

Study of multibeam techniques for bathymetry and seabottom backscatter applications

R.R. Nair and B. Chakraborty

National Institute of Oceanography, Dona Paula, Goa - 403004, India.

In this paper, a brief discussion is carried out on the application of the different techniques of echosounding. A detailed appraisal of the presently used multibeam technique is mentioned. Some of the important discoveries of seabed features around Indian ocean is presented using Hydrosweep-multibeam installed onboard ORV *Sagarkanya*. A seabottom classification model is proposed which can be applied for multibeam backscatter data. Certain aspects of the multibeam backscatter signal data processing method is discussed. A new beamforming application is proposed for obtaining high density/resolution bathymetry/backscatter information.

Introduction

Around 100 years ago, the ocean bottoms were thought to be flat and featureless. But with the advent of modern echosounding techniques the picture has significantly changed (Dysart & Ogushwitz, 1991). The aim of shallow water bathymetry (measurement and charting of the seabottom) is connected mostly with navigational safety whereas for deep ocean survey, it is generally of an exploratory nature. Rough mountainous terrain, including the mid-ocean ridge system, is known to cover large portions of the seabed. Apart from establishing the feasibility of offshore exploration of mineral deposits, especially in the Exclusive Economic Zones (EEZ), by the study of seafloor bathymetry, dynamic processes related to the shape of earth may be understood. Single beam echosounder replaced the lead-line methods from the 1920s onwards and with this, continuous records of depths along each track of the ship were available (deMoustier, 1986). Single beam echosounding technique came into common usage around the 1950s which was only possible after the improvement of transducer technology. The resolution of such systems is a function of the half power beam width, and the transducer beam widths were available around 30°-60°. In order to have higher resolution, narrow beam (half power beam widths, 2°-5°) techniques were introduced

in bathymetric survey system from the 1950s. These systems became fully operational using phased array network for real-time attitudes like roll pitch correction since the 1960s (*i.e.*, introduction of electronic stabilisation). Beam steering techniques were used for such applications (Chakraborty & Dey, 1994). Using narrow single beam echosounding system, seabed relief from metres to kilometres can be recorded continuously along the ship's track. But in order to generate a bathymetric map several parallel profiles at short intervals are required. Multibeam system, which is a present day technique, gives bottom profiles which are correlated with respect to the single central track, and allows more reliable correlation of intersecting tracks in a single strip high density depth survey. To have greater coverage as well as a high precision map, a multi-narrow beam concept was realised. In 1970, the multibeam bathymetric system became commercially available with additional facilities like real-time compilations and data storage capabilities (Renard & Allenou, 1979). Apart from depth determination, this sounding system is useful for various objectives, such as geological surveys to characterise the seabed, geotechnical properties and resource evaluation of polymetallic nodules. This high resolution and high density bathymetry data is found to be economic since it maintains higher depth accuracies.

In this paper, a theoretical presentation of the multibeam beamforming technique is described, and certain related important aspects are also discussed. During 1989, the Hydrosweep-multibeam system (manufactured by M/s STN Atlas Elektronik GmbH, Germany) was installed onboard ORV *Sagarkanya*. An extensive survey was conducted around the Indian Ocean, the Arabian Sea and the Bay of Bengal to generate bathymetry maps. Some of the important areas where maps have been generated are presented here mentioning the Hydrosweep's general working conditions. In recent days, many other applications of the multibeam systems have been developed *i.e.*, introduction of seabottom backscatter study for seabed classifications. An application of measured backscattered values to infer seabottom parameters are mentioned in this paper. In addition, the present discussion also expresses some of the present

difficulties and possible solutions of the multibeam system to generate artefact free high density/resolution bathymetry.

Multibeam Techniques

In a multi-narrow beam system, geometrically a cross fan beam is created using two hull mounted linear transducer arrays at right angles to each other. A narrow beam is produced in the direction which is perpendicular to the transducer's short axis. In general, the arrays are designed using a number of identical transducer elements which are equally spaced and driven individually. An assumption of an array which is kept at the origin of the co-ordinate system in a xy-plane, is made here. The separation between the elements is equivalent to 0.5λ , where λ is assumed to design wavelength of the transducer array.

The farfield pattern for a linear array is given by (Collin & Zucker, 1969):

$$|F(\theta, \phi)| = |f(\theta, \phi)| |\text{Element Pattern}| \quad (1)$$

The array factor $f(\theta, \phi)$ is presented by Collin and Zucker as:

$$f(\theta, \phi) = \sum_{n=1}^N A_n \exp(jk \vec{r}_n \cdot \vec{R}) \quad (2)$$

where A_n is the complex excitation coefficient (which is assumed to be unity) and $k = 2\pi/\lambda$. n is the number of the array elements. For above linear array:

$$\vec{r}_n = d_n \vec{i} \quad (3)$$

where d_n is the element separation from the origin, and \vec{i} is the unit vector along the x-axis. The polar unit vector

\vec{R} can be expressed as:

$$\vec{R} = (\sin \theta \cos \phi) \vec{i} \quad (4)$$

The array factor for a linear array can be written as:

$$f(\theta, \phi) = \sum_{n=1}^N \exp(jk(d_n \sin \theta \cos \phi)) \quad (5)$$

According to Steinberg (1976), the amount of phase delay required between the radiators to steer the beam along the specified direction (θ_0, ϕ_0) may be expressed as:

$$\alpha_n = d_n k (\sin \theta_0 \cos \phi_0) \vec{i} \quad (6)$$

The above term is to be applied to the farfield pattern of a uniformly excited linear array of the additive type. The farfield beam pattern in the final form is rewritten as:

$$f(\theta, \phi) = \sum_{n=1}^N \exp(jk(d_n \sin \theta \cos \phi_0 - d_n \sin \theta_0 \cos \phi_0)) \quad (7)$$

In equation (1)

$$\text{Element Pattern} = \frac{\sin(\pi l \sin \theta \sin \phi)}{\pi (\sin \theta \sin \phi)} \quad (8)$$

where l is the length of the element and is equivalent to the 3.0λ . The final expression for the vertical farfield pattern can be obtained by substituting equation (7) and equation (8) in equation (1). The farfield pattern of a multibeam array of 40- elements is shown in Figure 1.

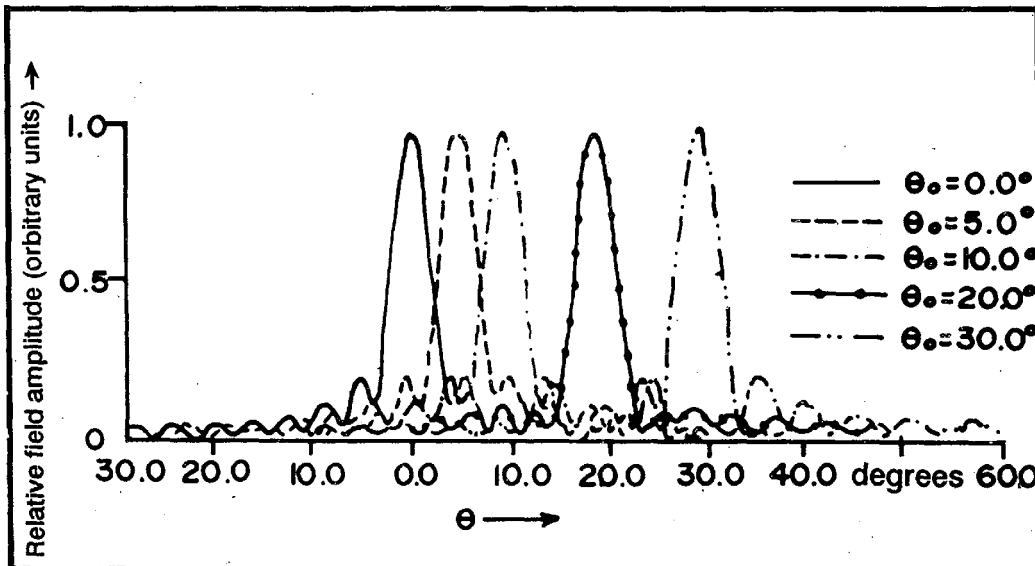


Fig. 1. Beam pattern for a 40-element linear array.

The half power beam widths slowly increase: 3.0°, 3.0°, 3.1°, and 3.6° at the angles of half power beamwidths are generally narrow and are useful for high resolution bathymetric applications. A sidelobe levels around -13 dB for all the incidence angles are also seen. Sidelobes are also a concern in echosounding. There are certain techniques for suppression of the sidelobes which significantly affect the performance of the array. For multibeam applications where many beams for different look directions are forming at a particular instant of time, sidelobes are assumed to be suppressed below -25 dB. This is necessary to avoid interference between the sidelobes and the main beam of the other directions. These sidelobe suppressions are accomplished by using Dolph-Chebyshev window methods (Dolph, 1946). Apart from that, sidelobe levels cannot be suppressed extensively beyond certain levels, because it increases the width of the main beam and thus decreases the resolution. So suppressed sidelobe beam patterns around -25 dB for multibeam transducer array is an acceptable limit considered by echosounder designers.

Using array transducers for beamforming purposes, the preformed beam directions are dependent on the used acoustic wavelength which is a function of the sound speed C , *i.e.*, $\lambda = C/f$, where C is in m/s and f is in Hz. For any changes in the sound velocity (C), λ will change. The sound speed is dependent on temperature, salinity and pressure (depth). Mackenzie (1981) had proposed a nine term equation to compute the sound velocity. For the transducer array of an echosounding system which is hull mounted, sound speed changes occur mostly due to temperature and salinity variations. Hence, variations of λ value with the variations of sound velocity, will change the half power beamwidth of the array and also shift the beam direction. Sound speed changes of 6.6 percent are possible for an echosounding system operating at Arctic and Tropical waters (temperature difference of 30°C). Similarly for λ variation of 3.3 percent, a beam rotation of 0° to 45° will introduce an error amount of 1.9° for a narrow beam of 2°. Also for swath bathymetry application, the variation of sound speed over entire water column must be considered. The angle of arrival of the different beams are affected due to the refraction effect which is dominant for the outer beams of the array system. In order to correct the refraction error in echosounding systems, computation of the sound system should be performed by integrating the sound speed profile from the depth of the array to the bottom. The harmonic mean of the sound speed is preferred over the average sound speed (Maul & Bishop, 1970).

For development of echosounding devices, certain parameters are of paramount importance to obtain optimum signal to noise ratio. Source level *i.e.* the transmitted power measured at 1 metre from the

transmitting array is an important parameter. Similarly, transmission loss in the medium is also compensated at TVG (Time Varied Gain) module of the receiver. Apart from that, the noise level is also another important issue for the designer of the multibeam system. The noise level parameter is dictated by the location of the array in the hull, *i.e.* array should be kept in the forward part of the ship's hull, which is closest to the central line. The machinery noise is minimum in this area of the ship. The positioning of the array should also be decided based upon the ship's movement due to roll and pitch, *i.e.* the array should be maintained submerged throughout the ship's movement. The major signal processing event which is known as beamforming takes place at the receiver end of the array. The received signals are pre-amplified and each channel signal (array element) undergoes a correction for TVG loss in the correction unit and then beamforming techniques are applied to obtain multiple beams using predetermined delays for different directions. The theoretical background of the multibeam signal processing methods have already been mentioned. The beamformed waveforms are tracked at a bottom echo module for the depth determination at different preformed beam directions.

Hydrosweep-Multibeam System

The Hydrosweep system consists of two identical arrays mounted at right angles to each other. The coverage of this system is around 90° (Gutberlet & Schenke, 1989). Each array is a combination of three sub-arrays consisting of 96 elements each, making a total of 288 elements. Since both the arrays are identical, they can be used for either transmission or reception. Such facility includes a great advantage for calculating the mean sound velocity for the entire column of the water. This mean velocity of sound is used for refraction corrections. In the receiving mode, 72 channels (using four elements in series each channel is constituted) are pre-amplified, attenuation corrected and thereafter beamforming is performed using appropriate delays. Total 59- beams are formed within the 90° swath. The beams are 1.5° apart with average beamwidths of 2.3° for deep water surveys. The half power beam width is 4.5° when the system is operated in shallow mode. The sidelobe levels of the beam patterns are around 25 dB below the main beam. This is achieved using windowing technique mentioned above. The beam formed outputs are tracked at the bottom echo module to determine the exact depth from the different directions. In order to obtain uniform insonification over 90° swath, the system works in a sector scan mode. For deep water operation three beams are transmitted, each having beamwidths of 45° in the directions of 0° and +30°. The system enters in the calibration mode to compute mean sound velocity, which is done using interchangeability of

transmitting and receiving function of the array. This technique is similar to the determination of root mean square velocity of the bottom layers with Normal Move Out (NMO) corrections in the seismic (Kodagali & Chakraborty, 1994). The mean sound velocity is computed by comparing two depth profiles measured in two different modes of the multibeam system. A least square analysis is performed between the profiles for the selection of accurate mean sound velocity.

Bathymetry Data

The Exclusive Economic Zone (EEZ) of India is covered with a variety of minerals of economic interest. The EEZ extends upto 200 nautical miles from the coastline. The coastal state has the right to explore and exploit the resources and protect the environment. The minerals present in the EEZ around India constitute an important scope for the exploration of hydrocarbons, calcium carbonate and phosphorites (Nair *et al.*, 1994). Apart from that, it has also been realised that the tectonic conditions are also suitable for hydro-thermal minerals in the Andaman back arc basin. Multibeam mapping (high resolution and high density) is essential to understand the seabed morphological aspects of these areas. A study conducted around the western continental margins using Hydrosweep-multibeam system reveals the presence of many small to medium scale seabed topography features which were not seen in the single beam echosounding data. Figure 2A shows a depth contour map of the Gaveshani bank, studied using multibeam system and the shape of the bank obtained using single beam echosounding data (Rao *et al.*, 1993). A significant amount of variation is observed between the shape of the Gaveshani Bank observed using single and multibeam techniques. The area of the bank is calculated to be $\sim 0.23 \text{ km}^2$ and $\sim 3.0 \text{ km}^2$ using single and multibeam sounding devices respectively. Area-wise, the bank is found to be approximately 14 fold bigger in size—a considerable variation—while using Hydrosweep-multibeam system. Similarly, detailed Hydrosweep-multibeam studies using multibeam system around Laxmi basin-Eastern Arabian Sea revealed some linear seamounts. Ocean floor seamounts are generally assumed to record the passage of the ocean crust over loci of magma generation (Bhattacharya *et al.*, 1994). Their study may help to understand the evolutionary history of the ocean basins. Figure 2B presents the 3D bathymetric map of the seamount chains as seen from the Hydrosweep-multibeam data. These seamounts are elongated in plan and have heights and basal areas varying between 1068-2240 m and 300-1210 sq. km. respectively. Detailed understanding of these areas may be made from the above-mentioned paper.

Using Hydrosweep system a regional scale bathymetric map was prepared around the 79°E fracture zone in the Central Indian Ocean basin while using multibeam sounder (Raju *et al.*, 1993; Raju, 1993). The survey data of Hydrosweep-multibeam system clearly reveals the 79°E fracture zone, depicting a ridge and trough topography. With an elevation difference of over 300 m E-W bathymetric lineations and several new features are observed in the processed multibeam bathymetry data (Fig. 2C). It is expected that many more points related to the evolution of the Oceans around India will be probed in the near future, and detailed bathymetry map of the kind shown here will contribute significantly.

Backscatter Study

However, bathymetry only provides the shape of the seafloor features and depends on the resolution of the sounding system. To characterise the nature of the seafloor surveyed, studies of signal waveforms and their variations must be made, *i.e.* understanding of the backscatter signal is essential. Using the capabilities of multibeam system to provide backscatter signals from different incidence angles, a modelling can be performed for seabed classification (deMoustier, 1986; Hagen *et al.*, 1994).

Multibeam systems are useful to derive angular dependent backscatter function of the seafloor (deMoustier & Alexandrou, 1991). Besides bathymetry, different types of seabottoms can be differentiated based on the backscatter values obtained at different incidence angles by the multibeam echosounder. The aim of such study is to determine whether bottom types can be determined using angular backscatter functions. In addition, determination of the influence of the interface roughness or sediment volume scattering parameters is possible.

There are many steps required for the determination of the backscatter angular dependence functions: 1. Determination of the time of arrival and mean energy of the return for each beam; 2. Bottom slope corrections; 3. Beam pattern (insonified area normalisation); 4. Refraction correction to determine angle of arrival, and 5. Sidelobe interference removal. In the Hydrosweep system, the determination of the time of arrival and mean energy of each beam is performed at the bottom tracking module. Recently a modification is incorporated in the Hydrosweep-multibeam Echosounder onboard *ORV Sagarkanya* to procure echo energy data and successful trial was conducted in the Arabian Sea. In order to compute the backscatter strength, presently work is initiated in the direction of computing seafloor slope and beam area normalisation. The necessary corrections for arrival angle computation are essential in real time. However,

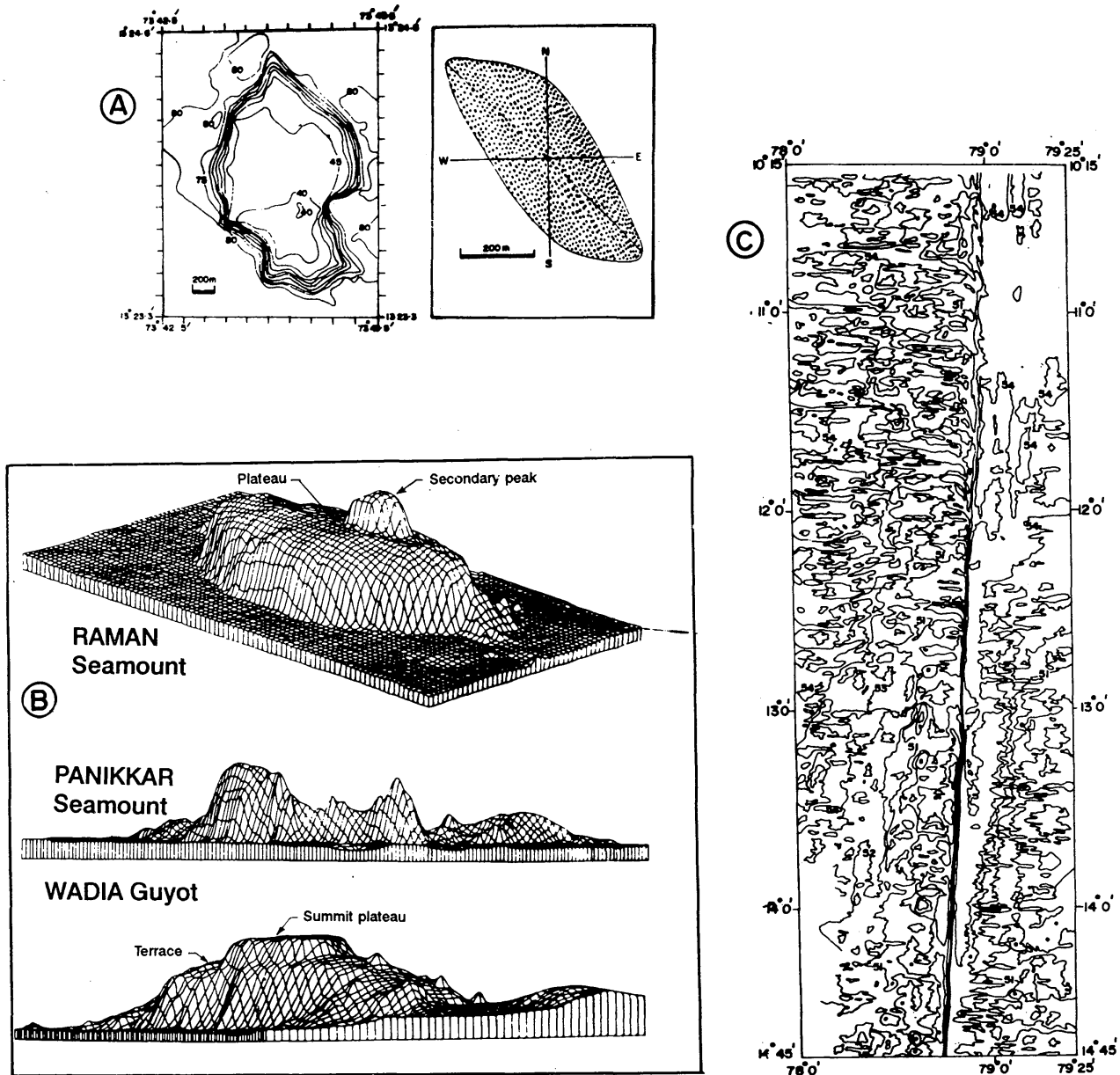


Figure 2. Hydrosweep-multibeam bathymetric profiles for different topographic domains:

- A. Depth contour map of the Gavesheni bank (contour interval 5 m) obtained from Hydrosweep-multibeam system, and shape of the bank drawn from single beam echosounder (based on Nair *et al.*, 1994).
- B. Isometric view of the Raman seamount, the Panikkar seamount and the Wadia Guyot. Hydrosweep bathymetry data collected from eastern Arabian Sea (based on Bhattacharya, *et al.*, 1994).
- C. Bathymetry map generated from Hydrosweep in Central Indian Ocean 79°E fracture zone (based on Raju *et al.*, 1993).

'Sidelobe interference removal' is not considered in the Hydrosweep-multibeam system of the *ORV Sagaranya*. 'Sidelobe interference removal' is an essential technique that must be made before backscatter energy computations (deMoustier & Kleinrock, 1986). In the multibeam system during the beamforming process, the sidelobe of the rest of the beams looks toward the main beam of a particular beam. This is an inherent problem in the multibeam geometry. This problem is more serious near the specular region where sidelobe returns and bottom echoes overlap. This effect is more pronounced in flat bottom areas, where saturation of the specular main beam is common. Such effects cause the computation of wrong signal threshold values for the outer beams. These sidelobes create artefacts in bathymetry and register wrong backscatter energy.

The multibeam geometry is particularly suitable to the task of deriving angular dependence of seafloor acoustic backscatter because it provides both high resolution related to such measurements and bathymetry. Though it is difficult to calibrate the backscatter data, quantitative estimation may be made for the relative values. The use of composite roughness theory is currently being made to obtain seabottom parameters. In the composite roughness theory, Helmholtz-Kirchoffs interface scattering conditions were used upto the incidence angles of 20° , thereafter Rayleigh-Rice approximations are used. The volume scattering term is added upto the interface roughness term to obtain total backscattering strength. Backscatter studies were initiated using a 16-beam multibeam-Seabeam by deMoustier and Alexandrou (1991) and Matsumotu *et al.* (1993). Their study could not reveal any information regarding seabed volume scattering because of the limitation of the angular range of the Seabeam system used (volume scattering is dominant beyond 20° angle). Because, the Hydrosweep system has the measurement facility upto 45° incidence angles, it can be a useful tool to obtain volume scattering information of the seabed. Using a curve matching method, the measured backscattering strength alongwith the theory based on the composite roughness will provide some insight of the backscattering process (Chakraborty *et al.*, 1995). Figure 3A presents computed backscatter angular values for two different areas like clayey sand and clay sediments for different volume in homogeneity. The seabottom interface roughness parameters are assumed to be $\alpha = 0.5$ and $\beta = 0.003$ *i.e.* for smooth seafloor areas. The composite roughness theory is used and variation in the shape parameters for seabottom material is clearly observed for similar interface/volume roughness.

High Resolution Beamforming

In multibeam sounding system, the delay-sum method (the method mentioned above) is used to obtain the

beamformed output in different directions. The size of the transducer array is a function of the beam width *i.e.*, the spatial resolution of the system.

At 15 KHz design frequency for a beam width of 2° , the approximate size of the transducer array has to be around 3 meters, which is relatively bulky. So a study is important to examine the effect of various methods of beamforming which require a smaller array size by using increased signal processing at the dry end of the multibeam system. These techniques are the 'Multiplicative Array Technique' (Chakraborty, 1994), 'Maximum Likelihood Method' (MLM), and 'Maximum Entropy Method' (MEM) (Chakraborty & Schenke, 1994). The situation is more complicated when multibeam systems are operated over seamounts, slopes or ridge areas. The multiple sources of interference arrivals from different directions are well known. This condition significantly affects the resolution of the map so that an assumption of coherent and incoherent source arrival conditions should be introduced to study the performance of the high resolution techniques. In Figure 3B, we present high resolution (MLM) beam patterns for incoherent and coherent sources. We assume that the sources are separated at 2° and 8° for different input signal to noise ratio. We observe that for closely placed sources (2°), the sources are unresolvable for coherent and incoherent sources. For larger source separation of 8° the sources are resolvable for both the source conditions. The number of elements was chosen to be 16 which is one-fourth of the conventional array size used for multibeam systems. The high resolution study should be extended using different algorithms such as ESPRIT, MUSIC, etc. The high resolution beamforming technique must also consider its application towards real time use. It is unlikely that a single algorithm will satisfy all the necessary conditions to generate noise free bathymetry or backscatter output. Development of a decision making network will be the next stage of development. This network will find suitable high resolution algorithms in real time and generate useful beam patterns for multibeam applications.

Imaging Techniques

The sidescan modifications to the multibeam system is a popular technique (deMoustier, 1986). The raw sidescan data requires significant image enhancements. Extensive work on image enhancement techniques has been carried out for sidescan systems such as GLORIA and SEAMARC. In future, these techniques will be implemented for multibeam systems. In order to develop sediment classification techniques using sidescan data from multibeam systems, as well as improved images, the angular backscatter function of the seabed can be used.

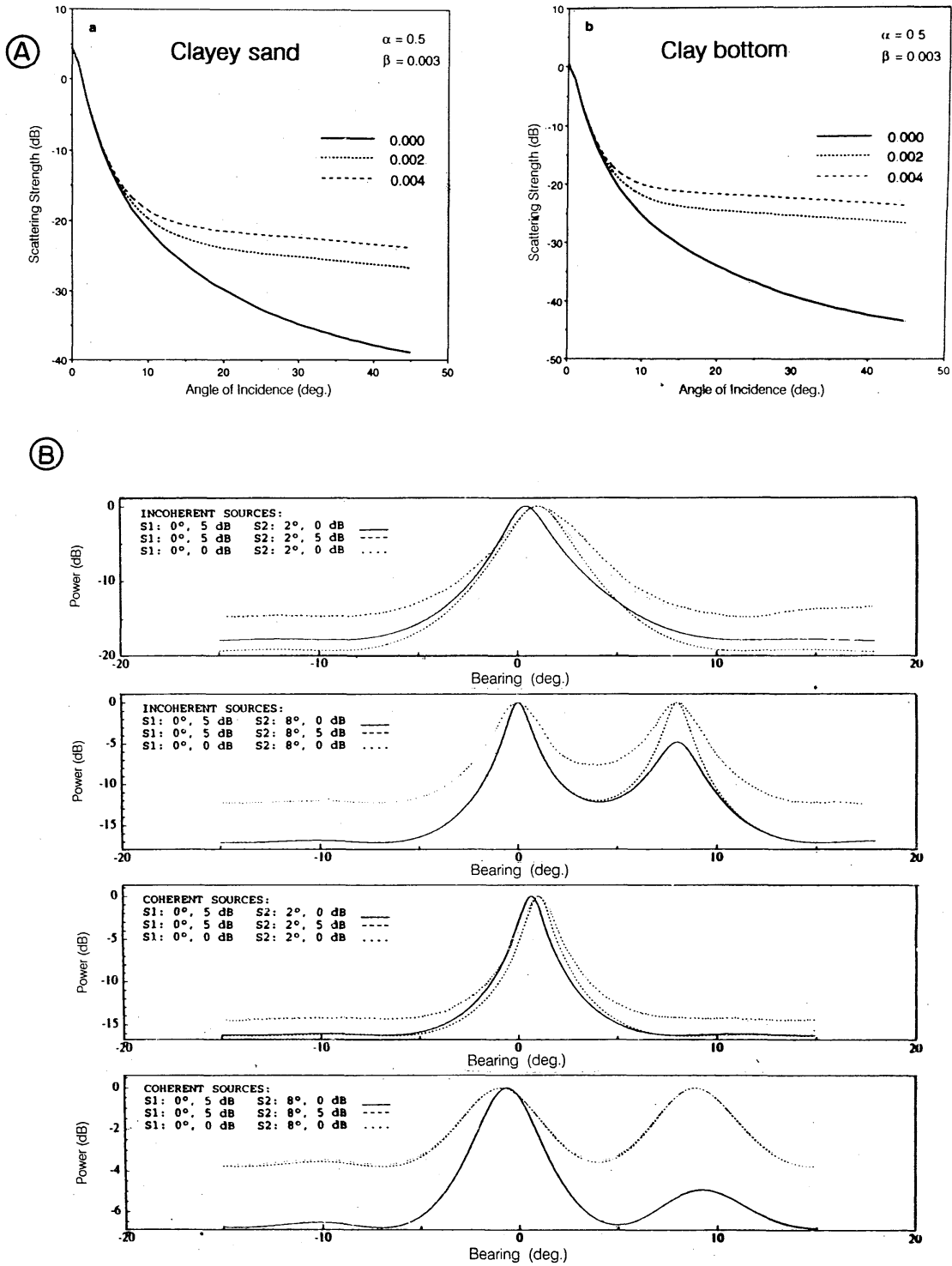


Figure 3.

- A. Computed angular dependence function of the smooth sediment bottom of the different materials of clayey sand and clay.
- B: Multibeam-High resolution beam patterns (Maximum Likelihood Method) for 16-element array. The sources are incoherent and coherent types of different signal strengths.

Conclusion

In this paper, a short presentation of the historical background of echosounding system is made. The advantages of multibeam systems over conventional single beam sounding systems are discussed. Theoretical analysis of the multi-beamforming method is also mentioned including the importance of sound velocity measurements. The technical details of the Hydrosweep-multibeam system which is installed onboard *ORV Sagarkanya* is elaborated. Some of the important seabottom features discovered using this instrument are presented. Apart from that, techniques for seabottom classifications using multibeam system are discussed. This discussion also includes necessary modifications of the multibeam systems. A result of studies using the high resolution beamforming methods are presented for MLM (Maximum Likelihood Method) *i.e.*, possibilities of some improvement in the existing technique is discussed.

References

- Bhattacharya, G.C.B., Murty, G.P.S., Srinivas, K., Chaubey, A.K., Sudhakar, T., & Nair, R.R. (1994) Swath Bathymetric Investigation of Seamounts Located in the Laxmi basin, Eastern Arabian Sea. 17, 169-182.
- Chakraborty, B. & Dey, K.K. (1994) Optimal estimation of ship's attitudes for beam pattern correction in Coaxial Circular array. *Mar. Geo.* 17, 223-236
- Chakraborty, B. & Schenke, H.W. (1994) Studies of high resolution algorithms for Multibeam bathymetry applications. *Int. Symp. on Marine Positioning (INSMAP)*. 311-320.
- Chakraborty, B. (1994) Application of Multiplicative Array Techniques for Multibeam Sounder System. *Acoustica*. 80, 573-575.
- Chakraborty, B., Hagen, R. & Schenke, H.W. (1995) Estimating Seafloor Interface and Volume roughness parameter using Multibeam-Hydrosweep systems (communicated).
- Collin, R.E. & Zucker, F.J. (1969) *Antenna theory*, pp. 141, McGraw Hill, NY, USA.
- deMoustier, C. (1986) Approaches to acoustic backscatter measurement from the deep sea floor. *Trans. American Society Mech. Eng. Ocean Eng. symposium*. 11, 137-143.
- deMoustier, C. & Kleinrock, M.C. (1986) Bathymetric artefacts in Seabeam data: How to recognise them, what causes them. *J. Geophys. Res.* 91(B3), 3407-3424.
- deMoustier, C. (1986) Beyond Bathymetry: Mapping acoustic backscattering from the deep sea floor with Seabeam. *J. Acoust. Soc. Am.* 79, 316-331.
- deMoustier, C. & Alexandrou, D. (1991) Angular dependence of 12 KHz seafloor acoustic backscatter. *J. Acoust. Soc. America*. 90, 522-541.
- Dolph, C.L. (1946) A current distribution of broadside arrays which optimises the relationship between width and sidelobe level. *Proc. IRE.* 34, 335-348.
- Dysart, P.S. & Ogushwitz, P.R. (1991) Computer simulation of Multibeam Technology. *Sea Technol.* 6, 10-15.
- Gutberlet, M. & Schenke, H.W. (1989) Hydrosweep: New era in high precision Bathymetric surveying in deep and shallow water. *Mar. Geo.* 13, 1023.
- Hagen, R., Chakraborty, B. & Schenke, H.W. (1994) Preliminary backscatter results from the Hydrosweep Multibeam System. *Proc. Int. Symp. on Marine Positioning (INSMAP)*. 355-364.
- Kodagali, V.N. & Chakraborty, B. (1994) Performance appraisal of multibeam system. *Proc. Symp. Ocean. Technol.* 335-346.
- Maul, G.A. & Bishop, J.C. (1970) Mean sounding velocity, a brief review. *Int. Hyd. Rev.* 47, 85-92.
- Nair, R.R., Rao, P.S. & Kodagali, V.N. (1994) Multibeam mapping of the Exclusive Economic Zone of India. *Proc. Symp. Ocean Technol.* 327-334.
- Raju, K.A.K., Ramprasad, T., Kodagali, V.N. & Nair, R.R. (1993) Multibeam Bathymetry, Gravity and Magnetic studies over 79°E fracture zone, central Indian Basin. *J. Geophys. Res.* 98(B6), 9605-9618.
- Raju, K.A.K. (1993) Magnetic lineations, fracture zones and seamounts in the Central Indian Basin. *Mar. Geology*. 109, 195-201.
- Rao, P.S., Kodagali, V.N., Ramprasad, T. & Nair, R.R. (1993) Morphology of a Coral bank, Western Continental Shelf of India: A Multibeam study. *J. Geo. Soc. India*. 41, 33-37.
- Renard, V. & Allenou, J.P. (1979) Sea Beam Multibeam echosounding in Jean Charcot: Description, evaluation and first results. *Int. Hyd. Rev.* 56, 35-67.