REDUCTION OF REFRACTION EFFECTS DUE TO INADEQUATE SOUND VELOCITY PROFILE MEASUREMENTS IN MULTIBEAM ECHOSOUNDER SYSTEMS

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DEDICATION

To my beloved parents and my loving Biyani ...

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ABSTRACT

The single most important acoustical variable in the water is its speed. The average speed of sound in the ocean is about 1500 m/s, but its precise value in a location is strongly depends on temperature, pressure and salinity of that particular location. These factors change rapidly in time and space due to various reasons. In data acquisition, the collection of these denser sound speed data becomes critical. These inadequate sound speed measurements cause unknown propagation through the water column that adds a major uncertainty to the multibeam echosounder measurements (MBES). There are two types of sound speed measurements made in the flat array multibeam sonars. Surface Sound Speed (SSS) is measured at the face of the transducer and Sound Velocity Profile (SVP) is measured through the water column. SSS is used to determine the beam pointing angle (beam steering) and SVP is used to determine the depth and position (ray-tracing) of each beam. From these, the SSS is measured almost at each ping vies and SVP may be once or twice a day depending on the situation. When it comes to ray tracing, one has the options of using either the SSS or the surface value of SVP (SSVP). Some multibeam software manufacturers use the SSS in Snell's refraction constant determination while others use the surface value of the last performed SVP. In this study, both methods of refraction constant determination are evaluated. The results clearly showed that the use of SSS for Snell's refraction constant determination gives about 25% to 30% better results in multibeam bathymetry against refraction than the use of SSVP. A combined solution of SSS and SSVP provide a better, simpler and cost effective method of reduction of refraction effects in MBES. The results also demonstrated that the effects of inadequate sound speed measurements in each phase of bathymetric calculations would result in both depth and positional errors.

ABSTRAK

Salah satu pemboleh ubah akustik bagi air yang penting adalah kelajuan air. Purata kelajuan bunyi dalam laut adalah 1500 m/s, akan tetapi nilai kejituannya bagi sesuatu kawasan bergantung kepada suhu, tekanan dan ketumpatan bagi kawasan tersebut. Kesemua faktor ini berubah dengan cepat mengikut masa dan keluasan disebabkan oleh pelbagai punca. Pengumpulan data kelajuan bunyi yang banyak menjadi kritikal ketika kutipan data dilakukan. Pengukuran kelajuan bunyi yang kurang berupaya untuk menghasilkan perambatan yang tak diketahui melalui lapisan air telah menambahkan ketidakpastian kepada pengukuran pemerum gema berbilang alur (MBES). Terdapat dua jenis kelajuan bunyi yang dilakukan dalam susunan mendatar sonar berbilang alur. Kelajuan permukaan bunyi (SSS) adalah diukur pada paras muka tranduser manakala profil halaju bunyi (SVP) diukur melalui lapisan air. SSS digunakan untuk menentukan sudut arah alur dan SVP pula digunakan untuk menentukan kedalaman dan kedudukan setiap alur. Dari sini, SSS diukur pada hampir setiap ping dan SVP diukur sekali atau dua kali dalam satu hari bergantung pada keadaan. Apabila hendak mengesan sinar, kaedah yang boleh dilakukan adalah sama ada menggunakan SSS atau nilai permukaan bagi SVP (SSVP). Beberapa pengeluar perisian pemerum gema berbilang alur menggunakan lebih banyak SSS dalam penentuan angkatap biasan Snell, manakala pengeluar lain menggunakan nilai permukaan bagi SVP terakhir yang diperolehi. Dalam kajian ini, penilaian terhadap kedua-dua kaedah penentuan angkatap biasan dilakukan. Hasil kajian yang diperolehi jelas menunjukkan penggunaan lebih banyak SSS bagi penentuan angkatap biasan Snell memberi keputusan yang lebih baik bagi batimetri berbilang alur berbanding dengan penggunaan SSVP iaitu antara 25% ke 30%. Gabungan penyelesaian SSS dan SSVP menghasilkan kaedah lebih baik, mudah dan penjimatan untuk mengurangkan kesan pembiasan dalam MBES. Hasil kajian juga menerangkan tentang kesan kurang upaya bagi kelajuan bunyi dalam setiap fasa pengiraan MBES akan menyebabkan selisih kedalaman dan penentududukan.

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CHAPTER 1

INRODUCTION

1.1 Background

One of the most impressive hydrographic survey technique developed during the past few decades is the Multibeam Echosounder System (MBES). It is a rapid and more automated depth measurement system, guaranteeing the full bottom coverage. Therefore it has become the number one choice for most of the hydrographic surveys. Multibeam sonars uses sound as a remote sensing tool. The fundamental data collected by these sonars are the two way travel time of the short acoustic pulse travelling between the transducer and the bottom surface and the direction from which the echo is reflected. A typical MBES (eg. RESON Seabat 8124) has some 80 separate beams, spanning 120 degrees are sounded across the ship's track on each acoustic ping, which will normally covers an area of 3.5 times of the depth.

Use of MBES for accuracy–critical applications has now become wide spread with the improvement in acoustic transducer design and digital data processing. Now MBES have become a cost effective, reliable tool and being increasingly employed in ocean mapping, dredging operations, route surveys and various other underwater engineering works (Dinn *et al.*, 1995). Along with the adoption of the MBES as the instrument of choice of the most hydrographic applications, has come the challenge of minimising any associated errors (Cartwright and Clarke, 2002).

Final sounding data from the MBES system is a result of processing information from several data sources. These include the ship's heading and attitude data from the gyrocompass and the motion sensor; vertical reference data from the tide gauge; positional data from the Global Positioning System (GPS) unit and sound velocity data from the Conductivity Temperature Density (CTD) or Sound Velocity Profile (SVP) probe in addition to the basic MBES data itself. Data from each source is subject to individual errors contributing to overall data quality. To limit these, system planners often have established error budgets for various components of the system.

The International Hydrographic Organization (IHO) recommends accuracy limits for the type of hydrographic surveys and the depth of water in which a survey is conducted. These accuracies are divided in to two categories, horizontal accuracy and depth accuracy. Horizontal accuracy refers to the horizontal positioning accuracy of each sonar beam and depth accuracy includes amongst other things like tidal measurement errors, data processing errors and measurement system and sound velocity errors (Batton, 2004).

Thanks to the intensive researches carried over the last decade, system manufactures have introduced equipments advertised to achieve positional uncertainties of 2 cm or better (Real Time kinematics GPS), tidal measurement uncertainties less than 2 cm (Real Time Tide) and vessel altitude uncertainties of 0.02 degrees. The uncertainties of these instruments contribute to the surveys are within or if not better, than the accuracy suggested by the IHO (Batton, 2004). Therefore with the advent of the new technologies, the last remaining obstacles to absolute precision are sound speed variance and roll biases (William and Capell, 1999).

This chapter outlines the core areas of this study including research problem statement, aim and objectives, research scope, significance of the study as well as the discussion of related previous works. Chapter 2 provide a detailed theoretical overview of the marine acoustical environment, sound wave propagation, MBES system and need of sound speed in MBES. The next chapter (Chapter 3) discusses the field data collection. The computer program development part is explained in Chapter 4. Here the algorithms used and the flowcharts of each program are discussed in detail. In Chapter 5, data processing techniques are presented. The results and data analysis are discussed in Chapter 6 and finally, Chapter 7 concludes the results obtained and the recommendations for the future studies also presented.

1.2 Research Problem

The nature of the sea environment is the most fundamental factor, which separates land and sea surveying. The sea is fluid and dynamic. It is coronial and full of living organisms that changes the structure. The characteristics of the medium through which measurements are made are always subjected to variation (Ingham and Abbott, 1992). These variations must be understood and corrections to be applied in order to achieve precise results.

When it comes to acoustic depth measurements in the oceans, the dominant character is speed of sound. The speed of sound in the oceans is subjected to significance changes caused by rapid changes in temperature, pressure and salinity over a short period of time. These changes are more prominent in continental shelf regions; as a result of rapid heating and cooling of the water surface due to solar heating, interactions with fresh waters carried by rivers, tidal and current mixing and so on (William and Capell, 1999).

Measuring these physical properties that control the speed of sound in the ocean (using CTD probe) or direct sound speed measurements (using SVP probe) is the standard procedure for collecting the sound speed information. These physical oceanographic variables have clearly demonstrated temporal and spatial scale variation during common hydrographic surveys that are usually extending from days to weeks and survey lines from kilometers to tens of kilometers. As a result, in most hydrographic operations one must take discrete measurements of sound speeds at periods of more than once a day; bringing a survey vessel to a halt, lowering a sensor several hundred meters and then taking care of all the data quality assurance and data transfer protocols necessary. This would commonly involve at least 30 minutes of ship time.

Because of this, agencies are reluctant to take more frequent observations and thereby implicitly assumed that the space and time variability of the ocean could adequately be described using these sparse observations. Even more, now the swath of the multibeam sonars have moved to ever wider angular sectors in order to achieve even wider coverage, as the other sources of uncertainties have been gradually eliminated, which means they are more sensitive to refraction (Clarke et al. 2000). When applying these SVPs, there are two principal limitations exists:

a) The water mass really does change over time scales much shorter than the standard sampling period.
b) The application of SVP is almost universally done based on the prior observations only.

This inadequate sound speed measurements cause an unknown propagation (refraction errors) that adds a major source of uncertainty to depth measurements, resulting artifacts can create short-wavelength topographic features that may be misinterpreted as sea floor relief (Gardner, *et al.*, 2001) as shown in Figures 1.1 and 1.2.

ct># 5
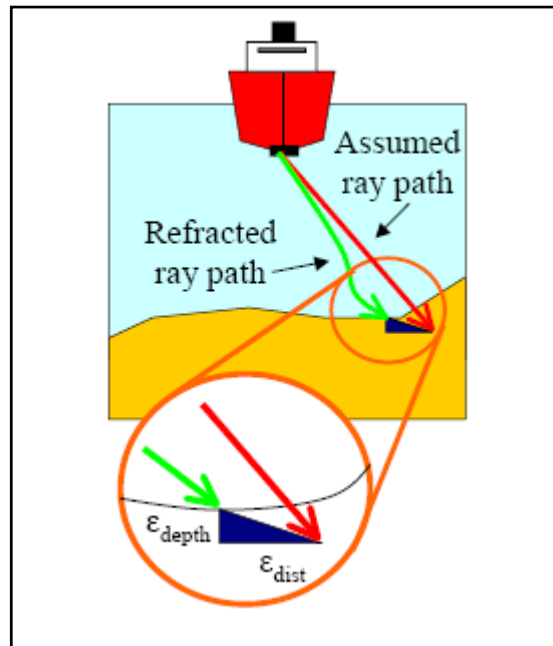
Figure 1.1 Illustration of how refraction degrade the accuracy of MBES data (OMG-UNB, Canada)

(a)   (b)
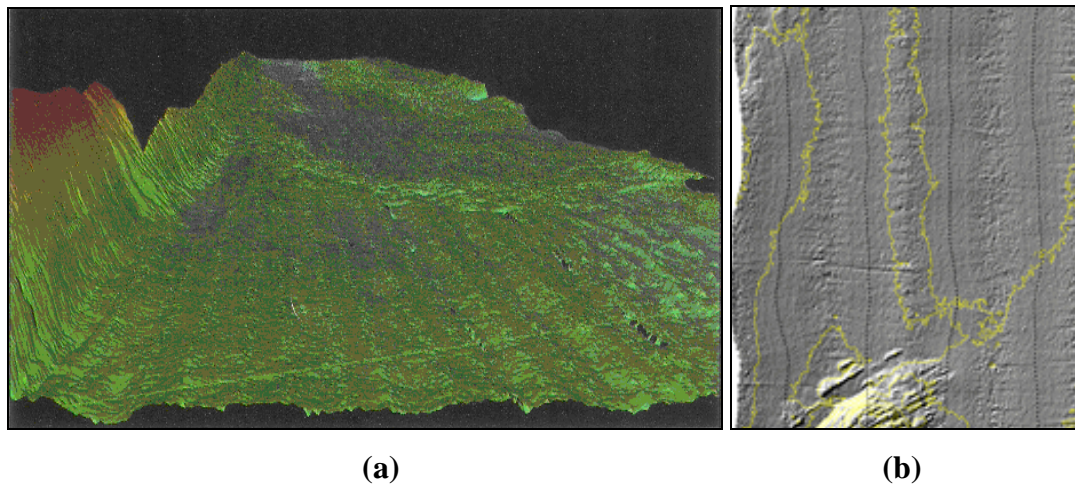
Figure 1.2 Observe the Parallel ridges and valleys due to sound speed errors (a) Exhibits an artificial wave-like pattern in DTM (Jeroen, 2007) (b) Exhibits how contours are altered by these artificial features (OMG-UNB)

Almost all of the flat array MBES (eg. RESON SeaBat 8124) measures two types of sound speed measurements. The surface sound speed (SSS) measured using the probe near the sonar head is used for beam steering purpose and the sound

velocity profile (SVP) measured through the water column used for depth and position calculation of each beam (ray tracing). The SSS is measured continuously through out the survey period, while the SVP is only measured in discrete of times. Therefore the dominant uncertainty remaining to be solved is caused by the fact that we have an imperfect knowledge of the water column and accompanying changes in sound speed with depth (Cartwright and Clarke, 2002).

In this case, to address this imperfect knowledge on SVP, some multibeam system manufacturers use more frequent (real-time) SSS measurements, measured at the sonar head along with spares SVP in ray tracing. Here, they use SSS in refraction (Snell's) constant determination for each beam, measured almost at each ping vies (about >10Hz). While other manufacturers use SSS in beam steering purpose only and the SVP is used alone in ray tracing (here they use the surface value of the SVP for refraction constant determination). This seems that, still there is no agreement in the hydrograplic community, which one gives better results against refraction.

1.3 Aim of the Research

The aim of this research is to evaluate, the most appropriate value in the determination of refraction coefficient for the ray tracing purpose to perform the refraction calculations. That is, either the surface sound speed (SSS) or the surface value of the sound velocity profile (SSVP) giving the best results in ray tracing.

1.4 Research Objectives

The objectives of this research are;

1) To study the effects caused by inadequate sound speed measurements in each phase of the multibeam echosounder system. The effects from:
      a) The surface sound speed.
      b) The sound speed through the water column.

2) To develop two computer programmes for MBES bathymetric calculations using SSS and SSVP as refraction constant.

3) To perform a comparative test between the above two approaches to identify any significance difference between the two methods of refraction constant determination.

1.5 Research Scope

      Unlike in the open oceans, where the sound velocity profile has a predictable and stable shape, in coastal and shallower areas, (continental shelf regions) the SVPs are irregular and unpredictable. Therefore, for this study the fieldwork is carried out in shallow coastal waters in Lido beach, Johor Bahru, Malaysia. In addition to that, the effects are simulated for a 100m deep synthetic flat seabed for each case.

      Over the years various types of multibeam echosounder system configurations have been designed and developed for various purposes. Curved array, flat array, dual flat array are some of them. Each individual system behaves differently in refraction. This study is limited to the Mill's cross type, flat array multibeam configuration. RESON SeaBat 8124 is a typical system of that kind.

The SSS is measured using the surface sound speed-measuring probe located at the face of the transducer and SVP-15 probe is used to measure the sound velocity profile through the water column.

QINSy version 7.5 software was used to collect, extract raw data and process the multibeam data. AutoCAD R14 and QuickSurf 5.1 software are used in visualization of bathymetric data and Digital Terrain Model (DTM) generation.

MATLAB- R2006a is used to develop the computer programmes. Here the ray tracing is performed assuming that each sound speed layer has a constant sound speed. The bathymetric calculation procedures used in the developed programs are the same as the QINSy software procedures, except the refraction constant determination method. The bathymetric results from the QINSy software are used to validate the results from the developed programs.

Nadir beams are least affected by refraction, therefore in this study the nadir beams were used for benchmarking or as reference depths (true depths) in comparison of refraction effects. SBES data is also used for this purpose.

Corresponding profiles from SSS and SSVP DTMs, SBES lines and adjacent MBES nadir area are compared to each other in the final comparative test to determine the significance between the two approaches.

1.6 Significance and Contributions of the Study

Since MBES is a recent development, very few researches have been carried out in the issue of refraction. For Malaysia, MBES is even newer. There is hardly any proper study carried out in Malaysian waters of this kind.

This study will completely address how the variation of the sound speed affects in multibeam echosounder bathymetric measurements, both in beam forming and in ray path calculations. This is very much important in equatorial waters where the sound speeds are more critical due to solar heating, tidal and current mixing.

This knowledge will be very much useful to the survey planners to make extra measures to overcome the effects caused and hence improve the efficiency and accuracy of the works.

Finally, this will give more insight to MBES system and software developers to come up with advanced systems and software that will suffer less effects from sound speed variation (refraction) in future.

1.7 Review of Relevant Literature on Refraction Issue in MBES

Over the years hydrographers and oceanographers have faced greater challenges when they dealt with oceanic parameters, especially when they began to use the acoustic techniques. Because of this, many researchers have done much research and experiments on these matters. Some tried to understand how this really affect the measurements, while other researchers tried to come up with a solution for it. These solutions can be discussed in two phases. The first one is in post processing content like applying ray tracing techniques, while the next approach is addressing the roots (in data collection stage) of the problem; that is to collect the near continuous sound speed profiles.

Badiey *et al.* (2002) try to understand the correlation between the oceanographic features and the high-frequency acoustic wave propagation. Their results clearly showed a direct relationship between salinity and temperature changes with acoustic wave propagation in shallow waters. Furthermore, the hydrodynamic parameters such as surface waves, tides and current can influence amplitude and travel time of signal transmissions.

Gardner *et al.* (2001) have highlighted that the refraction is the single biggest limitation on the quality of bathymetric data, and strong water stratification causes problems for the beam steering and ray tracing in MBES. They suggested measuring sound speed profiles more frequently to minimize these effects.

But measuring highly variable and dynamic oceanographic components is not that easy. Clarke (2002) illustrated how fast water masses changes in oceans, in time and space, using observed sound speed cross-sections. He also stated that when beams become less vertical, the affects get worse. As a result one could see parallel ridges in MBES data, along the ship-track direction where neighbouring lines get overlapped.

Tonchia and Bisquay (1996) and Dinn *et al.* (1995) have shown that the inadequate sound speed measurements effects in two phases in MBES. That is, the surface sound speed affects the beam forming and the sound velocity profile affects the ray path. Beam forming depend on the transducer configurations (flat-level, flat-tiled, circular-faced), and they mathematically illustrate the effects in each transducer configuration. Furthermore, they have shown that when the vessels roll is significant, the roll modulate the depth errors contributed by sound speed uncertainty. Finally, they suggested measuring the surface sound speed continually and to use adaptive modeling of the error regime coupled with deliberately introduced redundancy in the depth data in an effort to enable interpolation between temporally and spatially sparse SVPs.

Kammerer *et al.* (1998) faced the same problem while they try to monitor the temporal changes in seabed morphology, using multibeam sonars in Saguenay River in France. The local mixing of fresh and salt water has introduced more uncertainties than they first expected, due to the refraction. They dealt with this by separating the different lines corresponding to the different sound velocity profiles (SVP) taken during the survey and distinguished them geographically within each of these sets, assuming that the water masses are affected differently and requiring different refraction coefficients. Then, they applied estimated refraction corrections to each of these groups of lines; hence reduce the curvature of the swath.

Batton (2004) found out that the sound velocity formula used to compute the speed of sound in the water column is also a source of uncertainty related to the horizontal position of the chart depths. She measured the temperature, conductivity and pressure in North Atlantic Ocean and used Chen and Millero, Meckenzie and Medwin formulae for the estimation of sound speed. Then, she performed ray tracing to compute the horizontal distances of refraction for the beams through the water column. Through this, she concluded that the sound velocity formula used to compute the sound speed also contribute to uncertainties associated with outer swath of MBES.

William *et al.* (1999) described a method to determine the magnitude of the SVP errors using the MBES data itself, by running cross lines. These crossing swaths are obtained from the check lines used in most hydrographic surveys. Here, in addition to refraction errors they observed the roll bias and tidal differences also.

Beaudoin *et al.* (2004) demonstrated that it is possible to correct soundings corrupted by incorrect surface sound speed in post-processing. During their multibeam survey in Amundsen Gulf, Canada; their surface sound speed probe has failed in several occasions. This caused a greater uncertainty in their measurements. Then they interpolated SSS from the measured SVP's and recalculated the beam steering angles. Through this they were able to improve the accuracy of the data.

Furlong *et al.* (1997) had come up with a solution to measure oceanographic parameters in real-time using a computer-controlled winch and a davit. The winch deploys a 'free-fall' fish that can be instrumented with a sound velocity sensor (like CTD). They named this as "Moving Vessel Profiler" (MVP). The initial system was capable of profiling down to 100 meters even at the vessel speeds up to 12 knots and the entire procedure from the launch to recovery take about 4 minutes. This technique improved the accuracy of the MBES data and do not interrupt the survey process as it operates while the vessel is underway.

Clarke *et al.* (2000) and Clarke and Parrott (2001) had used the above technique (MVP) to study the sound speed variability of the oceans and with the use of MVP along with MBES, frequent water column information allowed a much better control of sounding errors due to the spatial and temporal variations in the water column; making the wider swath (160°) MBES more reliable.

Cartwright and Clarke (2002) also faced serious problems with refraction when they carried out a survey in Fraser River delta, Canada. This River deltaic area was considered being an extreme refraction environment with strong sound speed anomaly. Even with the MVP, it was not possible to collect those large number of spatially dense sound velocity profiles. There they recalculated the departure angles and ray tracing using the spatially interpolated SVPs in order to increase the accuracy of the data in post processing.

Kammerer and Clarke (2000) presented another method of removing refraction effects in MBES using the MBES data itself. They tried to develop a systematic analysis and correction software package for multibeam in post-processing context. The methodology consists of the estimation of the variation in the water sound speed distribution by using the information given by the MBES dataset. This was done by the evaluation of appropriate modelized SVPs, which was added to an already existing SVP or applied directly to the raw data. Here they considered two methods, the first one was using two neighboring parallel lines and the second method was cross-line method. In both cases they assumed that the nadir beams are unaffected by refraction.

Beaudoin *et al.* (2004) developed a sound speed decision support system for multibeam sonar operations in the Canadian Arctic. This helps hydrographers make better decisions by integrating the various types of information relating to sound speed into a single software application.

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