

AquaPix – A Low-Cost Interferometric Synthetic Aperture Sonar for AUVs: Sea Trials and Results

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Abstract— Kraken Sonar Systems Ltd, based in St. John's, Canada, produces an Interferometric Synthetic Aperture Sonar (InSAS) system, suitable for integration on a wide range of AUVs and towed platforms. In 2012, Kraken entered into a Cooperative Research and Development Agreement (CRADA) with the Naval Undersea Warfare Center (NUWC) in Newport, Rhode Island. This paper seeks to present a background of Kraken's InSAS technology, and detail the results of the CRADA. The primary focus of the paper (and the CRADA) is the integration and testing of an AquaPix InSAS on NUWC's medium-sized 12.75" diameter REMUS600 AUV, manufactured by Hydroid. Kraken designed a payload section for the R600, and assisted NUWC operators with integration onto the AUV. After a very short integration, the resulting integrated SAS-AUV was able to produce ultra-high resolution 3cm imagery and co-registered 25cm bathymetry with no vehicle re-tuning necessary. The main conclusion from this trial was objective evidence that SAS is achievable on medium sized AUVs without extensive tuning or additional control planes.

I. INTRODUCTION

Until recently, sidescan sonars and multibeam echosounders have been the leading technology for detailed mapping and imaging of the seafloor. However, commercially available Interferometric Synthetic Aperture Sonars (InSAS) now combine ultra-high image resolution with 3D seabed bathymetry and superior area coverage rates. SAS offers high resolution imagery at longer ranges than conventional side-scan sonars, done by replacing traditional sonar hardware with sophisticated signal processing software. The principle of SAS is that the receive transducer array is "synthesized" in software by the coherent recombination of many sonar pings overlapping an area of interest. This represents a major savings in sonar hardware and enables much higher resolution than is possible with conventional sonars.

Despite these advantages, the high capital cost, complexity and export considerations of SAS technology have proven to be a barrier to many commercial AUV operators, thus restricting access to SAS technology to only a few military and defense applications. Additionally, due to the strict micronavigation requirements of SAS algorithms, traditional

SAS systems have required rigorous integration with AUV navigation systems, a time-consuming and costly process.

Headquartered in St. John's, Newfoundland, Kraken Sonar Systems Inc. is a marine technology company engaged in the design and development of high performance sonars and sensors for military and commercial applications. The Kraken team includes internationally recognized experts in undersea remote sensing applications. Kraken's experience includes a long history of research and development of SAS systems and Autonomous Underwater Vehicles (AUVs). Kraken was spun out from Marport Deep Sea Technologies in September 2012.

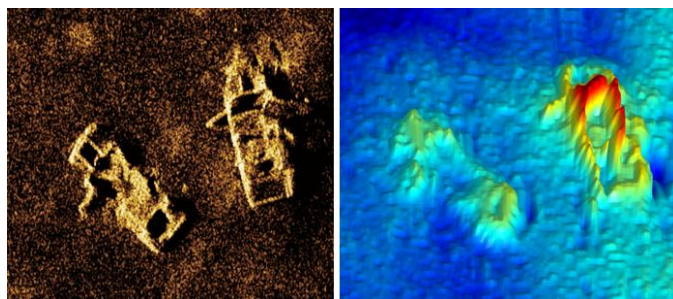


Figure 1: Co-registered InSAS Imagery (3x3cm) and Bathymetry (12.5x12.5cm)

Kraken Sonar Systems currently produces an InSAS system called AquaPix®. The AquaPix InSAS delivers area coverage rates in excess of 2 km²/hr, ultra-high 3x3cm seabed image resolution and co-registered bathymetry at up to 12.5x12.5 cm resolution (see Figure 1 above) which exceeds capabilities of currently available multibeam and sidescan sonar systems.

Suitable for integration on AUVs, ROVs or surface towed installations, AquaPix does not require real-time integration with a vehicle inertial navigation system (INS) and uses a modular variable length physical array depending on the platform. When compared to traditional sidescan sonar and multibeam echosounders, InSAS offers a step change in range, resolution and bathymetry accuracy.

Although SAS signal processing is more intensive than sidescan 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.



Figure 2: InSAS2 on DRDC's Arctic Explorer AUV

After 18 months of development, Kraken was given the opportunity to demonstrate the AquaPix system on a large-diameter Arctic Explorer AUV owned by Defense Research and Development Canada (DRDC), and manufactured by International Submarine Engineering Ltd (ISE). Integration of an AquaPix system on the ISE AUV was performed at DRDC's facility in Dartmouth, Nova Scotia, in August, 2012. Figure 2 above shows the InSAS2 in the forward payload section of the Arctic Explorer AUV. Trials of the integrated AquaPix were performed in Bedford Basin with the support of the Bedford Institute for Oceanography (BIO). The results of these trials were extremely positive, and after only three days of integration, AquaPix was able to provide 3x3 cm resolution imagery at ranges up to 265 m.

Following the successful AquaPix trial with DRDC, Kraken entered into a Cooperative Research and Development Agreement (CRADA) with the Naval Undersea Warfare Center (NUWC) in Newport, Rhode Island. The purpose of the CRADA was to integrate and test an AquaPix InSAS on NUWC's medium-sized 12.75" diameter AUV, a REMUS600 made by Hydroid. The following sections discuss the AquaPix system configurations, AUV integration considerations, the specific work done with NUWC and the results obtained.



Figure 3: AquaPix InSAS1 Typical Dual-Sided Configuration

In addition to the DRDC and NUWC AUV integrations, an AquaPix system was also integrated and sea-trialed on the Marlin AUV from Lockheed Martin, and a REMUS600 owned by the Defense Science and Technology Organization (DSTO) of Sydney, Australia.

II. AQUAPIX CONFIGURATION

AquaPix systems are differentiated by their number and placement of receiver arrays; the InSAS1 (shown in Figure 3) consists of one set of receivers per side, one upper and one lower, as well as one transmitter per side, and one sonar electronics bottle. Standard configurations are dual-sided, although single-sided systems have been tested for engineering trials. Transmitters and receivers are broadband, and can operate at any frequency from 200-400 kHz.

	InSAS1	InSAS2
Operating Speed	3 kts	3 kts
Range	132.5m	265m
Swath	265m	530m
Area Coverage Rate (Without Gap Filler)	1 km ² /h	2.1 km ² /h

Figure 4: AquaPix InSAS1 vs. InSAS2

The InSAS2 consists of two sets of receivers per side; this effectively increases the real aperture of the receiver, and allows for either higher speed or longer range operation, as shown in the comparative specifications in Figure 4.

Power consumption of a typical InSAS1 system is approximately 65W, configured to record to onboard storage. Options are also available for high-capacity removable storage modules, and real-time embedded processing.

III. CHALLENGE OF SAS ON MEDIUM-SIZED AUVS

In order to accurately synthesize the Synthetic Aperture, SAS payloads typically have very strict requirements on platform stability, and require a real-time data input from a high-grade inertial navigation system to provide input to the SAS micronavigation algorithm. The high cost of these inertial navigation systems has historically meant that SAS systems were demonstrated on AUVs with such an INS already integrated into the vehicle, and the SAS was then integrated with the vehicle's INS. This could be a time-consuming and costly effort, depending on the INS used and the architecture of the AUV.

These stability and integration requirements can be challenging and limits the platforms available, typically seeing SAS demonstrated on large diameter AUVs, although the literature does show some exceptions [1] [2]. Similarly, Kraken's CRADA with NUWC sought to demonstrate off-the-shelf SAS performance on a medium-sized 12.75" diameter AUV with minimal integration cost and time.

The AquaPix system was intentionally designed to eliminate the need for any real-time integration with the AUVs navigation system, performing image focusing and motion compensation using low-cost onboard fiber optic gyros (FOG) integrated directly with the sonar electronics. As a result, SAS images can be formed without any vehicle navigation or

stability information, and vehicle navigation data is only required for georeferencing the resulting imagery and bathymetry maps in post-processing.

IV. STABILITY

Although many parameters can affect the quality or range of SAS imagery, platform stability has the most significant impact, particularly when considering long range imagery; small perturbations in platform stability may be negligible in short-range imagery, but become magnified at long ranges. Large diameter vehicles most notably achieve a higher stability through a large vertical separation between the vehicle's centre of gravity (Cg) and centre of buoyancy (Cb). The resulting large metacentric height increases passive pitch and roll stability.

Previously publications describing SAS on 12.75" diameter AUVs [2] have noted extensive tuning of vehicle controllers to achieve necessary platform stability, and in some cases required additional forward control surfaces. As a result, integration of SAS onto these platforms can become time consuming and costly. The need for re-tuning controllers is significantly reduced by the robust stability tolerance of the SAS algorithms used in the AquaPix image formation.

V. PROCESSING TIMELINE

Post-processing and visualization of sonar data is a significant consideration for any sonar system; data collection and recovery is only one step in the processing chain. The operational tempo can degrade quickly if operators must spend significant amounts of time analyzing data for targets of interest, such as military target surveys, or salvage surveys. Traditional sidescan "waterfall" viewing means an operator must scroll through every ping, and accelerating the viewing of data creates a risk of missed targets. Several sonar post-processing software packages now include mosaic-ing capabilities for producing rectilinear images of area surveys from raw sidescan sonar data, however this can be time-consuming and the natural degradation of resolution with range in a sidescan image negates some of the gains.

The nature of SAS processing lends itself very well to parallelization, and data is automatically produced in rectilinear "tiles" during image formation, which can also be automatically georeferenced if vehicle navigation data is available. Combined with the large swath, this means large mosaics of constant resolution can be quickly and easily viewed by operators soon after data recovery, in a number of formats, and targets of interest can be identified quickly and efficiently.

The AquaPix is capable of recording raw sonar pings in onboard storage for download, or in a removable storage module for immediate recovery and post-processing. Kraken's InSAS processing software toolkit, INSIGHT, processes raw sonar data into multiple formats at twice real-time, meaning a 1 hour mission will only take 30 minutes to process. These results are achieved on a standard processing laptop, using i7 2.4GHz Quad-core CPU, 8GB RAM, and an NVidia GeForce GTX660M GPU. In addition, the faster-than-real-time processing software and off-the-shelf computing hardware

lend itself very well to in-situ real-time processing; a real-time embedded processor is currently under development.

VI. AUV INTEGRATION

In December 2012, as part of the CRADA between NUWC and Kraken, integration began of the AquaPix InSAS payload into the NUWC REMUS 600. A payload section was designed by Kraken, and Kraken engineers travelled to Rhode Island to assist NUWC AUV staff with integration of the InSAS payload section onto the REMUS600 AUV.

The AquaPix REMUS600 payload module was designed to be a wet flooded and allow for the pass-through of cables for the vehicle's multi-function nose. Overall the section was 1.38m long, increasing the length of the REMUS600 by about 6" from its original configuration.

The arrays are precisely mounted to within 0.01mm and 0.01 degrees on a CNC milled flat plate. Care had to be taken to rigidly mount the arrays and the electronics pod with integrated FOG to eliminate any errors after calibration of the system. To save on overall weight, the array mounting bracket was also part of the payload module's structure. This was a critical factor in the design of the bracket, as it had to support the full vehicle weight during launch and recovery, and significant drag when the vehicle would be towed by its nose. The mechanical section can be seen during assembly in Figure 5.



Figure 5: Single-sided InSAS2 being attached to AUV

One key goal of the CRADA was a comparative analysis of InSAS1 vs. InSAS2 configuration performance. To avoid mechanical changes to the AUV during trials, it was decided that a single-sided InSAS2 system would be used, and the system could be virtually "down sampled" to simulate an InSAS1 by ignoring half of the receiver arrays in post-processing.

The single-sided system presented a unique challenge; as the transducers are negatively buoyant in seawater, the resulting system would have to be balanced in roll. To address this issue, a significant amount of trim weight was added to the starboard side of the vehicle. Unfortunately the placement of the weight reduced the normal Cb-Cg separation down from a nominal $\frac{3}{4}$ " to approximately $\frac{3}{8}$ ". This reduction in metacentric height was expected to have a

significant impact on stability. The added weight also increased the mass (and reduced buoyancy) of the payload section; the resulting section weight was 88Kg in air, and neutrally buoyant in water.



Figure 6: AquaPix InSAS2 on NUWC's REMUS600 AUV

Ethernet communication and power were supplied to the SAS payload through a REMUS guest port, using a single combined power / Ethernet bulkhead. This required only one bulkhead connector installed into the AUV, and minimized the amount of electrical integration required. Connecting the SAS payload to the REMUS Ethernet network allowed the sonar operator and the AUV operator to both remotely connect independently to the SAS payload and the AUV control computer via the AUV's Wi-Fi network without interfering with one another.

The integrated AUV with SAS was trimmed and ballasted in NUWC's freshwater trim tank, and taken to sea shortly thereafter. Total integration time from delivery of all SAS payload components to first in-water test was approximately one week.

INSAS	REQUIRED	OBSERVED
Surge velocity	± 0.2 m/s	± 0.025 m/s
Sway velocity	± 0.2 m/s	± 0.029 m/s
Heave velocity	± 0.1 m/s	± 0.049 m/s
Static pitch offset	$\pm 5^\circ$	$\pm 1.0^\circ$
Pitch rate	$1^\circ/\text{s}$	$\pm 0.5^\circ/\text{s}$
Static roll offset	$\pm 2^\circ$	$\pm 0.5^\circ$
Roll Rate	$2^\circ/\text{s}$	$\pm 0.9^\circ/\text{s}$
Yaw Rate	$1^\circ/\text{s}$	$\pm 0.2^\circ/\text{s}$
Altitude (max/min)	30/5 m	25/10m

Figure 7: InSAS1 Stability Requirements

Acoustic interference between the SAS and other vehicle sensors was identified as a potential risk factor, and was evaluated both in the trim tank and at sea. The other sensors (600 kHz DVL, acoustic modem, etc.) were seen to be far enough outside of the SAS 200-400 kHz frequency bands, so as to not cause any issue.

Following integration, one week of sea trials commenced in which several areas of Narragansett Bay were surveyed.

Targets consisted of both known pre-laid targets, and a variety of seabed clutter such as old moorings, lobster traps, etc.

VII. SAS IMAGERY

Several AUV stability missions were performed to evaluate in-water stability. Initially, vehicle controllers were not modified, and vehicle stability was impacted by significant tidal currents and reduced metacentric height. Despite these factors, and without installing additional forward fin control surfaces, vehicle stability was sufficient for SAS image formation (see Figure 7). A successful series of SAS data collection missions were then performed. Following the completion of December trials, a second set of trial missions were also conducted in January 2013 in order to revisit particular sites of interest and acquire more SAS data.

The AquaPix consistently produced imagery at ranges exceeding 10x vehicle altitude, up to 220m during InSAS2 missions, and maintained constant 3x3cm resolution across the entire range. The large quantity of seabed clutter in Narragansett Bay provided a plethora of interesting targets to evaluate the sonar performance. Figure 8 below shows an abandoned anchor with a very unique shape, easily identified as a "Baldt" anchor, and originally designed by the Baldt Anchor & Chain Company.

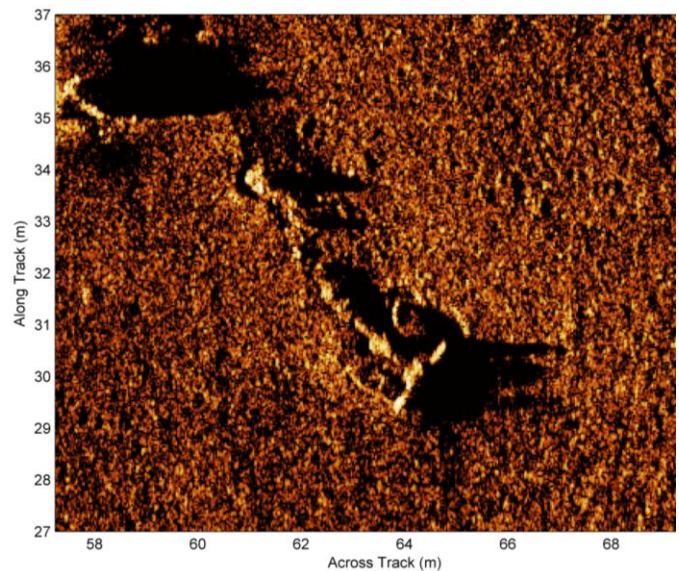


Figure 8: Baldt Anchor @ 64m range

Figure 9 shows an image of a shipwreck at 120m range. The shipwreck was resting on top of an incline, so the grazing angle of the SAS to the wreck was very shallow, resulting in an elongated shadow. In addition, the very strong return from the tip of the wreck resulted in some saturation of the sensitive receiver elements, which causes the grating lobes seen.

Figure 11 below shows a long-range image while operating in InSAS2, using all four receivers to achieve a range of 220m. The small targets seen are abandoned lobster pots.

Figure 12 shows an example of the interferometric SAS bathymetry that can be achieved with the AquaPix InSAS system; in particular, note the small bumps and highlights. These bumps are the individual lobster pots, which can be seen in Figure 13.

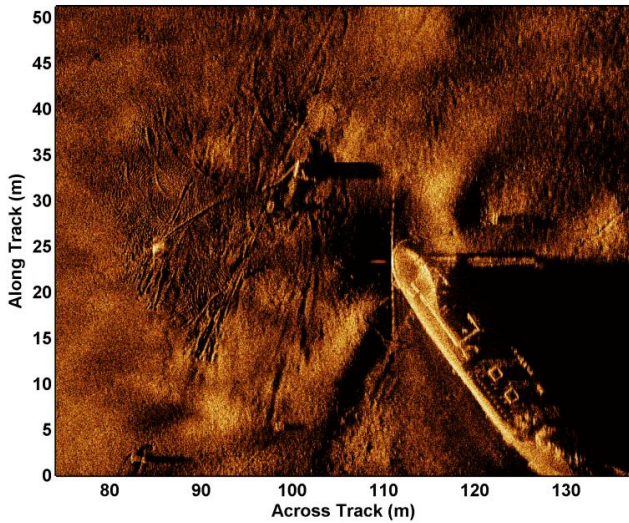


Figure 9: Shipwreck at 120m range

VIII. CURRENT AND FUTURE WORK

Following the successful NUWC trials, Kraken has continued work on the AquaPix InSAS, particularly improving the ease of AUV integration. At the time of this writing, several features are now standard including; acoustic slave triggering for DVL synchronization, time synchronization between SAS and AUV log files, time-varying gain (TVG) to prevent saturation from hard targets, and an improved sonar command and control protocol.

Kraken is currently participating in a second series of AquaPix sea trials with DRDC-Atlantic, on the Arctic Explorer AUV. A key aspect of the trial will be the evaluation and validation of Kraken's DataPod, a hot-swappable removable storage solution. Use of the DataPod allows not only for faster mission turnaround (whether post-processing or processing in real-time), but also enables a high level of data security and integrity for military users during survey of sensitive targets.

Kraken has also designed and manufactured a standard dual-sided InSAS1 wet-flooding payload module for the REMUS 600 AUV, with a goal of a complete off-the-shelf solution to be easily integrated into existing REMUS600 systems (see Figure 10)



Figure 10: Kraken's REMUS600 InSAS1 Payload Module

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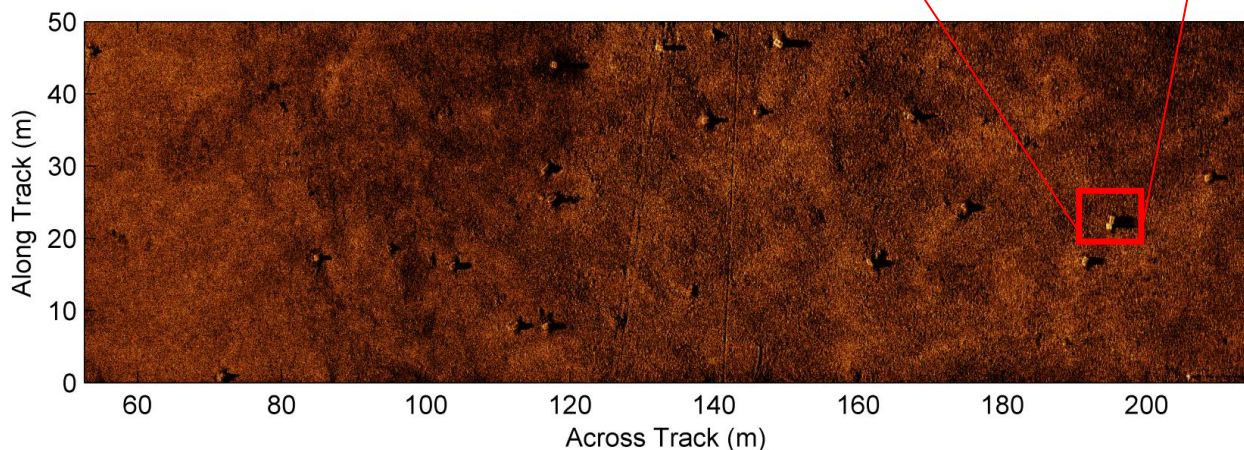
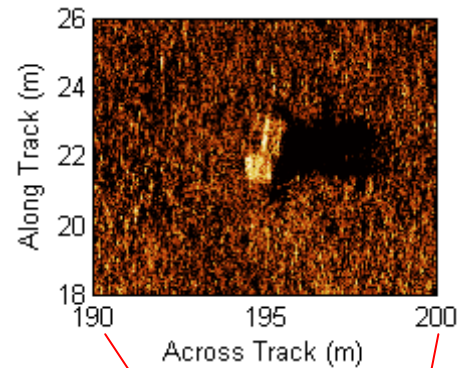


Figure 11: SAS Imagery to 220m range, showing lobster pots at 195m

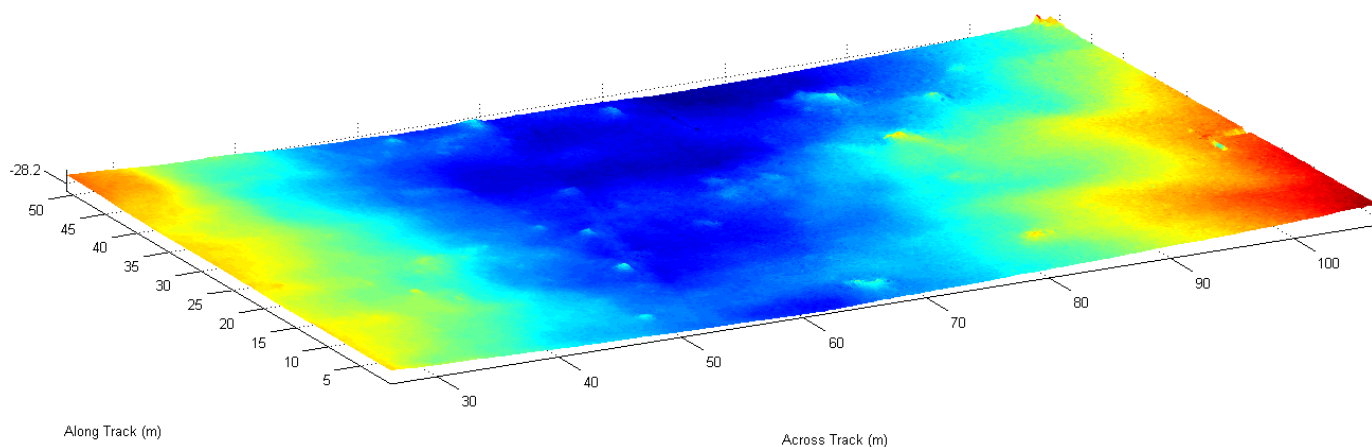


Figure 12: Interferometric SAS Bathymetry

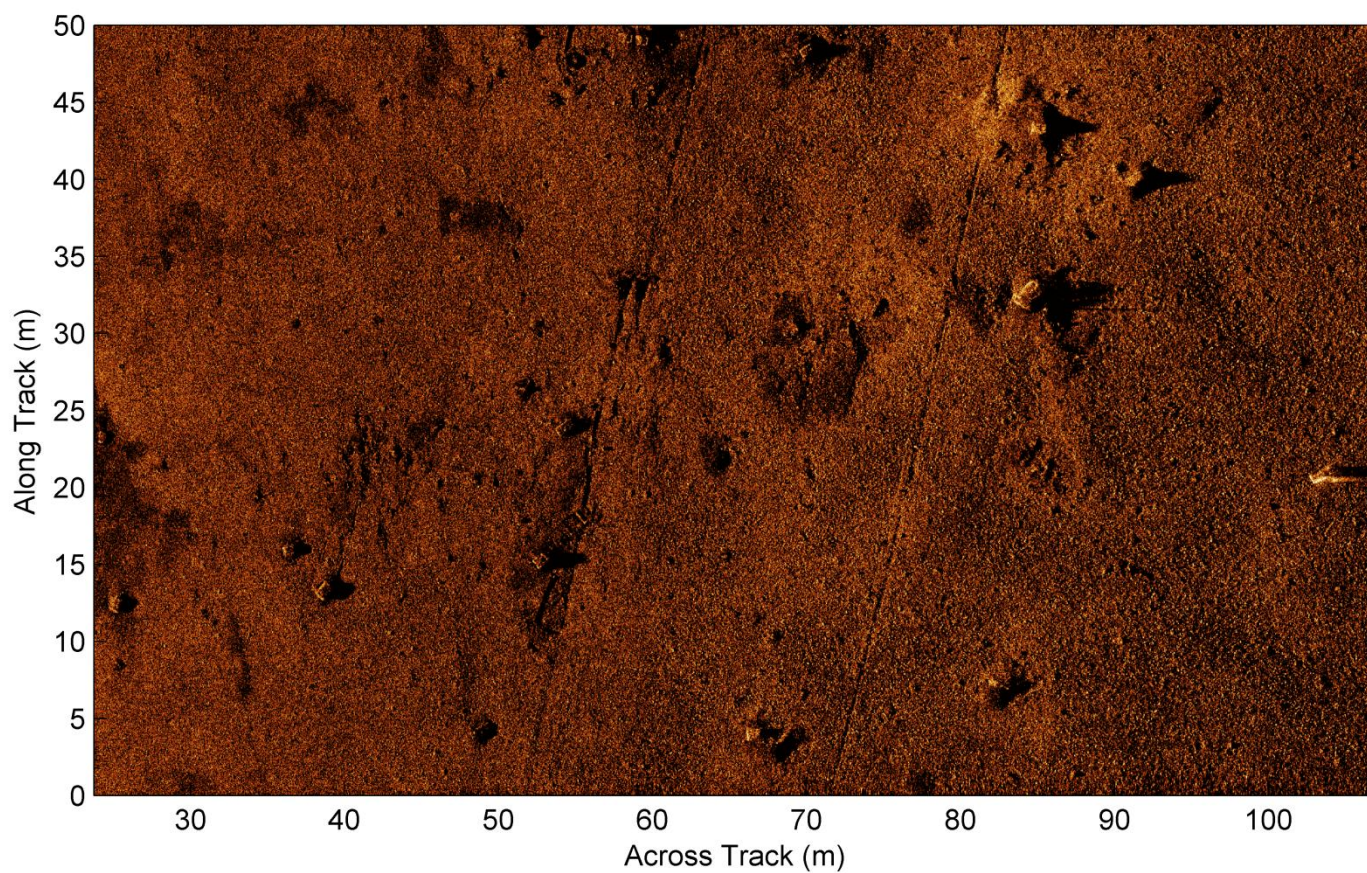


Figure 13: SAS Imagery Co registered to Interferometric SAS Bathymetry