	
0.000000	0.000000	0.000000	0	
……	……	……	……	
55.000000	-21.466597	-1.460450	2752	
56.000000	-20.824013	-2.103034	35092	
……	……	……	……	
179.000000	0.000000	0.000000	0	
……	……	……	……	
Mode number	Center frequency(Hz)	Sector number	Tx pulse length	Pulse type
19	27700.000000	7	0.007500	0
Beam Launch Angle(deg)	Average Beam Intensity by Stacking(dB)	Intensity Differential	Number of Beam Samples	
……	……	……	……	
……	……	……	……	
179.000000	0.000000	0.000000	0	

Table5. 4 The new beam pattern correction file that is designed to fix the beam pattern problem that cause by multi-sector, multi-swath and multi-mode.

In the Table 5.4, the number of the first row is the total number of unique sector beam patterns. This number describes how many unique sectors have been identical according to comparing the 4 attributes. Each sector is described by four parameters which individually are, center frequency (Hz), sector number, transmitter pulse length, and pulse type. Under the 4 pieces of information, each mode has its beam pattern correction that is separated by launch angle (in one degree bins) in the old beam pattern correction format. Although the backscatter strength differential of new sector beam pattern correction file is calculated individually for each sector, the average of all the sector intensities is used. That means the backscatter strength differential is calculated by the average of all sectors backscatter strength and each angle's backscatter strength. The ultimate aim is to level off the seafloor response for all sectors. By calculating the backscatter strength average of all sectors, therefore, the ***getBeamPattern*** can adjust each sector to the same common backscatter strength response.

By using the new beam pattern correction file, for example, it can display the beam pattern for each mode as Figure 5.2. Figure 5.2 is the new beam pattern correction file for the EM302 multibeam echo sounder. The survey modes of the survey line are from Deep' mode to Deep mode. The backscatter strength is between -15 to -40 dB. The launch angle is between +/- 60°. For Deep mode, there are 8 sectors with dual swath that are shown as blue lines and red lines; for Deep' mode, because of the fixed swath width, the number of sectors are 6 sectors with dual swath which are from sector 1 to sector 6 (see Figure4.3).

Each of the relative sectors of these two survey modes has the same frequency. The sectors of the Deep mode are all CW pulse. However, the sector 1 and 6 of Deep' mode are FM pulse and the sector 2, 3, 4, and 5 are CW pulse. Therefore, refer to Table5.3, the total mode number of this survey line can be calculated as:

*Deep mode: 8 sectors × 2 (dual swath) =**16 modes***

*+)Deep' mode: 6 sectors × 2 (dual swath) = **12 modes***

*−)The same attributes of the sectors: 4 sectors× 2 (dual swath) = **8 modes***

*Total modes = **20 modes***

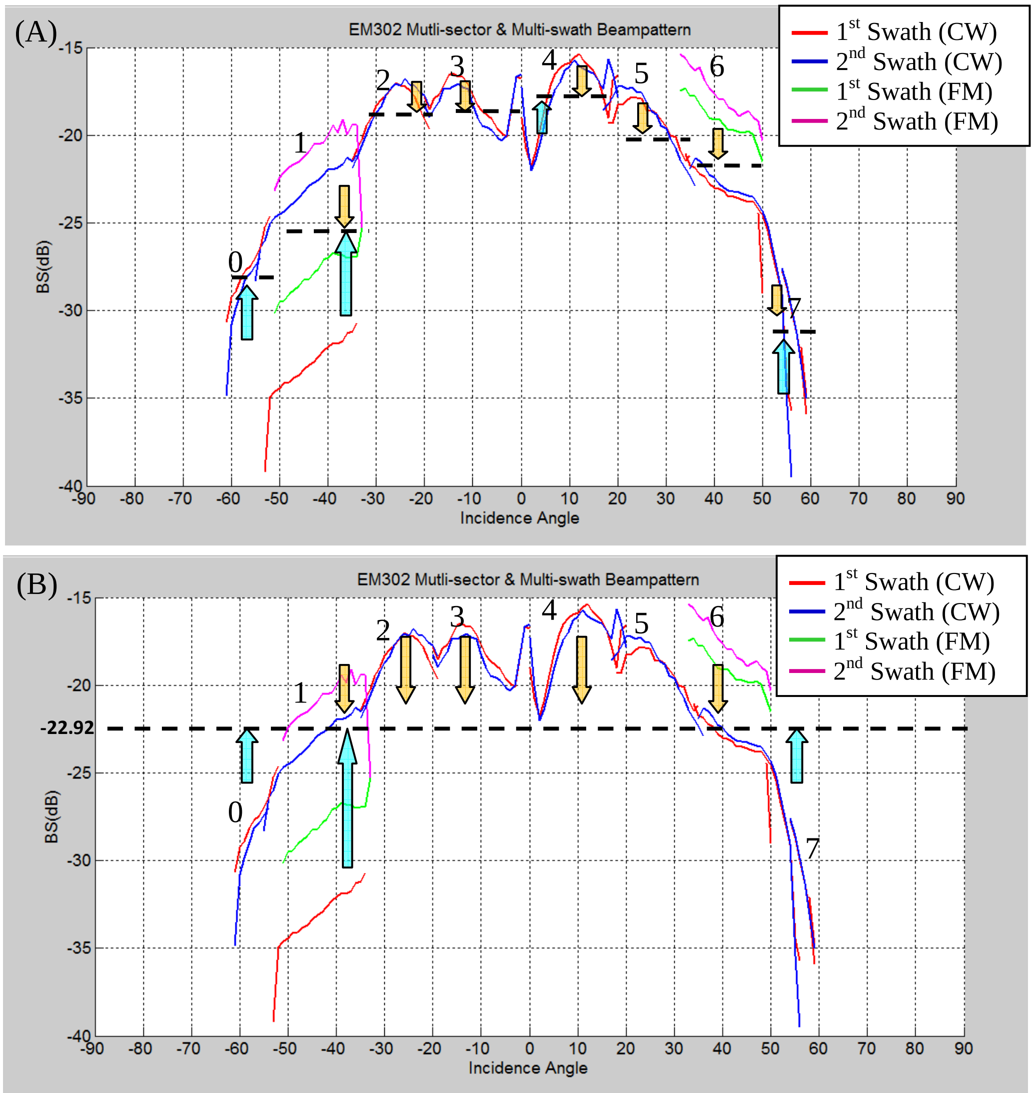


Figure5. 2 The beam pattern of the different modes that depend on the center frequency (Hz), sector number, Transducer pulse length, and pulse type. (A) illustrates the black dash lines are the average backscatter strength response of each sector and the arrows are the backscatter strength differential. (B) shows the black dash line is the average of the all sectors and the value is -22.92(dB).

5.4 Apply the beam pattern correction file to makess software

The ***makess*** software is designed to generate a sidescan strip image using the individual beam trace backscatter strength time series. The ***makess*** software can also accept the beam pattern correction file to be the compensation of the beam pattern residuals. However, once the new modified beam pattern correction file has been generated by ***getBeamPattern*** software, the ***makess*** software also has to be modified to read in and then correctly apply the beam pattern correction file.

Previously a single beam pattern was passed to ***makess*** for the entire swath. Now an array of beam patterns are passed together with an array of attributes. An additional test has to be performed on a beam by beam basis to identify which pattern to use.

The algorithm of the ***makess*** software modifications can be presented as follow:

(1) Use the new beam pattern correction file to be a list to match and fix each beam's beam pattern.

(2) Each beam will compare its information (frequency, number of the sector, pulse length, and pulse type) to the beam pattern correction file. Previously a single beam pattern file was used for an entire swath. No check was made to distinguish potentially different beam patterns for each individual beam.

(3) Once the beam matches one of the beam pattern modes in the beam pattern correction file, the beam will apply the backscatter strength differential of this beam pattern mode to be the compensation value by using the beam's launch angle.

(4) Repeat step (2) and step (3) until all beams of the entire swath are addressed, then do next swath.

Figure 5.3 shows the EM302 data that was modified by the new ***getBeamPattern*** and ***makess*** software. Figure 5.3 (A) presents the original data without beam pattern correction. There are multi-sector beam pattern residuals, pulse length changed beam pattern residuals, and the bad sector signals. After applying the new OMG beam pattern correction software, the original data can be compensated by the backscatter strength differential of the new beam pattern correction file. Not only the problems of the multi-sector beam pattern residuals and the bad sector signals are solved but also the pulse length changed beam pattern residuals are improved. (See Figure 5.3 (B) & (C)) Figure 5.3 (B) shows the compensation value image. The beam pattern residuals that are caused by multi-sector and multi-swath are either adjusted by the average beam pattern value. Especially, the problem sector of the 1st swath has obviously been corrected by the new OMG beam pattern correction software.

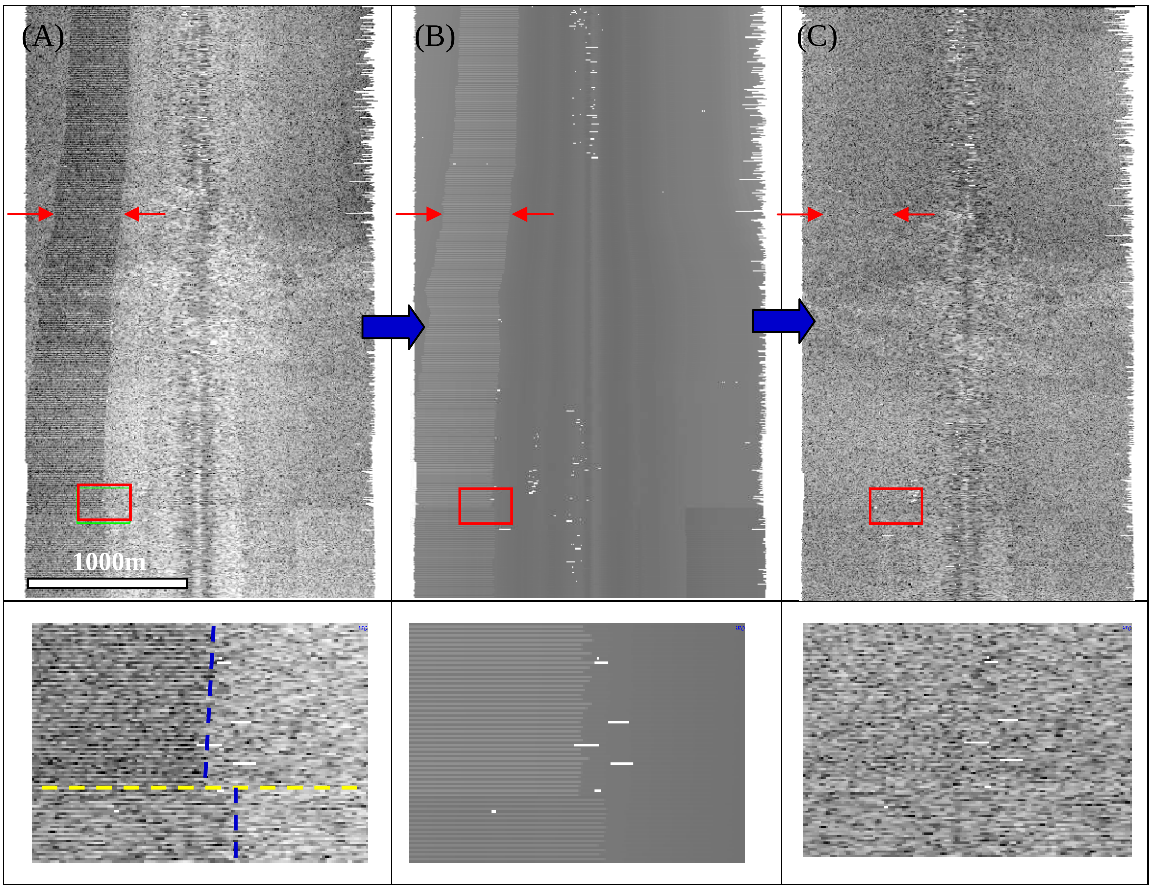


Figure5. 3 The comparison of the original data and the compensated data of the EM302 multibeam system. (A) shows the original backscattering mosaic image. (B) shows the compensation that is provided by the new beam pattern correction file. (C) shows the backscatter mosaic image after the compensation. The red arrows show the problem sector of the 1st swath. The blue arrows present the processing procedures.

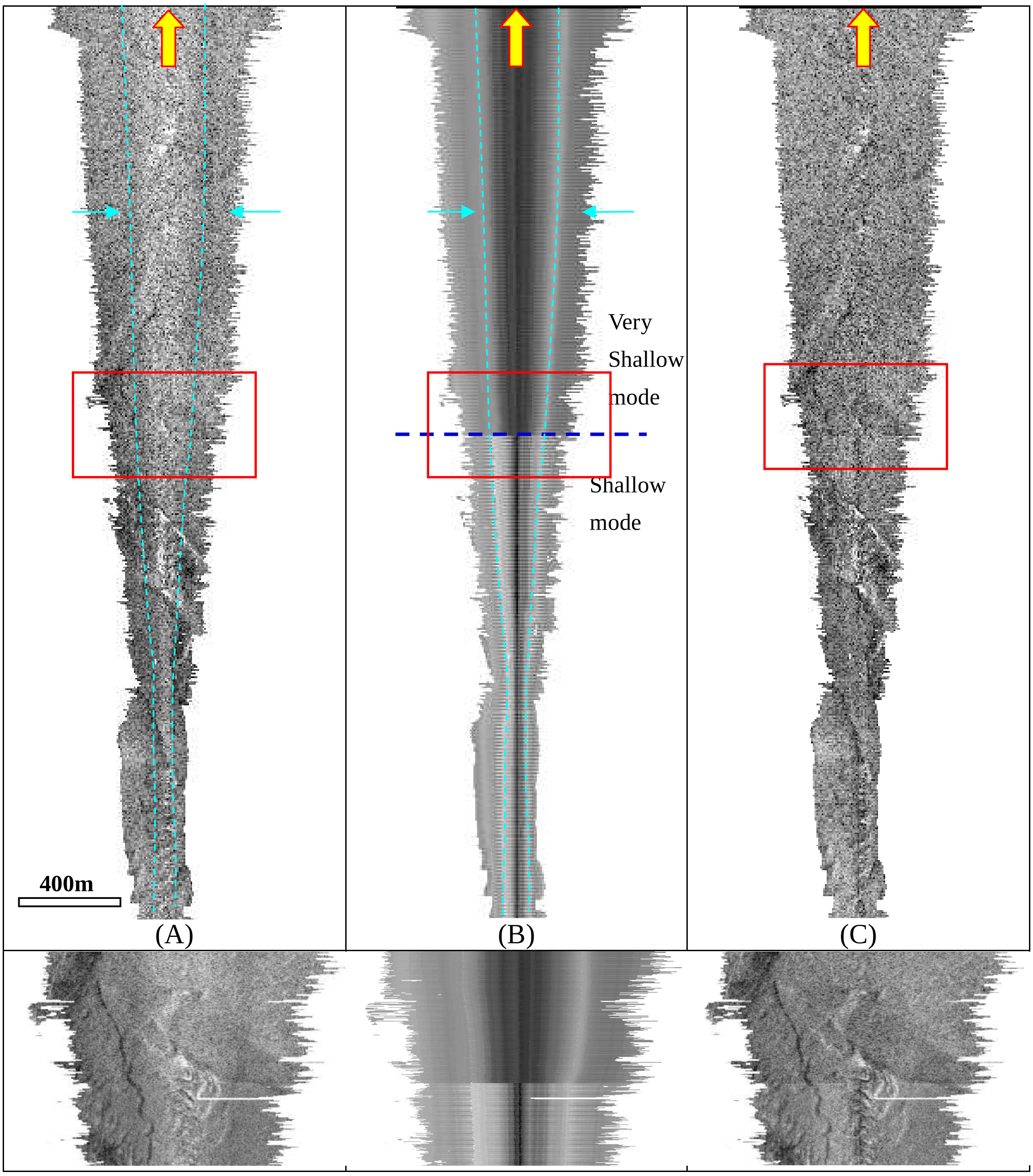
Chapter 6 The new OMG beam pattern correction software application in Kongsberg Maritime multi-sector and multi-swath multibeam data

As Chapter 2 mentioned that there are 4 types of the Kongsberg Maritime multi-sector and multi-swath multibeam systems. All of them faced the same beam pattern residuals problems of backscatter strength which are caused by multi-sector and multi-swath. Each though, have a different numbers of sectors and sector boundary geometries. Since the OMG beam pattern correction software has been modified to improve the problems, the next contribution will be presented for each of these Kongsberg Maritime Mulitbeam systems by using the new OMG beam pattern correction software.

The original new OMG beam pattern correction software, ***getBeamPattern***, was tested on the specific problems of the EM302 on solving the multi-sector, pulse length changed beam pattern residuals and the specific sensitivity problem sector. It now can be use to examine and apply this software to the other types of the Kongsberg Maritime multi-sector and multi-swath multibeam systems.

EM710

Figure 6.1 illustrates the beam pattern residuals and correction of the EM710 multibeam data that is collected from Squamish, British Columbia, Canada in June-14th 2011 . The data of this EM710 multibeam system has 3 sectors, dual swath, and 2 modes are utilized over the depth range of the example (35-170m) which are very shallow mode to shallow mode. The beam pattern residuals as Figure 6.1 (A) illustrates have two stripes between sectors. By using the compensation image (show as Figure 6.1(B)) to examine the data, the beam pattern residuals between sectors are revealed. The beam pattern residuals can also be presented by backscatter strength as Figure 6.1 (D). The black dash line in Figure 6.1 (D) shows the average reference backscattering value which is used to adjust the individual sector backscatter strength. After the compensation of the new beam correction software, the beam pattern residuals can be removed and presented as Figure 6.1 (C).



Very
Shallow
mode
Shallow
mode
400m
(A)
(B)
(C)

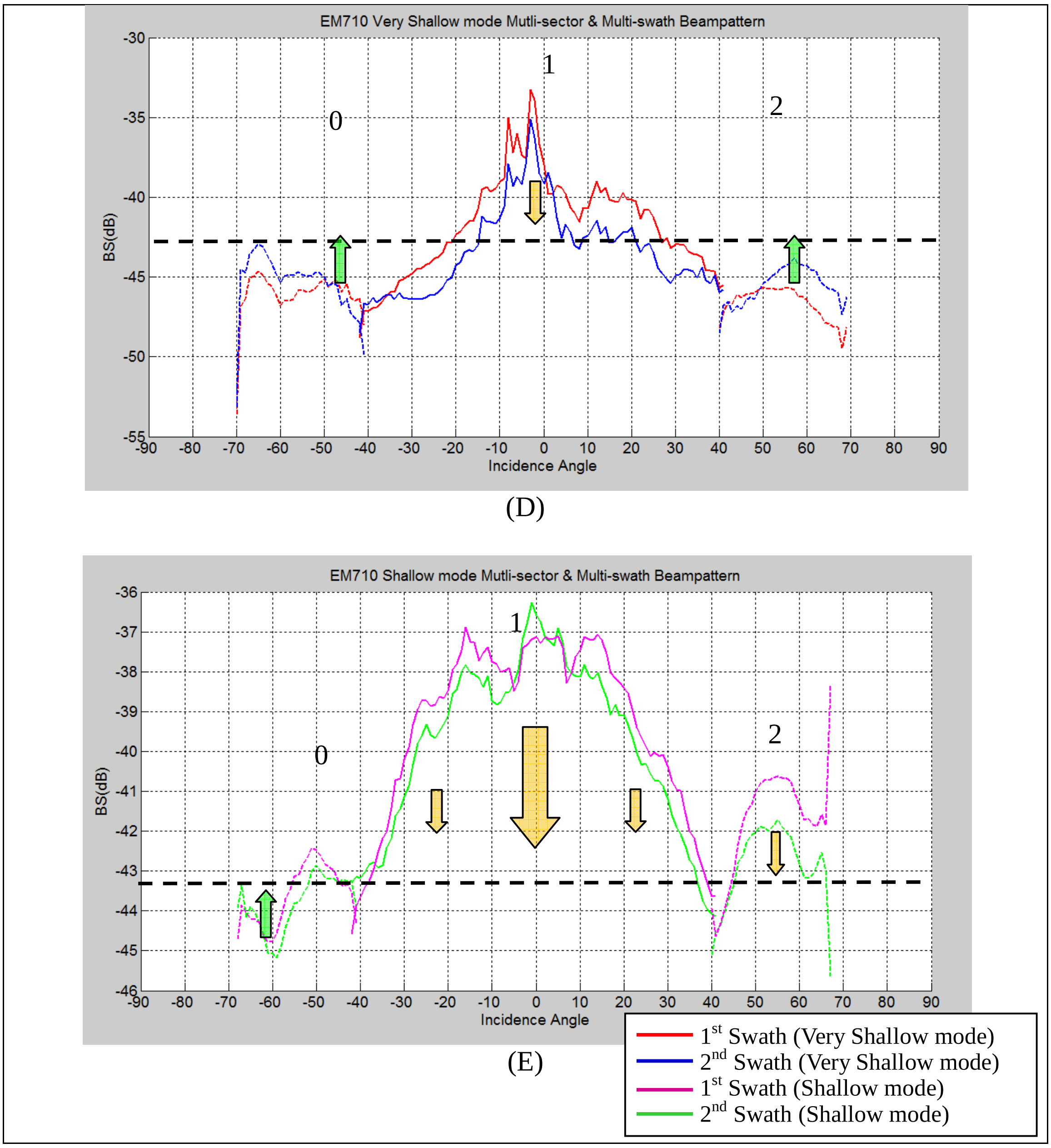


Figure6. 1 The data of the EM710 multibeam system that surveyed from Squamish, British Columbia, Canada in June-14th 2011. (A) shows the original backscatter image. (B) shows the compensation that is provided by the new beam pattern correction file. (C) shows the backscatter image after the compensation. (D) shows Very Shallow mode multi-sector and multi-swath backscatter strength. (E) shows Shallow mode multi-sector and multi-swath backscatter strength. In (A), (B), and (C), the yellow arrows are the sailing direction; the cyan arrows and dash lines show the beam pattern residuals. The black dash line in (D) & (E) is the average of intensities and the value is -43.35(dB); dash curve present different sector.

EM2040

The EM2040 is the newest Kongsberg Maritime multibeam system type which has 3 nominal center frequency combinations (400kHz, 300kHz, and 200kHz). Figure 6.2 to 6.5 display the short mode and medium CW pulse modes of 400kHz and 300kHz modes. The depths of these data are about 50m. The total available angular sector of 400kHz mode is +/- 60° and the receiver angle of 300kHz mode is +/- 70°. All of the original data have the multi-sector and multi-swath beam pattern residuals. After corrected by the ***getBeamPattern***, the multi-sector beam pattern residuals are all removed.

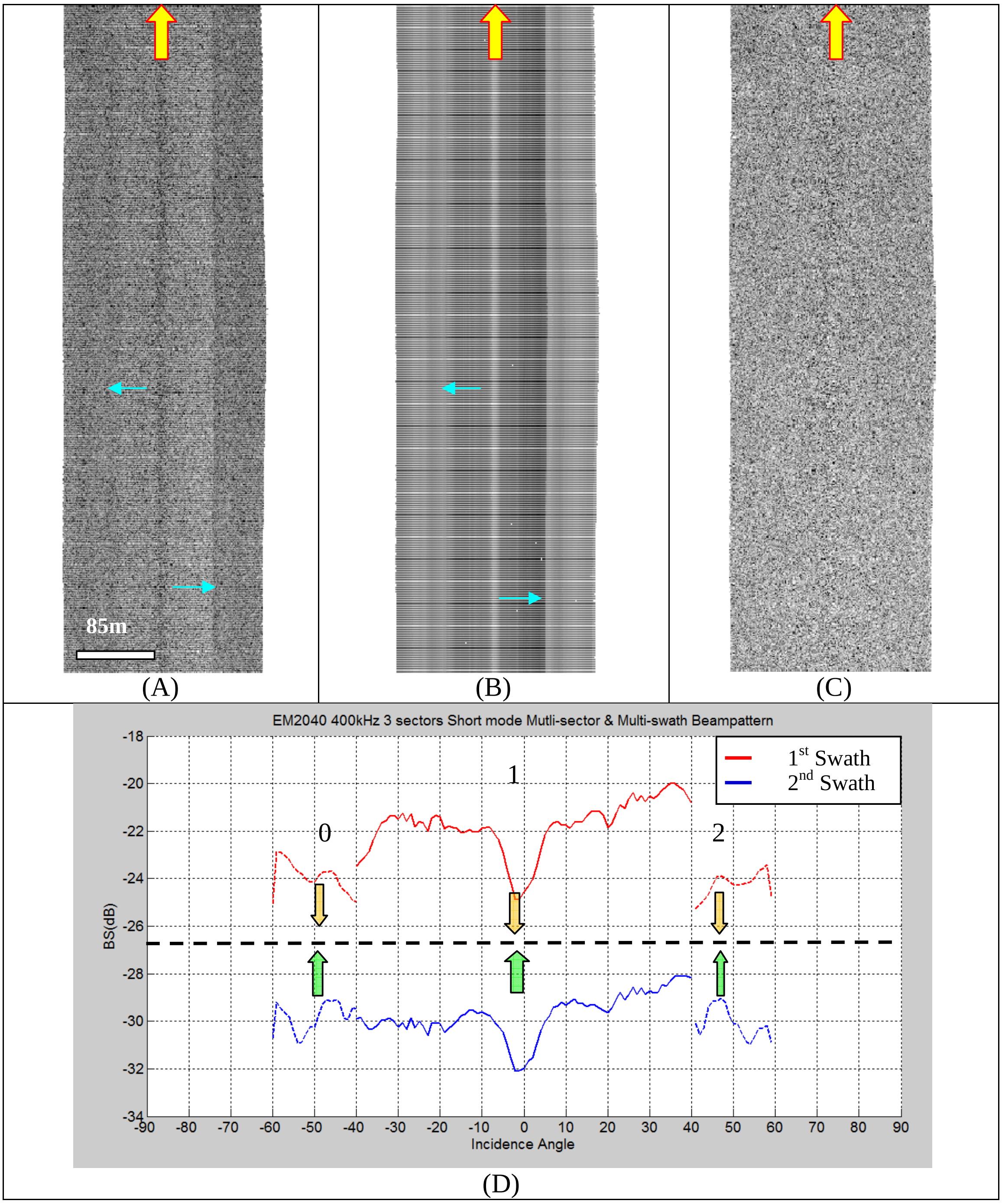


Figure6. 2 The backscatter data of the EM2040 multibeam system by using 400kHz Short CW pulse mode (pulse length is 73us) with dual swath. The depth is 50m. (A) shows the original backscatter image. (B) shows the compensation that is provided by the new beam pattern correction file. (C) shows the backscatter image after the compensation. (D) shows multi-sector and multi-swath backscatter strength; the different sectors use line types (solid or dash) to distinguish. The yellow arrows in (A), (B), and (C) are the sailing direction; the cyan arrows show the beam pattern residual between sectors. The black dash line in (D) is the average of intensities and the value is -26.59(dB).

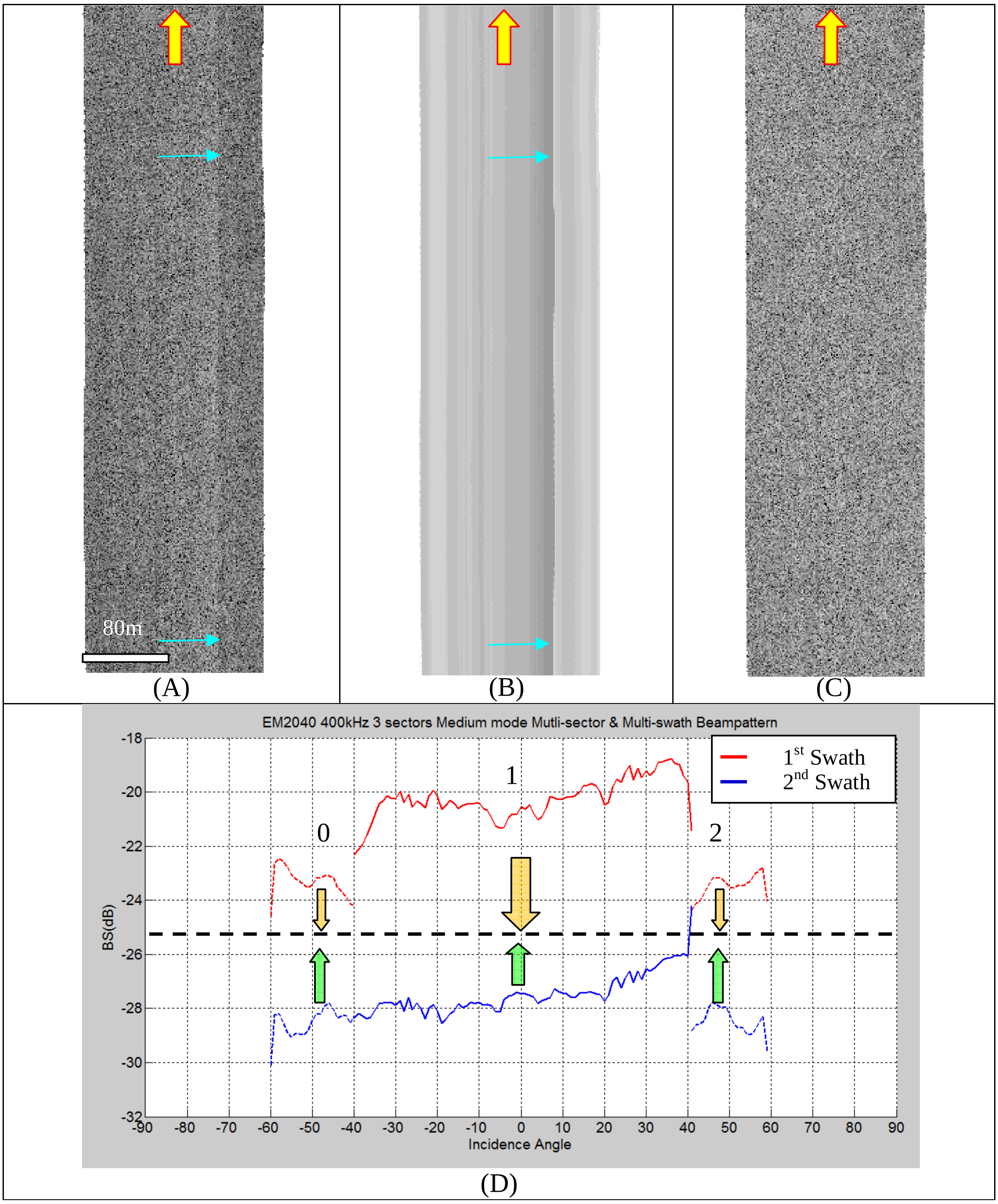


Figure6. 3 The backscatter data of the EM2040 multibeam system by using 400kHz Medium CW pulse mode (pulse length is 145us) with dual swath. The depth is 50m. (A) shows the original backscatter image. (B) shows the compensation that is provided by the new beam pattern correction file. (C) shows the backscatter image after the compensation. (D) shows multi-sector and multi-swath backscatter strength; the different sectors use line types (solid or dash) to distinguish. The yellow arrows in (A), (B), and (C) are the sailing direction; the cyan arrows show the beam pattern residual between sectors. The black dash line of (D) is the average of intensities and the value is -25.25(dB).

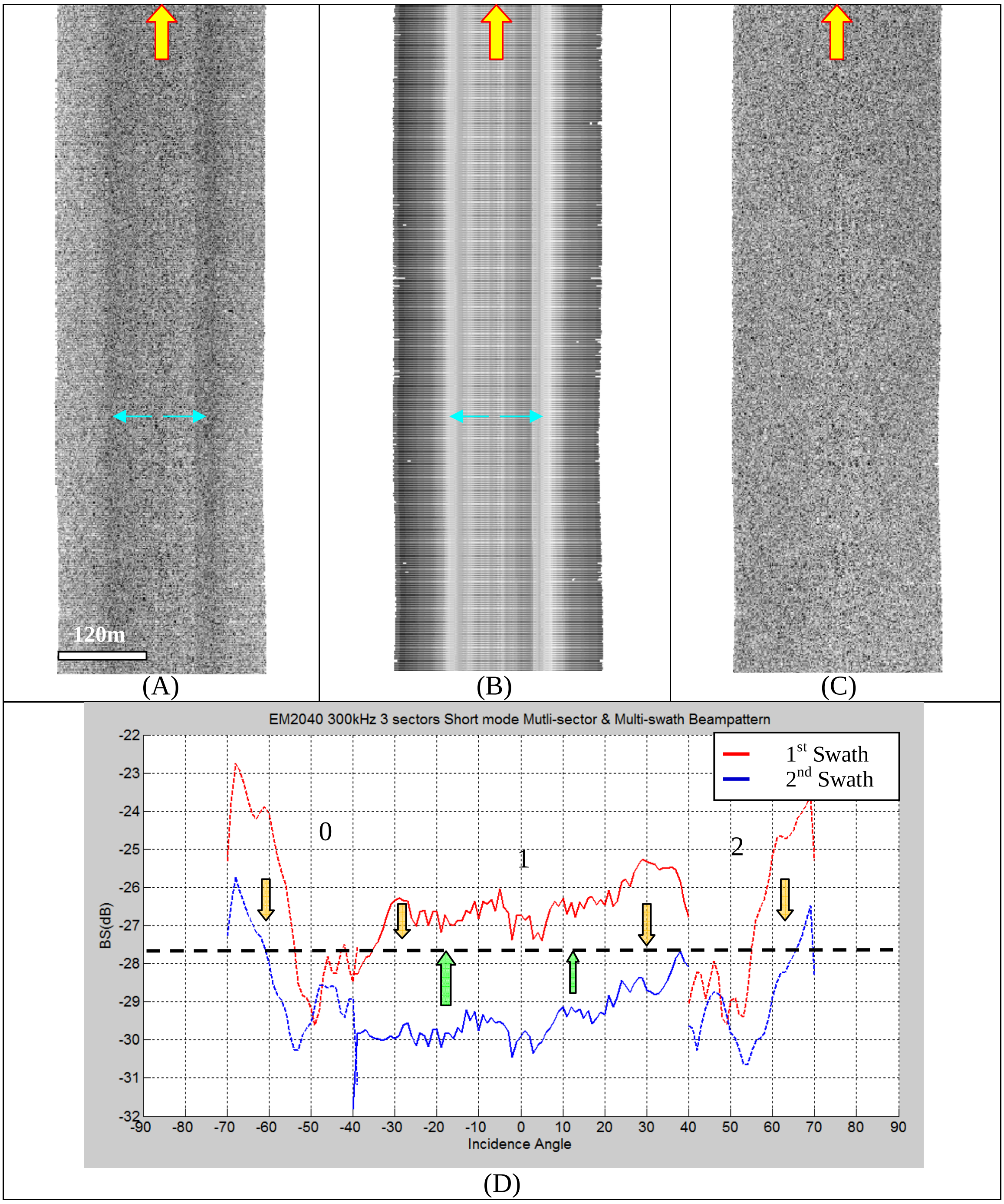


Figure6. 4 The backscatter data of the EM2040 multibeam system by using 300kHz Short CW pulse mode (pulse length is 101us) with dual swath. The depth is 50m. (A) shows the original backscatter image. (B) shows the compensation that is provided by the new beam pattern correction file. (C) shows the backscatter image after the compensation. (D) shows multi-sector and multi-swath backscatter strength; the different sectors use line types (solid or dash) to distinguish. The yellow arrows in (A), (B), and (C) are the sailing direction; the cyan arrows show the beam pattern residual between sectors. The black dash line of (D) is the average of intensities and the value is -27.79(dB).

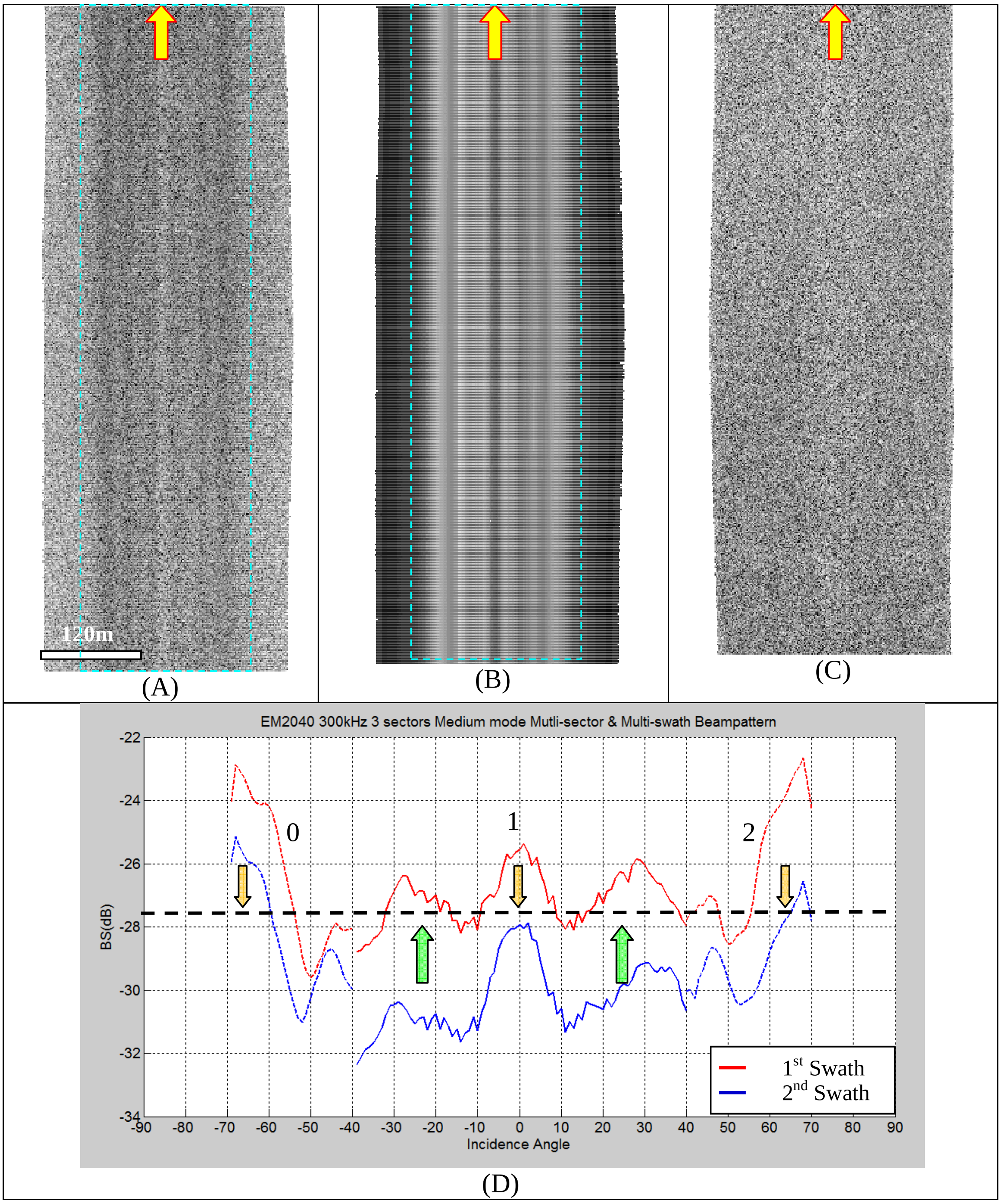
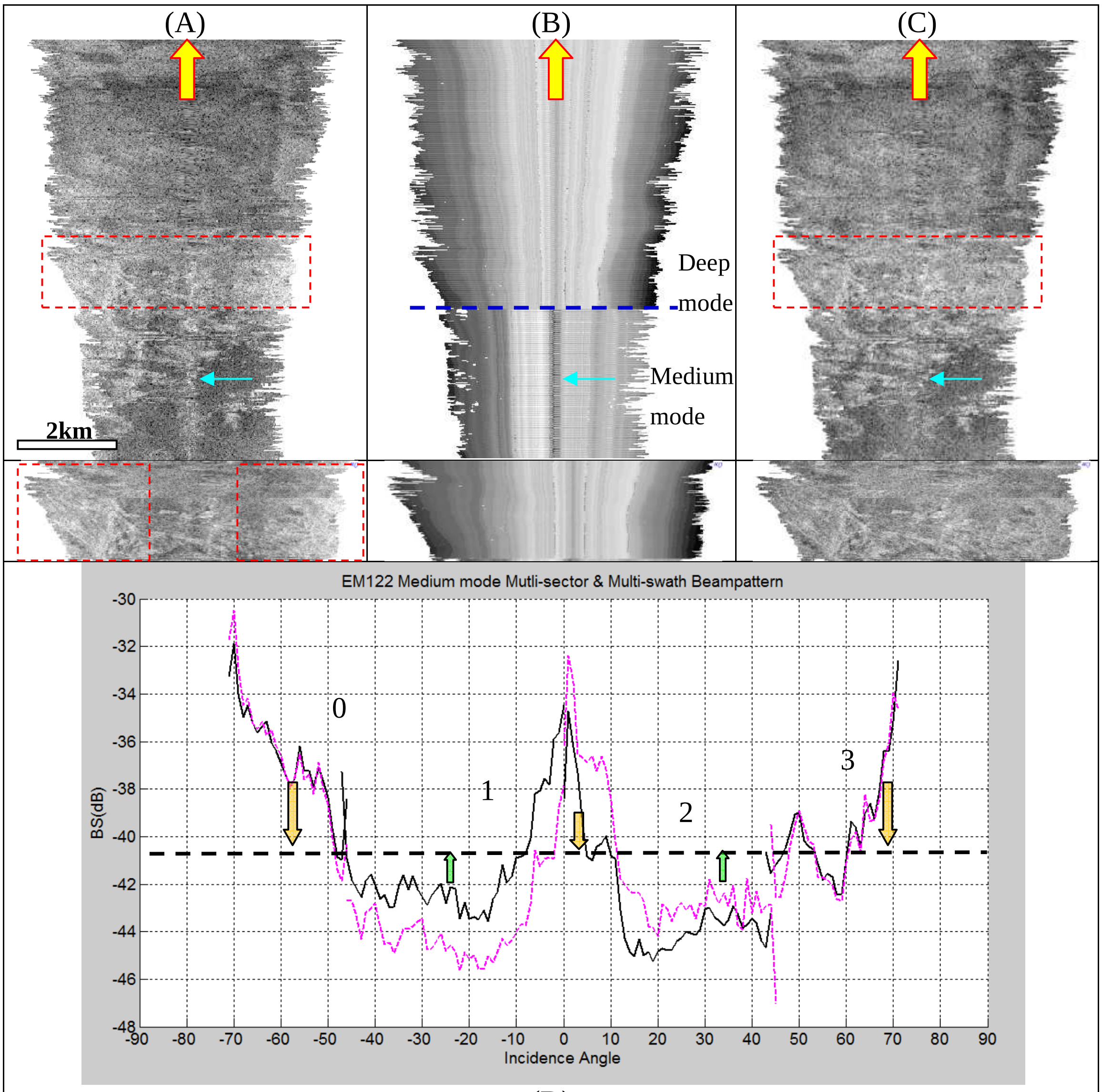


Figure6. 5 The backscatter data of the EM2040 multibeam system by using 300kHz Medium CW pulse mode (pulse length is 288us) with dual swath. The depth is 50m. (A) shows the original backscatter image. (B) shows the compensation that is provided by the new beam pattern correction file. (C) shows the backscatter image after the compensation. (D) shows multi-sector and multi-swath backscatter strength; the different sectors use line types (solid or dash) to distinguish. The yellow arrows in (A), (B), and (C) are the sailing direction; the cyan dash squares show the beam pattern residual between sectors. The black dash line of (D) is the average of intensities and the value is -27.85(dB).

EM122

The EM122 is the Kongsberg Maritime deep sea surveying multibeam system. Figure 6.6 is the backscatter data which was collected by U.S. Navy (USNS Heezen) in Pacific Ocean, 2011 summer. The depth is from 750-1350m. The EM122 switched the mode from Medium mode to Deep mode. By observing the backscatter strength profile (Figure 6.6 (D)), it was found that the most dramatic beam pattern residuals are in the nadir and the outer sectors. Moreover, because the most dramatic nadir's beam pattern residuals occurred in the medium mode, after the beam pattern residuals are corrected by the new ***getBeamPattern***, the nadir beam pattern residuals of medium mode are changed the most. See cyan arrows in Figure 6.6 (A), (B), and (C).

The outer sector beam pattern residuals are also adjusted in strength. The red squares in Figure 6.6 (A) shows the sediments in the outer sectors are different. However, after the new ***getBeamPattern*** corrected the the beam pattern residuals, the result shows the sediments in this red square area are probably the same (Figure 6.6 (C)).


(A)
(B)
(C)
2km
Deep
mode
Medium
mode
EM122 Medium mode Mutli-sector & Multi-swath Beampattern
BS(dB)
Incidence Angle
0
1
2
3

(D)

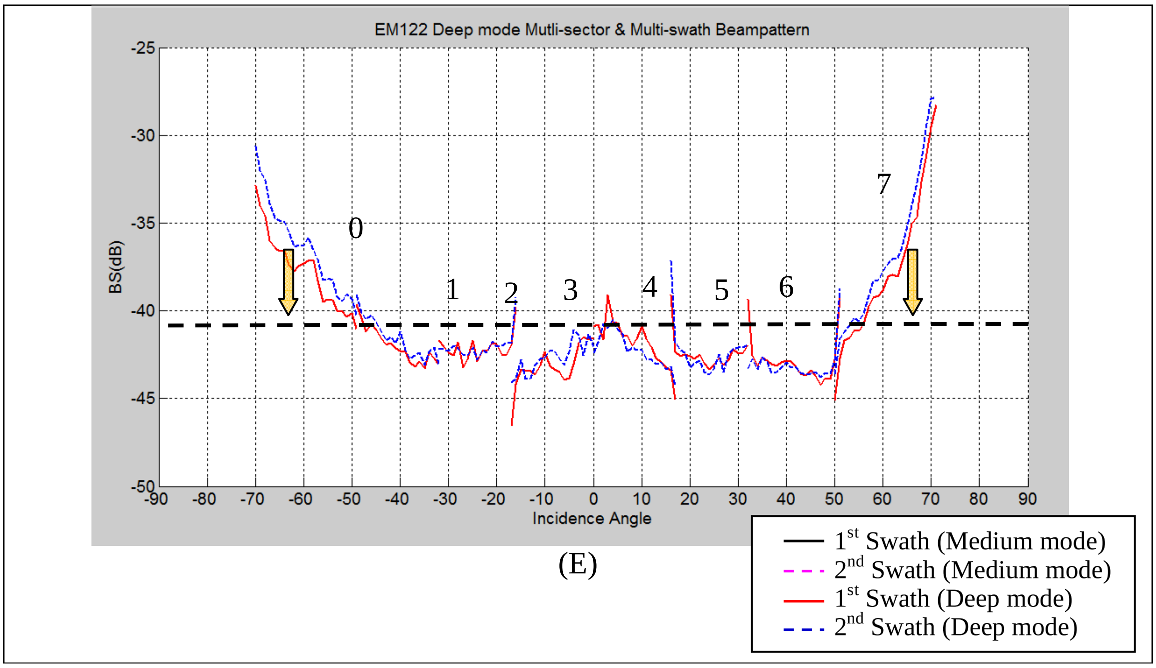


Figure6. 6 The backscatter data of the EM122 multibeam system which by using Medium mode (pulse length is 6.8ms) and Deep mode (pulse lengths are 10.999ms and 20.4ms) with dual swath. The depth is 50m. (A) shows the original backscatter image. (B) shows the compensation that is provided by the new beam pattern correction file. (C) shows the backscatter image after the compensation. (D) shows Medium mode multi-sector and multi-swath backscatter strength. (E) shows Deep mode multi-sector and multi-swath backscatter strength. In (A), (B), and (C), the yellow arrows are the sailing direction; the cyan arrows show the beam pattern residuals of the nadir; the red dash squares show the beam pattern residuals of the outer beams. The black dash line in (D) & (E) is the average of intensities and the value is -40.77(dB).

Chapter 7 Conclusion

The aim of this thesis was to improve the OMG beam pattern correction software, ***getBeamPattern*** and ***makess***, and remove or minimize the beam pattern residuals which are caused by the Kongsberg Maritime multi-sector and multi-swath multibeam echo sounders in the backscatter image. The algorithm developed for eliminating the multi-sector and multi-swath beam pattern residuals is :

1. Use ***getBeamPattern*** to generate a multi-dimensional beam pattern correction file which is indexed by 4 uniquely identifying parameters which are sector frequency, sector number, pulse length, and pulse type.
2. According to these 4 information, the intensities of sectors and swaths can be separately stacked.
3. Calculate the average of backscatter strength which must consider all sectors.
4. Calculate the backscatter strength differentials for each sector with respect to the average of all sectors backscatter strength.
5. Importing the improved sector specific the beam pattern correction file in the ***makess.***
6. Adjust the backscatter strength on a beam by beam basis using the backscatter strength differentials of the modeled sector-specific beam pattern correction file.

Using this approach, the multi-sector and multi-swath beam pattern residuals can be reduced significantly.

The improvement to the OMG beam pattern correction software, undertaken as part of this thesis, has been demonstrated to be capable of removing a major component of the multi-sector and multi-swath beam pattern residuals. As has been explained in Chapter 3, however, there are still a number of significant remaining problems with the proper reduction of the backscatter data. Some of the most significant problems are linked to proper use of attenuation coefficients and proper accounting for seafloor grazing angle. It is hoped that future developments can address the ambiguity inherent in separating the seabed angular response from the beam pattern effect with Kongsberg Maritime multi-sector and multi-swath multibeam systems.

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