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Acoustic Remote Sensing as a Tool for Habitat Mapping in Alaska Waters

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Abstract

This paper discusses the basics of acoustic remote sensing (ARS), whereby information may be inferred about the environment through measurements of backscatter. The physical process of backscatter is described with emphasis on the different outcomes that are associated with a variety of common seabed materials. It is shown that the potential information, which can be inferred from measurements of backscatter, depends on the system design. Important system design parameters include acoustic frequency, pulse length, beamwidth, and deployment technique (towed or hull-mounted). The operational deployment of towed sidescan sonar, in particular whether it is towed close to the seabed or towed higher in the water column, can modify the potential utility of the backscatter measurements to habitat mapping.

Introduction and background

Habitat mapping seeks to associate particular species with their various habitat(s). This is a compound problem because there does not seem to be a single survey technology that can uniquely establish the connection between species and habitat (i.e., distribution and abundance of marine organisms that make up the complex marine biomass pyramid). Direct sampling is a well-established, effective survey technology for habitat mapping, but faced with the vast amount of physical area in Alaska waters it is necessary to strive for a more efficient method. ARS, which is composed of closely aligned survey technologies, may provide an efficient method of mapping fisheries habitats. ARS may be particularly applicable to Alaska fishery habitat mapping, because it provides rapid collection of data over large areas of the seabed.

Table 1. Parameters and their descriptors that may segment habitat (Madden et al. 2005).

Water condition	Physical character	Spatial variety	Geomorphologic
Salinity Oxygen Temperature Turbidity	Energy (currents, waves) Tidal range Depth Photic regime	Physical structure and complexity	Profile Slope Relief Substratum type and composition Geology Grain size

Table 1 lists four basic parameters that have been used to differentiate between habitable zones without being species specific. The table also lists properties that may be used to make finer distinctions between habitats. ARS can measure some of the properties that appear in Table 1. None of the parameters in the first column can be measured using the ARS technologies discussed in this paper. In the second column, depth can readily be measured using ARS. In the third column, physical structure and complexity can readily be measured using ARS. In the fourth column, profile, slope, relief, substratum type, and geology can readily be measured using ARS. In the fourth column, grain size and substratum composition, which may be distinctive to a particular fishery habitat, can be estimated via ARS. However, the grain size and substratum composition results may be imprecise, even with the addition of supporting groundtruth data from physical samples and/or pictures of the seabed.

ARS systems involve interaction between an outgoing pulse of acoustic energy and the environment, which presumably imparts information into an echo about the environment. The interaction occurs at an interface that is "remote" relative to the acoustic transducers (transmit and receive). ARS techniques have been used for many years as a preferred approach for mapping the seabed and detecting objects that may lie on or below the seabed. The basic principles of ARS have led to trade-offs between transducer size and acoustic frequencies in order to achieve different operational ranges and resolutions. Those trade-offs have led to the development of particular systems for addressing specific problems. This paper will describe issues related to the technologies of three particular system types (with some variations of those types): vertical beam (including subbottom profilers), sidescan (including synthetic aperture and interferometric sonar), and multibeam. The utilities of those three basic system types, and their variations, are different and those differences stem largely from issues of frequency and deployment geometry. Fig. 1 illustrates a survey operation utilizing multibeam sonar mounted on the hull of the survey vessel and a towed sidescan sonar. Although not shown in the figure, a vertical-beam echosounder will most likely be mounted on the hull of the survey vessel and potentially will provide additional information about the seabed.

When planning a fishery habitat-mapping project, it is important to balance the desire to survey a large area against

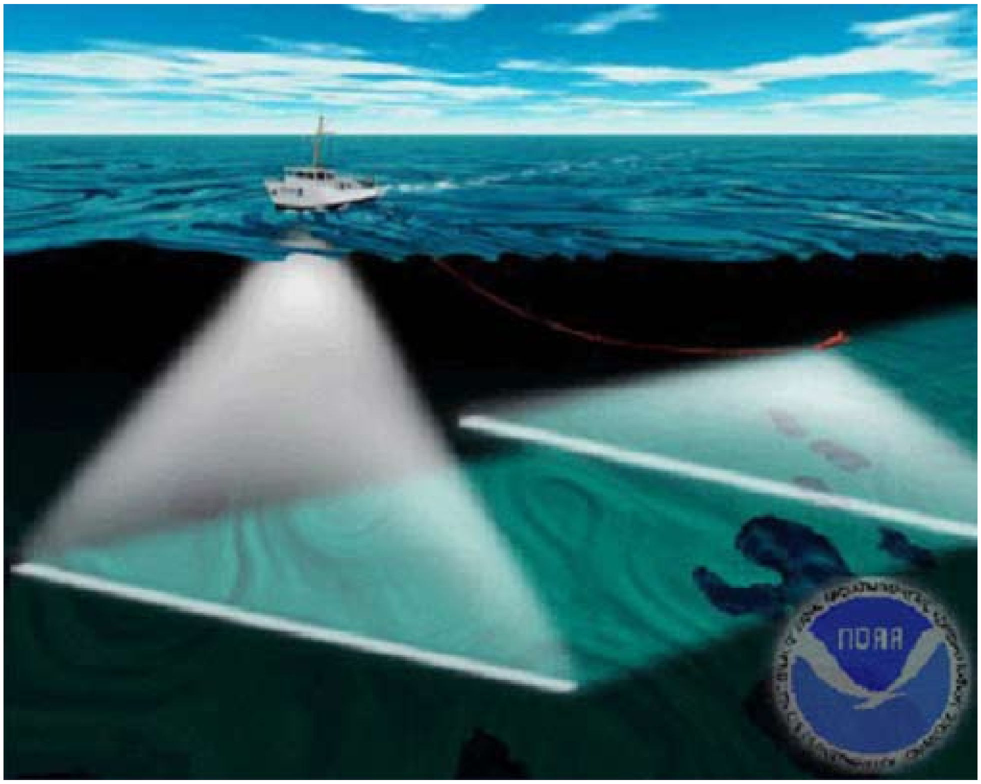

Figure 1. **Typical survey configuration (multibeam and sidescan) that can be used for acoustic remote sensing of fisheries habitats in Alaska waters.**

the requirements for percent of bottom coverage and for resolution of spatial details. It is the intent of this paper to provide discussions that will allow one to make informed choices related to the use of ARS for fishery habitat surveys in Alaska waters. It is recognized, however, that the choice of survey technology will likely depend on the sonars that are readily available to any given research project.

Basic physics principles of acoustic remote sensing

Acoustic waves in a medium are vibrations of that medium and are manifested as periodic variations of pressure in the medium. As a result of this physical nature of acoustic waves, the composition of the material through which an acoustic wave travels will impact its speed and the energy that is lost due to absorption as the wave propagates through the material. When a propagating acoustic wave encounters a sudden change in the acoustic impedance (product of sound speed and density) of the medium, a portion of the acoustic wave will change its propagation direction (i.e., it will be reflected or scattered) and a portion of the wave will continue to propagate in the same general direction of the transmission. The portion of an acoustic wave that reverses its propagation direction may be received and exploited for ARS.

Fig. 2 shows a variety of outcomes from the interaction between an incident acoustic wave front and the seabed. The interactions that may occur include reflection, scattering, and penetration. The latter may also involve refraction. The relative distribution of energy between reflection, scattering, and penetration is the result of interactions that are controlled by the frequency of the acoustic wave, the roughness scale (relative to the acoustic wavelength) of the seabed, the acoustic impedance and absorption properties of the seabed, and the angle at which the sound is incident upon the seabed. The occurrence of one type of interaction does not preclude another type from also occurring. In the instance of penetration through the water/seabed interface there also may be refraction and scattering within the seabed.

If the interaction is a reflection, the same 2-D symmetry, or asymmetry, of the incident acoustic energy is maintained beyond the reflection (angle in equals the angle out). If the interaction is scattering, the simple ray path geometry of one ray in and one ray out (as in reflection) is not maintained. For each ray path going into a scattering interaction, there are multiple possible ray paths going out from the interaction. If the interaction is penetration, then several things may happen. The simplest is that acoustic energy enters the seabed and is "lost" by conversion into heat. The loss by conversion to heat depends on the acoustic wavelength. Subsurface

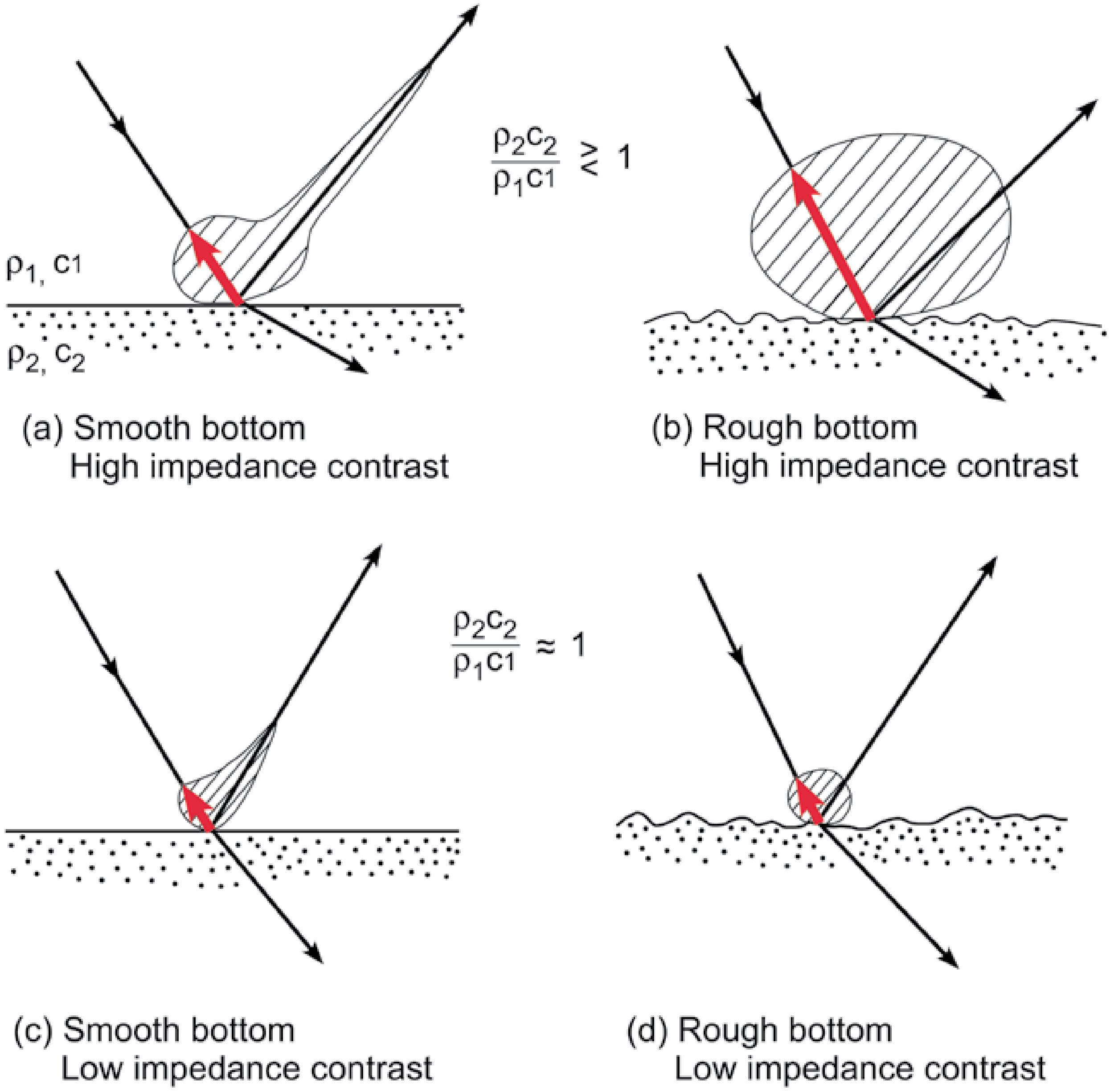

Figure 2. Backscatter (red arrows) as a function of seabed roughness and acoustic impedance contrast. After Urick 1983.

layers with high impedance contrasts may cause subsurface reflections and a small amount of the energy that penetrated the seabed may exit the seabed in a direction that will eventually lead to the ARS receiver. Non-homogeneities in the seabed material may result in a portion of the energy that penetrated the seabed being scattered, and a very small amount of energy may exit the seabed propagating in the right direction to eventually return to the ARS receiver.

For acoustic energy to reflect, the interaction site must be smooth (Fig. 2, panel a). For acoustic energy to scatter, the interaction site must not be smooth (relative to a wavelength) as scattering will only occur if the site of the interaction is rough (Fig. 2, panel b). The spatial pattern of the scattering (i.e., how much energy goes in which direction) depends on the roughness at the location of the interaction. Based on the spatial scattering pattern, a portion of the energy will be scattered back along the path by which the acoustic pulse approached the interaction site. That portion of the energy is specifically designated backscatter.

The amplitude of backscatter from any given seabed depends on the incidence angle associated with the particular interaction event that resulted in the backscatter. Fig. 3 illustrates the effect of incidence angle on backscatter for an acoustic frequency of 100 kHz. The curves show incidence

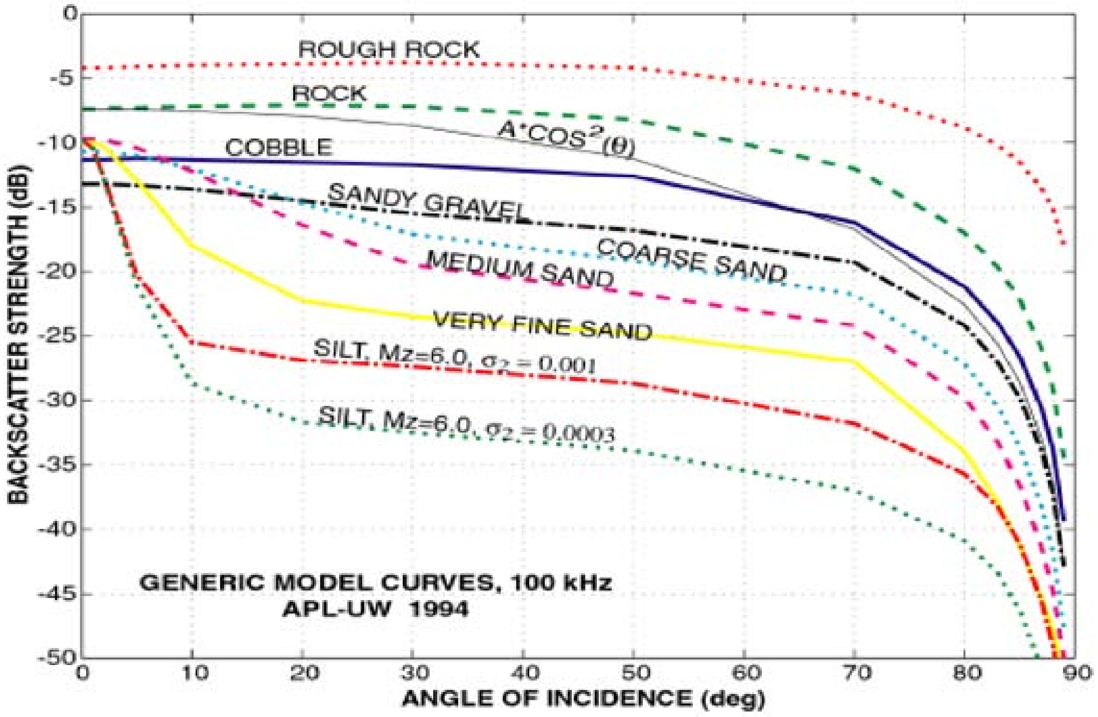

Figure 3. Graphical representation of the impact that bottom type and angle of incidence have on backscatter at 100 kHz. The curves are calculated from the APL-UW generic backscatter model.

angles that vary from 0 to 90°; however, the range of incidence angles associated with an ARS system depends on the particular type of ARS system. Multibeam bathymetric sonars have incidence angles that vary from 0° to one-half the included angular width of the sonar swath. Vertical-beam echosounders have incidence angles that vary from 0° to one-half the width of the sonar beam. Sidescan sonars have incidence angles that vary from 0 to 80°. The labels on the curves in Fig. 3 represent classes of sediment grain size, but they can also be viewed as a ranking of bottom roughness (at the wavelength of the particular acoustic frequency). A set of curves for backscatter at 50 kHz might have a “cobble curve” that is similar to the 100 kHz curve in Fig. 3 for “sandy gravel.” Likewise a set of curves at 200 kHz might have a “very fine sand curve” that is similar to the 100 kHz curve in Fig. 3 for “medium sand.” Moving up in acoustic frequency causes the backscatter response curve versus angle of incidence, for any particular sediment, to move up through the (roughness) ranks. That is because moving from a lower frequency to a higher frequency moves toward shorter wavelengths, which causes any particular sediment to be rougher (in an acoustic sense). In order to realistically estimate the impact of incidence angle for a particular combination of seabed and sonar, it is necessary to have knowledge of both the sonar’s acoustic frequency and the seabed material. The sonar frequency can be easily measured, if it is not already known. However, the need to know the seabed material easily leads to a circular argument if one attempts to estimate the seabed material using only ARS.

The ability to resolve a feature of the seabed with sonar will depend on the system design parameters and environmental factors. All sonars have fundamental constraints and trade-offs with respect to frequency of operation, range and lateral resolution, and range of transmission. Increased range resolution is typically achieved by increasing the frequency of operation, but at the price of greater attenuation and thus shorter propagation ranges. Range resolution is the ability to distinguish between two targets that are separated in range from the sonar. It is often stated that a sonar’s range resolution is equal to $ct/2$, where c is the speed of sound and t is the pulse length. Alternately, since the bandwidth (BW) of a pulse is equal to the reciprocal of its length, the range resolution is equal to $c/2\text{BW}$. Lateral resolution is determined by the beamwidth, which will be a function of the operating frequency of the sonar as well as the length of the transducer array (the longer the transducer, the narrower the beam). Lateral resolution is the ability to distinguish between two targets that are at the same range from the sonar but at different bearings from the sonar. Thus the key to achieving high lateral resolution at a given frequency is increased array length. However, increased array length also increases the range to where the contributions of the different element

Table 2. **Frequency, wavelength, range, and penetration for typical acoustic remote sensing frequencies.**

Frequency (kHz)	Wavelength (mm)	Useful range in seawater (m)	Penetration in sandy seabed (mm)
3	500	30,000	10,000
10	150	6,000	8,250
30	50	2,500	1,200
50	30	1,000	300
100	15	600	90
500	3	150	12
1,500	1	30	3

Table 3. **Bandwidth, pulse duration, and range resolution for typical acoustic remote sensing frequencies in seawater, assuming Q of 5-10 and speed of sound in seawater of 1,500 m per second (after de Moustier 2007).**

Resonate frequency (kHz)	Bandwidth near transmit resonance (kHz)	Minimum effective pulse length (ms)	Range resolution (mm)
3	0.3-0.6	1.66-3.33	1,250-2,500
10	1-2	0.50-1.00	375-750
30	3-6	0.17-0.33	125-250
100	10-20	0.05-0.10	37.5-75
500	50-100	0.01-0.02	7.5-15
1,500	150-300	0.0033-0.0066	2.5-5

points on the transducer face are nominally in phase. That range (numerically: array length^2/ acoustic wavelength) is designated as the transition from "near-field" to "far-field." The complexity of the emitted acoustic waves in the near-field makes it difficult to work in this region, and thus most sonar systems limit their working range to the far-field where the emitted energy can be considered plane waves. The requirement to work in the far-field limits the lateral resolution that is achievable by most sonar systems. Fortunately, this far-field limitation is being addressed in a new generation of dynamically focused sonars.

The backscatter from the seabed depends on the operating frequency of the ARS system. To the extent that the sonars commonly in use today (e.g., single beam, sidescan, and swath multibeam) operate at different frequencies, the backscatter information measurable from each of these systems will be different. The operating acoustic frequency is a fundamental aspect for determining the capabilities of a given sonar system and consequently the various operating acoustic frequencies are strongly coupled with the specific applications.

Table 2 presents predicted through-water ranges and penetration distances in sandy sediment for different ARS frequencies that might be employed in fishery habitat mapping. Penetration distance into the seabed is the distance at which the friction forces have totally converted the acoustic energy to heat.

The choice of operating frequency impacts the potential range resolution of the sonar, because range resolution is a function of the bandwidth of the system and typically the bandwidth is 5 to 10% of the operating frequency. Table 3 provides an overview of the expected range resolution associated with several frequencies typically used in seabed mapping and imaging sonars. The assumptions made in creating Table 3 are a nominal speed of sound in seawater of 1,500 m per second and a transmitting transducer Q (ratio of frequency to bandwidth) of 5 to 10.

Applicable environment for acoustic remote sensing

The fundamental processes controlling sonar propagation in marine or freshwater environments are scalable, and thus it is possible to use ARS in almost any depth of water. Trade-offs between achievable propagation range (requiring lower frequencies for longer ranges) and resolution (requiring higher frequencies for broader bandwidth) imply that the farther a target is away from the sonar source the poorer the resolution that target will be. In very shallow waters (<1-2 m depth), one of the largest advantages of sonar systems—their ability to cover a relatively large area at one time—is reduced because sonar coverage typically diminishes in very shallow waters.

There are certain seabed conditions that may prove more difficult for ARS than others. Seabeds containing gas (e.g., biogenic or thermogenic methane) and seabeds composed of medium-to-fine sand present special challenges to ARS systems. The presence of gas bubbles results in very high volume scattering and attenuation, which may make it difficult to determine the bulk reflecting/scattering characteristic of the sediment. In the instance of sandy sediments, the problem for an ARS system lies in the high acoustic attenuation, which makes it very difficult to maintain sufficient signal level for any distance into the seabed.

Common applications for acoustic remote sensing

ARS in the marine environment is typically conducted for the following reasons: hydrography, regional bathymetry, engineering applications, geologic and oceanographic studies, military applications, and habitat mapping.

Hydrographic surveys are conducted to support safety of navigation. This type of surveying is most often conducted with single-beam, multibeam, and/or sweep sonar (a series of single-beam echosounders mounted on booms extending athwart ships to simultaneously cover a wide swath). The objective is to produce very accurate measurements of depth that will provide input to nautical charts and to locate objects on the seabed that could be hazards to navigation. Depending on the morphology of the local survey area, hydrographic surveys are often augmented with towed sidescan sonar to ensure full coverage of the seabed.

Regional bathymetric surveys are conducted to determine the distribution of depths and seabed morphology in areas where safety of surface navigation is not a primary concern. These surveys are often conducted to support scientific research aimed at understanding seabed processes (e.g., processes associated with the creation of new oceanic crust at mid-ocean ridges, understanding the destruction of crust at deep-sea trenches, and deep-sea sediment transport mechanisms) or establishing boundary conditions for deep-sea circulation models (e.g., identifying passages and constraints for deep-sea circulation).

Surveys conducted for engineering applications include pipeline and cable routing, dredging and site selection for offshore platforms, and exploration for offshore resources (oil, gas, sand, and gravel deposits). This type of surveying typically obtains information about bathymetry, seabed and sediment type, the mobility of the seabed, and risks associated with potential hazards like gas blowouts or sediment failure.

Geologic studies are conducted for mineral exploration and for research. They require bathymetry, as well as identification of characteristics of the seabed and the subsurface, that can potentially convey information about the geological processes that may have occurred in the past as well as geological processes that are active. Recent efforts to directly invert seabed and subsurface acoustic data for seabed properties are adding an important new dimension to these efforts.

Military applications of ARS include antisubmarine warfare (ASW), mine countermeasure (MCM) activities, and applications to support amphibious operations. There is a rich history of ASW activities that have promoted development of sophisticated transducer design, acoustic models, and signal processing techniques. MCM surveys are conducted to understand the potential for the burial of mines as well as the potential for post-deployment burial/unburial. In surveys of this type, the ability to identify different sediment regimes and to detect targets of appropriate sizes and shapes are primary concerns in the selection of a sonar system.

Habitat mapping is becoming an increasingly important application of ARS. In the habitat mapping application, both detailed bathymetry (for morphology and rugosity) and backscatter (to provide information about seabed types) are essential. These data are interpreted, either manually or using automated image-processing algorithms to extract regions of common properties that may be relevant to the habitat of various organisms.

Acoustic remote sensing systems with application to fisheries habitat mapping

Vertical-beam echosounders (VBES), sidescan sonars, and multibeam swath sonars (MBES) are three different types of ARS systems that may be used in fisheries habitat mapping. The similarities and differences among the three basic types of ARS systems are discussed separately below. Due to the different applications, the different types of sonars tend to be deployed such that their ARS geometries are different. Fig. 4 shows how the potential amount of data (cross-track samples) provided by different sonar types and different deployment schemes (hull-mounted and towed) changes with water depth. Because towed sidescan sonar (TSSS) is typically towed at a given height above the bottom, its number of samples is independent of water depth. VBES and MBES are typically hull-mounted. The difference in data samples between MBES bathy and MBES imagery stems from the fact that the bathy is constrained to the number of formed beams, whereas the imagery in not necessarily subject to the same constraint.

Vertical-beam echosounders

Vertical-beam echo sonars are primarily designed to produce quantitative information about water depths although they may also be used for quantitative measurements of biomass within the water column. The received echoes in a vertical-beam depth sounder may be subjected to various signal processing schemes to provide information that allows the user to infer variations in the interaction of the transmitted acoustic pulse and the seabed that might, in turn, imply spatial variations in the composition of the seabed or the presence of man-made objects on the seabed.

Vertical-beam echo sonars have one, and sometimes two, transducer(s) that are each used for both transmitting and receiving acoustic energy at a given frequency. The vertical orientation of the beam(s) means the transmitted acoustic waves will most likely interact with the bottom at near vertical incidence, which will maximize the energy in the echo returns. In detecting the return signal in a vertical-beam echo sonar, one looks for a significant rise in voltage level above the mean level of the noise fluctuations that are always present in the output of the receiving transducer. The ability to distinguish one arrival time from another is limited by the bandwidth of the receiver and the bandwidth of the transmitter. Given the relationship between pulse length and range resolution where range resolution increases as pulse length decreases, the pulse length is typically decreased as a means of increasing the range resolution. If the acoustic pulse length becomes too short to contain sufficient energy for a particular ARS application, then sonar designers resort to using frequency modulated (FM) waveforms on transmit and pulse compression (matched filter processing) on reception. This technique, shown in Fig. 5, is referred to as "chirp

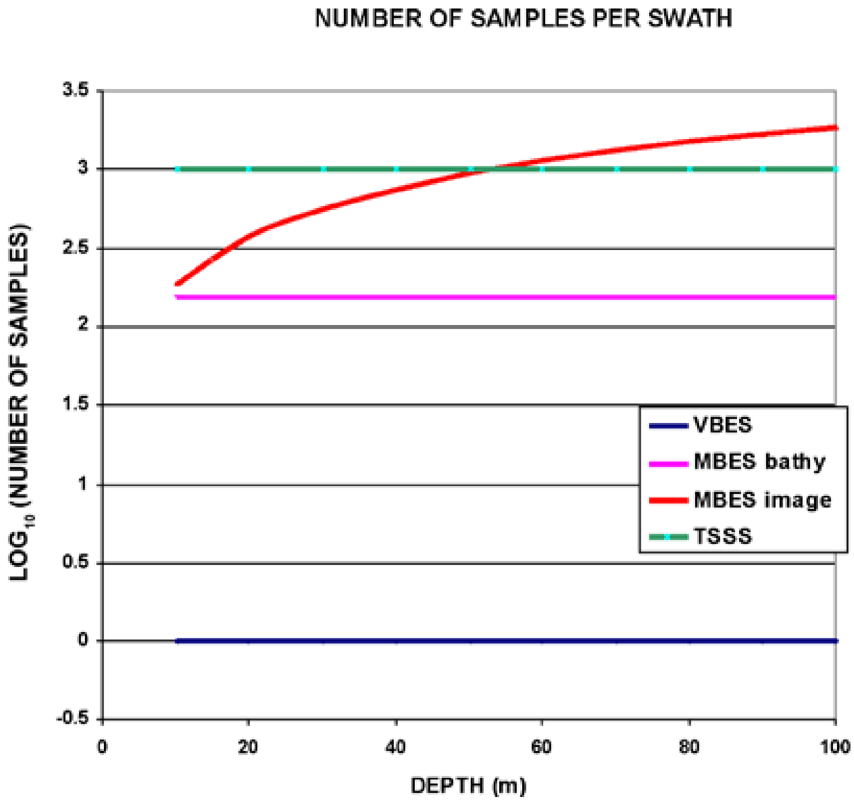

Figure 4. Potential for cross-track data from vertical-beam echosounder (VBES), multibeam echosounder bathymetry (MBES bathy), multibeam echosounder backscatter imagery (MBES image), and towed sidescan sonar (TSSS).

sonar" and is used in many sidescan sonars as well as echosounders and subbottom profilers (Mayer and LeBlanc 1983). Chirp technology provides deep subbottom penetration due to the total transmitted energy (time-bandwidth product) while providing good vertical resolution due to the wide bandwidth of the FM transmitted waveforms. Subbottom profilers are included in this ARS discussion because they are a specialized form of single-beam echosounder. However, it is not clear that the information contained in subbottom profiles contributes significantly to the understanding of fisheries habitat (but see Barrie and Conway 2008).

The detection and identification of specific objects is limited not only by the temporal resolution (radial range resolution) but also by the lateral resolution of the echosounder as determined by the beam footprint. Lateral resolution is measured in the plane that is perpendicular to the radial direction. The radial range resolution of a sonar system is set by the bandwidth of the system's acoustic transmission and reception. The lateral resolution is set by the beamwidth of the ARS transducers. Vertical-beam echosounders typically have beamwidths on the order of 10-30°, resulting in poor lateral discrimination. The first return received from within the beam footprint of a vertical-beam echosounder is assumed to come from directly below the vertical, whereas it might actually come from anywhere in the footprint. This assumption therefore limits the effective resolution in the horizontal plane (lateral resolution) to roughly the size of the footprint.

Given their limited lateral resolution, most vertical-beam echosounders would be an inappropriate choice for use in an ARS search for all but large scale features of a habitat. There are approaches to narrowing the footprint of a vertical-beam echosounder but these typically come at the cost of greatly increasing the size of the transducer or greatly reducing the operating range of the sonar by greatly increasing the frequency to the point where the acoustic energy suffers increased attenuation. Table 4 presents nominal transducer dimensions to achieve specific beam footprints at ARS frequencies.

One way to address the problem of limited lateral resolution is the use of parametric transmission. This mode of operation employs the very high power simultaneous transmission of two high frequency acoustic signals, where nonlinear interaction results in propagation of low frequency acoustic energy whose beamwidth is that of the high frequency energy. Using this technique it is possible to achieve

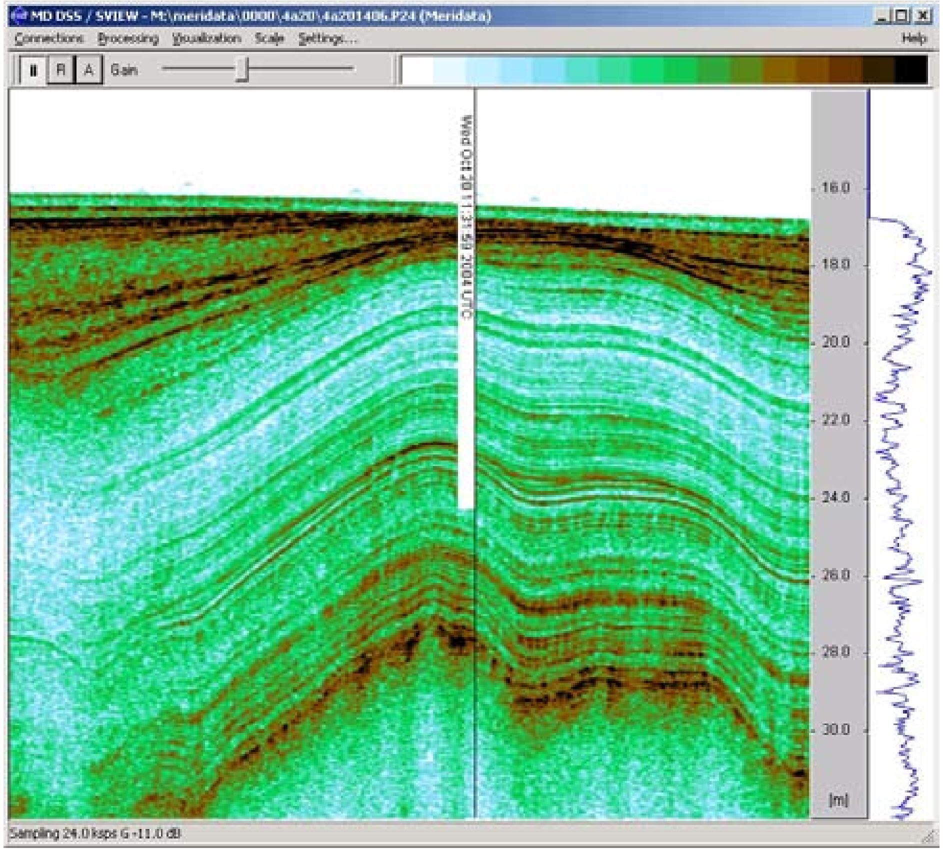

Figure 5. **Example of a chirp subbottom profiler record. This example is from a Meridata MD-DSS system operating over a range from 10 to 40 kHz. Subsurface penetration on this record is on the order of 15 m. From http://www.meridata.fi/mddss.htm.**

beamwidths on the order of 10° for frequencies on the order of 5 kHz. Parametric systems have been commercially developed, but they tend to be relatively inefficient in their conversion of electrical to acoustic energy.

Sidescan sonar

Given the lateral resolution constraints of standard vertical-beam echosounders, sidescan sonars were developed using a geometry that is more appropriate for the detection of targets on the seabed rather than measurement of water depth (Fig. 6). The objective of sidescan sonar is to provide a detailed presentation of seabed features and man-made objects that may lie on the surface of the seabed, in the form of an image. The first sidescan sonar was developed in 1960 at the Institute of Oceanographic Sciences (IOS) in England (Tucker and Stubbs 1961). The first sidescan sonar was a shallow water system. In 1969, IOS developed the Geological Long Range Inclined Asdic (GLORIA) side-looking sonar for surveying in the deep ocean (Laughton 1981).

The spatial resolution capabilities of a sidescan sonar are different in the cross-track and along-track directions. Both the cross-track and along-track resolutions vary with the cross-track distance from nadir; however, the character of those variations differ between the two directions. Along-track resolution, which changes linearly with slant range, is determined by the horizontal beamwidth of the transmit/receive transducer. Cross-track resolution is determined by the sonar's range resolution and by geometric effects that vary nonlinearly with slant range. The nonlinearity of the cross-track resolution is set by the height of the tow fish above the bottom and the cross-track distance from nadir.

In the design of a sidescan sonar a high premium is placed on achieving transmit/receive beams that are narrow in the along-track direction. Sidescan sonars tend to use high frequencies and long (with respect to a wavelength) arrays in order to achieve narrow beamwidths with transducers of moderate length. Due to the high frequencies, the height of the tow fish over the bottom must be limited and the useful operating range of sidescan sonar is typically less than 200 meters to either side of the tow fish. A notable exception is GLORIA II, which operates at a frequency of 6.5 kHz and has a maximum imaging range of 60 km (Mitchell 1991).

The transmit and receive beamwidths of the sonar set fundamental limitations of small target detection. In this

Table 4. **Estimates of transducer dimensions to achieve different beam footprints as a function of ARS frequency and beamwidth.**

Beamwidth	0.5°	1.0°	2.0°	5.0°	10°
Transducer size at 12 kHz	18 m	9 m	4.5 m	1.8 m	0.9 m
Transducer size at 30 kHz	7.2 m	3.6 m	1.8 m	0.7 m	0.36 m
Transducer size at 100 kHz	2.2 m	1.1 m	0.6 m	0.2 m	0.1 m
Transducer size at 300 kHz	0.6 m	0.3 m	0.2 m	0.1 m	0.03 m
Transducer size at 455 kHz	0.5 m	0.2 m	0.2 m	0.05 m	0.02 m

context the definition of "small" is an object whose lateral extent is on the order of the beamwidth (Table 4) and a vertical extent that is on the order of the range resolution (Table 3). The along-track beamwidth will be a function of the ratio of the acoustic wavelength and the length of the array. Standard sidescan sonars have ratios of approximately 1:60-1:400, which results in a lateral resolution of approximately 1 m at 60 m range for the ratio of 1:60 and 0.5 m at 200 m range for the ratio of 1:400.

When small object detection is the primary purpose of a sidescan sonar survey, the transducers are most often placed on a platform and deployed near the bottom. Typically, the tow altitude is approximately 10% of the sonar's achievable range. By placing the sonar near the bottom, the angle of incidence is large thereby producing long shadows from protrusions above the seabed. A problem faced in trying to detect small objects with sidescan sonar is the spatial divergence of the beam in the horizontal plane as the acoustic pulse travels farther from the tow fish. For maximum ability to detect specific small targets at any given range, the along-track width of the transmit/receive beam, at that range, should be less than the least cross section of that specific target, and the range resolution should be much less than the largest cross section of that specific target.

An image of the seabed obtained with sidescan sonar, like the image shown in Fig. 7, will almost always contain spatial variations in the intensity of the received backscatter signals. In Fig. 7 higher backscatter values are presented as darker. The imagery in Fig. 7 is presented with slant range to starboard of the trackline as the horizontal axis, and along-track distance as the vertical axis. In this presentation it is possible to identify the outgoing pulse, a return from the sea surface, and the onset of the bottom return. If there had been targets within the water column, like a school of fish or a subsurface buoy, their echoes may have occurred either prior to the onset of the bottom echo or may have been superimposed on the bottom returns.

Several possible effects can be used to explain the majority of the spatial variations observed in the intensity of the received signals presented in Fig. 7. The first possible cause is an actual spatial change in the materials that make up the seabed. The relative backscatter characteristics differ for different materials based on their inherent acoustic impedance and their roughness relative to a wavelength. As presented in Fig. 3, at most frequencies, rock and gravel will backscatter more of the incident acoustic signal than sand. Sand will backscatter more of the incident acoustic signal than mud. A second possible cause of the spatial variation is a change in the angle between the propagation direction of the outgoing (transmitted) acoustic pulse and the seabed, which is designated the angle of incidence. The angle of incidence varies across the ensonified swath. Portions of the seabed (sand waves, for example) with slopes that face toward the transducer on the tow fish will backscatter more of the incident acoustic signal than surfaces with slopes that face away from the transducer. A third cause of the spatial variation is the presence of a small target, which produces a high return followed by a region of very low return (acoustic shadow). Similar effects of high and low returns are associated with the rock outcropping. Manual interpretation of sidescan sonar imagery requires considerable experience and first-hand knowledge about the particular backscatter characteristics of various rock types, gravels, sands, and characteristic bed forms associated with them such as bedding, jointing, ripple marks, and sand waves (Flemming 1976, Fish and Carr 1990).

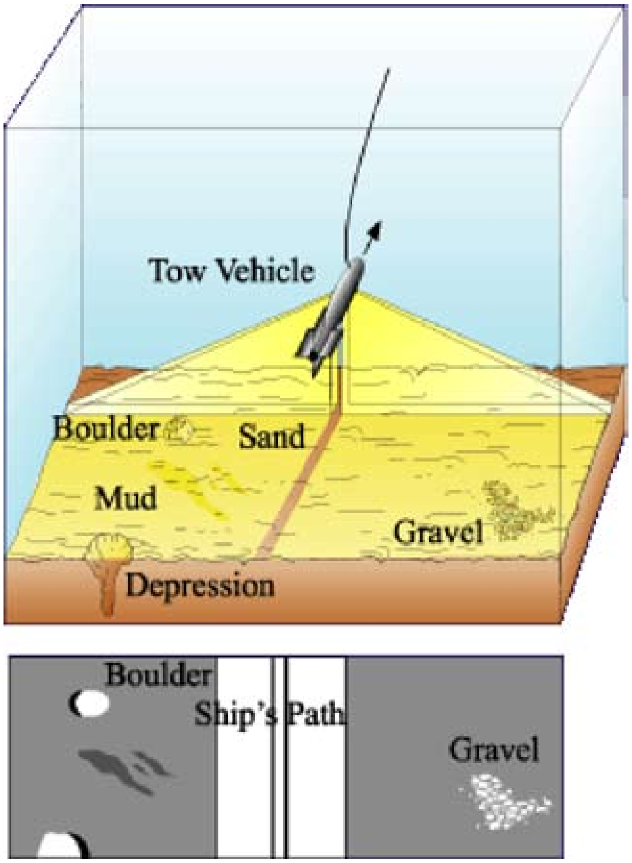

Figure 6. **Basic geometry of sidescan sonar (from a tow vehicle in this case). From http://woodshole.er.usgs.gov/operations/sfmapping/sonar.htm, after Able (1987).**

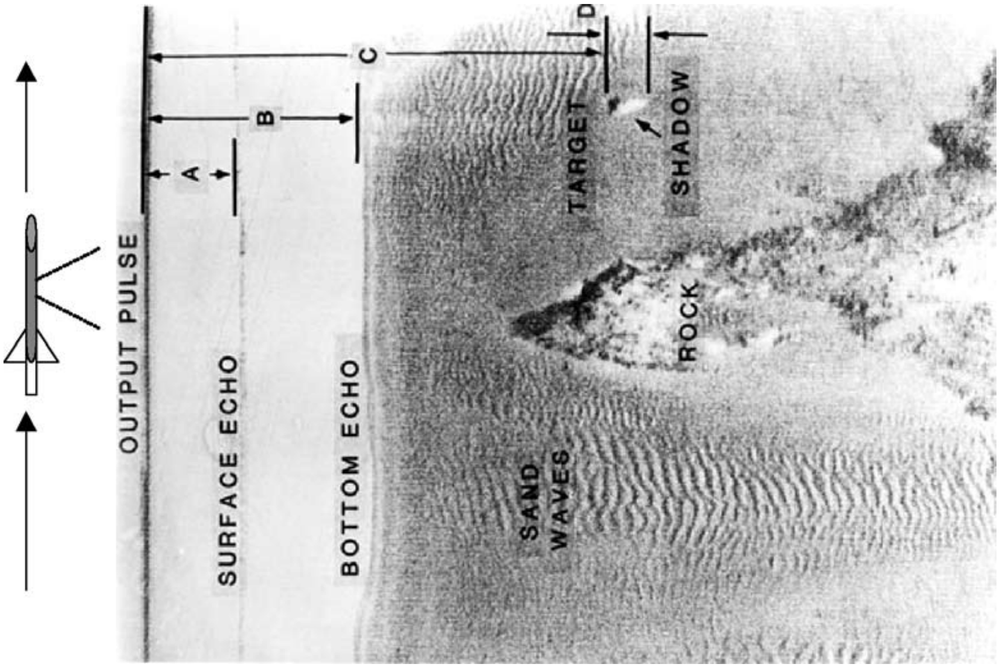

Figure 7. **Sample sidescan sonar image of seabed with various textures and a small target. From http://www.l-3klein.com/operator_tips/optips/geometry/geometry.html.**

Sidescan sonars are typically towed close to the seabed to control the geometry of the interactions between the acoustic transmit pulse and the seabed. The higher the tow fish is above the bottom, the longer the outgoing pulse is in the range of incidence angles where the variation in backscatter is more sensitive to small changes in incidence angle (Fig. 8).

Two variations on the sidescan sonar

The Edgetech 4700 sidescan sonar and the Klein System 5000 sidescan sonar utilize dynamic focusing to improve small target detection at ranges that normally would fall inside the near-field of the transducer. Another approach to overcoming the small target detection limitation is through the use of "synthetic aperture" sonar (SAS), which coherently combines the returns from multiple pings to create a long "virtual" acoustic aperture. Coherent integration of data from a number of transmissions as the sonar moves along the track yields images with theoretical along-track (lateral) resolution at all ranges equal to one-half the lateral size of the receiver element. In reality, the achievable resolution is more coarse by 150 to 200% than the resolution predicted by theory. Along-track resolutions have been achieved in SAS systems that are on the order of a few centimeters. Fig. 9 shows a small (tens of centimeters) target at a cross-track range on the order of 100 m. The insert to the right side of the figure is a spatially expanded subset of the larger image on the left. SAS sonars provide the highest number of independent image pixels per unit time.

In general, designers of sidescan sonars have not responded to the needs for fisheries habitat surveys, where the requirement is for ARS tools that are quantitative rather than qualitative. However, Teledyne Benthos, with their C3D, and GeoAcoustics, with their GeoSwath, are moving toward being more nearly quantitative by manufacturing high-frequency sidescan sonars that provide bathymetry as well as backscatter. Interferometric (phase-comparison) sonars like the C3D and GeoSwath produce sidescan sonar imagery of the seabed but also produce depth information. With knowledge of the bathymetry, it is possible to be more precise in adjusting observed backscatter for the impact of incidence angle. To be fully quantitative it would also be necessary to have detailed knowledge of the pulse length, the transmit source level, the receiver sensitivity and gain, and the beam patterns for both transmit and receive transducers.

The measurement geometry of interferometric sonars is similar to that of sidescan sonar except that multiple, parallel rows of transducers are used to receive the backscattered energy. Interferometric sonar differs from multibeam sonar in that not only is the travel time of the echo measured, but the vertical angle of arrival for each time sample of the echo must also be measured. This is done using the phase differences between the returns coming to multiple receivers, which are separated in the vertical plane (Cloet and Edwards 1986, Denbigh 1989). Sidescan sonars with bathymetry measurement capabilities provide co-located/co-registered backscatter and bathymetry data. This allows the development of digital elevation models (DEM) of the seabed that can be

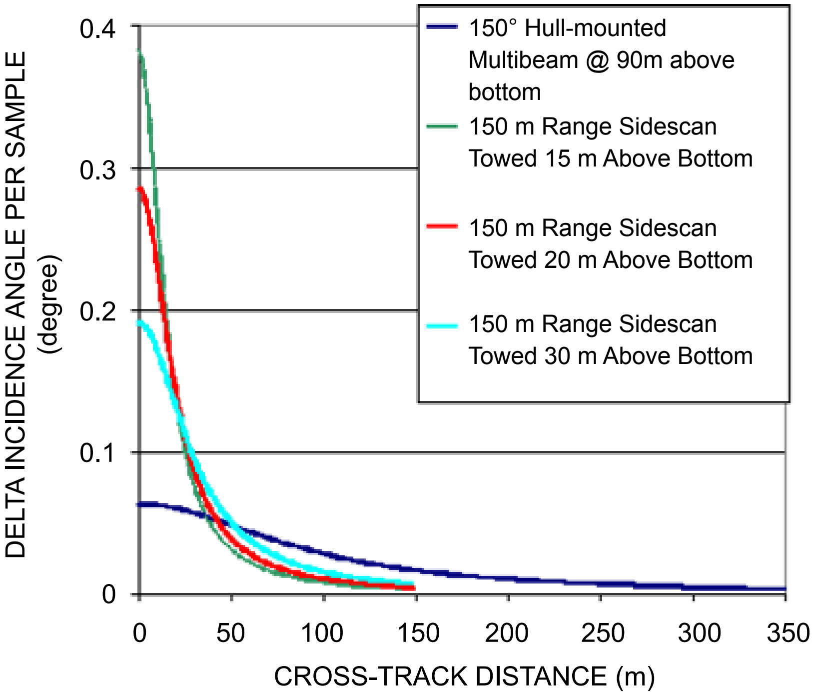

Figure 8. **Sensitivity of angle of incidence to deployment geometry (tow fish height above the bottom) and cross-track distance.**

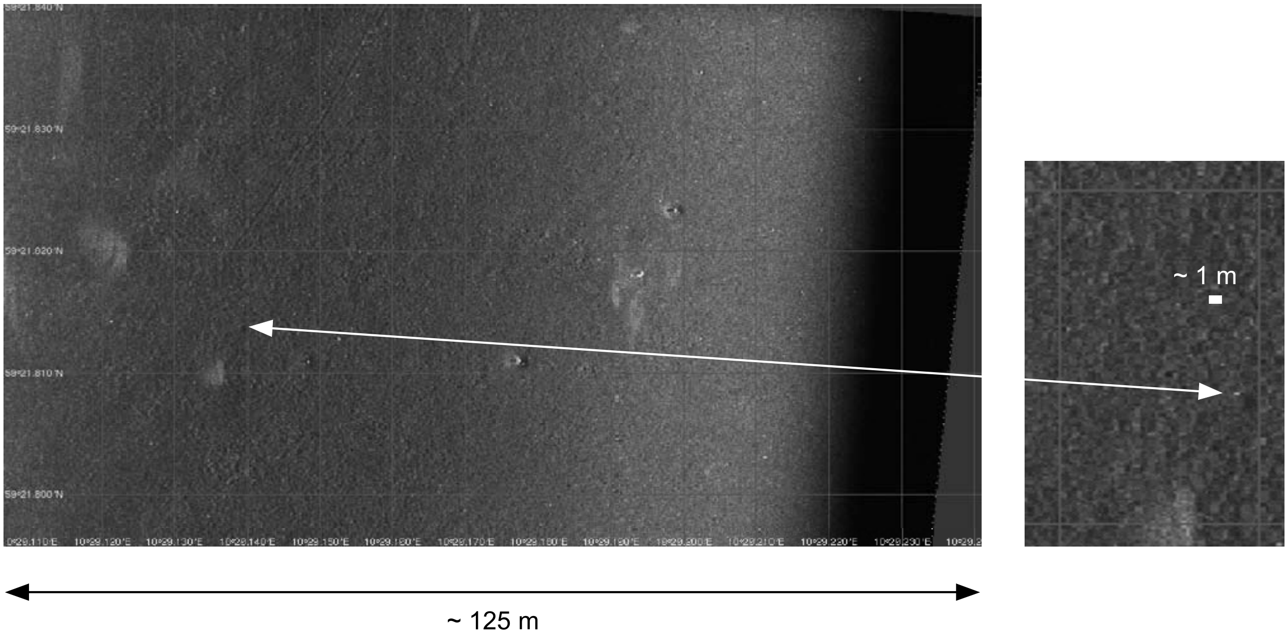

Figure 9. **Example of a synthetic aperture sonar (SAS) image showing small (tens of centimeters) targets at ranges on the order of 100 m. On the right, a subset of the image is enlarged to show detail. Grid lines on the image are drawn at 0.01° intervals; thus the latitude line spacing is 18.5 m. Image collected with HISAS 1030, courtesy of Kongsberg Maritime.**

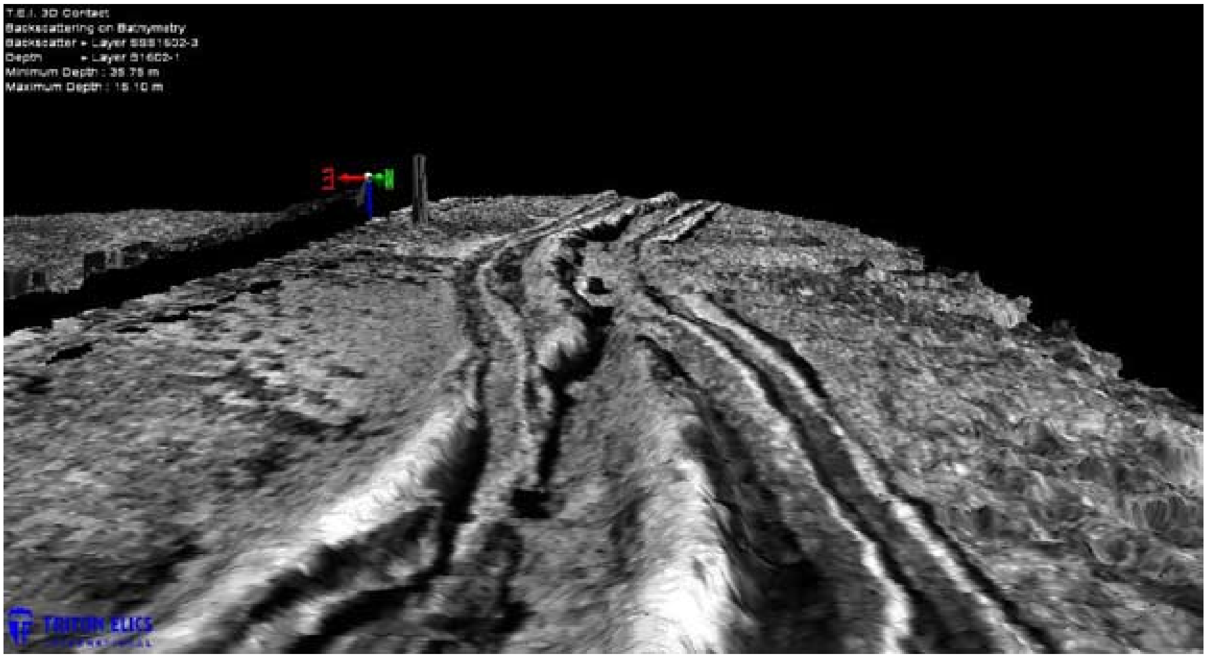

Figure 10. 3-D presentation of C3D backscatter draped on C3D bathymetry. Courtesy of Teledyne Benthos.

draped with backscatter data whose amplitudes have been adjusted for the impact of incidence angle and whose cross track distance have been adjusted for the seabed topography. Fig. 3 shows a 100 kHz example of how the impact of incidence angle depends on the actual seabed material, as in rock, sand, or mud. Fig. 10 shows a DEM developed from the Teledyne Benthos C3D phase-comparison sonars that has been draped with imagery simultaneously acquired by the C3D. In this presentation no attempt has been made to adjust the backscatter for angle of incidence effects. It is clear that the bright stripes in the "unadjusted" imagery correspond to ridges in the bathymetry.

Multibeam swath sonar

While the narrow along-track beam and low incidence angles associated with sidescan sonars offer the opportunity to detect small objects, the detection is typically through a relative change in backscatter or the identification of a shadow produced by an object in the path of the beam. With the exception of interferometric systems, most sidescan sonars do not produce information on the height of an object and thus lack an important piece of information required to map depths and identify objects. Multibeam swath sonars address this issue by adding angular resolution in the across-track direction, typically by using separate transmit and receive arrays that are mounted orthogonally in a pattern known as either a Mill's Cross or Mill's T. In this configuration, the transmitter is aligned with its long axis in the bow to stern direction resulting in a beam that is narrow in the fore-aft direction and broad (typically ranging from 90 to 150°) in the athwart-ship direction. This transmit geometry is similar to that of standard sidescan sonar. Unlike sidescan sonar, which typically receives backscattered energy on the same transducer array, multibeam sonars use an independent array oriented with its long axis in the athwart-ship direction to form receive beams. As shown in Fig. 11, the receive beams of a multibeam swath sonar intersect the transmit beam on the seabed producing a series of discrete, small area footprints throughout the cross-track swath. In multibeam sonar the along-track beamwidth of the transmit pattern and the cross-track beamwidth of the receive beam patterns are both on the order of 0.5 to 3°.

The ability to detect small objects is a function of temporal resolution within the system's projected footprint onto the seabed. Therefore the ability to detect small objects depends on both the system bandwidth and beamwidth. Increased lateral resolution (narrower projected footprint) is achieved by using increased array length, relative to a wavelength. However, with long arrays the transition from near-field to far-field is at a considerable distance from the transducers. Multibeam sonars have, in the past, been limited by their design to work in the far-field where the wave front approaches a plane. The requirement to work in the far-field limited the lateral resolution achievable by multibeam sonar. New signal processing capabilities, however, have recently enabled manufacturers to dynamically focus beams in the near-field. This dynamic focusing compensates for curvature of the wave front in the near-field and allows the sonar to achieve the beamwidth predicted by the array length. An example of this type of system is the Reson 8125

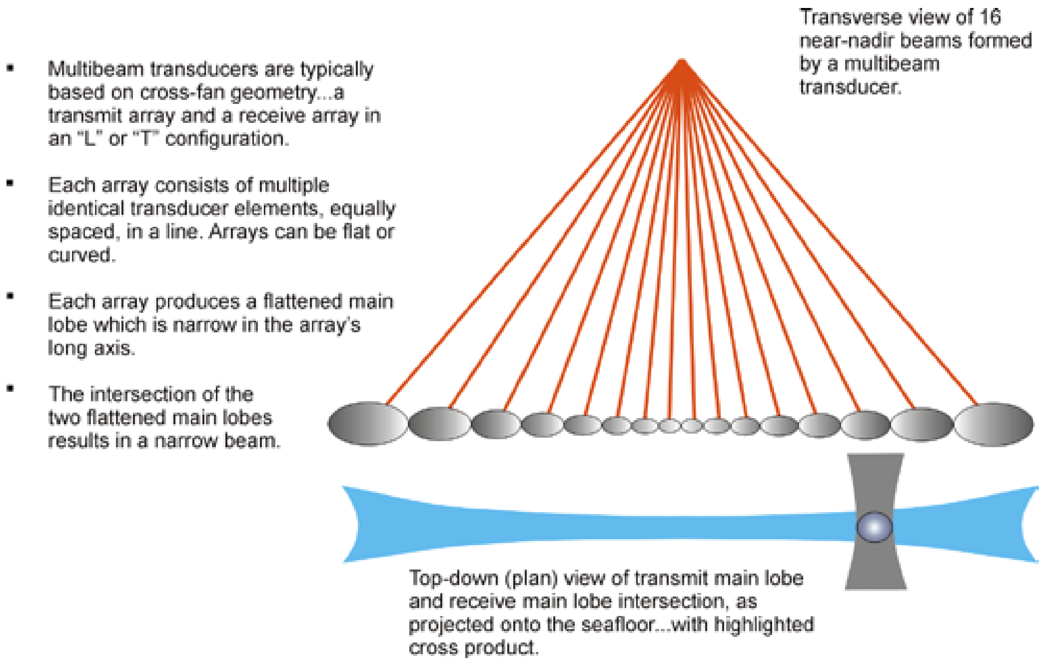

Figure 11. Geometry of multibeam swath sonar beam patterns synthesized using Mill's T transducer arrangement.

multibeam sonar which operates at 455 kHz, forming 240, 0.75° (across-track) beams at 0.5° spacing over a swath of 120°. The along-track beamwidth is 1°. The manufacturer's claim for vertical resolution for this sonar is 6 mm (determined by the pulse-length); field results indicate achievable vertical resolution on the order of approximately 1.5 cm. The dynamic focusing allows maintenance of the narrow well-defined beamwidth (across-track) even at short ranges. With a 0.75° beamwidth, the across-track lateral resolution of the sonar (near nadir) is less than 10 cm in 12 m water depth, which defines a lower limit to the size of small objects that can be detected on the seabed. An advantage of using multibeam sonar instead of sidescan sonar for the detection of small objects is that the multibeam sonar provides a full three-dimensional description of the shape of the objects (to the limit of its resolution), offering the opportunity to use shape and dimensions in the identification of targets.

In conjunction with the time-of-flight (range or depth) measurements for each beam, multibeam sonars can also collect backscatter information for each beam, either as an average value of backscatter for each beam or as a time-series of backscatter values across the beam footprint. Where full time-series backscatter is available across the beam footprint, the multibeam can provide backscatter information at a resolution that is determined by the bandwidth or sampling resolution rather than the beam footprint. For smaller features, the information added by this high-resolution backscatter may be an important aid in detection, as the backscatter of the target may vary from that of the surrounding substrate. This capability might be important in the determination of small-scale roughness (rugosity). Rugosity is presumed to be an indicator of the amount of habitat available for colonization by benthic organisms which attach themselves to the seabed, and an indicator of the availability of shelter and foraging area for mobile organisms. For marine geologists and geomorphologists, rugosity is a useful characteristic in distinguishing different types of seabeds in remote sensing applications, because of the role that roughness plays in backscatter.

Technology advances in acoustic remote sensing

A key area of sonar technology advancement that will potentially be useful in ARS for fisheries habitats is the manner in which beams are electronically formed. Recently, a new generation of sidescan sonars that use dynamic focusing has been introduced. Examples are the Klein System 5000 and the Edgetech 4700 sidescan sonars that simultaneously form several focused beams in the along-track direction. Focusing provides the ability to considerably increase the ship speed at which sidescan imagery can be obtained without having gaps in the along-track coverage. That translates into a considerable reduction in ship time for a particular sidescan survey and in turn provides a cost benefit. The benefit of focusing is evident in the Simrad EM3002 and Reson 7125 multibeam bathymetric systems which form focused beams. In these examples, focusing can provide exceptional definition of bottom features and man-made objects on the seabed. This translates into better resolution of small details on large complex targets, which leads to improvement in the quality of range (depth) measurements.

Advances in beam-forming are also being incorporated into 3-D chirp profiling systems (e.g., Gutowski 2005), which employ a two-dimensional array of transmitters and receivers. Such systems require highly accurate knowledge of the platform position and attitude to support the focusing and beam-forming. When this is achieved the result can be particularly relevant to the detection of small objects both on and below the seabed. Of particular interest is the buried object scanning sonar (BOSS) being developed at the Florida Atlantic University (Shock and Wulf 2003). The BOSS system uses time-delay focusing, coherent summing, and SAS processing to create a 3-D matrix of focal points. This approach has been successful in identifying small objects both on and below the seabed.

Positioning for acoustic remote sensing

If a system is to be useful for the investigation of fisheries habitats, it must be able to measure an aspect of the seabed such as depth or acoustic backscatter, and it must also be able to accurately report the position on the seabed associated with the measurement. Positioning is especially important with respect to ARS techniques, given their ability to detect objects at a significant distance from the acoustic source. When the acoustic source is rigidly attached to a vessel that can be positioned with GPS, then the position of a target will have an accuracy associated with the positioning system, although degraded by the ability to correct for sound speed in water column, offsets between the acoustic sensor and the GPS, and vessel motion. GPS can provide positioning accuracy that is on the order of centimeters. When an acoustic source is on a subsurface towed vehicle, the ability to accurately position targets is greatly degraded as positions are relative to the towed vehicle whose position is often known only on the order of meters.

Post processing for acoustic remote sensing

In habitat mapping, various processing techniques are applied to echoes, which are observed subsequent to the outgoing acoustic pulse having interacted with the environment of the seabed. The intent of those processing techniques is to infer information about the seabed based on characteristics of the time series (echo) output from the acoustic receiving transducer.

An important aspect of post processing for ARS is the ability to assemble the information from individual survey lines into an overall view of the survey results. The assembly of such a view is referred to as mosaicking. Once several swaths of sidescan have been mosaicked, geological and sedimentological features are easily recognizable. Mosaics provide qualitative insight into the dynamics of the seabed.

For a variety of reasons, amplitudes in backscatter among several survey lines covering the same area of seabed are often noticeably different. This problem limits the utility of the mosaic. Without knowing the bathymetry it is difficult to distinguish changes in backscatter that are due to changes of incidence angle, from those that are due to changes of an acoustic property of the seabed, from those that are due to changes induced by the sonar operator. Backscatter values are often "adjusted" to what they would have been if the incidence angle had been 45°. Such adjustments are typically mischaracterized as "corrections." Before any significant interpretations or meaningful adjustments can be made of backscatter, the recorded data must be "correct"—meaning the system response monotonically increases with received signal level and the system noise is low.

In order for the received backscatter to be "adjusted" to the equivalent level for 45° incidence angle, it is necessary to know the impact of the angle of incidence on backscatter from the particular seabed materials. This can easily lead to a circular argument. In order to properly utilize the information presented in Fig. 3 (angle of incidence effects for different seabed materials) it is necessary to have a reasonable estimate of the materials that make up the seabed, which often was the initial objective of the ARS. Post processing techniques are under development, which attempt to break the circular argument by using the observed pattern of backscatter, as a function of the incidence angles (nominally from 0 to 80°), in an inversion algorithm to estimate the seabed material type before adjusting the backscatter to the equivalent level for 45° incidence angle (Fonseca and Mayer 2007).

Figs. 12, 13, and 14 present mosaics resulting from different levels of post processing. The simplest level of post processing is the creation of a mosaic using the sonar receiver outputs, which just attempts to place the individual measurements of backscatter in their correct geographical position. The accuracy of that placement depends on the accuracy of the positioning system, but it may also depend on assumptions made concerning the shape of the local bathymetric surface. In Fig. 12 it is possible to determine the layout of the survey lines because the impact of angle of incidence has not been removed from the mosaic. The main scheme survey lines and the scheme of cross-check lines have clearly produced a striped pattern within the mosaic.

In Fig. 13 the survey lines are much less obvious than they were in Fig. 13. That is because the post processing of backscatter measurements from each survey line has included an adjustment for the cross-track variations in angle of incidence. Based on manual interpretation of the mosaic in Fig. 12, the seabed materials were estimated to be course to fine sand. Given that the backscatter was measured at an acoustic frequency of 300 kHz, a generic "rough" surface estimate was used to adjust for the angle of incidence effects. Fig. 13 shows backscatter values after being adjusted to what they would have been if the angle of incidence had been 45° across the entire width of the swath. That adjustment gives the imagery a character that is more pleasing to the eye, but that character of the imagery is not necessarily more nearly correct. However, it is important to observe that

Figure 12. Direct mosaic of backscatter from multibeam sonar receiver output.

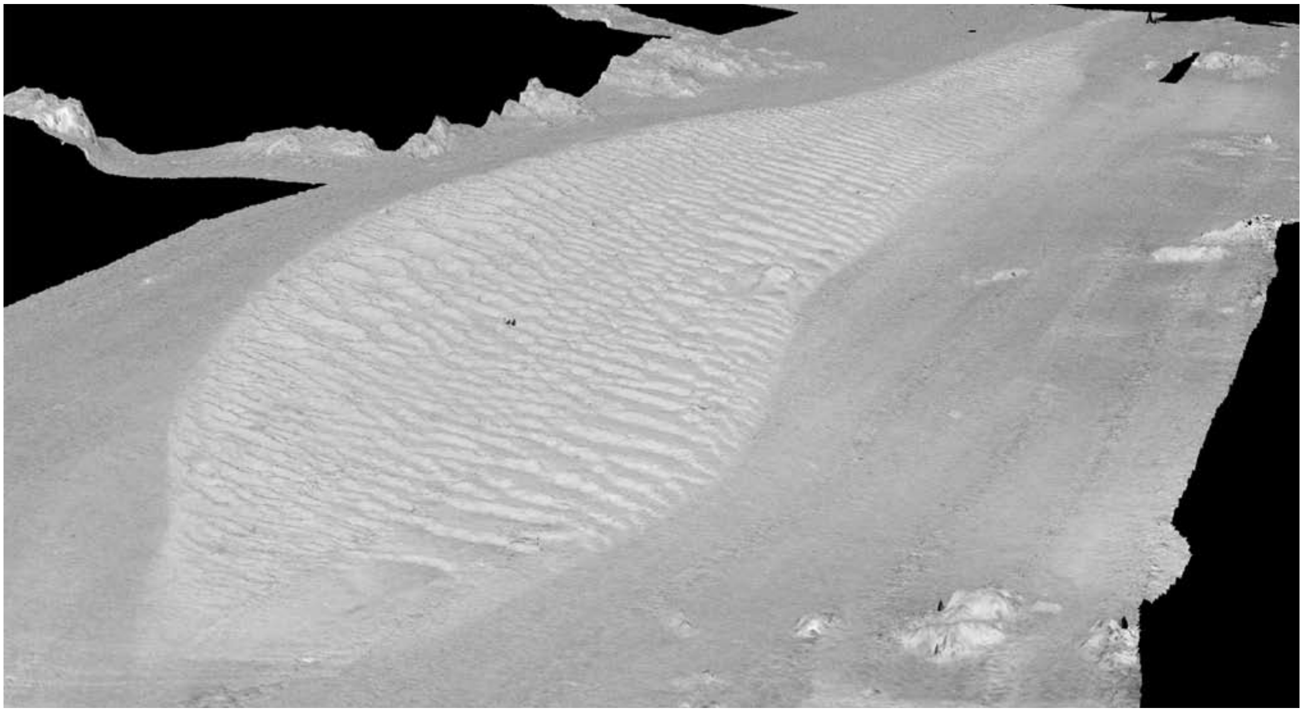

Figure 13. Mosaic of backscatter that has been adjusted to 45° angle of incidence.

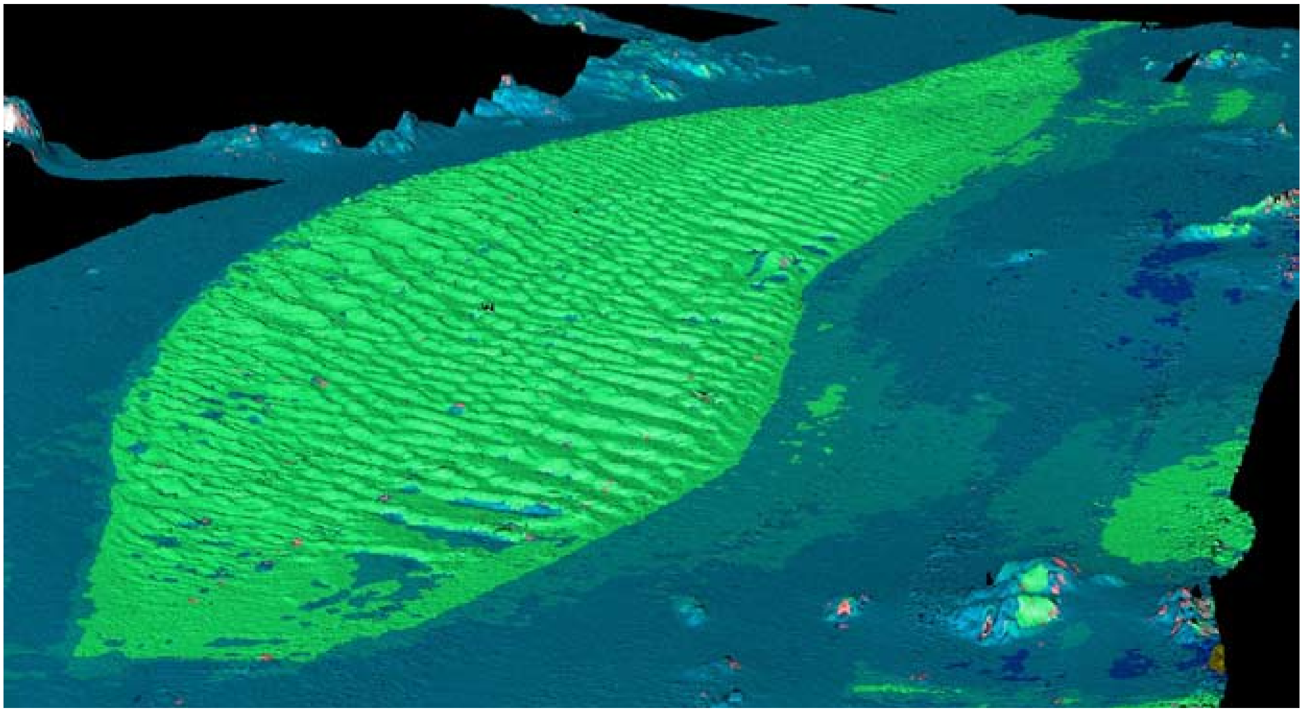

Figure 14. **Mosaic of backscatter that has been adjusted to 45° angle of incidence and segmented by seafloor character (texture). Each pixel in the mosaic is colored according to this segmentation of the data set.**

some geologic features in the mosaic are more distinctive following the adjustment for the angle of incidence.

Fig. 14 presents a mosaic where the post processing involved an adjustment to 45° using an assumed generic "rough" surface, after which the adjusted backscatter was segmented into regions with a common character (texture). Each pixel in the mosaic is assigned a color based on which of seven distinctive textures most closely matched the statistics of the pixel. The color-coded segmentation further enhances the ability to recognize subtle features in the mosaic, but it does not uniquely classify the seabed materials in the different segments.

Ongoing topics for consideration in Alaska fishery habitat mapping

There are advocates for the use of hull-mounted multibeam systems for fishery habitat mapping who contend that multibeam systems have an advantage compared to towed sidescan sonars. That perceived advantage is a direct result of the fact that multibeam sonar data can be quantitative. Quantitative backscatter data are much more amenable to robust schemes of classification and imaging processing, when contrasted against qualitative data. There are also advocates for using towed sidescan sonar systems for fishery habitat mapping who contend that those systems, albeit qualitative, provide the fine spatial resolution that is necessary to distinguish between different sediment types and to highlight low-relief bed forms. A third group within the community promotes conducting fishery habitat mapping surveys with a combination of hull-mounted multibeam and towed sidescan sonars. That third group advocates using the different frequencies and different geometries of towed sidescan sonar and hull-mounted multibeam sonar to improve the quality of information that ARS can provide for fishery habitat mapping. It is realistic to believe that in the near future manufacturers could provide the necessary information (transmit levels, sensitivity and gain of the receiver, or the transmit/receive beam patterns) to raise sidescan sonar data from qualitative to quantitative. When that goal is achieved, the differences in opinions as to whether a fishery habitat mapping survey should be conducted with multibeam or towed sidescan sonars may not change. What will change is that the value of a fishery habitat mapping survey that combines both towed sidescan sonar and hull-mounted multibeam will definitely be increased.

Despite the present differences of opinion as to which form of ARS is best suited for fishery habitat mapping, the planners and managers should be mindful of the capabilities and limitations of ARS to establish the spatial distribution of depths, physical structures and complexities of the seabed, substratum types, and sediment grain sizes, and aware that those capabilities and limitations are tightly coupled with the acoustic frequency and the deployment methodology. The planners and managers should consider the fact that fishery habitat mapping using ARS can be very expensive and that the cost is driven by the requirements placed on the total area to be surveyed, the percent bottom coverage of the survey, and the spatial resolution of the ARS system. It must be recognized that ARS post-processing algorithms are essential to the interpretation of the survey data. Finally it should be recognized that both ARS systems and ARS post processing algorithms are continuing to evolve, although at present more emphasis seems to be on the latter than the former.

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