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# ANALYSIS OF BEAM ANGLE INFLUENCE AND ITS RELATIONSHIP TO BACKSCATTER USING ANGULAR RANGE ANALYSIS

# ANALISIS PENGARUH DAN HUBUNGAN *BEAM ANGLE* TERHADAP HAMBUR BALIK DENGAN METODE *ANGULAR RANGE ANALYSIS*

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## ABSTRACT

The shallow waters of Pari Island exhibit diverse seafloor substrates, making them an ideal site for hydroacoustic seabed characterization studies. This study aims to analyze backscatter variations at different beam angles and evaluate the mathematical relationship between beam angle and backscatter intensity using the Angular Range Analysis (ARA) method. The novelty of this study lies in modeling the beam angle-backscatter relationship in tropical shallow-water environments in Indonesia, which remains relatively limited in the literature. Data were acquired using a 300 kHz Teledyne Reson SeaBat T50-R Multibeam Echosounder (MBES) and processed using the Fladermaus Geocoder Toolbox (FMGT), while surface sediment samples were collected using a Van Veen grab sampler. ARA generated angular response curves showing that the highest backscatter values consistently occurred at nadir (0°) and gradually decreased toward grazing angles. Backscatter values ranged from -19.27 dB to -37.41 dB. The average backscatter values for sand, silty sand, and coral fragments or rock were -32 dB, -34 dB, and -30 dB, respectively. The beam angle–backscatter relationship was modeled using second- and third-order polynomial regressions, yielding coefficients of determination of 0.9064-0.998 and 0.9251-0.999, respectively. The results indicate that changes in beam angle adequately explain the backscatter variation. These findings demonstrate that ARA is effective for characterizing backscatter angular response patterns and support MBES data interpretation in tropical shallow waters.

Keywords: Angular Range Analysis, beam angle, MBES backscatter, Pari Island, polynomial pattern

## ABSTRAK

Perairan dangkal Pulau Pari memiliki keragaman substrat dasar laut yang menjadikannya lokasi ideal untuk kajian karakteristik dasar laut secara hidroakustik. Penelitian ini bertujuan untuk menganalisis variasi nilai hambur balik pada berbagai *beam angle* serta mengevaluasi hubungan matematis antara *beam angle* dan intensitas *backscatter* menggunakan metode *Angular Range Analysis* (ARA). Kebaruan penelitian ini terletak pada pemodelan hubungan antara *beam angle* dan hambur balik pada lingkungan perairan dangkal tropis Indonesia menggunakan pendekatan *Angular Range Analysis* (ARA), yang masih relatif terbatas dalam literatur. Data diperoleh menggunakan *Multibeam Echosounder* (MBES) Teledyne Reson SeaBat T50-R berfrekuensi 300 kHz dan diolah menggunakan *Fledermaus Geocoder Toolbox* (FMGT), sedangkan sampel sedimen permukaan dikumpulkan menggunakan Van Veen Grab Sampler. Analisis ARA menghasilkan kurva respons sudut yang menunjukkan bahwa nilai hambur balik tertinggi secara konsisten terjadi pada sudut nadir (0°) dan menurun menuju *grazing angle*. Nilai hambur balik pada area penelitian berada pada rentang -19,27 dB hingga -37,41 dB. Rata-rata nilai hambur balik pada sedimen pasir, pasir berlanau, dan pecahan karang atau batuan masing-masing sebesar -32 dB, -34 dB, dan -30 dB. Hubungan *beam angle* dan hambur balik dimodelkan menggunakan regresi polinomial orde dua dan tiga dengan koefisien determinasi masing-masing berkisar antara 0,9064–0,998 dan 0,9251–0,999. Hasil menunjukkan bahwa variasi hambur balik dapat dijelaskan dengan baik oleh perubahan *beam angle*. Temuan ini menunjukkan bahwa ARA efektif untuk mengarakterisasi pola *angular response backscatter* dan mendukung interpretasi data MBES di perairan dangkal tropis.

Kata kunci: *Angular Range Analysis*, *beam angle*, *MBES backscatter*, pola polinomial, Pulau Pari

## INTRODUCTION

Seafloor characterization is a crucial aspect of various oceanographic studies and coastal area management, particularly for benthic habitat mapping, seafloor resource identification, and monitoring marine environmental changes (Diesing *et al.* 2014; Menandro *et al.* 2022). Information on the type and distribution of seafloor substrate is crucial for coastal area management because it directly relates to environmental stability, benthic ecosystems, and human activities, such as navigation, coastal development, and marine conservation. As an archipelagic nation with vast maritime territory, Indonesia requires efficient and accurate methods to identify seafloor characteristics, particularly in shallow waters characterized by high levels of complexity due to sediment variations and active hydrodynamics.

One widely used method for seafloor characterization is the hydroacoustic approach using a multibeam echosounder (MBES). MBES technology not only produces high-resolution bathymetric data but also provides backscatter intensity information that can be used to interpret the physical properties of the seafloor substrate (Hughes *et al.* 1996). Acoustic backscatter is the reflection of sound wave energy, which is influenced by several physical parameters, such as surface roughness, sediment grain size, material density, and substrate heterogeneity (Brown and Blondel 2009). Therefore, backscatter analysis has become a key approach for classifying seafloor sediments and mapping benthic habitats.

Interpreting backscatter data is not always straightforward because the resulting intensity values are influenced not only by substrate characteristics but also by acquisition geometry factors, particularly beam angle. Beam angle significantly influences the distribution pattern of backscatter intensity, with the highest values generally occurring at nadir angles and gradually decreasing toward the grazing angle (Amiri-Simkooei *et al.* 2009). This phenomenon causes variations in observed backscatter values in a single sediment type to change depending on the beam position. Therefore, understanding the relationship between beam angle and backscatter is crucial for improving the accuracy of MBES data interpretation.

One approach used to understand this relationship is Angular Range Analysis (ARA). ARA allows analysis of variations in backscatter values at various beam angle ranges to produce angular response curves that can describe the acoustic characteristics of a substrate in more detail (Fonseca and Mayer 2007). This approach has been widely used in sediment classification studies, benthic habitat identification, and seabed roughness analysis (Fonseca *et al.* 2009; Adi *et al.* 2016). Through ARA, the pattern of changes in backscatter intensity relative to the beam angle can be used to differentiate sediment characteristics based on their acoustic response.

Most previous research still focuses on sediment classification or benthic habitat mapping (Janowski *et al.* 2018; Trzcinska *et al.* 2020; Runya *et al.* 2021), while studies that specifically evaluate the mathematical relationship between beam angle and backscatter intensity are still relatively limited, especially in tropical shallow water environments. Tropical water conditions have different characteristics compared to subtropical or deep-sea waters, such as more active sediment dynamics, more complex substrate heterogeneity, and the influence of higher wave energy and currents. These factors have the potential to produce different angular response patterns and have not been widely documented, especially in Indonesian waters.

The waters of Pari Island, Thousand Islands, were chosen as the research location because they have shallow water characteristics with a variety of substrates, ranging from sand and silty sand to coral fragments. This diversity makes the region a suitable location to test beam angle and backscatter relationship patterns in shallow tropical environments. Apart from that, Pari Island is an area that has high ecological value, so understanding the characteristics of the seabed is relevant to supporting sustainable management of coastal areas.

This research models the mathematical relationship between beam angle and backscatter using a polynomial regression approach based on ARA data collected in Indonesia's tropical shallow-water environment. In contrast to the study by Brown *et al.* (2019), which primarily focused on sediment classification, the present study emphasizes the identification of mathematical patterns of angular response as a quantitative basis for understanding the acoustic characteristics of seabed substrates. By providing a quantitative description of the beam angle–backscatter relationship, this study is expected to contribute to the development of MBES data interpretation methods, particularly for hydroacoustic applications in tropical shallow waters. Specifically, this study aims to characterize the variation in backscatter intensity across beam angles for major substrates such as sand, silty sand,

and rubble in Pari Island waters and develop and evaluate polynomial regression models that describe the beam angle-backscatter relationship to establish a quantitative reference for interpreting angular response patterns in tropical shallow-water MBES surveys.

## METHODS

Data collection was conducted over a single survey period, from June 27 to July 4, 2024, in the waters off Pari Island, Seribu Islands, DKI Jakarta Province. The data obtained represent seabed conditions at the time of observation. Seasonal variability, potentially affecting water column conditions, suspended sediment concentrations, and hydrodynamics, was not evaluated in this study. However, because the study focused on analyzing the relationship between beam angle and backscatter intensity, which represents the physical characteristics of the seabed substrate, the data obtained were deemed adequate to describe the angular response patterns at the study site.

This study used 300 kHz MBES data, commonly used in shallow-water surveys due to its high spatial resolution of seabed surface characteristics. This frequency can distinguish substrates with distinctly contrasting physical properties, such as sand, mud, and coral (Ferrini and Flood 2006). However, its discrimination ability against sediments with similar physical characteristics is relatively limited compared to multifrequency approaches, and there is a predominance of finer sediment readings compared to real-world conditions (Huang *et al.* 2018; Handoko *et al.* 2025; Yusaini *et al.* 2025). Therefore, this study focused on analyzing the relationship between beam angle and backscatter patterns using the Angular Range Analysis (ARA) approach, rather than on detailed sediment classification.

The tools and materials used in this study included an MBES with a frequency of 300 kHz, a Trimble BX992 DGPS, a 12 GT survey vessel, a Van Veen grab sampler, a Valeport Swift CTDplus, Fledermaus Geocoder Toolbox (FMGT) software, and MATLAB 2023 for data processing and analysis. The specifications of the MBES used are presented in Table 1. Data acquisition followed the survey path shown in Figure 1 with an average vessel speed of approximately 4 knots.

### Hydroacoustic data

The acquired data consisted of two survey lanes in *.gsf and *.s7k formats, which were then processed using Fledermaus Geocoder Toolbox (FMGT) software. Data acquisition was conducted using a parallel lane pattern with 50% overlap to meet the full seafloor coverage principle according to the IHO S-44 hydrographic survey standard while maintaining the consistency of the observation geometry required for Angular Range Analysis (ARA). This pattern was chosen so that variations in observed backscatter values better represent the influence of beam angle than changes in survey trajectory orientation and to provide adequate spatial coverage to represent seafloor heterogeneity in the study area.

The data processing process began with a preprocessing stage, which included data filtering and cleaning, as well as standard radiometric corrections available in FMGT. These corrections included beam pattern correction, transmission loss correction, insonified area correction, angle-varying gain correction, and angle normalization to reduce the influence of observation geometry on the obtained backscatter values. The preprocessing results were then used to generate backscatter mosaics in GeoTIFF and ASCII formats.

Table 1. Teledyne Reson SeaBat T50-R Multibeam Echosounder (MBES) Specifications (Teledyne Marine 2025).

| Parameters | Specification |
|---|---|
| Frequency | 190–420 kHz |
| Number of beams | 10–512 beams |
| Maximum depth | 450 m |
| Minimum depth | 0.5 m |
| Ping rate | 50 pings/s |
| Pulse width (CW) | 15–300 µs |
| Pulse width (FM) | 300 µs – 10 ms |
| Depth resolution | 6 mm |
| Depth rating (sonar head) | 50 m |
| Input voltage | 100–230 VAC 50/60 Hz |

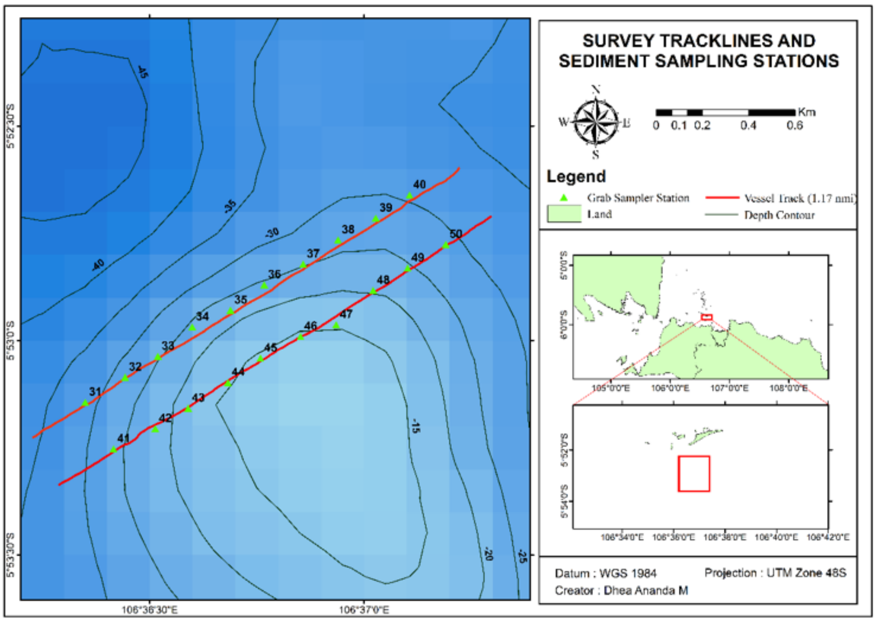



Figure 1. Map of the research location in the waters of Pari Island showing the MBES sounding route and sediment sampling stations.

This study did not perform absolute backscatter calibration using a reference target or a specific calibration area; therefore, the obtained backscatter values were relative and are used to analyze the pattern of changes in backscatter intensity against beam angle, not to obtain absolute backscatter values. The preprocessing data were also exported in *.txt format and then processed using MATLAB 2023. The processing output includes backscatter values in each observation lane, ARA curves based on a certain beam angle range, and backscatter mosaics that represent the spatial distribution of seabed characteristics in the study area.

## Grab sampling (sediment)

Surface sediment sampling was conducted at 20 stations spread across the survey area using a stratified sampling approach. The sampling locations were determined by considering the spatial distribution of the study area and variations in acoustic characteristics observed in the backscatter data, ensuring that each station represented different substrate conditions. The number of stations used encompasses the various backscatter characteristics identified during the survey, thus supporting the interpretation of acoustic data at the scale of the study area. Sediment samples were collected using a Van Veen grab sampler and subsequently analyzed at the Naval Technology College Laboratory (STTAL). Laboratory analysis was performed through dry sieving using seven sieve sizes to obtain the sediment grain size distribution. The data obtained were used to identify the dominant sediment fraction and classify sediment types based on Shepard's (1954) classification system. Shepard's classification system was applied owing to its widespread use and practicality in sediment classification. The results of the sediment analysis were used as supporting data in the interpretation of seafloor acoustic characteristics and as descriptive verification of the variations in observed backscatter values.

## Angular Range Analysis (ARA)

Angular Range Analysis (ARA) is a method used to analyze the relationship between the beam angle of acoustic waves and the backscatter value received by a multibeam echosounder receiver. Each integrated beam has a specific angle that influences the magnitude of the received backscatter value. Signals originating from nadir have higher intensity than signals arriving from farther angles.

The ARA method was first developed from research conducted by Fonseca and Calder (2005) and then refined into the Geocoder method by Fonseca and Mayer (2007). Backscatter analysis based on angle consists of two main components: surface backscattering and volume backscattering, which are expressed by the equation (Fahrulian *et al.* 2016):

$$Backscattering = Surface\ backscattering + Volume\ backscattering$$

Where surface backscattering:

$$\sigma r(\theta, f) = F(\theta, f; \xi.\rho(\xi), v(\xi), \delta(\xi), \omega_2, \lambda)$$

Description:
$\theta$ = Angle of incidence of acoustic waves
$f$ = Frequency (Hz)
$\rho$ = Ratio of sediment density to water density
$\upsilon$ = Ratio of the speed of sound in the sediment to the speed of sound in the water column
$\delta$ = Parameter of the imaginary ratio of the number of sound waves in the sediment
$\omega_2$ = Spectral strength of the water bottom relief
$\lambda$ = Spectral exponent of bottom waters
$\xi$ = Gas volume to total sediment volume

The volume backscattering:

$$\sigma_v = \frac{5(\xi \sum h + \sigma^2 \alpha(\xi))c_\omega \mid 1 - R^2(\theta) \mid)}{40\pi f \mid P(\theta) \mid^2 Im \mid P(\theta) \mid}$$

Description:
$\xi\sum h$ = Backscatter cross-section in the gas bubble distribution region
$\sigma^2$ = Volume backscatter parameter
$R(\theta)$ = Reflection coefficient
$P(\theta)$ = Complex energy loss function
$a(\xi)$ = Attenuation coefficient in dB/m for sediment
$c_\omega$ = Speed of sound in water

### The relationship between backscatter value and beam angle

An analysis of the relationship between acoustic backscatter intensity and beam angle was conducted to understand the angular response of the seafloor substrate using the ARA method on MBES data. The resulting ARA curve generally shows a peak value around the nadir angle (0°) and decreases with increasing angle, reflecting the influence of sediment composition and grain size. This pattern was quantified by curve fitting using a second-order (quadratic) polynomial, as low-order polynomial regression has proven quite effective in modeling nonlinear relationships between two continuous variables (Cantera-Cantera *et al.* 2022). Furthermore, modeling using second-order polynomials has demonstrated adequate accuracy and precision and is considered sufficient to represent data patterns without increasing the risk of overfitting that often occurs with the use of higher-order polynomials (Chen and Chen 2013). The general equation used is:
Polynomial of order 2:

$$y = a_0 + a_1x + a_2x^2$$

Polynomial of order 3:

$$y = a_0 + a_1x + a_2x^2 + a_3x^3$$

where $y$ is the backscatter intensity (dB), $x$ is the beam angle (°), and an is the polynomial coefficient.

## RESULTS AND DISCUSSION

### Hydroacoustic data

The backscatter intensity on the mosaic map (Figure 2) ranged from -19.27 dB to -37.41 dB. The spatial appearance of the map indicates variations in the seafloor substrate at the study site. The results of the sediment sample analysis indicate that each substrate type has different backscatter value characteristics. Sand sediment has an average backscatter value of -32 dB and silty sand -34 dB, while coral or rock fragments show an average value of -30 dB. These differences in values indicate that substrates with coarser grain sizes and higher hardness levels tend to produce greater backscatter intensity than finer-grained sediments.

The distribution of backscatter values on the mosaic map shows that areas with higher intensity generally correlate with the presence of coarser substrates such as coral rubble or coarse sand, while areas with lower intensity are more associated with finer sediments such as silty sand. This pattern aligns with the research of Brown *et al.* (2011), which showed that increasing seafloor substrate roughness and density contribute to increased acoustic backscatter values. Therefore, variations in backscatter values within the mosaic can be used as an initial indicator to describe the distribution of physical characteristics of seafloor sediments.

All survey lanes were used in the initial processing stage to generate the backscatter mosaic and evaluate the general characteristics of the study area. However, detailed ARA focused on Lanes 8 and 10, as these two lanes had the widest range of backscatter values, ranging from -37.41 dB to -19.2 dB, respectively, compared to the other lanes, which ranged from -32 dB to -23.1 dB. Furthermore, these two lanes have the most comprehensive supporting sediment data, with 10 sampling points each, resulting in a total of 20 sediment samples distributed across the analysis area. The combination of high backscatter value variation and the availability of more comprehensive ground truth data makes these two lanes more representative for analyzing the relationship between beam angle, backscatter, and seafloor sediment characteristics.

**Sediment data (grab sampling)**

Analysis of the physical characteristics of the bottom sediments of Pari Island waters was conducted on 20 samples collected in the field. Sediment fraction data at Stations 44 and 48 showed different characteristics in the form of coral/rock material, indicating a hard substrate that could not be further fractionated. Fraction weight data were then used to calculate the percentage of coral fragments, sand, silt, and clay as the basis for sediment type classification using the Shepard system. The results of sediment classification based on the Shepard system in Figure 3 show the variation of sediment types in the Pari Island waters study area. The identified sediment types include sand in samples such as numbers 31, 34, 35, 37, 38, 40, 41, 43, 45, 49, and 50, and silty sand in sample numbers 32, 33, 36, and 39. Of the 20 planned sampling stations, only 15 yielded usable sediment samples. The remaining five stations could not be sampled due to the presence of hard coral substrate at the seabed, which prevented effective grab sampler penetration, as well as unfavorable weather conditions during the survey period that restricted access to certain stations. This variation indicates that the Pari Island area has varied sediments. In situ data are used as comparative data to support the interpretation of backscatter patterns, but this study has not yet conducted quantitative classification accuracy testing.

**The relationship between beam angle and backscatter value**

Analysis of the relationship between beam angle and bottom backscatter intensity was conducted using a polynomial regression approach on ARA data at each observation station. Two types of models were tested to describe the relationship pattern: a second-order (quadratic) and a third-order (cubic) polynomial. The selection of the best model was based on the coefficient of determination ($R^2$), which indicates the level of closeness of the relationship between the variables. The results of the second-order polynomial regression analysis for each station are presented in Figure 4.

The analysis results for Lane 8, from Station 31 to Station 40, and Lane 10, from Station 41 to Station 50, indicate that the models have an excellent fit with the observed data. The $R^2$ values obtained ranged from 0.9064 to > 0.99. This means that most of the differences in the analyzed data can be explained by differences in the beam angles used in the models used. This finding aligns with the basic theory of seafloor backscattering, which states that beam angle is a key factor influencing the strength of backscattering (Jackson *et al.* 1986).

Comparison of $R^2$ values between the quadratic (second-order) and cubic (third-order) models shows that the cubic model tends to produce slightly larger or equal $R^2$ values at most stations. The difference in $R^2$ indicates that the third-order model can represent subtle variations in the shape of the ARA curve, including possible asymmetries due to micromorphological conditions or sediment heterogeneity on the seafloor. The relatively small difference between the models is considered not to provide a significant difference, and the quadratic model has sufficiently described the main pattern of changes in backscatter values against beam angle so that it can represent the geometric influence of the incident angle on backscatter.

The ability of the regression model to represent the influence of beam angle is important in advanced analysis of backscatter data. The ARA curve can be interpreted as a more representative signal of the physical characteristics of seafloor sediments by separating the components of variation caused by angle effects (Lamarche *et al.* 2011). Modeling the relationship between beam angle and backscatter also provides a deeper explanation of curve-derived parameters, such as nadir intensity and slope, which play an important role as acoustic indicators in distinguishing sediment types.

This research has shown that characterizing angular dependencies has the potential to be an important component in acoustic interpretation of sedimentary substrates (Brown *et al.* 2019). However, interpretation must consider sources of uncertainty to avoid bias in the backscatter modeling process and the possibility of discrepancies between acoustic classification results and laboratory analysis. Evaluation of FMGT results and laboratory analysis is important to understand the limitations of acoustic methods in representing actual sediment conditions. The discrepancies found at several station points represent differences in observation scale, sediment variations, and the influence of other factors that can influence acoustic response.

**Variation of backscatter value against beam angle at each station along the lane**

Variations in backscatter values with respect to beam angle show different characteristics for each type of seabed sediment. Angles of 0°, ±10°, ±20°, ±30°, ±40°, ±50°, and ±60° were chosen to illustrate changes in backscatter intensity from the nadir center to the edge of the beam. This angular range provides a balance between data accuracy and clarity of the curve pattern, as too close an angular interval tends to produce insignificant differences in values between observation points. An even angular distribution is recommended to maximize the ability to identify sediment characteristics through angular response patterns (Schimel *et al.* 2024).

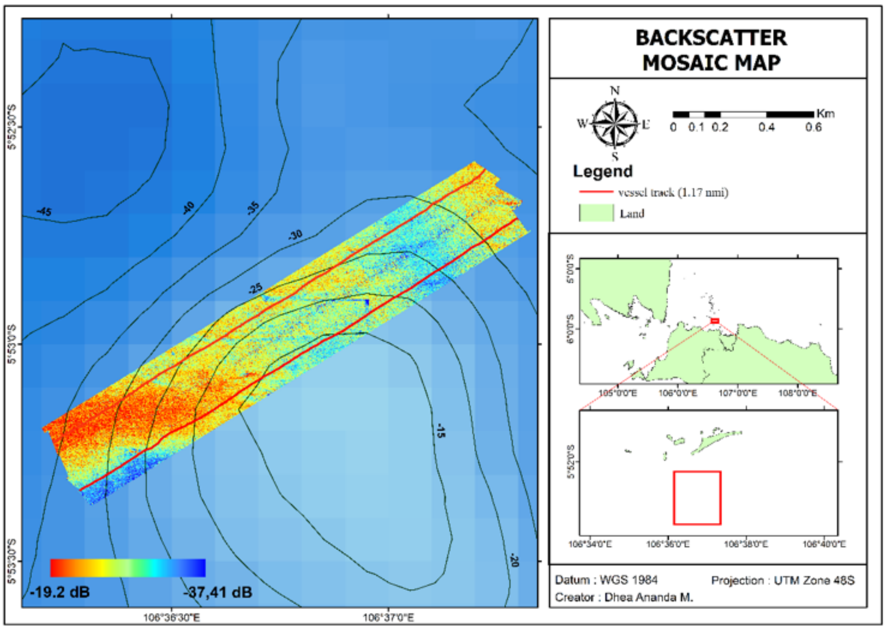



Figure 2. Seabed backscatter mosaic map in the waters of Pari Island showing the MBES sounding path and depth contours.

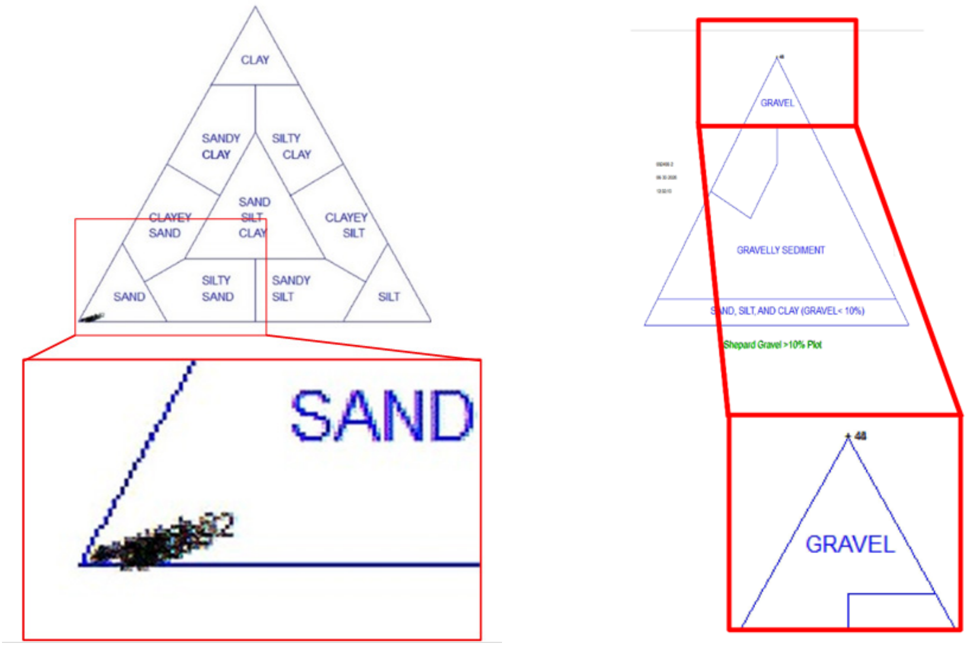
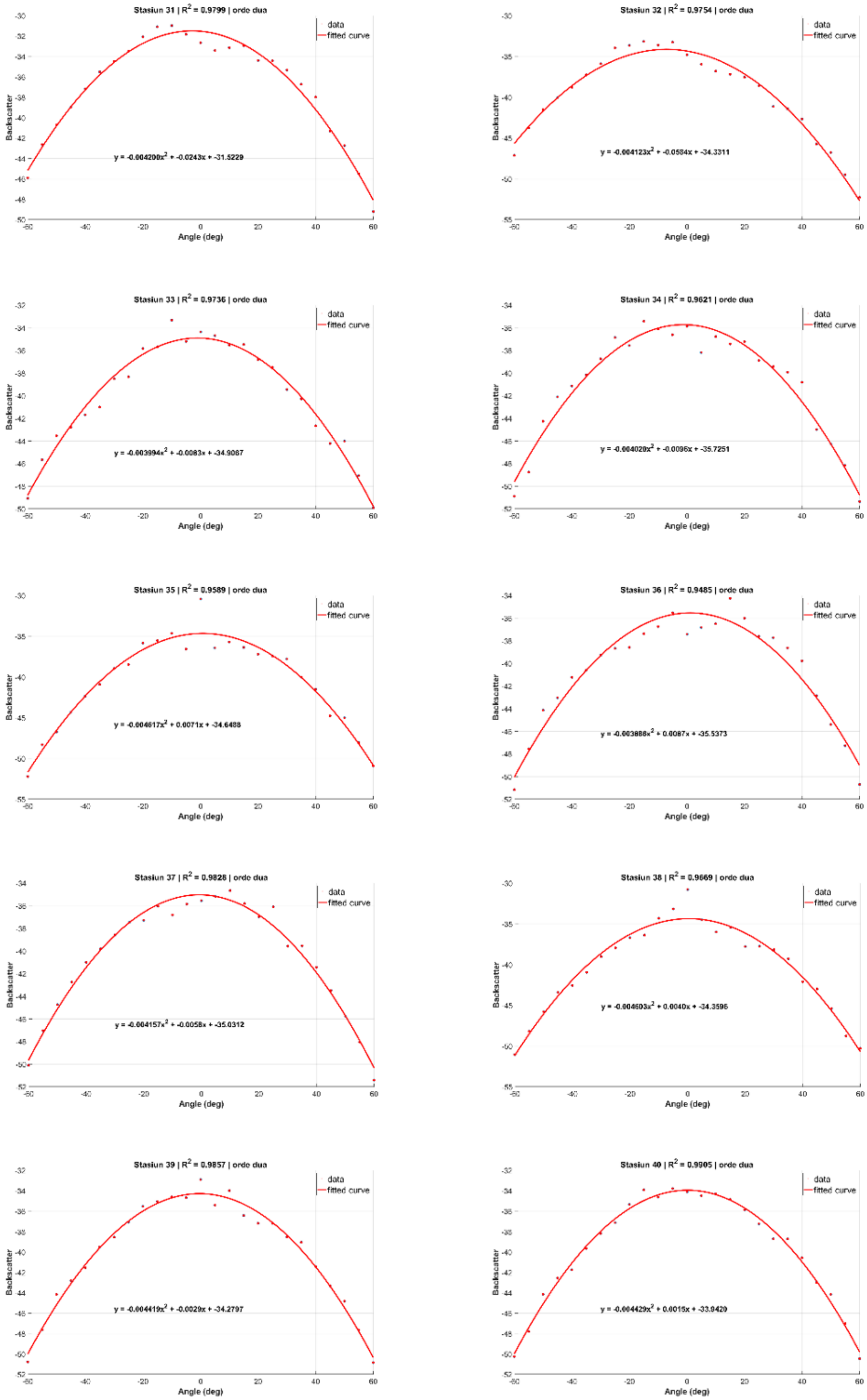



Figure 3. Results of the classification of basic sediment types in the waters of Pari Island based on Shepard's classification system (1954).


Stasiun 31 | R2 = 0.9799 | orde dua
y = -0.004200x2 + -0.0243x + -31.5229
Stasiun 32 | R2 = 0.9754 | orde dua
y = -0.004123x2 + -0.0584x + -34.3311
Stasiun 33 | R2 = 0.9736 | orde dua
y = -0.003994x2 + -0.0083x + -34.9087
Stasiun 34 | R2 = 0.9621 | orde dua
y = -0.004020x2 + -0.0096x + -35.7251
Stasiun 35 | R2 = 0.9589 | orde dua
y = -0.004617x2 + 0.0071x + -34.6488
Stasiun 36 | R2 = 0.9485 | orde dua
y = -0.003888x2 + 0.0087x + -35.5373
Stasiun 37 | R2 = 0.9828 | orde dua
y = -0.004157x2 + -0.0058x + -35.0312
Stasiun 38 | R2 = 0.9669 | orde dua
y = -0.004603x2 + 0.0040x + -34.3596
Stasiun 39 | R2 = 0.9857 | orde dua
y = -0.004419x2 + -0.0029x + -34.2797
Stasiun 40 | R2 = 0.9905 | orde dua
y = -0.004429x2 + 0.0015x + -33.9420
data
fitted curve
Backscatter
Angle (deg)

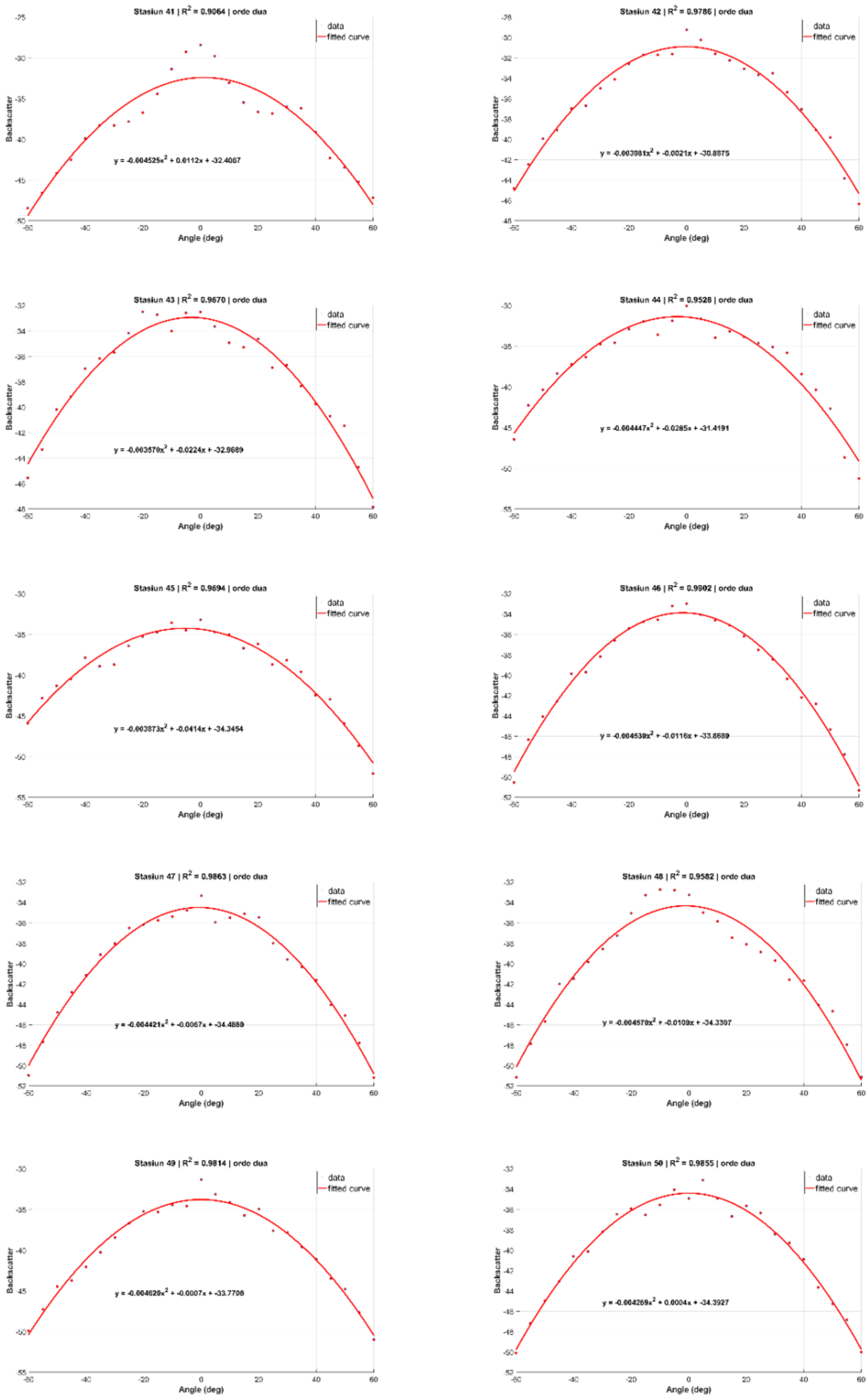



Figure 4. Relationship between beam angle and backscatter intensity based on Angular Range Analysis (ARA) data, with second-order polynomial fitting for each sampling station.

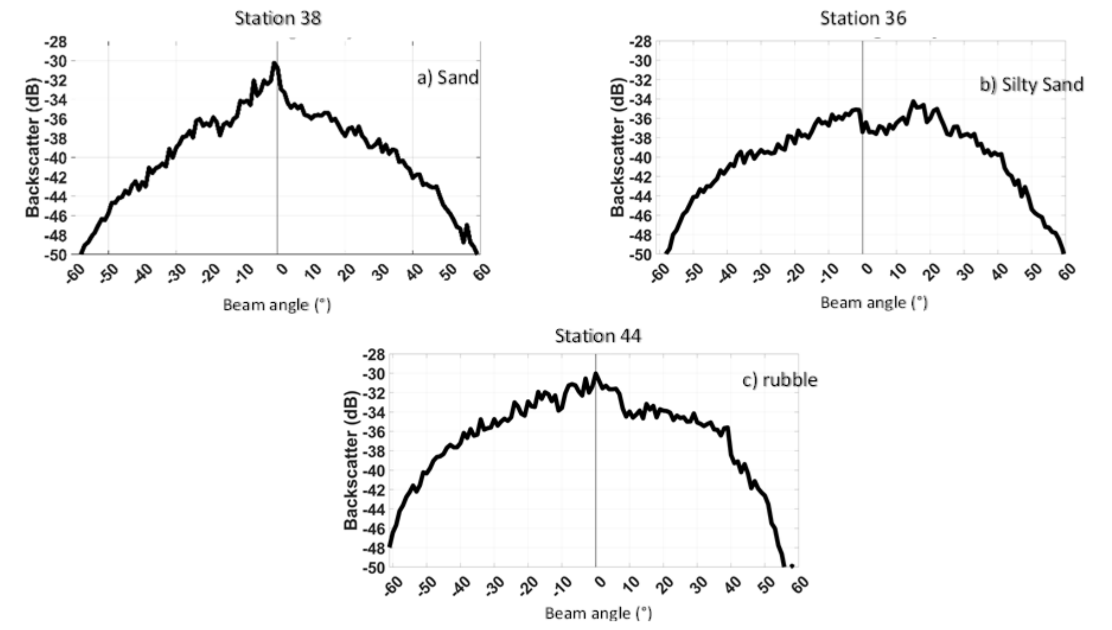



Figure 5. Angular response curve showing the relationship between backscatter and beam angle values for three types of sediment in Pari Island waters.

Figure 5 displays the variation in backscatter curves across three sediment types: sand, silty sand, and rubble. The graph showing the relationship between backscatter and angle shows a relatively higher peak intensity and a curve pattern that tends to be symmetrical to nadir, indicating stronger reflection due to the harder and rougher surface characteristics. Silty sand sediment exhibits a more gradual pattern with a lower maximum intensity around the nadir, reflecting a softer and smoother surface. Meanwhile, coral debris sediment exhibits more irregular intensity fluctuations across beam angles, indicating a higher degree of heterogeneity and surface roughness.

Although visual interpretation of the angular response curves indicates visual tendencies in backscatter patterns between sediment types, statistical tests indicate that these differences are not statistically significant. The Kruskal-Wallis test yielded an H value of 3.12 ($p = 0.210$), whereas the one-way ANOVA showed an F value of 2.13 ($p = 0.149$). These two results show that the backscatter variations between sediment groups still have a fairly large level of overlap so that separation based on backscatter intensity alone is not strong enough to clearly distinguish all sediment types.

This condition suggests that the overlapping ARA patterns observed between sediment groups are unlikely to result from genuinely similar acoustic characteristics, given that the sediment classes span a broad range, from silty sand to coral rubble. Instead, this overlap is more plausibly attributable to the limited number of samples within each sediment group, particularly the coral rubble category, as well as potential limitations in the physical sediment analysis method used for ground-truthing. A small or uneven sample size can reduce the statistical power needed to detect genuine differences between groups, even when underlying acoustic responses differ (Jackson *et al.* 1986; Brown *et al.* 2019). Thus, while ARA patterns show potential as a supporting parameter in sediment identification, larger and more balanced sample sizes, combined with more precise ground-truthing methods, are needed to confirm whether the observed overlap reflects a true acoustic similarity or a sampling limitation.

## CONCLUSION

This study shows that acoustic backscatter values in the shallow waters of Pari Island have a consistent relationship with changes in beam angle, where the highest intensity generally occurs at the nadir angle (0°) and decreases gradually towards the grazing angle. Angular Range Analysis (ARA) successfully describes different angular response patterns in each sediment type: sand, silty sand, and coral or rock fragments. Differences in average backscatter values between sediment types indicate a tendency for a relationship between the physical characteristics of the substrate and the resulting acoustic response. However, the results of statistical tests using Kruskal–Wallis ($H = 3.12$; $p = 0.210$) and one-way ANOVA ($F = 2.13$; $p = 0.149$) indicate that the difference is not statistically significant, so there is still a level of overlap in backscatter characteristics between sediment groups. Modeling the relationship between beam angle and backscatter using second- and third-order polynomial regression yielded high coefficients of determination, ranging from 0.9064 to 0.998 and 0.9251 to 0.999, respectively. These results indicate that changes in beam angle can explain most of the variations in backscatter intensity in the study area. Although the third-order model provided a slightly higher level of fit, the second-order model was able to represent the main pattern of angular response well.

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