Onboard Real-Time SAS Processing - Sea Trials and Results

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Abstract— **Interferometric SAS systems are rapidly becoming a commercially available viable alternative to traditional sidescan and multibeam systems for the commercial survey market. The high resolution, and high bandwidth data generated from InSAS systems has created several new challenges when compared to the traditional processing workflow of sidescan or multibeam sonar systems. The significant computational requirements for processing SAS data has created a requirement for onboard, in-situ, realtime SAS beamforming, as well as novel data management solutions and more compact, power and size efficient InSAS systems. This paper will present a number of new technologies and methodologies developed to address these new challenges, and provide an update on recent sea trials using these technologies.**

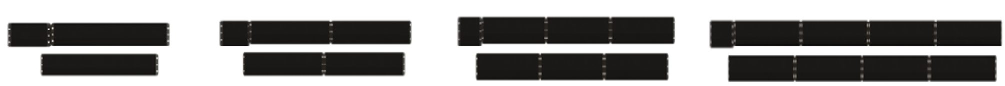
I. INTRODUCTION

Interferometric Synthetic Aperture Sonar (InSAS) combines ultra-high image resolution with 3D seabed bathymetry and superior area coverage rates. InSAS 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 InSAS 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.

InSAS systems use two vertically separated arrays to produce bathymetric maps that are exactly co-registered with the corresponding SAS images. This combination of synthetic aperture processing and interferometry solves the problems of limited resolution and coverage rates encountered with conventional swath bathymetric sonars and multibeam echo sounders, and allows for significant When the InSAS bathymetric resolution approaches that of the corresponding SAS image, it becomes possible to overlay the imagery and bathymetry to create a 3D images of the seabed. The ability to generate centimeter-scale resolution in all three dimensions has the potential to provide significant improvements in the detection, classification and identification of small seabed objects. Additionally, the high resolution, large swath coverage and high accuracy bathymetry can significant increase operational efficiency for seabed survey and hydrographic applications.

The traditionally high cost, complexity and export considerations of InSAS technology have restricted access to only a few military and defense applications, and prevented widespread use of the technology in the commercial survey market. However, commercial InSAS systems have recently become widely available, and have approached the technology level of being considered "off-the-shelf", competing directly with high-end sidescan sonars and multibeam echosounders. As a result of the high resolution, and the commercial availability, offshore survey operators are now requesting SAS as a survey tool for their customers.

Kraken Sonar Systems is a marine technology company headquartered in St. John's, Newfoundland, and engaged in the development and production of high performance InSAS systems, such as the AquaPix® (See Figure 1). Kraken has successfully delivered several InSAS systems to both commercial survey and defense customers, integrated on a variety of AUVs and towed platforms



	InSAS1	InSAS2	InSAS3	InSAS4
Operating Speed	3 kts	3 kts	6 / 8 kts	10 /15 kts
Range	132.5m	265m	200 / 150m	160/105m
Swath	265m	530m	400/300m	320/210m
Area Coverage Rate (Without Gap Filler)	1 km²/h	2.1 km²/h	3.2 km²/h	4.2 km²/h

Figure 1: InSAS Configurations

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The AquaPix InSAS delivers area coverage rates in excess of 2 km^2/hr, ultra-high 3x3cm seabed image resolution and co-registered bathymetry at up to 6x6cm resolution which exceeds capabilities of currently available multibeam and sidescan sonar systems.

The InSAS system is modular, and by the addition of physical modular receiver arrays, the InSAS system can operate at higher speeds, or correspondingly longer ranges. The InSAS system employs two sets of receive array elements, a long-range and a short-range row, within each vertically displaced receiver array. SAS processing is performed individually on each of these arrays, and subsequent interferometry performed on the corresponding displaced short range and displaced long range images. This allows the InSAS to achieve very good coverage in very shallow water (<10m) in both the near and far field, with a typical start range of 1.5x altitude, and an end range of 10x altitude, as shown in Figure 2 below

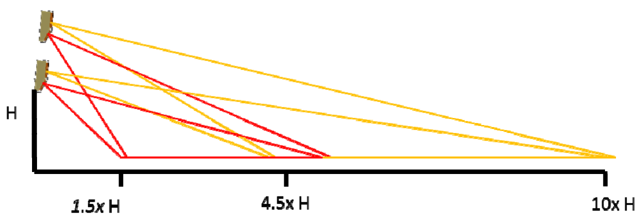

Figure 2: InSAS Coverage Illustration

One of the key challenges faced in transitioning SAS technology from the military and defense applications into the commercial survey market lies within the actual workflow. SAS data processing is computationally very intensive, requiring powerful computing hardware for post processing. Such hardware may be too large or power hungry to carry onboard an AUV, therefore raw SAS data must be recorded and recovered after a mission for post-processing. Raw SAS data is very high bandwidth, creating data storage, handling and processing challenges when employing traditional methodologies using onboard storage media. Once data is recovered, and processed, the resulting high-resolution imagery must be georeferenced, processed and compiled into bathymetry maps and imagery mosaics. Even after processing, this high resolution SAS data still requires significant bandwidth.

Several technologies and methodologies have been developed in order to meet these challenges, and further realize the significant benefits of InSAS technology for commercial survey applications.

II. SAS Processing

Operating SAS systems onboard autonomous underwater vehicles (AUVs) introduces several unique challenges not present in traditional sidescan sonar systems. Figure 3 above illustrates the typical AUV SAS processing workflow.

SAS processing has a significantly higher computational requirement than traditional sonar systems, due to very high bandwidth and large number of sampling channels. A typical Kraken InSAS1 system is composed of four 32-channel receivers, yielding a total of 128 receiver channels. After basebanding, each receiver channel samples data at 50kHz, and each sample is a 32 bit complex number. Therefore the resulting raw element-level data amounts to approximately 25MB/s. Larger InSAS systems require more bandwidth; InSAS2 requires twice the number of receivers as InSAS1 (4 per side vs. 2 per side), for a total of 256 receiver channels, with a total bandwidth of 50MB/s. This high bandwidth data output is supported with a standard 1000BASE-T Gigabit Ethernet link, and is then recorded onboard the sonar's internal storage.

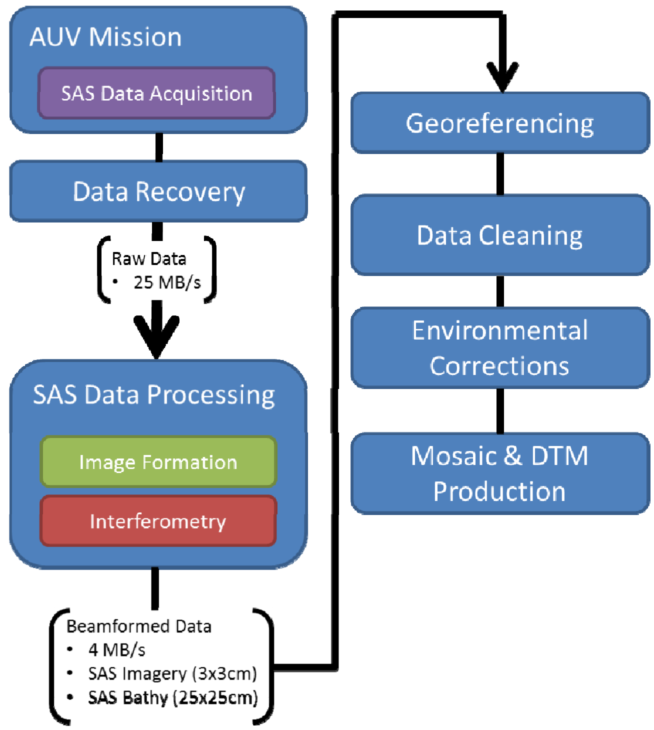

Figure 3: Typical SAS Data Processing Stages

Due to the challenging computational requirements and high bandwidth data handling, many AUV SAS systems require that SAS data be post-processed to achieve full SAS resolution, with onboard realtime processing only offering a reduced resolution comparable to that of a sidescan. The resulting workflow requires a number of stages from data acquisition to chart production, as shown in Figure 3. Recorded data must be downloaded from the AUV before processing can proceed, and processing speed will depend directly on the hardware and SAS algorithms available to the sonar operator.

Kraken's highly efficient SAS processing algorithms are able to use off the shelf processing hardware to meet these processing requirements. Leveraging GPU acceleration to significantly increase processing speed, and reduce overall processing, Kraken's INSIGHT software has enabled faster than real-time processing on standard gaming laptop hardware consisting of a mobile CPU and GPU. These results are achieved on a standard processing laptop, using i7 2.4GHz Quad-core CPU, 8GB RAM, and an NVidia GeForce GTX660M GPU. With this hardware, SAS data can be processed in 3-4 times realtime; for example, 1 hour of SAS data can be processed in 15 minutes. While this result is technically impressive, and significantly reduces the overall workflow, it still requires a potentially unnecessary stage of post-processing. Given that the hardware requirement for faster than real-time processing can be easily met with off-the-shelf mobile laptop hardware, it is therefore reasonable to expect that real-time onboard processing on an AUV could be achieved with similar or even lower-power hardware.

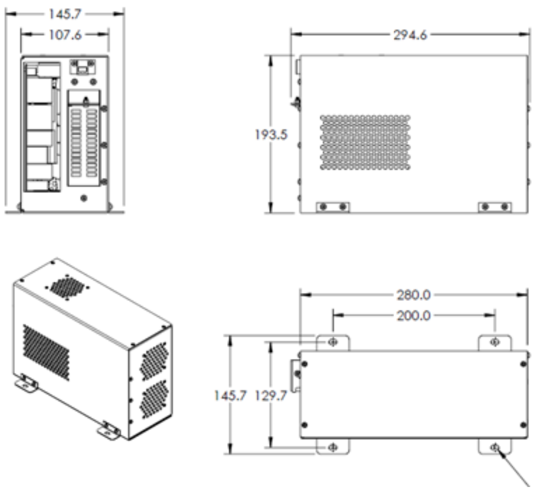

Figure 4: RTSAS Processor Dimensions

In response to this requirement, Kraken has proposed a Real-Time SAS Processor, the RTSAS. Based on commercially available mobile computing hardware, the RTSAS is a rugged, small-form factor subsystem for the real-time processing of AquaPix InSAS data. Designed not just for maximum imaging performance but optimal performance per watt, the RTSAS Processor creates a powerful, compact SAS processing capability.

Figure 5: RTSAS Processor with mug for scale

The RTSAS processor allows several stages of the SAS processing workflow to be compressed into one onboard, online processing stage. The RTSAS processor takes in real-time raw SAS data, and performs SAS micronavigation, image formation and interferometry in full resolution in real-time. The inclusion of the AUV navigation data stream (latitude, longitude, depth and heading) allows for real-time onboard georeferencing to take place as well, further reducing the overall workflow. The resulting dataset available when the AUV mission completes consists of full-resolution imagery and bathymetry, ready for mosaicking and production of digital terrain models (DTMs).

In addition to the reduced processing time in the overall SAS data workflow, the resulting processed imagery and bathymetry is an order of magnitude smaller than the raw data. At approximately 4MB/s, the processed SAS data could be recovered from the AUV in significantly shorter time, and could be reviewed wirelessly using off the shelf Wireless Ethernet hardware. This allows the operator to review processed SAS data without the necessity of recovering the AUV.

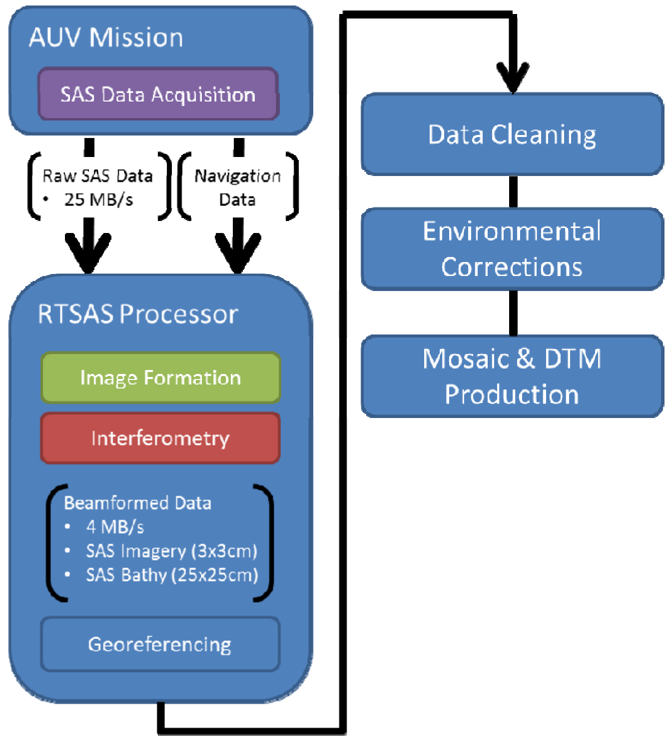

Figure 6: SAS Data Workflow with RTSAS Processor

III. "BIG DATA" HANDLING

Modern SAS systems have also introduced AUVs and sonar systems into the realm of "Big Data", with raw data rates on the order of hundreds of gigabytes per hour. The storage, indexing, integrity management and transfer of this data onboard AUVs have created key several challenges. On a typical 20 hour AUV survey, an onboard SAS system may generate two terabytes (2 TB) of raw SAS data. Without onboard processing available, the whole of this raw data set must be recovered from the AUV. Given that an AUV usually consists of sealed pressure hulls, it is assumed this data must be recovered without breaking any watertight seals on AUV pressure vessels.

Modern storage drives typically use SATA or eSATA, which provides very high bandwidth up to 6Gbps, but the connectors and high frequency are not well suited to existing off-the-shelf subsea connectors, and therefore cannot be directly accessed through a subsea bulkhead. USB has been used successfully with subsea connectors, but has limited bandwidth of only 480Mbps. Recently developments in Gigabit Ethernet connectors are ideal for subsea use, and a number of manufacturers have demonstrated and proven connectors for using Gigabit 1000BASE-T Ethernet, at sustained speeds up to 1Gbps. However, even downloading 20 hours of SAS data using Gigabit Ethernet will require a minimum of 4 hours (at 125 MB/s), therefore alternative methods of data recovery must be investigated. If storage media can be physically removed from the AUV, and replaced with fresh “empty” media, data recovery time becomes effectively a matter of minutes or even seconds.

The challenge of Big Data also introduces challenges of ensuring data integrity. Large volume SAS data requires distribution of storage across an array of media. Common technologies are available in commercial and industrial environments, the most well-known being RAID (redundant array of independent disks). There are a variety of RAID levels which allow either improved performance through large arrays of disks, or improved security through data redundancy across multiple disks.

Figure 7: Kraken DataPod Removed from an AUV

Traditional hard disk drives are not well suited for use in subsea environments due to the mechanically sensitive nature of the spinning disk platters and drive heads, as well as the high power consumption. Solid-state storage technologies are ideal for use in subsea platforms, due to the advantages of lower power, smaller size, robust tolerance to temperature variations, and high tolerance to vibration / shock. Historically, one major factor limited the widespread usage of SSD’s has been the high cost and size capacity; for example, in 2010, the highest capacity drive available was only 256GB. In 2014, for the same price, 1 terabyte SSDs can now be purchased off the shelf from a variety of online retailers.

In order to achieve a robust, hot swappable, low cost storage solution for AUVs, a combination of these technologies is the logical conclusion. Kraken sought to meet this requirement with its DataPod, designed to meet the ruggedized, removable, secure storage requirements previously described. The lightweight, compact unit enables high bandwidth data recording and can provide up to 2 Terabytes (2 TB) of solid state RAID storage in a compact, deep sea rated pressure module.

The DataPod can record raw SAS data up to 50MB/s and be easily removed from the vehicle via a wet-mate rubberized Power/Ethernet connector. It also simultaneously can record vehicle navigation data and other payload data, which allows for one unified storage medium for all AUV onboard systems. DataPod can also be combined with an RTSAS processor, to allow rapid recovery of fully processed SAS data as well. Ideally, one would use the RTSAS and the DataPod together to allow for real-time imagery and quick recovery of raw data for backing-up and future post-processing.

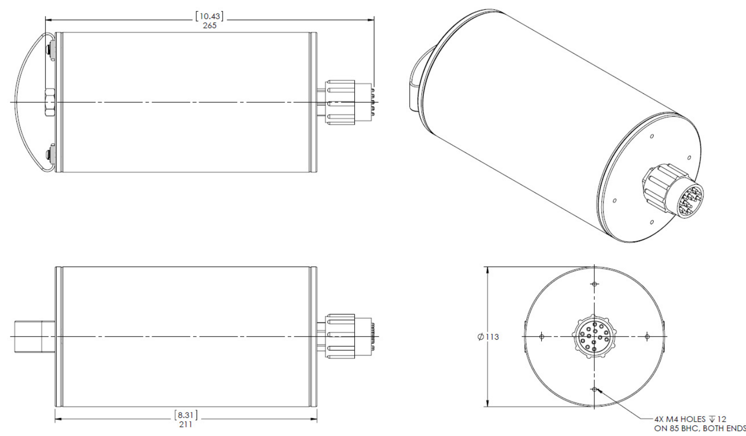

Figure 8: DataPod Dimensions

IV. Miniaturization of The InSAS

The power, size and weight requirements of SAS transducers and processing electronics have traditionally restricted SAS to medium (>12”) and large (>21”) diameter AUVs. However, the current prevalence of small-diameter, low-cost AUVs has created a demand for SAS on these smaller platforms. Recent developments in compact processing electronics have enabled the production of a miniature interferometric SAS system (MINSAS), which underwent sea trials in March 2014.

	MINSAS 60	MINSAS 120
Operating Speed	3 kts	3 kts / 6 kts
Range	120m	240m / 120m
Swath	240m	480m / 240m
Area Coverage Rate	1 km²/h	2 km²/h (at 6 kts)

Figure 9: MINSAS Specifications

The true differentiation in the InSAS and MINSAS are in the element designs, and application depths. The AquaPix InSAS was designed for very shallow water (VSW, <10m), specifically with mine counter measures (MCM) applications in mind, and a maximum depth rating of 300m. As previously described, InSAS uses two vertically displaced transducers, and each transducer includes two rows of elements at two different depression angles, a short range and long range row, with very narrow vertical beamwidths to significantly negate multipath. This has been demonstrated to achieve ranges of 10x altitude (per side) in water depths less than 5m.

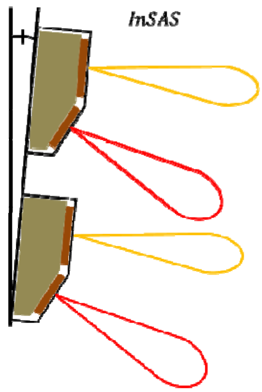

Figure 10: InSAS vs. MINSAS Transducer Design

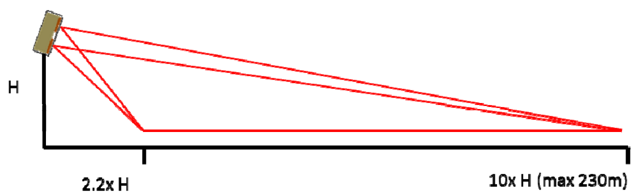

Figure 11: MINSAS Coverage Illustration

The MINSAS only requires a single transducer (vertically), and includes two rows of elements that are planar to one another within a single transducer array. Similar to InSAS, interferometry is performed between the upper and lower rows of elements. The MINSAS is a broadband system leveraging the same electronics and SAS processing algorithms developed for the InSAS, and operates from 200-400kHz. The image resolution and bathymetry resolution are the same on the MINSAS as the InSAS. Figure 10 and 11 above illustrate the transducer comparison. The resulting MINSAS system is more compact, suitable for installation on 6" diameter or larger AUVs or towed platforms. It has also been designed for deeper depth ratings, recommended for use in waters deeper than 20m, with the standard elements designed for 3,000m depth rating.

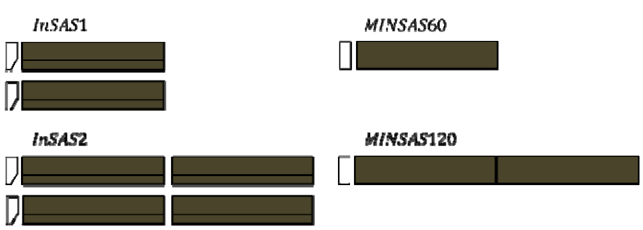

Figure 12: InSAS vs. MINSAS Transducer Configuration

Both systems, InSAS and MINSAS, are modular in that they can have a variable number of horizontal along-track arrays. MINSAS60 includes one RX per side (a 60cm length), and MINSAS120 includes two RX per side (a 120cm length). InSAS is similar, in that an InSAS1 includes one set of vertically displaced RX arrays, and InSAS2 includes two sets of vertically displaced arrays. Figure 12 above illustrates the transducer configuration, with an end view showing the two rows of elements in the InSAS design.

Figure 13: MINSAS120 Installed Below InSAS2

V. Sea Trials and Results

In March 2014, Kraken completed a series of sea trials with a MINSAS120 system installed onboard DRDC's Arctic Explorer AUV. DRDC currently owns a dual-sided InSAS2 system with RTSAS, so this provided an ideal platform for a side-by-side comparison of the RTSAS and InSAS vs. MINSAS performance and workflow. As shown above in Figure 13, the MINSAS was underslung, mounted in a bracket attached to the belly of the Explorer AUV. Calibration runs were completed to provide overlapping datasets from both the InSAS and MINSAS system. The InSAS system was operated with Kraken's RTSAS and DataPod, while the MINSAS used onboard storage.

Figure 14: DRDC Arctic Explorer with InSAS2 and MINSAS120

Results from the MINSAS test runs yielded very positive results. Image resolution and bathymetry resolution measurements were performed against known targets deployed in the DRDC "Mine Garden". The MINSAS was operated at a centre frequency of 337kHz, and maintained the 3x3cm resolution expected at target ranges of 110m when configured for MINSAS60, and 220m when configured for MINSAS120.

Results from the RTSAS with InSAS also were very positive. Imagery and bathymetry were produced onboard the AUV, which drastically reduced the turnaround time between missions and enabled data analysis via the AUV's wireless connection.

Additional RTSAS and MINSAS120 sea trials are scheduled for summer 2014 onboard a towed platform. Results were not available in time for this publication, but will be presented at the conference.

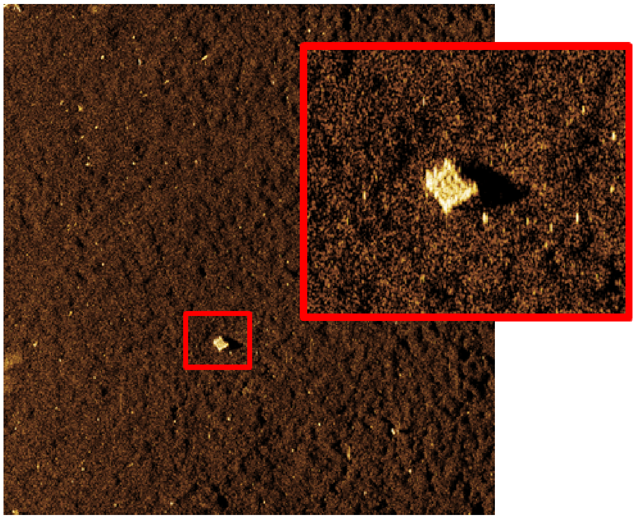

Figure 15: Sample MINSAS120 Target Image

VI. Current and Future Work

Following the successful MINSAS and RTSAS trials, Kraken has continued to further develop the real-time SAS software, which needs to perform online troubleshooting and dynamic closed-loop tuning of SAS parameters for optimal survey efficiency, as a result of environmental or operational changes throughout the survey. In the case of towed systems, the RTSAS software is also continuing to develop to provide online monitoring and real-time visualization of both raw SAS data and beamformed SAS imagery and bathymetry, for online quality assurance and quality control.

Kraken is also engaging in a project with the software company CARIS, to develop a capability to further compress the SAS processing workflow, by automated the traditional post-mission tasks such as mosaicking, DTM production, environmental correction (tidal, sound velocity, etc.) and generated fully mapped solutions directly onboard the AUV. Kraken are CARIS are working together to allow InSAS data to flow into CARIS Bathy DataBASE technology, reducing the time taken to generate modern survey deliverables.

VII. Acknowledgements

The authors would like to thank DRDC scientists and AUV technicians for their support during the integration and sea trials.