Dredging Volume Analysis Using Bathymetric Multifrequency

Khomsin,[1,2*] Mukhtashor,[1] Suntoyo[1] and Pratomo, D. G.[2]
[1]Ocean Engineering Department ITS Surabaya, Indonesia
E-mail: mukhtashor@oe.its.ac.id, suntoyo@oe.its.ac.id
[2]Geomatics Engineering Department ITS Surabaya, Indonesia
E-mail: khomsin@geodesy.its.ac.id, guruh@geodesy.its.ac.id
Corresponding Author

DOI: https://doi.org/10.52939/ijg.v19i4.2623

Abstract
Making a nautical chart for safe navigation is a bathymetric survey's primary goal. Multifrequency MBES, developed during the last few decades, has dramatically improved the efficiency, accuracy, and spatial resolution of coastal and ocean mapping. The goal of multifrequency MBES is to increase the sub surface's detection resolution. In order to obtain an accurate picture of the seabed, the user can lessen the impact of this subsidence by running surveys in five different modes at once. With the help of multifrequency MBES, this study will analyze bathymetry in shallow coastal waters. According to this study, each frequency's density equals one-fifth of the raw data. The digital bathymetric model (DBM) has identical frequencies. According to the produced DBM, the study site's depth value ranges from -2.5 m to -23.5 m LWS. Between 200 kHz and other depths, a bathymetric variation of little more than 50 cm. Between 200 kHz and other frequencies to -10 cm, the bathymetry range of 0 cm predominates. Dredging volume inter frequencies falls between 0.042 m^3/m^2 and 0.068 m^3/m^2. This amount is negligible compared to the overall dredging volume with a thickness of more than 1 m inside 1 hectare.

Keywords: Bathymetric Difference, Bathymetric Multifrequency, Digital Bathymetric Model Dredging Volume, Multifrequency MBES

1. Introduction

The main goal of hydrography is to determine the depth of waters both at sea and on land (rivers, reservoirs and lakes). Therefore, a hydrographer must understand special knowledge about media, underwater acoustics, depth measuring equipment, and procedures to meet nationally and internationally predetermined standards [1]. Depth measurement can be used in several methods, such as mechanical equipment (a lead line and sounding pole), acoustic (Singlebeam Echosounder (SBES) and Multibeam Echosounder (MBES), airborne lidar bathymetry, and remote sensing. The acoustic method is the most widely used because of its penetration depth of up to thousands of meters. While the mechanical, lidar and remote sensing methods have limitations related to depth.

The development of acoustic technology in measuring water depth begins with SBES and MBES. In the last two decades, the advent of multibeam echo sounders has enormously increased the efficiency, accuracy, and spatial resolution of coastal and ocean mapping [2]. MBES is also an acoustic tool that is often used to make observations and map the water column and seabed [3] [4] and [5]. The primary purpose of an MBES survey is to make a nautical chart used for navigational safety purposes [6] [7] and [8]. Some researchers and communities use bathymetric data MBES to support their needs, such as the modeling [9] and [10], planning [11], managing of marine resources [12], tourism [13], and delineating of national and international maritime law for maritime boundaries [14]. Bathymetric survey applications are not only in sea water but also in lakes, dams, and rivers [15] and [16]. MBES now advanced to a level where ultra-high resolution (cm) underwater seafloor mapping [17] and performed at the exact spatial resolution as remote sensing of the terrestrial environment [18]. In addition, MBES can be used to detect sub-surfaces.

ISSN: 1686-6576 (Printed) | ISSN 2673-0014 (Online) |

Fonseca et al., [19] expected MBES 95 kHz frequency, depending on sediment type and grazing angle, that penetration into, and interaction with, the subsurface would be limited to the upper few decimeters to perhaps 1 m. Fonseca et al., [19] used only MBES single frequency (95 kHz), which was not compared to other frequencies. In another study, Feldens et al., [20] detected that for sandy sediments, the penetration depth is limited to ~1 cm for 600 kHz, while 200 kHz may penetrate ~8 cm into the subsurface. According to [20], research only discussed little related to depth penetration to the subsurface and only for sandy sediments. This study has not discussed other sediments, such as mud, clay, and rocks. In addition, refers to [20] used MBES multifrequency, not ping-by-ping basis. As a result, acquiring bathymetric data at multiple frequencies would require running the same line multiple times, leading to inefficient and complicated data acquisition.

Gaida et al., [21], using multifrequency MBES, resulted in a bathymetric difference between the lowest (90 kHz) and highest (450 kHz) frequencies in muddy areas reaching a value of up to 60 cm. Menandro et al., [22] showed that the bathymetric differences, which can reach up to 20 cm, observed between the frequencies 700 kHz and 170 kHz conformed to expectations of the response of substrate frequency and the sea bottom type in the study area. In accordance with [21] and [22], used MBES on a multifrequency ping-by-ping basis, with one survey directly obtaining data with the desired frequency. This survey is faster and produces data simultaneously to minimize errors that occur during the survey. However, the data density of each frequency is 1/the number of frequencies. Both only discuss subsurface penetration between the highest and lowest frequencies (450 kHz - 90 kHz for [21]) and (700 kHz - 170 kHz for [22].

Single-frequency data collected with an MBES have been used for five decades to map the seabed. The latest generation of MBES has emerged as multifrequency MBES in the last seven years. In multifrequency MBES, the frequency can be modified on a ping-by-ping basis, providing multifrequency data with a single pass of the survey platform. The design of multifrequency bathymetry is for better detection resolution of the subsurface. Layers of suspended sediment create noise that hinders the precise and accurate resolution of the subsurface [23]. By conducting surveys at several high frequencies simultaneously (for example, 100kHz, 200kHz, and 300 kHz), the user can reduce the effect of this subsidence to get an accurate picture of the seabed.

One application of the use of bathymetric data is for the calculation of dredging volumes in the port area. So far, for dredging purposes, the bathymetric MBES data used at the actual time must be the same as the existing data at the same frequency. The goal is that the data used has the exact specifications related to penetration, beam angle, swath width, and others. Nevertheless, since the multifrequency MBES was first discovered in 2016 on an R2Sonic ping-by-ping basis, some researchers and hydrographic surveyors have widely used it with various advantages. It is possible once the survey obtains bathymetric data at different frequencies.

However, using multifrequency MBES will also provide problems in determining the depth (seabed bathymetry). Multifrequency MBES will produce different depths with different frequencies caused by the effect of depth penetration into subsurface sediments. The problem is which frequency is used to determine the seabed bathymetry, and what does the bathymetric difference inter frequencies? How does bathymetric multifrequency affect the bathymetric chart and dredging volume calculation? Therefore, this study aims to determine how great the multifrequency MBES produce the difference in depth with different frequencies in one survey MBES in the exact survey location and their impact on the bathymetric chart and dredging volume computation.

2. Materials and Methods

A bathymetric survey using multifrequency MBES was carried out in the shallow marine area at the port of PT. Gresik Jasa Tama (PT. GJT) (Figure 1), located in Gresik Regency, East Java Province, Indonesia, on Friday, 20 May 2022. The survey area is about 4 ha and is a port for loading and unloading wooden ships. The depth in the survey area is from -3 m to -24 m LWS.

A multi-frequency MBES dataset can provide high-resolution information on seabed bathymetry. This study acquired seabed bathymetry using an R2Sonic 2020 MBES, with the sonar head deployed through a moon pool in the side-mounted survey vessel. The MBES system collects data in a sequence of five pings at 200, 250, 300, 350, and 400 kHz operating frequencies in equiangular mode. The system settings, such as transmit power, gain, and pulse length, are all accessible to the user or predefined in automatic acquisition modes. Table 1 shows the technical characteristics of the R2Sonic 2020 MBES and some parameters used during the acquisition.

Figure 1: Research survey location at PT. Gresik Jasa Tama, Gresik Regency, East Java, Indonesia

Table 1: Characteristic of R2Sonic 2020 MBES used during acquisitions

Frequency	200 – 450 kHz; 700 kHz optional
Number of soundings	Up to 1024 soundings per ping
Beam width (Ω_{tx} and Ω_{rx})	1° x 1° at 700kHz (optional); 1.8° x 1.8° at 450kHz; 4° x 4° at 200kHz
Selectable Swath sector	10° to 130° User selectable in real-time
Nominal pulse Length τ_n	15 µs – 1 ms
Pulse type	Shape CW
Sounding Pattern	Equiangular Equidistant single / double / quad modes Ultra High Density (UHD

The raw data is extracted from the .sbd files (Eiva Navi Scan) and further processed using other software. This system uses an Inertial Motion Unit (IMU) sensor to measure the vessel's attitude (pitch, roll, and yaw) and differential GNSS for horizontal positioning and heading. In addition, it is also equipped with tidal observations during the survey and sound velocity profiler measurements at the beginning, middle, and end of the survey to obtain a correction for the speed of sound waves underwater.

This research method generally consists of collecting, processing, and analyzing. Before the survey begins, the first step is setting all survey equipment in the data collection. The next step is to measure the patch test (Figure 2) to calibrate the transducer's alignment to the ship's attitude (pitch, roll, yaw, and latency). After that, conduct a bathymetric survey with five frequency modes on a predetermined survey path. The patch test data is first processed to get the pitch, roll, and yaw correction angles. Then SVP data is used for sound velocity correction underwater, and tidal data is used to correct datum reference. Patch test, SVP, and tidal data were entered into each survey data line to get the data corrected. The next step is splitting the data into five files containing one frequency and data editing to eliminate existing noise [24] and [25]. Finally, in analysis, calculate the MBES data into corrected depth data for each frequency and the difference in depth between 200 kHz frequency to others.

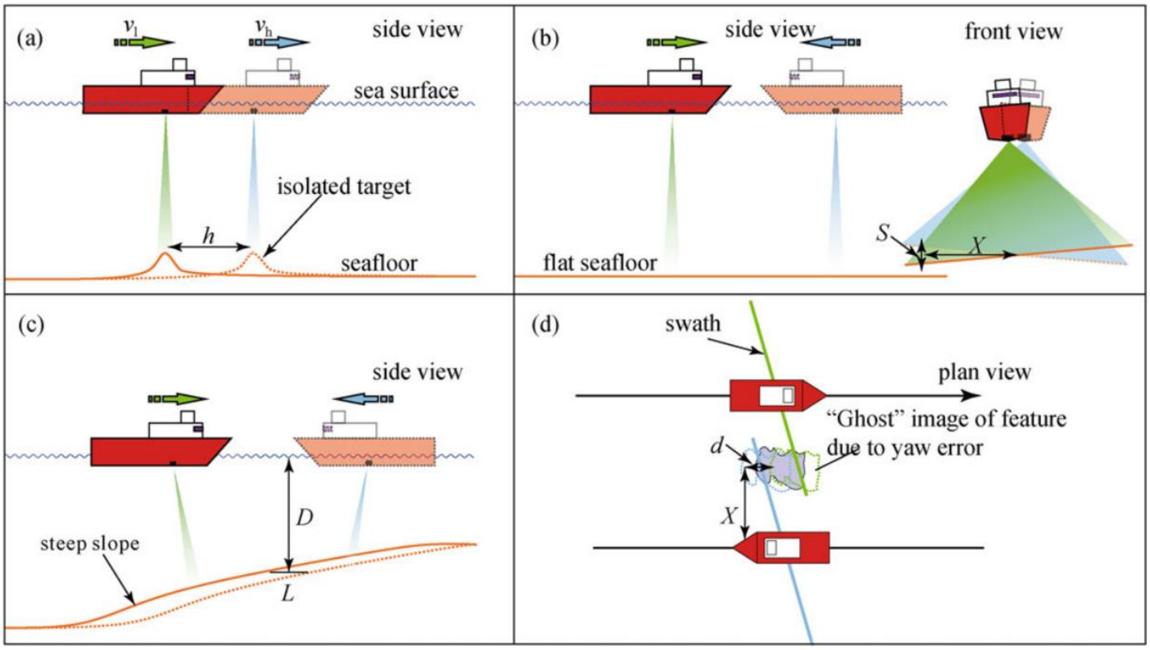

Figure 2: Bathymetric dataset for patch test survey (a) latency, (b) roll, (c) pitch, (d) yaw [26]

3. Result and Discussion

3.1 Patch Test

Sensors' misalignment or mistiming relative to one another can create dynamic residuals and a static bias (e.g., roll bias) [27]. Therefore, before the survey begins, the MBES system parameter calibration must be carried out by patch test. The patch test aims to align the transducer with the existing reference system on the ship, namely by calculating the rotation angle concerning the y-axis (roll), the x-axis (pitch), and the z-axis (yaw), and latency. The patch test on MBES requires a flat seabed measurement location for roll and a sloping seabed for pitch, yaw, and latency [28] and [29].

Most installations will incorporate GNSS time synchronization, and no latency is expected in the GNSS position. Roll measurement is conducted on one survey line, measured back and forth twice and at the same survey speed. An error in the roll will result in an error in sounding depths. Pitch measurement is the same as roll, measured back and forth and at the same speed but seabed slope. The effect of pitch error increases significantly with depth in the along-track position. The Yaw test uses two parallel lines with the ship in the same direction on the line. Yaw error will happen in-depth position error, which increases far from the nadir [26] and [29].

Figure 3 shows the patch test results where the pitch is -0.95^0, the roll is 0,63^0, and the heading is -0.45^0. The patch test values (pitch, roll, and heading) and latency should be entered into the appropriate areas in the data collection software.

3.2 Digital Bathymetry Model using Multifrequency MBES

This research used multifrequency MBES R2Sonic 2020 with five modes 200 kHz, 250 kHz, 300 kHz, 350 kHz, dan 400 kHz (Figure 4). The MBES multifrequency data from the survey is still a single file and must be separated into five files for each frequency. The data density of each file is a fifth of the original file.

Multibeam echosounders (MBES) are the most efficient and widely used sonar technology for seabed mapping. Beamforming in the across-track direction enables measurements of the signal travel time to the seabed for many beam angles. As such, it provides detailed and extensive information about seabed bathymetry. The primary function of MBES is to detect a certain amount of depth along the swath of the bottom. The transducer sends a sound pulse reflected from the bottom and received by a series of transducers to obtain this depth in a particular angular sector [30]. In the last decade, several manufacturers have made MBES that are not only capable of producing one frequency but more than one frequency with one survey on a ping-by-ping basis. One of the goals of using multi-frequency is to reduce the amount of noise encountered [31].

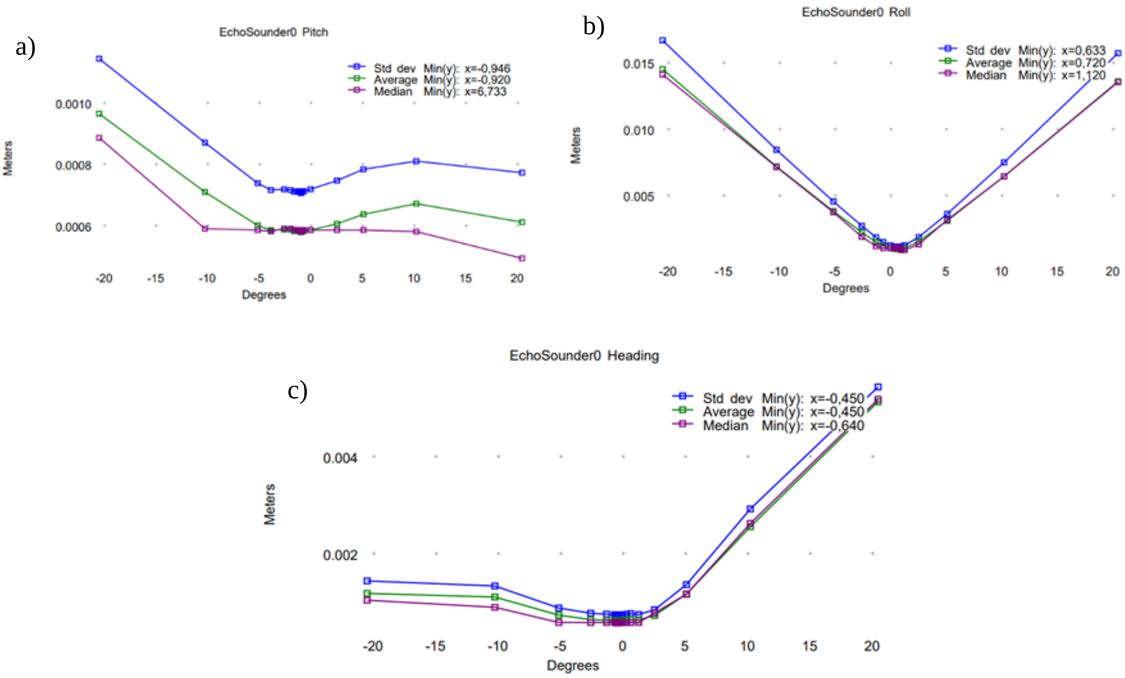

Figure 3: Graphical of patch test value (a) pitch, (b) roll, and (c) heading

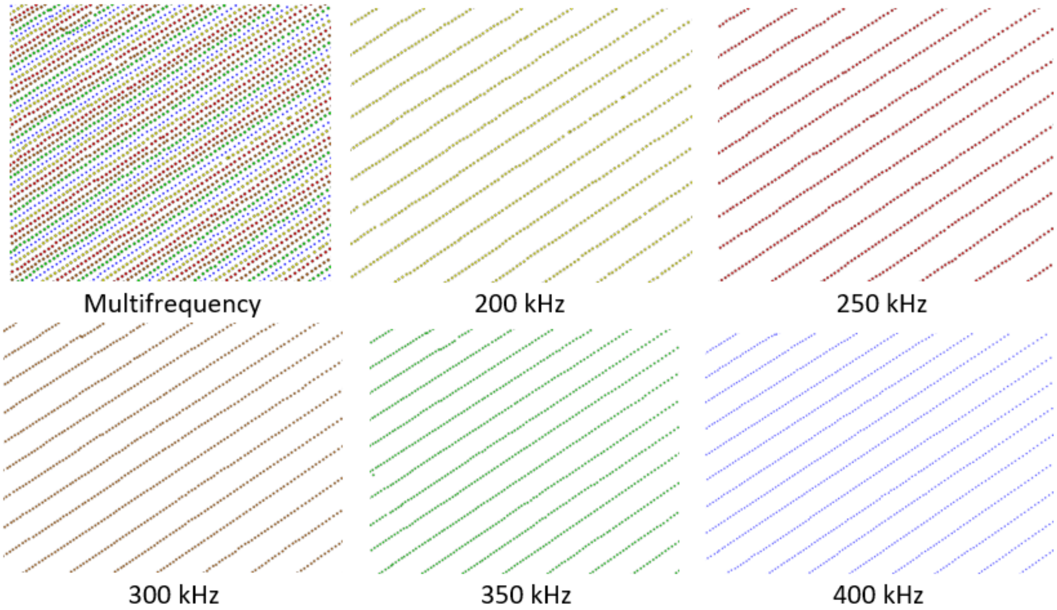

Figure 4: Data density of multifrequency MBES and each frequency

The bathymetry data obtained by multifrequency MBES must follow standards set by the International Hydrographic Organization (IHO) S-44 6th edition [32]. There are five categories of area surveys regarding the accuracy requirement of S-44 IHO for the bathymetric survey: Order 2, Order 1b, Order 1a, Special Order, and Exclusive Order. After data multifrequency MBES processing, the value of depth Total Horizontal Uncertainty (THU) for each frequency is 0.1 m, and the value of depth Total Vertical Uncertainty (TVU) for each frequency is 0.2 m.

These results refer to S-44 IHO concluded in a special order because the maximum allowable depth THU is 2 m, and the depth TVU is 0.25 m. The depth THU value follows the formula:

$$TVU_{max}(d) = \sqrt{a^2 + (b \times d)^2}$$
Equation 1

where a = 0.25 and b = 0.0075, and d is the depth. In this case study, the area survey is categorized by special order with under keel clearance is critical.

The digital bathymetry model (DBM) is a spatial computational model that automatically presents the ocean floor's depth information. DBM is required to display marine survey information. There are several methods for constructing seabed DBM, such as linear interpolation, inverse distance weighted (IDW), spline function, kriging, and others. This study uses the kriging interpolation method based on the theory of regionalized variables and the semi-variant function as a tool. Under minimal estimated variance, the Kriging interpolation method considers the randomness of field changes and discrete sample correlations [29]. This method gives the optimal linear unbiased estimate. Figure 5 shows the digital bathymetric model for each frequency 200 kHz, 250 kHz, 300 kHz, 350 kHz, and 400 kHz. The reference depth of this case is the lowest water surface (LWS). In general, the depth of the survey site for each frequency shows a depth between -2.5 m LWS and -23.5 m LWS. The depth of the northwest part (near the shoreline) is from -3 m LWS to -8 m LWS. In the center of the survey area, the depth ranges from -6 m LWS to -15 m LWS; in the northeast part, the depth is between -16 m LWS and -23.5 m LWS. All the DBMs have a uniform bathymetric shape and pattern. To the north, there is a cliff almost straight 90 degrees with a depth difference between -8 to -14 m. In addition, to the south, there is a channel with a depth of -15 to -20 m LWS.

3.3 Bathymetric Differences Inter Frequency

Bathymetric data processing is carried out with the Eiva software, applying manual and spline filtering to remove sounding artifacts. The bathymetry data is then separated per frequency and gridded into a 1 m × 1 m grid. Each DBM frequency is subtracted from a depth of 200 kHz, whereas the low-frequency depth is subtracted from the high-frequency depth. Figure 6 shows the path profiled from north to south (A – A') and west to east (B – B').

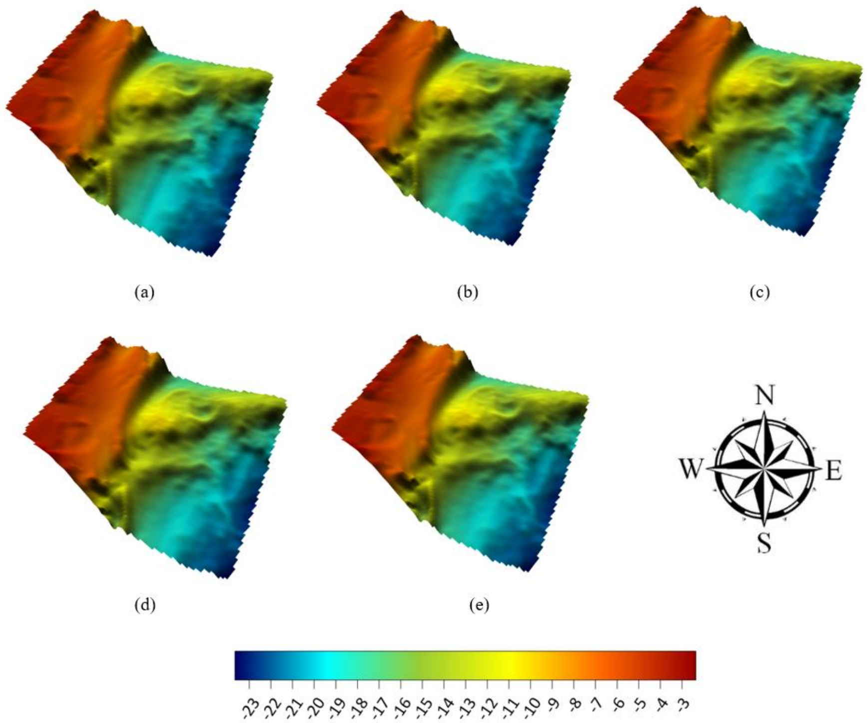

Figure 5: Digital bathymetric model for each frequency, (a) 200 kHz (b) 250 kHz (c) 300 kHz (d) 350 kHz (e) 400 kHz

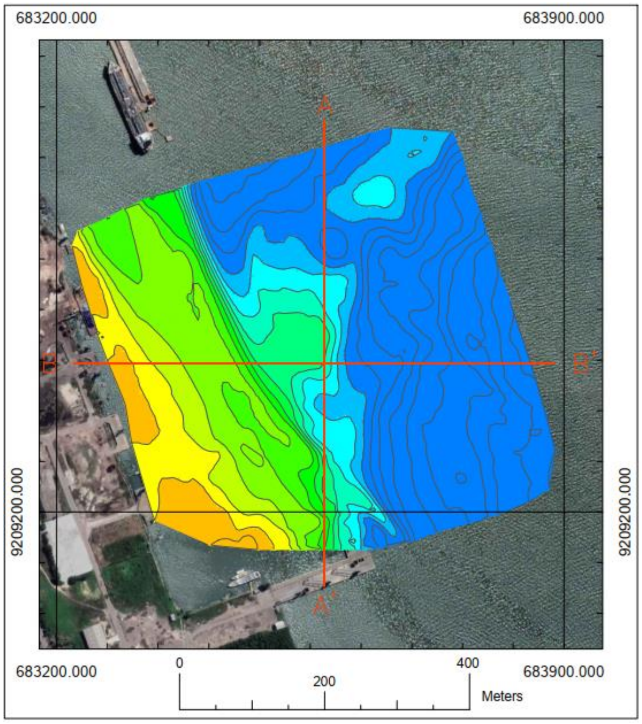

Figure 6: Cross section path of A – A’ (north to south) and B – B’ (west to east)

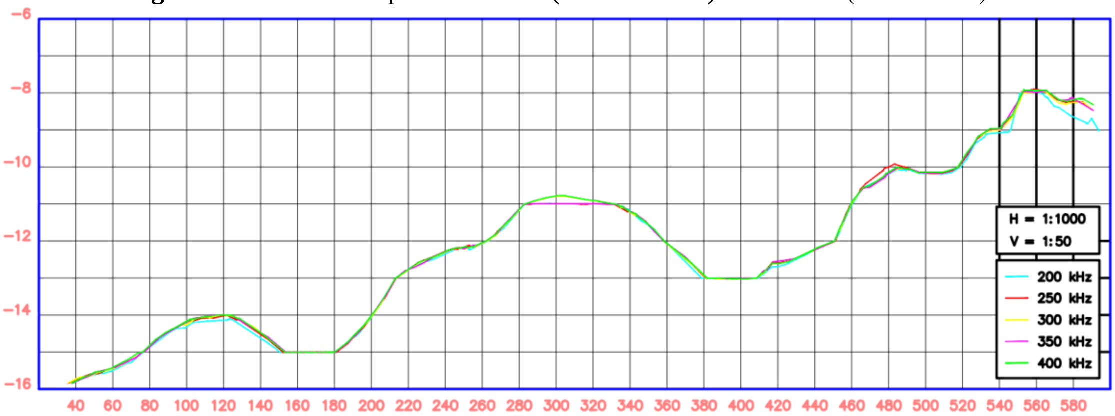

Figure 7: Depth overlay for each frequency in cross section from A – A’

Figure 7 describes the depth cross-sectional profile from A – A' for each frequency, and Figure 8 describes the depth-crossing profile from B – B' for each frequency. In general, it can be seen that the frequency of 400 kHz (green color) shows the shallowest depth (the top green line), and the frequency of 200 kHz shows the deepest depth (light blue color). However, there are several locations of the shallowest frequency, 250 (red), and the deepest frequency, 350 (magenta). Figure 9 shows all the results of each difference in depth between 200 kHz and other frequencies. All the depth differences are dominated by the orange color, which suggests a depth difference of 0 – 10 cm. In the northeast part, some locations with a small area show depth differences between 10 – 20 cm (red), 20 – 30 cm (brown), 30 – 40 cm (magenta), and 40 – 50 cm (green).

3.4 Volume Analysis Due to Frequency Differences

In dredging work, surface one (existing) and surface two (actual) depth data are required to calculate dredging volume. Surface one and surface two should be measured using an MBES survey tool with the exact specifications, such as the same frequency and beam width, to produce a consistent volume.

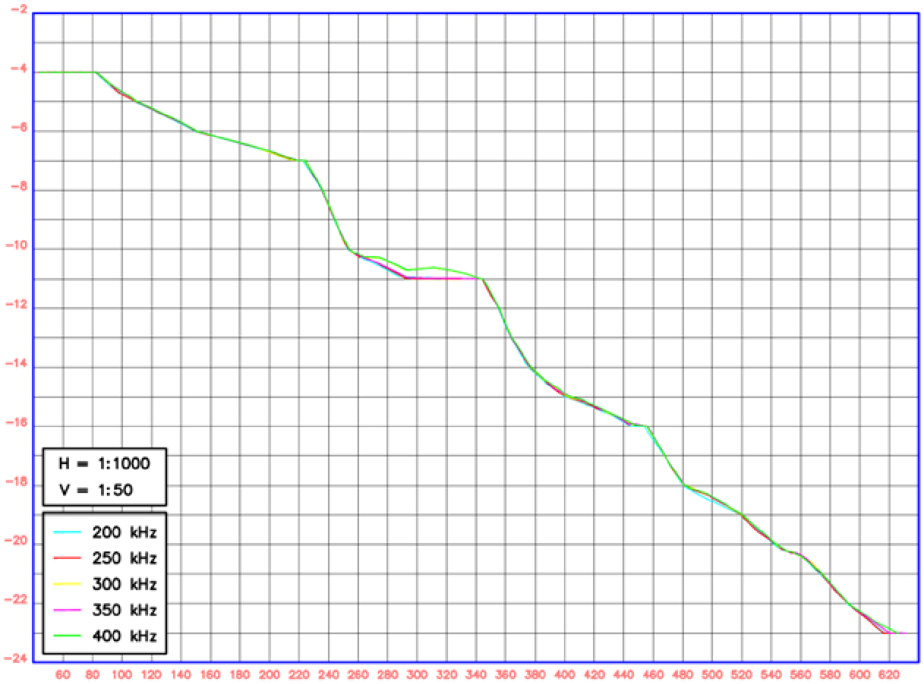

Figure 8: Depth overlay for each frequency in cross section from B – B'

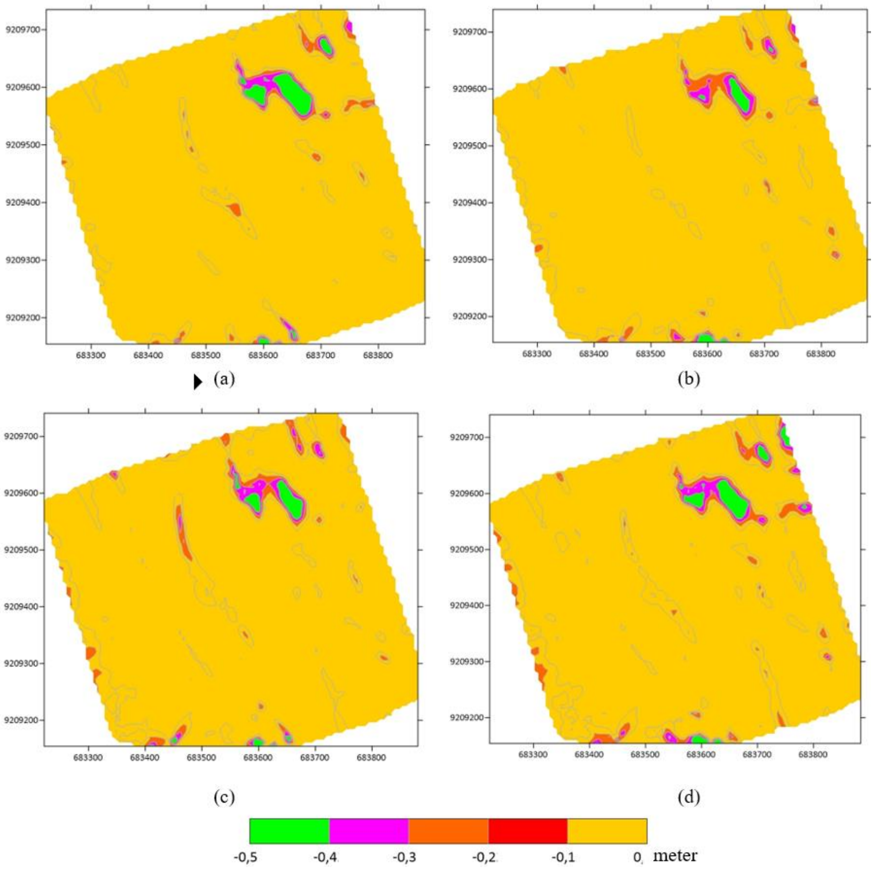

Figure 9: Bathymetric difference between (a) 200 kHz and 250 kHz (b) 200 kHz and 300 kHz (c) 200 kHz and 350 kHz (d) 200 kHz and 400 kHz

Table 2: Dredging volume inter frequencies between 200 kHz and other frequencies.

Volume Inter Frequency (m^3)	250 kHz	300 kHz	350 kHz	400 kHz
200 kHz	8746.292 (m^3)	9664.347 (m^3)	10957.777 (m^3)	14112.276 (m^3)

Table 3: The effect of using different frequencies on the dredging volume in 1 ha

Dredging thickness	Dredging Volume	Minimum difference (m^3)	%	Maximum difference (m^3)	%
1 m	10000	420	4.20	680	6.80
2 m	20000	420	2.10	680	3.40
3 m	30000	420	1.40	680	2.27
4 m	40000	420	1.05	680	1.70
5 m	50000	420	0.08	680	1.36

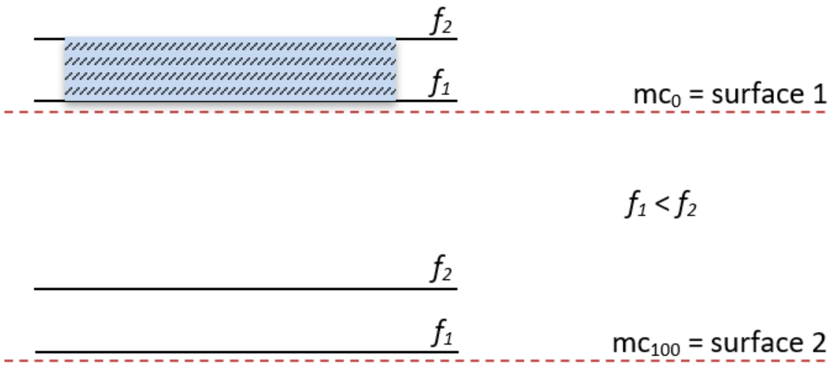

Figure 10: Excess dredging volume if mc_0 use f_1 and mc_{100} use f_2

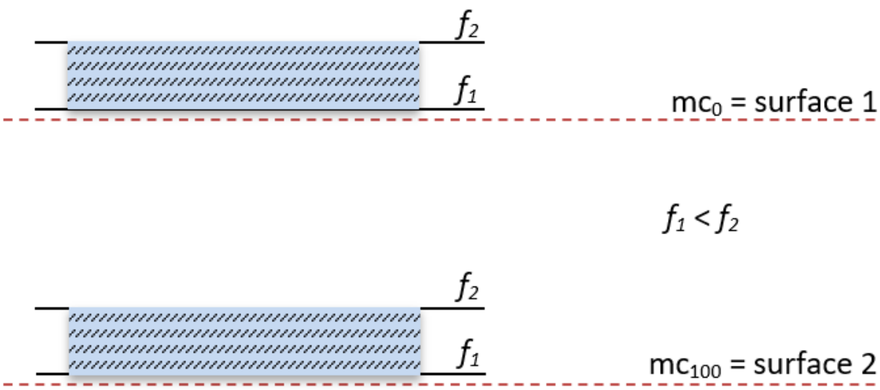

Figure 11: Excess dredging volume if mc_0 use f_2 and mc_{100} use f_1

In this case study, the difference in volume will be seen if the data used on existing and actual surface use different frequencies. The MBES multi-frequency data here uses the 200 kHz, 250 kHz, 300 kHz, 350 kHz, and 400 kHz modes, each of which simultaneously produces depth in the same survey area (ping by ping). The following Table 1 shows the dredging volume between a depth of 200 kHz and a depth of other frequencies. The existing surface, used to calculate the volume in Table 1 above, is a depth with the lowest frequency than the actual surface, that is, a depth with 200 kHz frequency. In the case of dredging work, the volume used is the cut (dredging) volume. Table 2 shows that the dredging volume between frequencies with a low frequency as existing surface means that the dredging volume value is much bigger than actual surface when a lower frequency is used. The minimum dredging volume is 8746.292 m^3 for 200 kHz (existing) and 250 kHz (actual), and the maximum dredging volume is 14112.276 m^3 for 200 kHz (existing) and 400 kHz (actual).

With an area of 41.5 ha, the dredging volume ranges from 0.021 m^3/m^2 – 0.034 m^3/m^2. This case means that if the existing surface (mc_0 survey) uses a lower frequency (f_1) than the frequency at the actual surface (mc_{100}), then there will be a difference (excess) of dredging volume between 0.021 m^3/m^2 – 0.034 m^3/m^2 (Figure 10). Furthermore, and vice versa, Figure 11 shows that the existing surface (mc_0 survey) uses a higher frequency (f_2) than the actual surface. There will be a two times excess dredging from 0.021 m^3/m^2 – 0.034 m^3/m^2 or 0.042 m^3/m^2 – 0.068 m^3/m^2. If it is assumed that the dredging area is 1 ha, the difference in dredging volume between the maximum frequency ranges from 420 m^3 to 680 m^3. This value is only 4.2 % - 6.8%, minimal compared to the total dredging in 1 ha conducted as deep as 1 m with a total volume of 10000 m^3. The deeper the dredging, the smaller the percentage difference (see Table 3).

4. Conclusion

The data density of each frequency is 1/5 of the data density of the original data. The MBES multifrequency 3D bathymetry model for each frequency (200 kHz, 250 kHz, 300 kHz, 350 kHz, and 400 kHz) has a similar model with depths ranging from -2.5 m to -23.5 m LWS. All depth differences inter-frequency between 200 kHz and other frequencies (250 kHz, 300 kHz, 350 kHz, and 400 kHz) are dominated by 0 – 10 cm. The most significant depth difference is 50 cm in some locations in the northeast. The dredging volume difference inter-frequency between depths of 200 kHz and others ranges from 0.021 m3/m2 to 0.034 m3/m2. This value is minimal compared to the total dredging volume with a dredging thickness of 1 m and an area of 1 ha less than 5%. This research benefits the industry for dredging purposes to produce optimal volume. Future research should be carried out in areas with varied terrain and different sediment types, from hard sediment (rock) to soft sediment (clay).

Acknowledgements

We thank our colleagues from PT. APBS who provided insight and expertise that greatly assisted the research related to the R2Sonic2020 multi-frequency MBES survey and Eiva Corporation who has licensed the Navi Edit Job Planner and Navi Model Producer software to the geomatics engineering department.

References

[1] IHO, (2005). *Manual on Hydrography*., Published by The International Hydrographic Bureau. Final Draft. Monaco.

[2] Hell, B., (2011). *Mapping Bathymetry from Measurement to Applications*., Doctoral thesis in Marine Geoscience. Department of Geological Sciences Stockholm University, Stockholm Sweden

[3] Lecours, V., Devillers, R., Schneider, D. C., Lucieer, V. L., Brown, C. J. and Edinger, E. N., (2015). Spatial Scale and Geographic Context in Benthic Habitat Mapping: Review and Future Directions. *Marine Ecology Progress Series*, Vol. 535, 259–284, https://doi.org/10.3354/meps 11378.

[4] Lamarche, G. and Lurton, X., (2018). Recommendations for Improved and Coherent Acquisition and Processing of Backscatter Data from Seafloor-Mapping Sonars. *Marine Geophysical Research*, Vol. 39, 5–22 https:// doi.org/10.1007/s11001-017-9315-6.

[5] Cui, X., Liu, H., Fan, M., Ai, B., Ma, D. and Yang, F., (2021). Seafloor Habitat Mapping Using Multibeam Bathymetric and Backscatter Intensity Multi-Features SVM Classification Framework. *Applied Acoustics*, Vol. 174, https://doi.org/10.1016/j.apacoust.2020.107728.

[6] Amirebrahimi, S., Picard, K., Quadros, N. and Falster, G., (2019). Multibeam Echosounder Data Acquisition in Australia and Beyond – User Needs Summary. *Geoscience Australia Record* 2019/08. 47. Available online at: http://www.aus seabed.gov.au/__data/assets/pdf_file/0006/8652 3/MBES_User_ Needs_Summary.pdf.

[7] Brown, C. J., Beaudoin, J., Brissette, M. and Gazzola, V., (2019). Multispectral Multibeam Echo Sounder Backscatter as a Tool for Improve Seafloor Characterization. *Geosciences*, Vol. 9(3), 1-19. https://doi.org/10.3390/geosciences 9030126.

[8] Wölfl, A. C., Snaith, H., Amirebrahimi, S., Devey, C. W., Dorschel, B., Ferrini, V., Huvenne, V. A. I., Jakobsson, M., Jencks, J., Johnston, G., Lamarche, G., Mayer, L., Millar, D., Pedersen, T. H., Picard, K., Reitz. A., Schmitt, T., Visbeck, M., Weatherall, P. and Wigley, R., (2019). Seafloor Mapping – The Challenge of a Truly Global Ocean Bathymetry. *Frontiers in Marine Science*, Vol.

6, 1-283. https://doi.org/10.3389/fmars.2019.00283.

[9] Gula, J., Molemaker, M. J. and McWilliams, J. C., (2015). Gulf Stream Dynamics Along the Southeastern US Seaboard. *Journal of Physical Oceanography*, Vol. 45(3), 690-715. https://doi.org/10.1175/JPO-D-14-0154.1

[10] Madricardo, F., Foglini, F., Kruss, A., Ferrarin, C., Pizzeghello, N. M., Murri, C., Rossi, M., Bajo, M., Bellafiore, D., Campiani, E., Stefano Fogarin, S., Grande, V., Janowski, L., Keppel, E., Leidi, E., Giuliano Lorenzetti, G., Maicu, F., Maselli, V., Mercorella, A., Gavazzi, G. M., Minuzzo, T., Pellegrini, C., Petrizzo, A., Prampolini, M., Alessandro Remia, A., Rizzetto, F., Rovere, M., Sarretta, A., Sigovini, M., Sinapi, L., Umgiesser, G. and Trincardi, F., (2017). High Resolution Multibeam and Hydrodynamic Datasets of Tidal Channels and Inlets of the Venice Lagoon. *Scientific Data*, Vol. 4(1), 1-13. https://doi.org/10.1038/sdata.2017.121

[11] Smith Menandro, P. and Cardoso Bastos, A., (2020). Seabed Mapping: A Brief History from Meaningful Words. *Geosciences*, Vol. 10(7).1-17. https://doi.org/10.3390/geosciences10070273.

[12] Lurton, X., and Lamarche, G., (Eds) (2015). Backscatter Measurements by Seafloor-Mapping Sonars. Guidelines and Recommendations. 1-200. https://niwa.co.nz/static/BWSG_REPORT_MAY2015_web.pdf.

[13] Šiljeg, A., Marić, I., Domazetović, F., Cukrov, N., Lovrić, M. and Panđa, L., (2022). Bathymetric Survey of the St. Anthony Channel (Croatia) Using Multibeam Echosounders (MBES)—A New Methodological Semi-Automatic Approach of Point Cloud Post-Processing. *Journal of Marine Science and Engineering*, Vol. 10(1). https://doi.org/10.3390/jmse10010101.

[14] Blondel, P., (2012). *Bathymetry and its Applications*. InTech Open Access Publisher, Croatia. ISBN 978-953-307-959-2.

[15] Huizinga, R. J., (2016). *Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River near Kansas City, Missouri*, June 2–4, 2015: U.S. Geological Survey Scientific Investigations Report 2016–5061. 1-93.

[16] Huizinga, R. J. and Heimann, D. C., (2018). *Hydrographic Surveys of Rivers and Lakes Using a Multibeam Echosounder Mapping System*; US Department of the Interior, US Geological Survey: Reston, VA, USA.

[17] Ierodiaconou, D., Schimel, A. C., Kennedy, D., Monk, J., Gaylard, G., Young, M., Diesing, M. and Rattray, A., (2018). Combining Pixel and Object-Based Image Analysis of Ultra-High Resolution Multibeam Bathymetry and Backscatter for Habitat Mapping in Shallow Marine Waters. *Marine Geophysical Research*, Vol. 39, 271–288. https://doi.org/10.1007/s11001-017-9338-z.

[18] Brown, C. J., (2015). Benthic Habitat Mapping: From backscatter to Biology. *J. Ocean Technol.*, Vol. 10, 48–61.

[19] Fonseca, L, Mayer, L., Orange, D. and Driscoll, N., (2002). The High-Frequency Backscattering Angular Response of Gassy Sediments: Model/Data Comparison from the Eel River Margin, California. *The Journal of the Acoustical Society of America*, Vol. 11(6). 2621–2631. https://doi.org/10.1121/1.1471911.

[20] Feldens, P., Schulz, I., Papenmeier, S., Schönke, M., and Schneider von Deimling, J., (2018). Improved Interpretation of Marine Sedimentary Environments Using Multi-Frequency Multibeam backscatter Data. *Geosciences*, Vol. 8. https://doi.org/10.3390/geosciences8060214.

[21] Gaida, T. C., Tannaz, H., Mohammadloo, T. H., Snellen, M. and Simons, D. G., (2020). Mapping the Seabed and Shallow Subsurface with Multi-Frequency Multibeam Echosounders. *Remote Sens.* Vol. 12(1). https://doi.org/10.3390/rs12 010052.

[22] Menandro, P. S., Bastos, A. C., Misiuk, B. and Brown, C. J., (2022). Applying a Multi-Method Framework to Analyze the Multispectral Acoustic Response of the Seafloor. *Front. Remote Sens.*, Vol. 3. https://doi.org/10.3389/frsen.2022.86028.

[23] R2Sonic, (2019). Multibeam Echosounder Specifications. R2Sonic Our Vision is Sound. 5307 Industrial Oaks Blvd. Suite 120. Austin, Texas 78735 USA MBES-Spec-US-03-02-2020.pdf (r2sonic.com).

[24] Rakotosaona, M. J., La Barbera, V., Guerrero, P., Mitra, N. J. and Ovsjanikov, M., (2020). Pointcleannet: Learning to Denoise and Remove Outliers from Dense Point Clouds. *Comput. Graph. Forum*, Vol. 39, 185–203. https://doi.org/10.48550/arXiv.1901.01060.

[25] Chen, C., Gawel, A., Krauss, S., Zou, Y., Abbott, A. L. and Stilwell, D. J., (2020). Robust Unsupervised Cleaning of Underwater Bathymetric Point Cloud Data. *Proceedings of the 31st British Machine Vision Virtual Conference*, Online, 7–10 September 2020. https://www.bmvc2020-conference.com/assets /papers/0977.pdf.

[26] Wu, Z., Yang, F. and Tang, Y., (2021). *Multi-beam Bathymetric Technology*. In: High-Resolution Seafloor Survey and Applications. Springer, Singapore.

[27] Clarke, J. E. H., (2012). *Optimal use of Multibeam Technology in the Study of Shelf Morphodynamics*. In Michael ZL, Christopher RS, Philip RH (eds) IAS Special Publication# 44. Sediments, morphology, and sedimentary processes on continental shelves: Advances in Technologies, Research, and Applications. Wiley-Blackwell, Oxford, 1–28.

[28] Johnson, P. D. and Jerram, K., (2014). *E/V Nautilus EM302 Multibeam Echosounder System Review*. University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center Durham, NH

[29] Brennan, C. W., (2017). *Multibeam Calibration: The Patch Test*. R2Sonic LLC Multibeam Training – The Patch Test.

[30] SeaBeam, (2000). *Multibeam Sonar Theory of Operation*. L-3 Communications SeaBeam Instruments 141 Washington Street East Walpole, MA 02032-1155.

[31] Lekkerkerk, H. J., (2020). State of the Art in Multibeam Echosounders. *The Evolution of a Bathymetric Workhorse. Article*. Hydro International.

[32] IHO, (2020). *S-44 6th edition IHO Standards for Hydrographic Surveys*. International Hydrographic Organization. Monaco.