# SEEING WITH SOUND:
## Why Sonar Resolution Matters for Seabed Mapping

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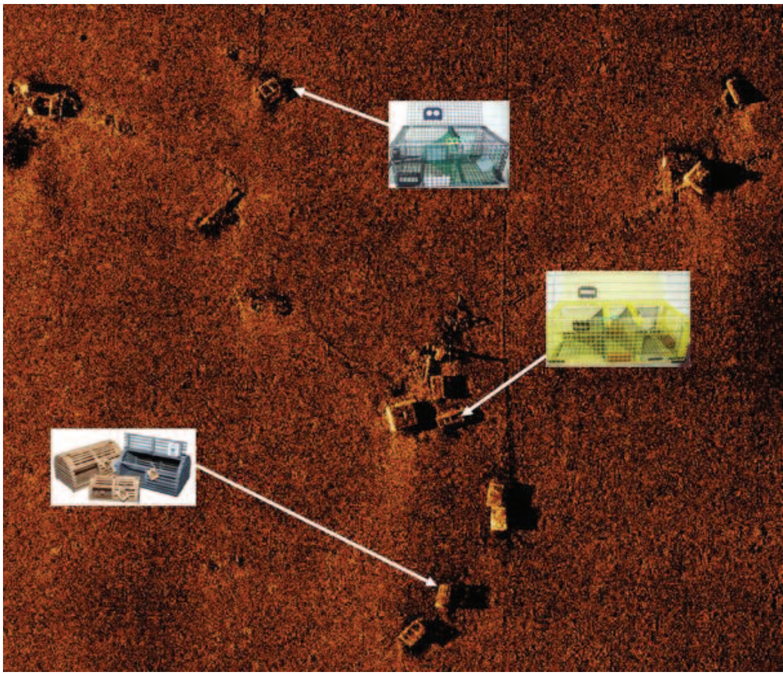
Seabed mapping is a key activity for many underwater applications such as offshore oil and gas exploration, pipeline surveying, ocean science, mine warfare, and hydrography. For each application, an increasing demand for high-resolution imagery arises from our desire to literally see beneath the ocean surface into a medium where light and radio signals cannot propagate effectively. Historically, side-scan sonars have been used to make reflectivity images whereas multibeam echo sounders have been the tool of choice for creating bathymetric charts. As technology evolves, many sensors integrate the capability to perform imaging and topographic mapping simultaneously. However, each design involves trade-offs between resolution, maximum range, size, power consumption, and cost that must be balanced to select the best sensor for a particular application.

The resolution of a sonar image is the size of the smallest object that can be detected. Minimizing this length is important because the information that can be extracted from a survey is determined by the size of the smallest details that can be observed. When the resolution is too coarse, small but potentially important details are unrecognizable or may be missed altogether. Sonar images often have different properties in the direction of the acoustic beam (across track) versus the direction of motion (along track). For example, side-scan sonar forms an image by sampling the received echo in time to form pixels in distinct range bins. The bandwidth of the transmit pulse determines the across-track resolution of a side-scan image. With modern wideband transducer technologies, centimeter-scale, across-track resolution can be achieved using chirp pulses with bandwidths on the order of 10 to 50 kHz.

However, along-track resolution is most often the limiting factor because the beamwidth is set by the ratio of the array length to the acoustic wavelength. Although the along-track resolution can be improved by increasing the frequency, this leads to a reduction of the achievable range due to increased attenuation of the acoustic signal (i.e., high frequencies are absorbed more readily than low frequencies). The same limitation applies to seabed reflectivity images formed with multibeam echo sounders. Multibeam sensors beamform the signals received from a multi-element array. The array dimensions, therefore, limit the resolution of a multibeam image in both the along- and across-track directions. Furthermore, the resolution of both side-scan and multibeam sonar degrades with range because the acoustic beams diverge as they propagate.

Seabed mapping for naval mine countermeasures provides an illustrative example of a survey requirement. If the resolution is too low, objects of interest appear as single pixels that could represent a variety of objects such as rocks, mines, or other man-made objects like lobster pots and debris. Also, a low-resolution survey averages the reflectivity over a large area, which reduces the image contrast. For mine-like targets, the objects of interest have a length scale on the order of 1 m, and recognition is only possible once the resolution is significantly smaller than the size of the target. Experimentally, it has been found that 5-cm resolution or less is required to achieve an oper-



***Synthetic Aperture Sonar (SAS) image of lobster pots at a range of approximately 100 m.***

ationally effective balance between maximizing the probability of detection while minimizing the false alarm rate.

The array length is typically constrained by the available space on a towed body or an underwater vehicle and by the mechanical distortion that results from subjecting a long array to pressure loads that vary with depth. A quick calculation illustrates the range versus resolution trade-off. Achieving 5-cm resolution at a stand-off range of 100 m requires an array length on the order of 2,000 wavelengths. If we use 2 m as a practical limit for the array length, a wavelength of 1 mm corresponds to an operating frequency of 1.5 MHz, which causes sound waves to be severely attenuated by absorption in seawater. For conventional side-scan sonar, high-resolution imagery requires a short operating range, which reduces the coverage rate and increases the survey time and cost.

A new technology called Synthetic Aperture Sonar (SAS) creates high-resolution imagery for accurate seabed imaging and mapping using a technique similar to Synthetic Aperture Radar (SAR). SAS was initially developed for military applications such as naval mine detection and classification, and it uses signal processing to circumvent the usual trade-off between range, array length, and wavelength in conventional sonar. The forward motion of the sonar platform is used to synthesize an array that is much longer than the physical length by combining multiple pings in software. The result is an along-track resolution proportional to the transmitter length and independent of both range and frequency. Therefore, 5-cm resolution can be achieved across the entire swath using a wide transmission beam with relatively low frequencies for long range to maximize the area coverage rate.

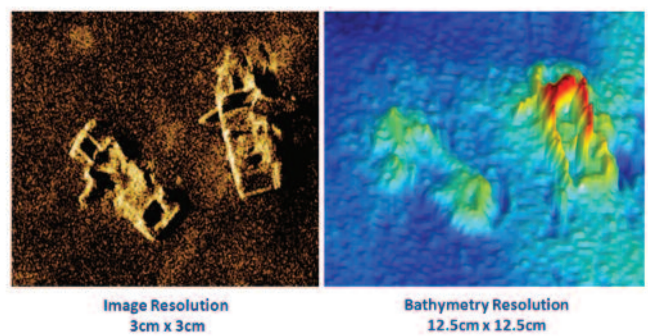
Although SAS signal processing is more intensive than side-scan and multibeam processing, advances in parallel computing technology and algorithm design make real-time processing possible using embedded processors with low power requirements. As SAS technology becomes more affordable, it is expected to find widespread use in civilian markets and become a valuable supplement to and, in some cases, a replacement for existing sonar technology.

In addition to reflectivity images, sonar can produce topographic maps of the seafloor by detecting the angle of arrival of seabed echoes coming from a given range bin. A multibeam echo sounder beamforms the echoes received from a multi-element array to separate signals into discrete, angular bins. As with side-scan sonar, resolution degrades with range and the resolution of each beam is limited by the ratio of the array length to the acoustic wavelength. Also, multibeam sonars are inherently downward-looking devices that suffer from low area coverage rate in shallow water.

An alternative approach is found in phase-differencing bathymetric sonar (also known as swath bathymetry systems or interferometric side-scan sonar), where side-looking geometry is used to increase the coverage rate in shallow water.

Like side-scan sonar, satisfactory across-track resolution is possible using wide bandwidth pulses. However, all side-scan design constraints apply, namely the trade-off between along-track resolution and range, which manifests in a variety of high-frequency, low-frequency, and dual-frequency systems — all of which require a compromise between image quality and area coverage rate.

The combination of synthetic aperture processing and interferometric processing solves the problems associated with limited resolution and coverage rates encountered with conventional swath bathymetric sonars and multibeam echo sounders. Such Interferometric Synthetic Aperture Sonar (InSAS) maps have range-independent and frequency-independent resolution and can achieve high resolution and high area coverage rates simultaneously. Two vertically separated sonar receiver arrays enable the production of bathymetric maps that are exactly co-registered with the SAS imagery because the bathymetry is derived by cross-correlating SAS images from each array. This allows bathymetric measurement out to the full imaging range, leading to significantly faster mapping operations with an ultra-high bathymetric resolution (on the order of 10 cm) that approaches the resolution of the corresponding reflectivity image. It then becomes possible to overlay the reflectivity and topographic datasets to create a true 3D picture of objects on the seabed. The capability of generating centimeter-scale resolution in all three spatial dimensions has the potential to provide significant improvements in the detection, classification, and identification of small seabed objects.




***Example of ultra high-resolution Interferometric SAS showing reflectivity image (L) and bathymetry (R); Targets were surveyed at 85 m from sonar broadside in 65 m depth.***

Choosing a type of sonar is much like selecting a tool from a toolbox. Each design involves many trade-offs to balance the constraints imposed by available technologies for electronics and transducers as well as the fundamental physics of underwater acoustic propagation. Side-scan, multibeam, and swath bathymetry sonars have proven to be effective for creating seabed images and for mapping the seafloor. However, conventional sonar technology has advanced to the point where resolution and range are determined by physical constraints such as array size and frequency-dependent acoustic absorption. Further evolution of seabed mapping technology will require more advanced signal processing to circumvent the traditional range-resolution trade-off, for example, by creating long arrays from multiple pings using synthetic aperture processing. High resolution in both across- and along-track directions is essential to truly see — and map — with sound.