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The Development of Seabed Sediment Mapping Methods: The Opportunity Application in the Coastal Waters

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The Development of Seabed Sediment Mapping Methods: The Opportunity Application in the Coastal Waters

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Abstract. Coastal areas have a significant role in human life worldwide, where world economic activities are concentrated in coastal areas. One of which is the activity of loading and unloading import-export goods through ports. Ports management must use a nautical chart to ensure the safety of shipping activities. The nautical chart contains graphical information from the sea and coastal areas, namely: seabed topography, natural and artificial seabed features, coastlines, navigation hazards, both natural and artificial navigation aids, tides, currents, human-made structures such as ports, buildings, and bridges. Seabed sediment is also essential information that must be available in the Nautical Chart. Several techniques and methods are used to make a seabed sediment map, namely mechanical grab (lead line, grab sampler, coring) and acoustic (side-scan sonar, singlebeam, and multibeam echosounder). This paper reviews seabed sediment mapping techniques and proposes techniques and methods in the future.

Keywords: nautical chart, seabed sediment, mechanical, acoustic, grab sampler, multibeam echo sounder

1. Introduction

Coastal areas (coastline, coastal environments, and seashore) have been known as a human attraction for thousands of years and are continuing today. Many human activities are concentrated in this coastal area. Besides, many major cities in the world are developing in this region. One of the coastal areas' economic activities is loading and unloading ships at the port, which requires a nautical chart to support economic activity. A nautical chart plays an essential role in sea navigation, which depicts seafloor and shoreline configuration. It contains graphical information from the sea and coastal areas [1]: bathymetry, both natural and artificial seabed features, coastlines, navigation hazards, both natural and artificial navigation aids, tides, and currents, human-made structures such as ports, buildings, and bridges. Also, information that is also important that must be in the nautical chart is seabed sediments characteristics.

Characteristics of seabed sediments are essential for ship safety [2], especially when the ship wants to stop while in the middle of the sea by throwing anchors. Seabed sediment characteristics are also essential for construction (installing gas and oil pipelines, laying cables of electricity, optics and telecommunications, and platform structure) and the environment (benthic habitat impacts, transport sediment, dredging material, and disposal offshore waste). Furthermore, the intensifying human exploitation of the oceans has led to an increased demand for accurate seafloor information maps—the information required for both the seafloor topography and the distribution of the seafloor composition. The problem is the unavailability of nautical charts, which contain necessary and complete seabed sediment information, or seabed sediment maps that are complete and accurate.



The need for very accurate seabed sediment maps near the coastal waters is increasing. It will take more than one century before mapping based on modern means [2]. The solution proposed here is to start from a rough knowledge established with the past and gradually supplement it with the more recent technology to make a seabed sediment map. Seabed sediment mapping methods have developed rapidly from year to year and from mechanical to acoustic methods. This paper explains the evolution of seabed sediment mapping technology and future development to accelerate the availability of complete and accurate seabed sediment maps.

2. Sediment Mapping Method

2.1 Sediment and Sedimentation

Sediment is solid particles such as sand produced by the natural process of erosion and weathering, transported to other locations by the actions of wind, water, ice, and mass wasting, all operating under gravity [3]. Eventually, sediment settles out and accumulates after transport; this process is known as a deposition. Sedimentation is a general term for the processes of erosion, transport, and deposition. There are three basic types of sediment: rock fragments (clastic sediments), mineral deposits (chemical sediments), and organic matter (biological sediments) [4]. This paper will focus on clastic sediment, which has three primary grain sizes: gravel, sand, and mud. Gravel refers to grains greater than 2 mm in size, sand refers to grains less than 2 mm but greater than 63 μm in size, and mud refers to grains less than 63 μm in size. These three significant classes can be subdivided further using the Udden-Wentworth grain size scale [5].

Table 1. Sediment Grain Sizes [5]

Class terms (x)	Particle Type	Size (mm)
Boulders	Gravel	>256
Cobbles		$256 \leq x < 64$
Pebble)		$64 \leq x < 4$
Granules		$4 \leq x < 2$
Very coarse sand grain	Sand	$2 \leq x < 1$
Coarse sand		$1 \leq x < \frac{1}{2}$
Medium sand grain		$\frac{1}{2} \leq x < \frac{1}{4}$
Fine sand grain)		$\frac{1}{4} \leq x < \frac{1}{8}$
Very fine sand grain)		$\frac{1}{8} \leq x < \frac{1}{16}$
Silt	Silt	$\frac{1}{16} \leq x < \frac{1}{256}$
Clay)	Clay	$x \leq \frac{1}{256}$

2.2 Sediment Sampling

2.2.1 Grab Sediment Sampler

Several tools can be used to collect seabed sediments depending on the contaminants and the information required. One of the tools used to collect sediment on the seabed is a grab sediment sampler. The grab sediment sampler is very easy to operate and can provide seabed samples suitable for grain analysis in the laboratory. It is also easy to deploy even from small vessels and in rougher sea conditions. There are several types of grab sediment samplers available on the market, and the most commonly used are Shipek, Van Veen (Figure 1), Petersen, and SmithMcIntyre types. Grab sediment samplers [6] [7] are

better for collecting fine-grained cohesive sediments, such as mud and clay, than non-cohesive sediment such as sand, cone shells, and gravel. These are usually easy to deploy (even from small vessels and in rougher sea conditions) and can give a very large sample.



Figure 1. Van Veen Grab Sampler

There are several drawbacks to seabed sediment sampling using a grab sampler. The first weakness is the limitation of this tool in taking the bottom sediment only for shallow waters. The deeper the waters, the more difficult it is to collect bottom sediment because the more in-depth the pressure is, the difficulty in taking sediment samples, incredibly hard sediments such as sand, rock, and gravel. The second is that this tool has difficulty extracting sediment samples that are too soft, such as silt and clay, so that the sediment is more comfortable releasing (loss of fine sediments). Another disadvantage is the low accuracy of determining the seabed sediment position. At the time of sampling, the ship's position had shifted to another location due to currents, waves, or something else. Besides, this tool cannot provide information on seafloor conditions, and samples only give information about the seabed surface.

Furthermore, a larger sampler will require a winch for deployment. It needs a time-consuming and costly process to analyze these samples in a laboratory [7] [8] [9]. The drawback of seabed sediment retrieval with the grab sampler is that it is static data retrieval, requiring a considerable time to create a seabed sediment map with many samples. The higher spatial resolution of seabed sediment it needs many sampling points (Figure 2). The more sample points cause the length of the observation time and, consequently, the more expensive. [10] shows the spatial distribution of the sediment textural data in Tauranga Harbour derived from grab samples (Figure 2). The color-coded clusters group similar sampling sites and does not mean representing the actual sediment class boundaries of the area.

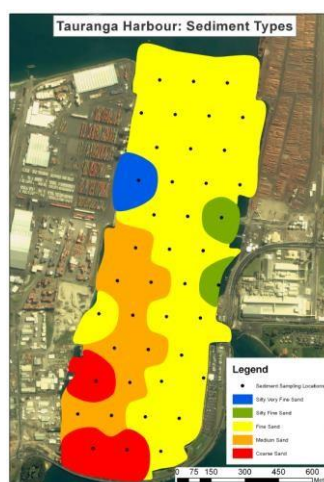


Figure 2. Seabed sediment map from grab samples [10]

2.2.2 Sediment Cores

Unlike the grab sediment sampler, core sediments can take sediment on the seabed surface and capture the stratigraphic layers with depth. Several types of sediment cores: gravity corers, multiple gravity corers, hydraulically damped corers, box corers, piston corers, freeze corers, Vibro corers, and drilling. Their application depends on environmental conditions and desired research [7]. Gravity core (Figure 3) is the type most often used to collect seabed sediments. It can quickly and continuously pick up bottom sediments to several thousand meters from the seafloor [8]. It can also be operated with various types of vehicles. The gravity core application is for dredging, offshore oil and gas engineering, pipeline and cable routes, and is very useful for controlling soil types in geophysical surveys.

Like the sediment grab sampler, this gravity core also has the same disadvantage if used for necessary seabed sediment mapping. It cannot produce continuous primary sediment data so that the more samples needed, the more time is required, and ultimately the costs incurred are also more significant. Gravity corers are only really suitable for collecting very soft to hard clays because penetration in hard clays or sand is usually limited [7]. Furthermore, the samples obtained are generally of average to moderate quality. Core samples are not easy to acquire as grab samples. These techniques can be expensive since they require dedicated ships and equipment, lengthy measurements, and a labor-intensive analysis afterward. Not only is the acquisition more expensive, so the core analysis and storage [8] [9]. Another essential drawback is that these techniques provide information on point positions only. As in the grab sampler (Figure 2), the seabed sediment distribution map from the gravity core has a low spatial resolution. The denser the sample points will produce a high resolution and vice versa. However, the closer the sample points are, it will take a long time and be expensive.

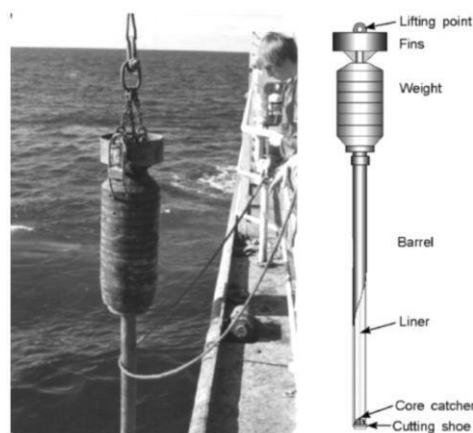


Figure 3. Gravity Core

2.3 Acoustic System Techniques

Remote sensing techniques based on acoustic waves such as single beam echosounder, side-scan sonar, and multibeam echosounder have provided technological solutions for seabed mapping such as mapping ocean depths and seabed features. Underwater acoustics is applied as one of the most efficient and accurate applications to understand the seabed characteristics and locate and identify marine objects in an accurate way [11]. One of the studies that have developed over time is the mapping or classification of seabed sediments in various areas with various spatial scale variations that aim to support marine areas' management. The sound scattering theory from the ocean floor emphasizes the different theoretical models currently in use and ongoing evolution [12].

2.3.1 Single Beam Echo Sounder

The principle of single beam echo sounder (SBES) generates an acoustic pulse that travels through the water column, is reflected off the seabed, and is received back on board the vessel by a transducer

(Figure 4) [13]. SBES can measure only one point per acoustic echo wave emitted. The specifications of SBES are defined by beam angle and frequency of the transmitted acoustic wave from the transducer. The sounder generates an acoustic pulse that travels through the water column. It is reflected off the seabed and received back on board the vessel by the transducer.

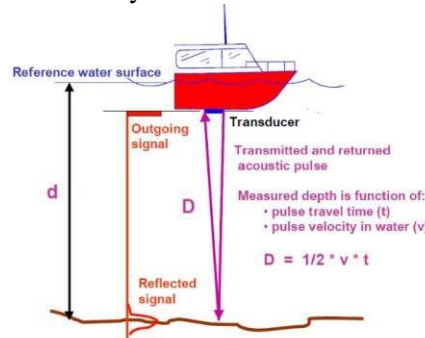


Figure 4. Acoustic Depth Measurement Principle [13]

The SBES systems offer relatively low acquisition costs, easy to use, ready availability and wide use, data processing efficiency, relative ease of understanding and operations, water-column backscatter availability, and use of multiple frequencies during a single survey [14] [15]. SBES data acquisition is only acquired directly underneath the transducer (Figure 4). SBES operations generally conduct systematic grid surveys and sometimes incorporate an adaptive star-like cruise track in selected shoal regions (Figure 5) [11]. Survey lines are run perpendicular to the coastlines, and the line spacing between the survey lines is dependent on the scale of the final product and resolution required (Figure 5). The shorter the distance between the survey lines from one another, the greater the resolution, but it takes longer. Furthermore, the features and possible hazards that lie between the survey lines will be omitted from the final product, and the resolution is of far lower quality [16] [17]. Besides, a single beam data resolution depends on the vessel's speed because the measurement directly under the vessel is obtained. Therefore, it is rather time-consuming to generate a region's 2D grid using a single-beam echo sounder. This instrument tends to be more suited to obtaining multiple 1D transects [18].

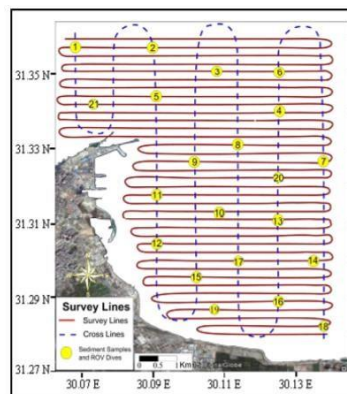


Figure 5. SBES Grid Survey Lines [11]

Generally, the main objective of a single beam echosounder survey is for seabed mapping (bathymetry). It can also detect empirically the type of bottom sediment used to predict coral sediments [16]. The single-beam echo sounder generates a seabed acoustic response to classify seabed sediments. The acoustic energy redirected to the transducer is called backscatter and affected by the seabed and sub-seabed. The backscatter strength (BS) quantifies the amount of acoustic intensity scattered back to the sonar receiver following a complex interaction of the transmitted signal with the seafloor. It results from an intricate combination of several physical factors: frequency, impedance contrast, roughness, the

sediment volume, and incidence angle [19]. Due to the various scattering properties of different seafloor substrates, backscatter can help determine the bottom type [20] [21] and possibly to infer some of its physical characteristics. The seabed characteristics, the sea surface's physical properties, or sea subsurface material influence the signal's shape [11]. An acoustic signal intensifies sediment seabed classification with SBES systems. Some factors will influence the reflected signal, such as hardness, roughness, and angle of acoustic incidence, which is affected by the seafloor's slope.

Figure 6 [11][22] shows that seabed sediment responds to SBES Signal. The length and intensity of the tail of the first echo (E1) and the intensity of the second echo (E2) can often be used to differentiate soft, hard, and rough habitats. These indices have often been related to seabed roughness and hardness, respectively. The first echo (E1) and the second echo (E2) intensity can often differentiate soft, hard, and rough habitats. These indices relate to seabed roughness and hardness, respectively. The first echo corresponds with grain size, topography, and seabed surface attenuation, such as large grain size or rough bottom, reflecting a narrow E1 envelope of higher amplitude. The E2 varies when the sound wave penetrates the seabed surface and is reflected by a substrate layer of different density. The attenuation of sound increases a higher density medium, such as when sound propagates from water to the seabed. The resulting backscatter intensity from a seabed made up of rock is significantly greater than that from a sandy substrate.

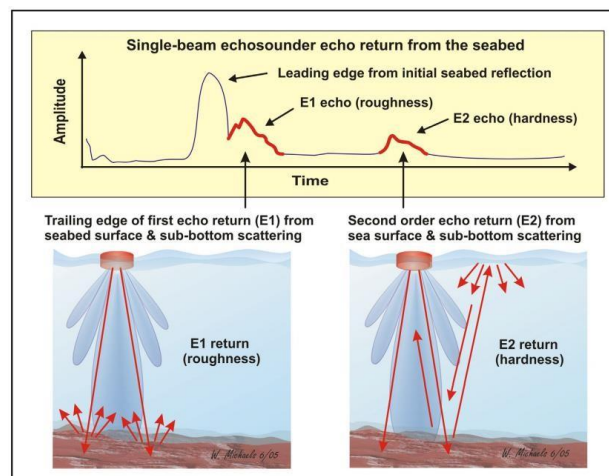


Figure 6. Roughness dan Hardness Responses of Seabed Sediment [22]

Another factor of influence reflected signal is the seabed angular response, which can vary within the acoustical footprint, and higher reflectivity is expected at nadir. Hence, the width of the footprint, angle of incidence, and the angular response from the seabed enhances the ability to discriminate the categories of seabed grain size (sand, gravel, and cobble). The optimal angular responses of SBES signal for classifying seabed made up of sand, gravel, and cobble occur at grazing angles ranging about 7–20° depending on the source level, frequency, pulse length, and operational range of the system [22]. Figure 7 [23] shows a seabed sediment map derived from a single beam echo sounder.

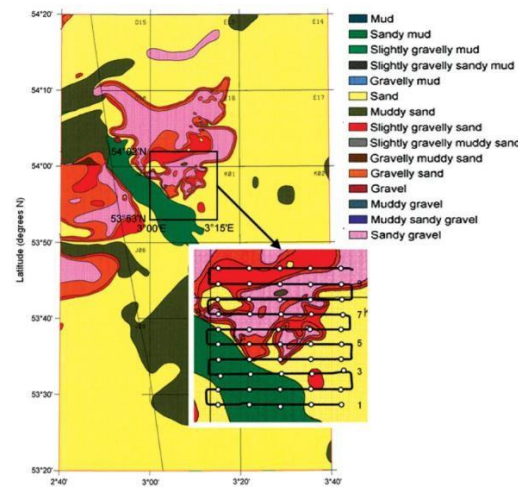


Figure 7. Seabed Sediment Map using *Backscatter SBES* [23]

2.3.2 Side Scan Sonar

Side-scan sonar (SSS) is one of the most potent types of equipment for underwater observation because it can efficiently measure a large area and produce a detailed image (high-resolution image) of anything on the seafloor. This equipment can conduct seabed mappings such as nautical charts, detection, and identification of underwater objects. It can also detect debris and other obstructions on the seabed that may be hazardous to shipping or seafloor installations for subsea field development [24] [25] [26] [27]. The SSS is examined as the most relevant acoustic device able to produce seafloor imagery by pulse emission of acoustic energy. The system amplifies and records the backscatter intensity of the seabed, generating the sonograph. It may be considered analogous to a continuous aerial photograph [25]. The SSS is most likely to provide the best high-resolution maps, particularly over vast areas. They provide information on sediment texture and bedform structure and allow dynamic processes (e.g., sediment transport) to be deduced [24]. Side-Scan Sonars are widely used in seafloor imagery, should remain short and also its ease of deployment: in some cases, they have a tow-fish structure, so there is no need for elaborate mountings on Autonomous Underwater Vehicles (AUV), Remotely Operated Vehicles (ROV) or ships [26].

Several factors affect the precision and accuracy of SSS images. For instance, the horizontal extent of the image is affected by the frequency and grazing angle, determined by the transducer's altitude above the seabed. Another factor is seabed conditions and altitude above the bed, a range of 300 m can be obtained at a frequency of 117 kHz and typically 150 m at a frequency of 234 kHz. Accuracy increases with decrease range. For example, 0.1 m accuracy is typically obtained at a range of 50 m (100 m swath), while only 0.3 m accuracy is received at 150 m [24] [28]. The disadvantage of side-scan sonar is its horizontal positioning of the tow-fish side-scan sonar. Although its position has used GNSS RTK, the position of tow fish that is moving or unstable causes, the resulting position is less accurate (Figure 8) [29]. Another disadvantage is, the more in-depth the ocean, the longer the cable needs to get clear and accurate objects in the sea bottom [28]. Side-scan sonar does not usually produce bathymetric data, so it must be combined with a single beam echo sounder (SBES) to get accurate depth [17]. Disadvantages associated with swath systems are their high costs and the need to have skilled interpretation. The output often requires considerable post-processing time and expense to obtain appropriate classifications [24].

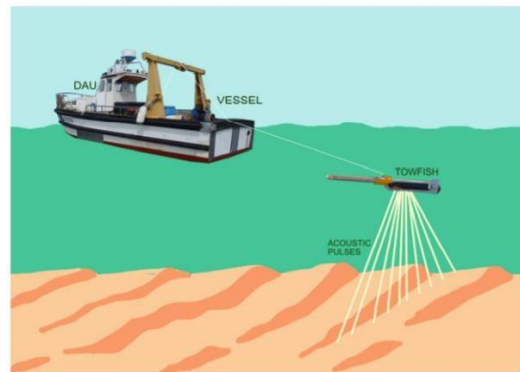


Figure 8. Tow-fish Side Scan Sonar [29]

The side-scan sonar scanning and combination with a certain amount of sediment sampling are the primary means of a survey. By analyzing the backscattered return signals of side-scan sonar and sediment sampling using grab sampler or sediment core, fine particles (clay and silt), coarse particles (sand soil), bedrock, and distinguish other types of sediment. For example, a seafloor sediment distribution map can be seen in Figure 9 [30].

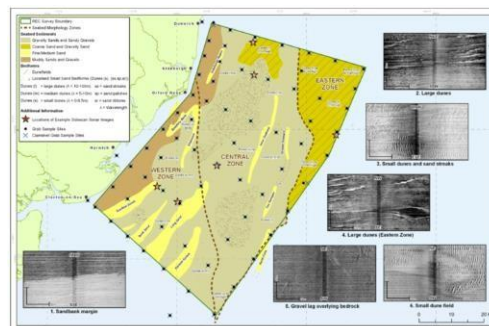


Figure 9. Seabed sediment map of the Outer Thames Estuary REC area [30]

2.3.3 Multibeam Echosounder

Multibeam Echosounder (MBES) is an acoustic instrument that can measure the seabed depth in more than one location with one beam (ping) [31]. The MBES systems measure the depth in a line extending outwards from the sonar transducer. The methods acquire data in a swath at right angles to the direction of the transducer head's motion, and the head moves forward, these profiles sweep out a ribbon-shaped surface of depth measurement known as a swath (Figure 10) [32] [18]. Therefore the MBES can map the seabed by a fan of narrow acoustic beams, thus providing 100% coverage of the bottom search to comply with special order by the International Hydrographic Organization's performance standards, S-44 edition 5. The MBES produce seabed maps are more detailed than those obtained using SBES, and the image data similar to a side-scan sonar image. Besides, the MBES dataset is useful for characterizing the seabed material properties and sometimes can detect small objects not visible in the sounding data because the MBES' ability to co-register high-density echo time, geometrical features, and intensity over large seabed swaths, providing depth and intensity data [24].

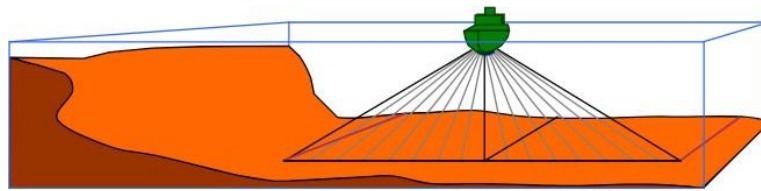


Figure 10. Sounder sonar system swath [32]

The cost of survey equipment using MBES is far more expensive than the SBES survey because the MBES survey equipment is far more complex and complete than SBES. However, conducting much faster surveys compensate for these expensive costs, saving the ship's reduced operating time. The spatial resolution of the data produced is also much denser compared to SBES. Another weakness of this MBES is the large data volume and requires complex calibration (pitch, yaw, roll, and sound speed profile) [18].

Initially, the multibeam echo sounder still focuses on the bathymetry mapping to fulfill the acquisition and accuracy of depth measurements IHO standard [33]. There is three main attraction of the MBES as the wide-area seabed coverage offered by the swath system. The first is a single trajectory of the survey platform, providing superior navigational data compared to SBES, which ultimately reduces the risk to surveyors at sea Figure 11 (a). In addition to the need for bathymetric mapping by sweeping the entire mapped area (full coverage), MBES can also be used for seafloor sediment mapping using backscatter (Figure 11 (b)) the acoustic signal it emits. The MBES backscatter is similar to the backscatter side-scan sonar [34]. It can be used to classify the seabed in the form of hardness and roughness characteristics and are precious measurements when studying the seabed sea surface's geology. Besides, acoustic wave returns can also be detected from objects in the water column such as fish, gas bubbles, sediments, etc. (Figure 11 (c)).

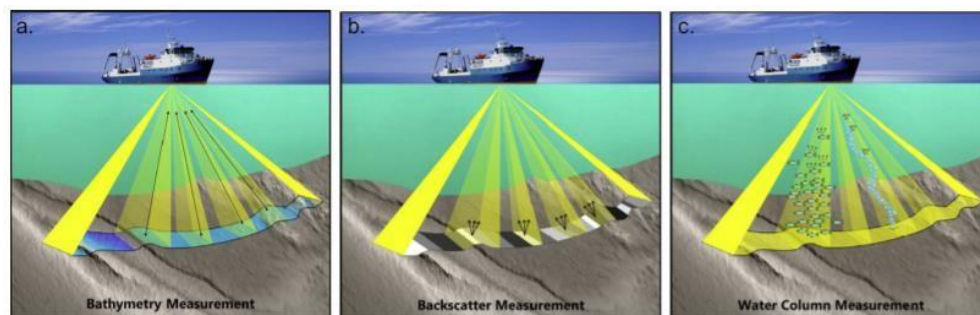


Figure 11. MBES application (a) bathimetri, (b) *backscatter* (c) *water coloumn* (Colbo, 2014)

Recently, MBES' backscatter intensity from the seafloor has attracted interest due to its ability to map the water-sediment-interface constituency. MBES can also be used for mapping seabed sediments by utilizing backscatter acoustic signals that emit. The acoustic wave backflow is an acoustic wave emitted by a transducer (transmitter-receiver) into the seabed sediments. It produces a portion of the reflected signal (backscattering) that is taken back by the transducer. The return signal's amplitude obtains the seabed reflectivity where high reflectivity indicates hard bottom sediments such as sand and gravel, and low reflectivity indicates soft seabed sediments such as mud and clay. MBES can characterize seabed sediments using geo-acoustic properties such as grain size, roughness, sound velocity, and porosity [35]. Indirect backscatter measurements and their comparison with theoretical models can determine the sediment character [36]. This backscatter is usually higher in rigid substrates, such as rock, and weaker in soft sediments such as mud [37]. MBES data supported by seabed sediment sample data taken with grab sampler or gravity core can produce a map of continuous base sediment distribution and has a better resolution compared to other data currently available (Figure 12) [10].

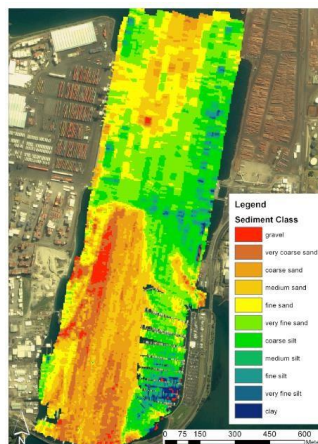


Figure 12. Seafloor Sediment Map Using Backscatter MBES [10]

2.4 Future trend of seabed sediment mapping and the opportunity application in the tropical coastal waters

Seafloor sediment mapping, as explained in the previous section, can be determined by mechanical methods such as grab sampler and gravity core, and also acoustic methods such as side-scan sonar (SSS), single-beam echo sounder (SBES), and multibeam echosounder (MBES). Each of these methods has advantages and disadvantages that complement each other. More acoustic methods are currently used with field data validation results from grab samplers and gravity cores analyzed in the laboratory. The acoustic method used in SSS, SBES, and MBES utilizes a backscatter or reflected wave from the seabed to the transducer (receiver). [38] use a reflective wave called reflectivity-based estimator for seafloor segmentation (BRESS). BRESS offers a new approach to quantitative analysis of seafloor sediment mapping data automatically, free of scale, reliable, and with efficient computing to segment the seabed (Figure 13).

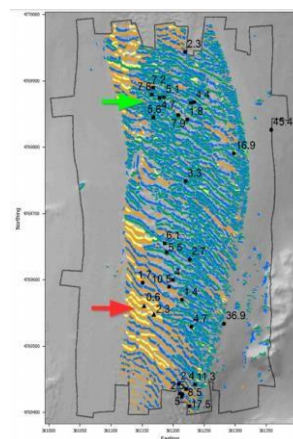


Figure 13. BRESS method for seafloor sediment segmentation [38].

Often the seabed sediment mapping that depends on environmental variables uses single scale data. [39] evaluated seafloor sediment mapping's potential using various scales (multiscale). The results of his study indicate that the data resolution of each terrain variable is not necessarily at the right scale to explain the grain size distribution of seabed sediments (Figure 14). A broader scale backscatter is the essential variable for distinguishing gravel from the sand. Based on the scale-dependent variables in this study, [39] concluded that the consideration of spatial scale is at least as important as selecting variables in the mapping of seafloor sediments.

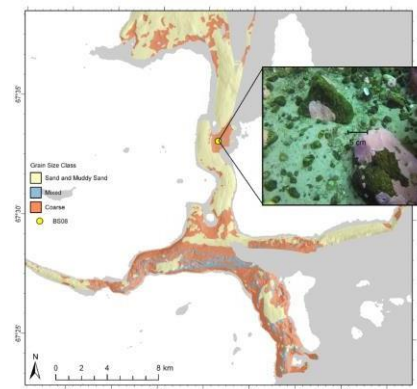


Figure 14. Seafloor Sediment Map using multiscale Backscatter [39]

Like the processing of signals on remote sensing imagery satellites using electromagnetic waves, MBES backscatter data processing to obtain classification results with high-resolution images, researchers generally use Pixel Based (PB) and Object-Based (OB) methods. [40] try to classify high-resolution MBES data by combining PB and OB. The results show that classification with PB and OB combinations produces a significantly more accurate base sediment map than PB classification alone or OB alone (Figure 15).

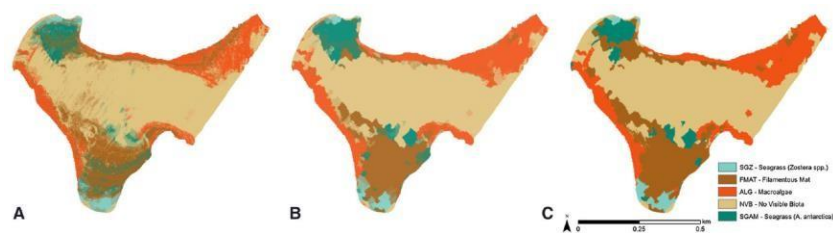


Figure 15. Seafloor sediment classification PB (left), OB (center) and PB and OB combination (right) [40]

In 2016, R2Sonic LLC produced a new variant of the MBES R2Sonic 2026, which allows more than one frequency (100 kHz, 200 kHz, and 400 kHz) to be modified on a ping-by-ping basis. This MBES product is the first product that can simultaneously (Figure 16) to collect data simultaneously from several frequencies at once in one data collection from the MBES system [41] [42].

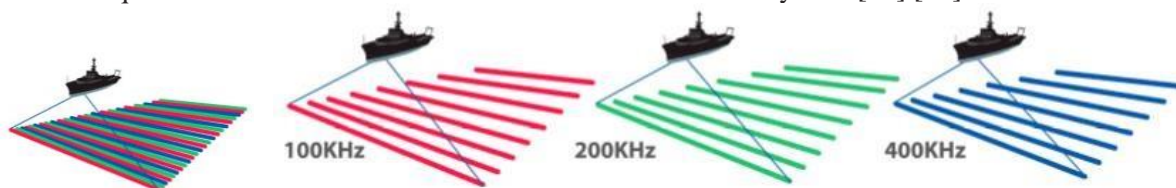


Figure 16. MBES Multi Frequency based on *ping by ping* [41]

The MBES multi-frequency survey results of each processed frequency can be combined (mosaic) with each other [41] [42]. Figure 17a shows the different backscatter intensity profiles of different frequencies at the same location. [41] and [42] evaluated the use of multi-frequency MBES (100 kHz, 200 kHz, and 400 kHz) to produce multispectral backscatter in a single survey measurement (Figure 17b). The basic idea of using multi-frequency is like a remote sensing satellite using multiple wavelengths (multispectral). The use of multispectral aims to improve seafloor sediment mapping results using MBES. The advantages of using MBES multispectral backscatter compared to single-frequency backscatter [43] is to provide more detailed information about seabed sediments, can be used

for wider acoustic wave differences, and can be used for optimal frequency selection that depends on the environment the bottom of the sea.

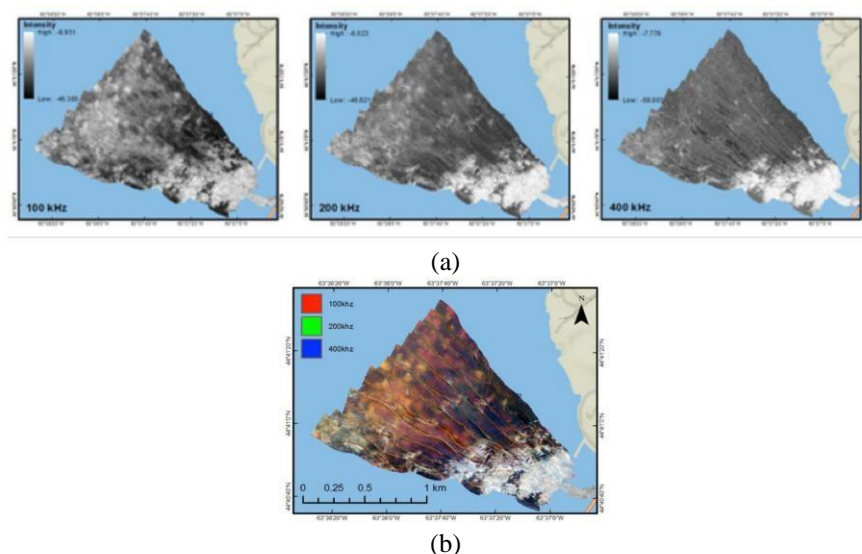


Figure 17. Seafloor Sediment Map (a) Single Frequency (b) *Multispectral Backscatter* [41]

Ping-based multi-frequency MBES is currently the latest technology that still has many study opportunities, especially regarding shallow waters in tropical coastal waters such as Surabaya waters. Different frequencies with relatively simultaneous times (the difference of a few seconds from one frequency to another) will produce a different response to water depth and bottom sediment. Future research will examine how far the depth differs from one frequency to another to determine the sediment's thickness. Finally, MBES multispectral backscatter combined with sub-bottom profiler data can make 3D seabed sediment map in tropical coastal waters. Hopefully, the results can provide seabed sediment distribution as an appropriate input for seabed sediment modeling.

3. Conclusion

Mapping of seabed sediment distribution can be done using mechanical methods (grab sampler and gravity core) and acoustic methods (single beam echo sounder, side-scan sonar, and multibeam echo sounder). Each method has advantages and disadvantages. Mapping of seabed sediments using mechanical methods will result in very low resolution. The higher the resolution required, it will take a long time and cost a lot. The acoustic method has a higher resolution than the mechanical one. The MBES seabed sediment mapping has a higher resolution than the SBES and SSS. Recently, the development of multi-frequency (multispectral) MBES technology has resulted in better seabed sediment mapping results than a single frequency, providing more detailed information. The opportunity for the multispectral MBES is still quite large, especially the mapping of seabed sediments. One of the options to be studied is combining MBES and sub-bottom profiler data to make the 3D mapping of seabed sediments in tropical coastal waters.

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