# Synthetic Aperture Sonar: Frontiers in Underwater Imaging

## *Revolutionary Sonar Imaging Technology for Undersea Warfare And the Commercial Marketplace*

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Synthetic aperture sonar (SAS) is a revolutionary underwater imaging technique that significantly rivals the breakthrough technical capabilities enabled by synthetic aperture radar (SAR)—extraordinary area coverage, providing both imagery and bathymetry at a high degree of spatial resolution.

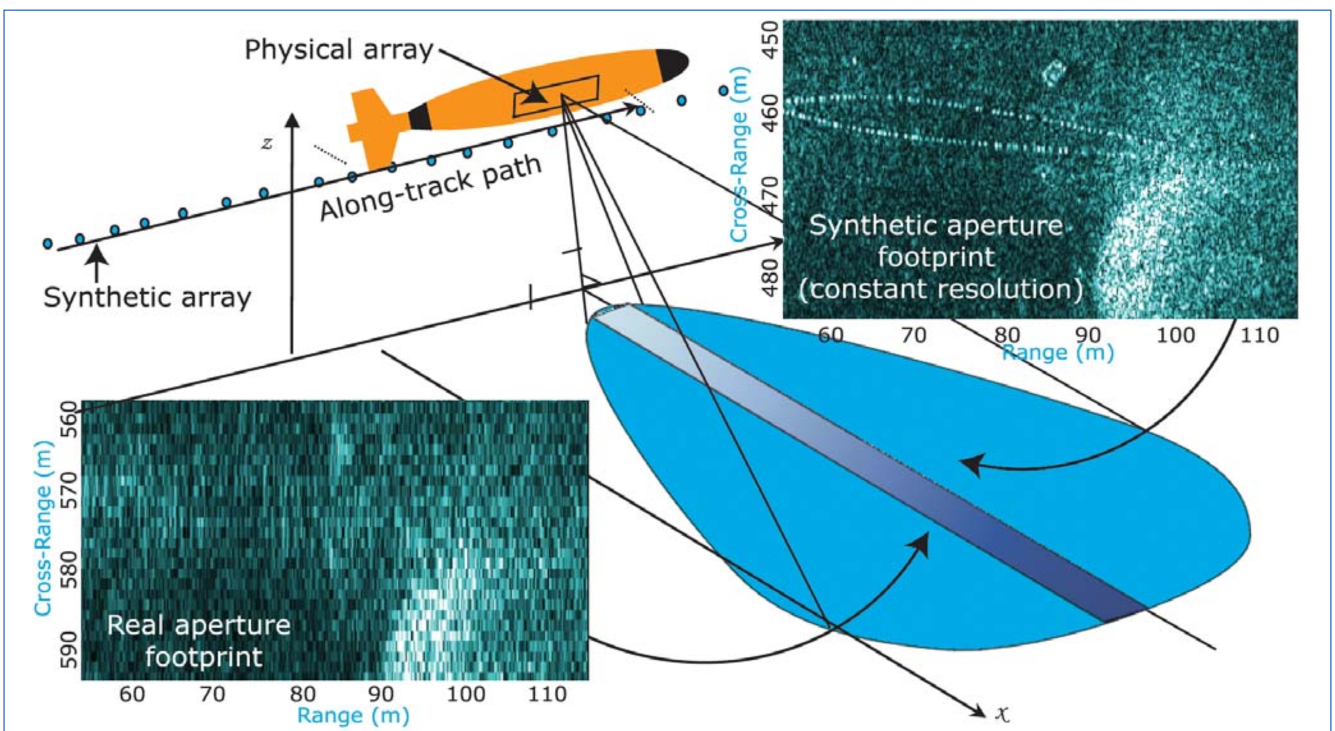
For a generation, innovators in underwater acoustics dreamed of replicating SAR concepts with side scan seafloor imaging sonars.

However, the implementation of synthetic aperture sonar—utilizing multiple pings to create a virtual long array for range-independent resolution—was thought to be untenable due to lack of coherence in the ocean medium, precise platform navigation requirements and burdensome computation rates.

With advances in innovative motion-compensation and auto-focusing techniques, signal-processing hardware, affordable and precise navigation sensors, and stable submerged autonomous platforms, synthetic aperture sonar is now being used in commercial survey and military surveillance systems.

Emerging applications for SAS systems include economic exclusion zone (EEZ) mapping, mine detection and the development of long-range imaging sonar for antisubmarine warfare.

***The synthetic aperture footprint reveals a cable and a rectangular shape with a shadow. In contrast, the real aperture footprint is blurry, making it extremely difficult to identify objects.***

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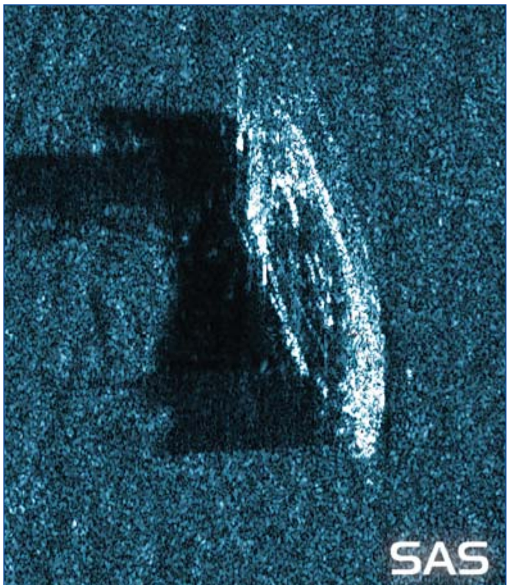
## Principles of SAS

High-resolution synthetic aperture sonars have a range of applications in all water depths for geological mapping and localization of submerged objects, such as telegraph cables, pipelines and sunken vessels. At this time, maritime nations are procuring SAS systems for locating sea mines that are moored to, or lay proud on, the seabottom, or those that are buried in the sediment. Mine hunting, requirements for stealthy surveillance in coastal waters and economic pressures to reduce commercial survey costs have fostered a worldwide interest in incorporating SAS payloads on autonomous underwater vehicles (AUVs), thus representing the transition of synthetic aperture sonar technology from research to practical applications in the commercial and military marketplace.




*This figure shows a SAS image of a sunken vessel. DTI's PROSAS system maintains constant resolution up to 300 meters to provide accurate high-quality seafloor images.*

Active SAS is a high-resolution acoustic imaging technique that coherently combines the returns from multiple pings to synthesize a large acoustic aperture. A direct analogue of synthetic aperture radar processing, SAS allows for the generation of sonar imagery with unprecedented resolution, independent of range and frequency. Coherent integration of data from a number of transmissions as the sonar moves along the track yields images with theoretical along-track (azimuth) resolution at all ranges equal to one half the lateral size of the receiver element ($d$), for which various applications can be tailored from several inches to less than an inch.

Due to spatial sampling requirements, the maximum platform velocity ($V_{SAS}$) achievable for distortion-free imaging is a function of the physical aperture length ($L$) and ping repetition interval (PRI),

$$V_{SAS} \leq \frac{L}{2PRI}$$

That is, the distance traveled between two successive pings should not exceed half the length of the physical aperture. For single element systems ($L = d$), this severely limits platform speed; however, multi-element (or vernier) techniques allow speeds of half an entire array length per ping, while maintaining fine $d/2$ resolution in azimuth. When SAS techniques are applied at sufficiently low acoustic frequencies, where sound absorption in the ocean medium is minimized, a modest-sized array can generate imagery with azimuth resolution comparable to that of higher frequency systems, but only for long ranges and large area coverage rates characteristic of lower frequency sonars.[1]

SAS satisfies both aspects of the tradeoff between sonar range and necessary resolution. Increased sonar range provides an increased area coverage rate, which significantly decreases survey time—a major cost driver. Increased resolution is typically achieved by larger arrays or utilizing a higher sonar frequency; however, larger arrays increase weight, volume and power that increase costs. On the other hand, higher frequency sonars decrease range. Only SAS processing, applied with suitable frequency and array characteristics, produces superior spatial resolution images and an aggregate improvement in area coverage rate compared to conventional side scan sonars.

## Real-World Applications

The advent of AUVs, and their growing application in the marine research and undersea warfare areas, heralds the entry for SAS into the oceanographic marketplace. AUVs require small payloads for low-power consumption and requirements of form, fit and function. The high-resolution mapping capabilities of small SAS sonars are well-suited for AUVs with missions that encompass wide-area sea-floor surveillance, sea-mine localization and geological surveys for cable and pipeline installation. As these auton-omous systems must traverse long distances with limited contact with the surface, they are typically engineered with navi-gation suites that can be used for the precise navigation requirements of SAS. Furthermore, the slow speeds of AUVs (typically one to five knots) are well-suited to the half-array displacement limitations for synthetic aperture processing.

SAS provides over 25 times greater resolution at a range with a 300-percent increase in area coverage over conventional side scan sonars. For creation of high-resolution seafloor images, synthetic aperture sonar requires navigation fidelity within typically 1/16 of an acoustic wavelength. For a 120-kilohertz system, this amounts to knowing where the array is to an accuracy exceeding one millimeter. This is made possible with the coordinated use of high-precision navigation devices such as inertial navigation units, Doppler velocity logs, precision compasses and updates provided by global positioning system receivers. These systems can be complemented and, in some cases, eliminated, by using estimates of array sway calculated directly from the ping-to-ping correlations of the array element data. Hence, high-performance (though not necessarily high cost) navigation processing is an integral part of a robust practical SAS system.

## PROSAS Signal Processing

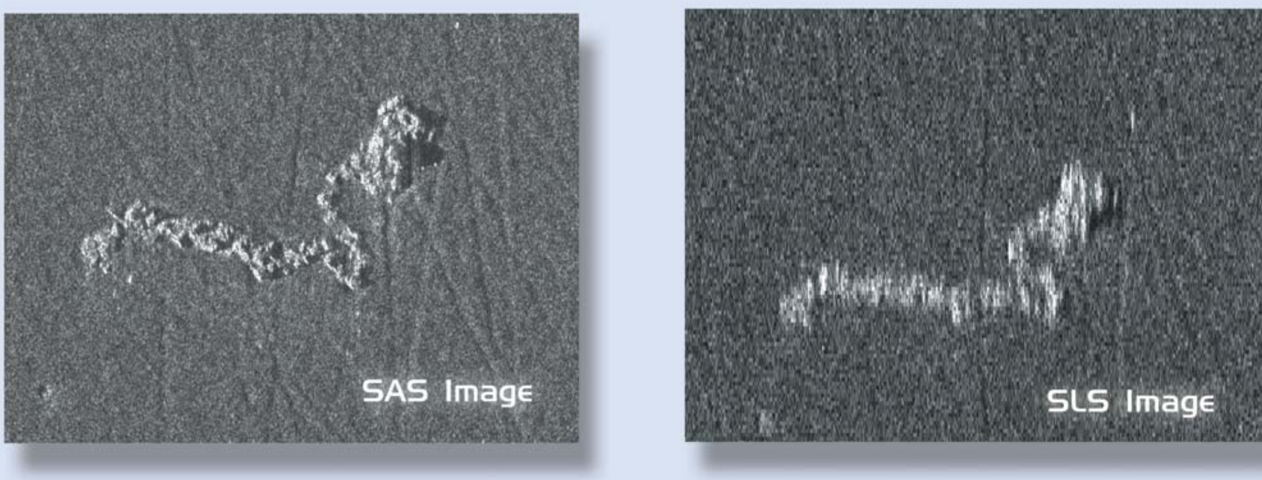
Synthetic aperture sonar produces high-resolution imagery by coherently combining data from multiple sonar pings. Dynamics Technology Inc.'s (DTI) real-time SAS processor, PROSAS™, performs three primary operations to produce high-quality SAS results: motion compensation, image formation and auto-focusing.

Initially, integration of multiple sonar returns must be referenced to a straight platform track with sub-wavelength accuracy. The motion of even, well-behaved platforms and phase distortions from the complicated underwater environment conspire to make this a challenging requirement. PROSAS is tailored to compensate for platform motion and phase errors. Motion-compensation algorithms estimate vehicle motion by performing range-wise correlations on data from overlapping segments of the hydrophone array on successive pings of the sonar. The refined platform trajectory removes the effects of platform motion and performs echo-phase compensation of the array using inputs from navigation sensors (if present) and from information extracted from the sonar data itself. The resultant echo returns appear to have been collected from ideal straight-line geometry.

SAS image formation is accomplished with a 2D, range-dependent matched filter. It operates effectively as a focused side scan processor that dynamically adjusts to the length of the array to achieve constant along-track resolution, regardless of the range to target.[2] PROSAS incorporates a novel form of image-formation processing that works to perform the matched filter calculations approximately two orders of magnitude faster than can be achieved by conventional delay-and-sum processing.


Photo courtesy of Kongsberg Maritime and FFI.

Remaining phase errors in the acoustic data are removed by applying auto-focusing techniques to the SAS image.[3] The auto-focus approach applied in PROSAS provides superior image enhancement, including the ability to discern multiple bright targets distributed in the cross-range direction and estimating phase errors extending over several range bins. Furthermore, PROSAS is the only commercially available system capable of operating faster than real time, enabling autonomous, hands-off processing for instant viewing of imagery during search operations.




*(Top) The HUGIN 1000.*

*(Bottom) Comparison of a side-looking sonar and synthetic aperture sonar image of a rock field. These images were processed during the Oslo sea trials. The SAS image provides greater clarity and allows for closer inspection of the clutter field to identify anomalous items.*

**Sea Trial Results**

Earlier this year, DTI and EdgeTech Inc. (West Wareham, Massachusetts) developed and fielded the first SAS sonar system to be incorporated on a commercial mission-ready AUV. An EdgeTech 4400 SAS and DTI's PROSAS signal processor were delivered to Kongsberg Maritime (Horten, Norway) for use on their HUGIN 1000 AUV, which has been delivered to the Norwegian Defense Research Establishment and the Royal Norwegian Navy for sea mine detection and classification.

This SAS system consists of port and starboard-side acoustic arrays that are 1.2 meters in length, each of which are made up of six 20-centimeter elements. For 500-meter total swath widths, an associated PRI of 0.35 seconds can be obtained. The range-independent resolution of this system is 10 centimeters out to the edge of the swath. With a vehicle speed of 3.5 knots, the area coverage rate is approximately 900 square meters per second, or 77 square kilometers per day. At the edge of the swath, the same sonar using conventional side scan processing would have an azimuth cell size of 2.6 meters—too coarse for resolving small man-made objects like mines. Even a 300-kilohertz sonar working at the edge of its range limit would have an azimuth cell size exceeding one meter.

The system worked over a variety of terrains in a number of exercises, including operations requiring severe vehicle maneuvers. The system was operated by Kongsberg Maritime, and as part of North Atlantic Treaty Organization fleet exercises with the Royal Norwegian Navy. This initial data was used to calibrate PROSAS with the HUGIN navigation system, resulting in updates in the trajectory estimation process in PROSAS. The system returned to sea in Oslofjord, off of Horten, in June 2004, where successful trials demonstrated the improvements of SAS processing over side scan processing in a real-world environment. During initial runs, SAS imagery met or exceeded anticipated performance over 92 percent of the area surveyed, with full evaluation of the sea trials still in progress.

**Future Innovations**

Over the last decade, DTI has applied SAS signal processing to more than a dozen different sonar systems, ranging from high-frequency systems with centimeter resolution out to 500 meters, to meter-scale resolution out to 25 kilometers. Today, DTI continues to advance the state-of-the-art through development of integrated synthetic aperture sonar and navigation suites, as well as the development of integrated mission and target analysis workstations. Through its primary research and development facility in Torrance, DTI is exploring for faster-than-real-time processing, digital signal processing implementation for low-power, in-vehicle applications and automatic target recognition.[4]

DTI provides the only currently available real-time SAS processor for commercial and military use. As techniques for determining vehicle displacements with only the acoustic array and inexpensive heading sensors continue to mature, SAS systems should eventually see more common use on towed platforms for extensive work in EEZ mapping, oil and gas, and undersea cable-management applications. Advances in SAS undersea imaging are being investigated for use in long-range imaging and detection for anti-submarine warfare applications. Continued advancement of synthetic aperture sonar technology will have a transformational effect on mine countermeasures and undersea warfare applications, with commensurate impact in the commercial marketplace. */st/*

**References**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