Using synthetic aperture sonar as an effective hydrographic survey tool

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Abstract

Synthetic aperture sonar (SAS) is becoming a powerful tool for hydrographic survey in addition to its original use as a mine detection sensor. This technology can provide very high resolution seafloor imagery and bathymetry over the full extent of the swath. SAS lends itself for use with AUVs because of the stable nature of these platforms. As the hydrographic industry begins to adopt AUV technology, especially given the efficiencies they can bring, it is clear that SAS will have a greater role to play. This trend is driving a requirement to support this data effectively in the data processing software tools that are used on a daily basis. It also creates new requirements to handle the increased data volumes, complex geometries related to SAS data, as well as further highlighting the need for near real-time data processing. This paper will explain how SAS data is being incorporated into data processing workflows, as well as highlight new considerations that need to be understood when using this technology as a hydrographic mapping tool.

Introduction

Synthetic aperture sonar (SAS) has been around for over a decade but its primary purpose has been in mine detection rather than hydrographic survey. To use SAS effectively a stable survey platform is required such as an autonomous underwater vehicle (AUV). These platforms are becoming more commonly used in hydrographic survey and as a result the viability of SAS as a survey sensor seems a logical progression for the industry with the suggested benefit of increased data quality, better resolution and a pathway to a more modern data centric survey deliverable. This paper will explain the basics of SAS technology, describe the growing applicability of AUVs as survey platforms, introduce the data processing requirements and will raise a series of questions that need to be considered in order to use this technology efficiently for hydrographic survey purposes.

SAS basics and benefits

SAS is a technique for creating high resolution seabed reflectivity images and bathymetry that shares many similarities with Synthetic Aperture Radar (SAR). The forward motion of the sonar is used to synthesize an array that is much longer than its physical length by combining multiple pings in software rather than adding more hardware as a way to gain higher resolutions. SAS uses signal processing to compare the multiple observations of the same area of seafloor to calculate its depth. See Figure 1. It

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also allows us to circumvent the usual trade-off between range and resolution in conventional sonar in that it provides high quality data over the entire swath.
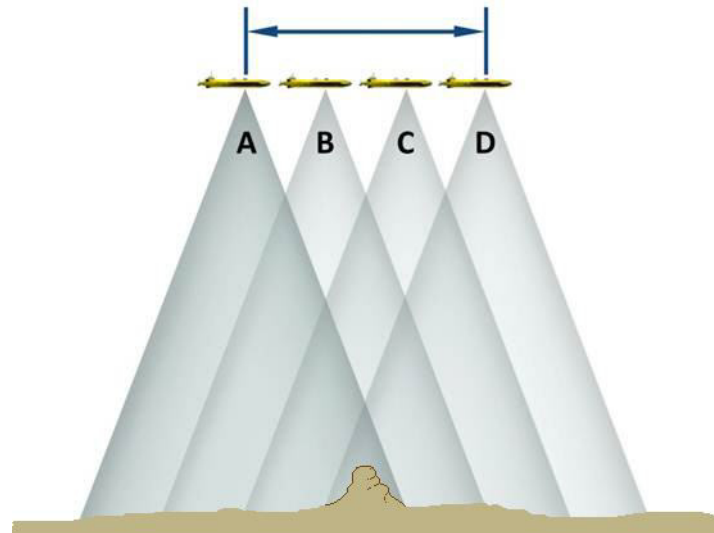

Figure 1. Synthesizing the size of the array gives higher resolution

Although military applications, such as naval mine countermeasures, have been the major driver of development, SAS is a multi-use technology with great potential for offshore oil and gas surveying, regional surveys for charting, underwater archaeology, benthic habitat mapping, and deep sea mining. Figure 2 shows an example SAS image from a sea trial conducted by the U.S. Naval Undersea Warfare Center (NUWC), which illustrates a constant 3×3 cm resolution to 200m range in a water depth of 27 m; this constant and high resolution is a major benefit of using SAS.
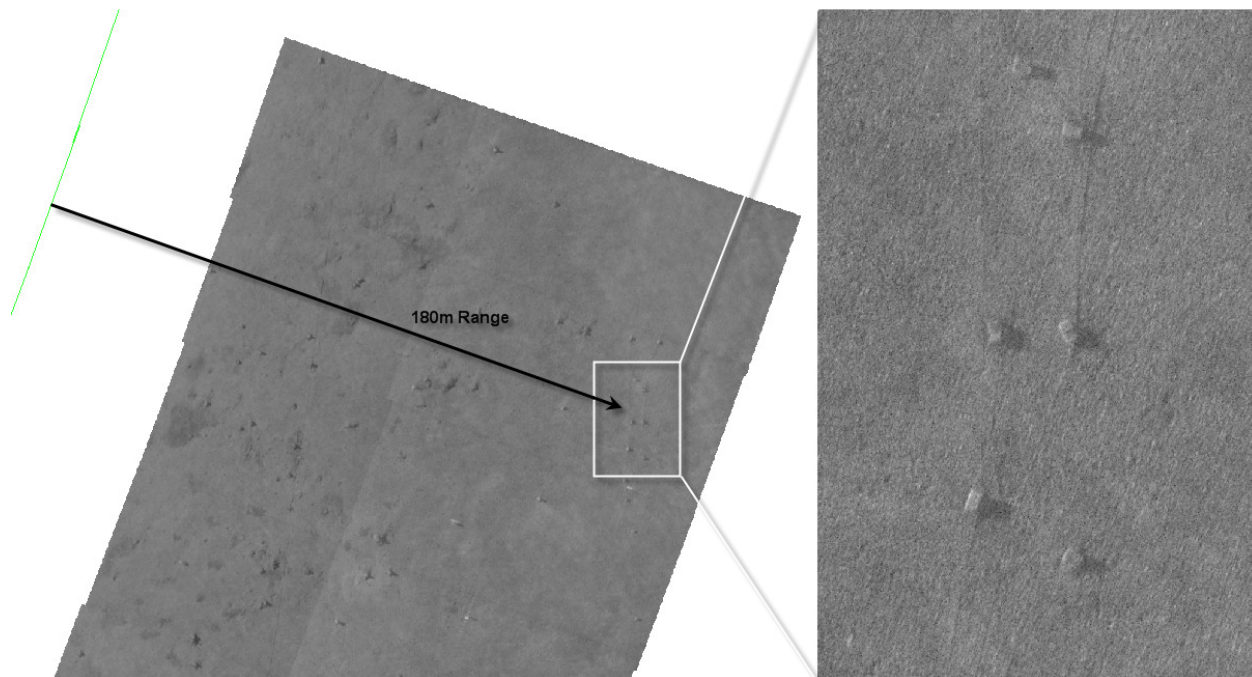

Figure 2. 3cm SAS mosaic highlighting lobster pots with connecting rope at 180 metres range

In addition to reflectivity images, SAS can produce highly detailed terrain models of the seafloor by detecting the angle of arrival of seabed echoes coming from a given range grid location. In a configuration known as Interferometric SAS (InSAS) used in the Kraken AquaPix® InSAS system, the returns from two vertically separated receive arrays are cross-correlated to measure the delay, which gives the angle of arrival that is used with the range to calculate the depth measurement. See Figure 3.
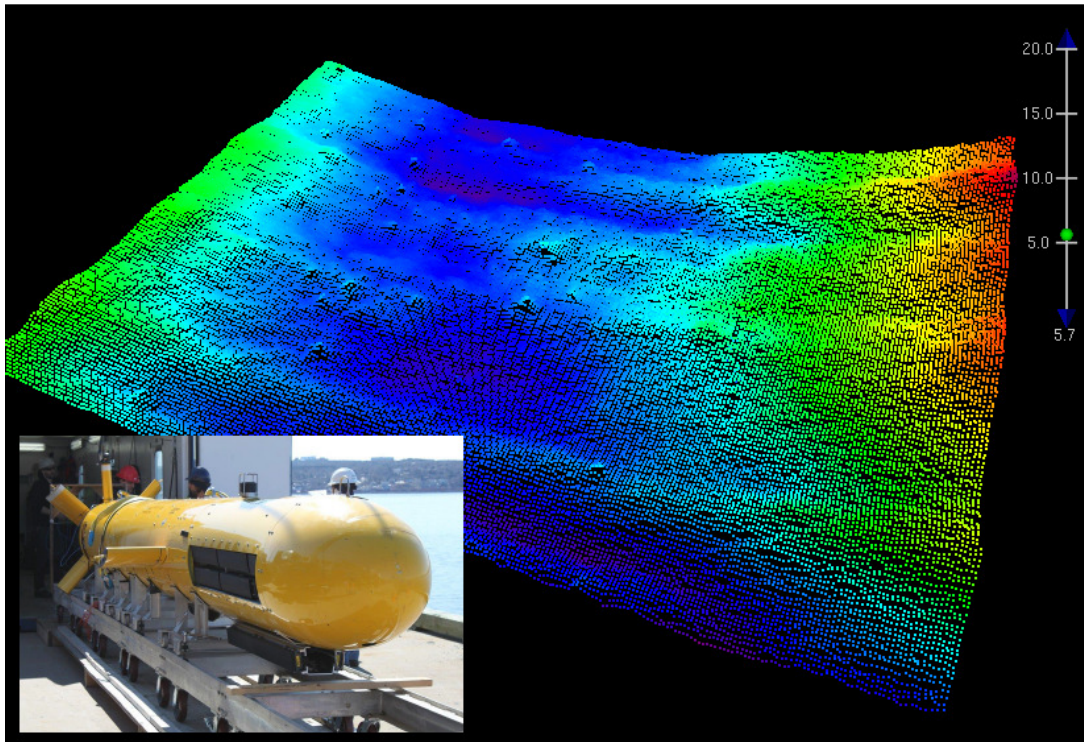

Figure 3. InSAS Bathymetry (inset shows ISE Arctic Explorer with InSAS arrays)

When the InSAS bathymetric resolution approaches that of the corresponding SAS image, it becomes possible to overlay the reflectivity and topography to create a true 3D representation of objects on the seabed, which is another benefit of using SAS as a hydrographic survey sensor. The ability to generate centimeter-scale resolution in all three dimensions has the potential to provide significant improvements in the detection and inspection of small seabed objects. See Figure 4.

A third benefit is as an alternative solution to video capture and review which has been a time consuming part of pipeline inspection survey projects with remotely operated vehicles (ROVs). By using an AUV that is capable of capturing a combination of SAS imagery, bathymetry and on-demand high definition still photography and delivering these as high resolution co-referenced datasets there is the potential to save data review time, and provide data from the field in a more coherent and modern way, as handling it in traditional ways may not be possible because of the data densities at play, which are described later. This advancement will also help drive adoption of survey data standards like the OGP Seabed Survey Data Model (SSDM) and IHO S-100.
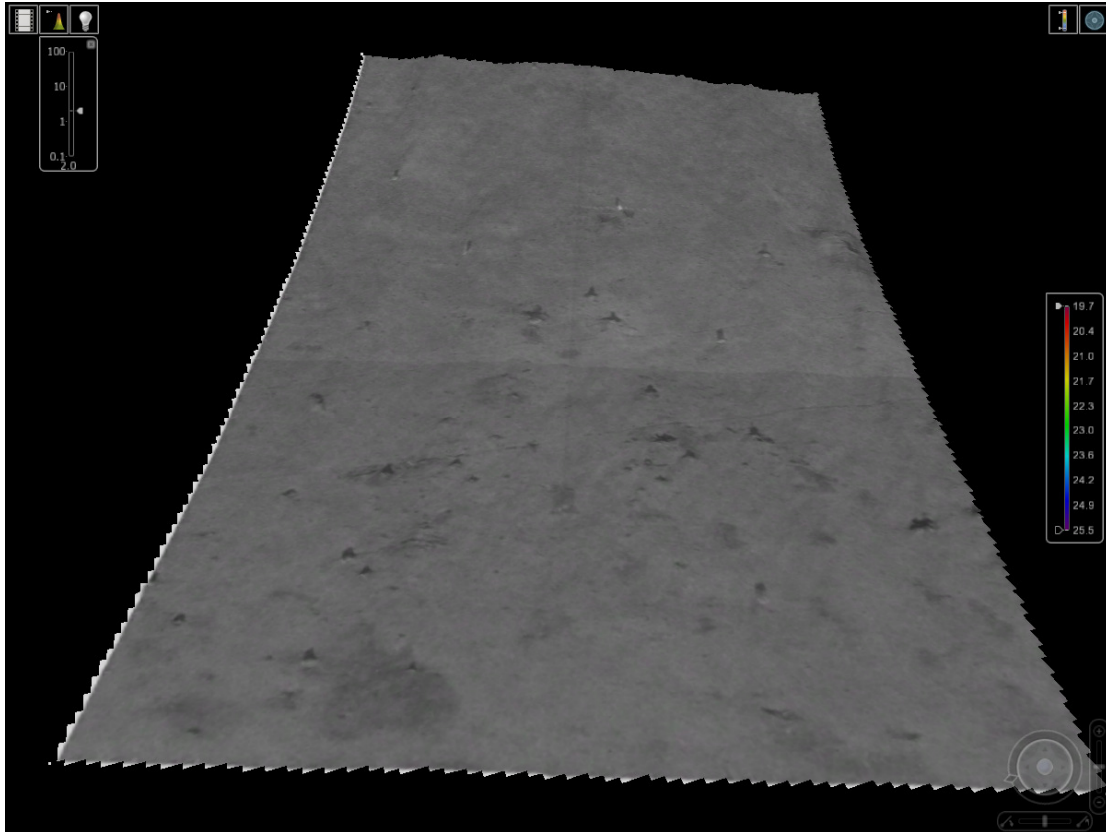
Figure 4. SAS imagery draped over bathymetry

Increased use of AUVs

According to a report written in 2012 by Brun, L. of the Duke Centre on Globalization, Governance and Competitiveness, for the Nova Scotia government, the global AUV market is expected to grow from $200 Million USD per annum in 2010 to $2.4 Billion USD in 2019. At the same time the much bigger ROV market will continue to grow, but at a slower rate. This increasing popularity of AUVs is resulting in them being used more commonly for hydrographic surveys and that brings some benefits and quite a few challenges, but importantly these can be solved.

On the positive side they can be deployed by small crews (two or three people) and go about their work with very little human input. AUVs are capable of carrying a similar array of sensors to those used on a survey vessel or ROV, however the smaller payloads required have driven the development of more compact multibeam and SAS systems (e.g. Kraken's MinSAS). SAS lends itself very well to AUV operations as they provide a stable platform which is critical when synthesizing the aperture length. Hull mounted SAS would be adversely affected by vessel motion or the jerky movements endured by ROVs because of their slow speeds and tethered relationship with the mother ship. Remotely operated towed vehicles (ROTVs) also make for a good platform for SAS surveys.

As mentioned, there are also a few challenges with using AUVs. Sensors like SAS and multibeam demand payload space and power. This can reduce mission endurance or require larger, more expensive AUVs to be used. Furthermore, to run an effective AUV survey multiple vehicles may be needed allowing the next AUV to be deployed as the first is recovered. While this is mostly due to battery life, it also provides a much needed opportunity to retrieve the logged sensor data. The volume of data collected is too large to transfer through the vehicle's communication system while in transit; the data has to be accessible on its return. This currently results in a data processing bottleneck as many hours of data needs to be processed at once, which is not the case with ship-based or ROV surveys. The solution to this is onboard and near real-time data processing so that what comes off the AUV is ready to be incorporated into the survey deliverable with far less human interaction. Another challenging requirement is to transmit survey images while the AUV mission is underway to ensure that coverage and quality is being achieved, compressed images of the onboard processed data is critical for this.

These benefits and challenges raise the question of when is it cost effective to conduct a hydrographic survey with an AUV and SAS. One obvious candidate is in the Arctic where sea ice is a factor, but charting is greatly needed as shipping and exploration increase. This will likely require the integration of various bathymetric data sources, not just SAS; for example, space-based surveys such as RADARSAT2 adapted to Arctic operations, airborne surveys using Light Detection and Ranging (LiDAR), vessel-based surveys using single and multibeam echo sounders and AUV surveys using multibeam and SAS. In addition to gathering data for charts, the AUV based systems could acquire data to illustrate the underside of submerged ice — information that would help oil and gas companies ensure protection of their assets. The oil and gas industry in general is an excellent candidate for this technology as the current survey methods are expensive and this technology could present a cost savings. Other examples might be in areas where surface navigation is challenging because of busy shipping routes, in conflict zones where human life is threatened, or when searching for downed aircraft in deep water areas.

As we see more AUVs being used for hydrographic survey we can expect to see an increased use of sensors like SAS. The further reliance on this equipment requires traditional data processing workflows to be revisited to ensure that they make sense and result in high quality data deliverables; this is the focus of the next section.

Processing considerations

<u>Sensor configuration</u>
SAS data may not necessarily have port and starboard channels, which is the normal configuration for traditional side scan sonars. It should be possible in post processing to specify whether the system configuration is a port or starboard mounted setup or has both, in much the same way as a single or dual headed multibeam would be configured. The locations of the arrays may also present a configuration challenge as dual receivers will likely be used for InSAS systems. The correct display of the data is important if subsequent image processing, target detection and contact digitizing tasks are to be efficient and accurate.

The SAS may also be accompanied by a gap filling sonar, to infill the nadir gap between port and starboard channels. These configuration aspects need to be understood in order to determine an effective line plan.

Line planning

When determining a line plan for a hydrographic survey using a SAS, two key factors need to be considered; the SAS transducer configuration, including whether the SAS is complemented by a downward looking or gap filling sonar and the scope of the survey, i.e. is it an area survey for charting or a route survey. The optimal survey line plan will change based on these variables.

For example, a pipeline inspection project requires the highest resolution bathymetry, imagery and photography to be captured along the pipeline and its immediate corridor. If the AUV flew down the pipe with the SAS transducers mounted port and starboard then no imagery and bathymetry data would be captured in the area of interest. The required approach would be to fly the AUV with an optimal horizontal offset from the pipe to ensure that the pipeline is fully captured. See Figure 5. Another consideration is that the horizontal offset may cast the far side of the pipe into shadow due to the low grazing angles needed to obtain the required resolution; this may require a second line offset on the other side of the pipe.

Unfortunately running lines offset to the pipe does not aid the capture of still photography directly along the pipe, which can be a survey requirement for the identification of damage. The need for camera or video capture could reduce the efficiency of conducting a survey with a sensor like SAS, if the SAS image resolution was deemed good enough for the inspection task then this would make for a more viable solution. It may be better practice if the camera's use was restricted to photographing areas of damage which have been initially identified with the SAS.
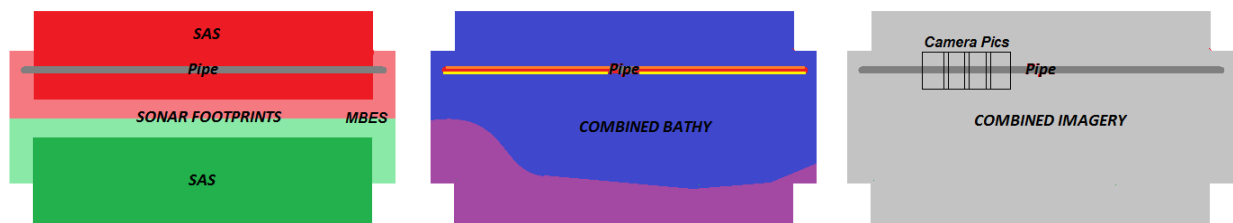

Figure 5. Sonar coverage of pipeline survey with SAS, multibeam and still camera

The resolution close to nadir of a modern narrow beam angle multibeam system would be close to that of the SAS and therefore could act as an excellent gap filler. This of course would increase the data volumes needing to be stored and processed, which seems to be the biggest challenge in using SAS for hydrographic survey work.

Many AUVs can utilize pipe tracker technology. How this is used in a SAS pipeline survey requires some additional thought because of the required offsets discussed to capture the pipe. If photographs are

required all along the pipe then these could be captured while using the pipe tracker and this original run-line can then be used to program the offset run-lines.

For a regional survey project, the aim would be to achieve the required survey order or level of accuracy with the minimum number of lines. An AUV with SAS, supplemented by a downward looking / gap filling sonar would be a highly effective mapping platform capable of high resolution and full coverage data collection. If the bathymetry from the SAS and gap filling sonar was able to meet the required IHO survey criteria (e.g. Special Order), which seems achievable, then SAS surveys should be able to meet the requirements needed for charting for safe navigation.

Line planning is an important consideration for SAS surveys, it also highlights the need to combine datasets together in a logical way (e.g. port and starboard SAS with gap filler), while maintaining the optimal resolutions, this topic will be explored in a later section.

Navigation

SAS typically requires integration with the AUVs Inertial Navigation System (INS), in addition to a series of other surface (e.g. GPS or Wi-Fi) and sub-surface positioning methods (USBL). Once the AUV has dove the INS will provide the primary position, the quality of position is generally good, but post processing is a common workflow step for gaining even better accuracy. The post processed navigation can replace the real time solution which can improve overall dataset quality. This position data can be read into CARIS HIPS[2] and SIPS, for example, through the Generic Data Parser.

Frame and data placement

Most SAS systems have a concept of frames or tiles of imagery and bathymetry. Early experiences suggest that these datasets will likely require further manipulation in order to display the data properly in processing software like HIPS and SIPS. The Kraken AquaPix® InSAS datagram contains a starting coordinate (bottom left) a heading value, min and max along track and across track distances and, of course, the depth and dB data. The HIPS format reader uses this information to determine the top left position of the frame which is required to interpolate the data correctly. It then positions the relative measurements by dividing the delta along track and across track distances by the number of rows and columns in the grid. See Figure 6.
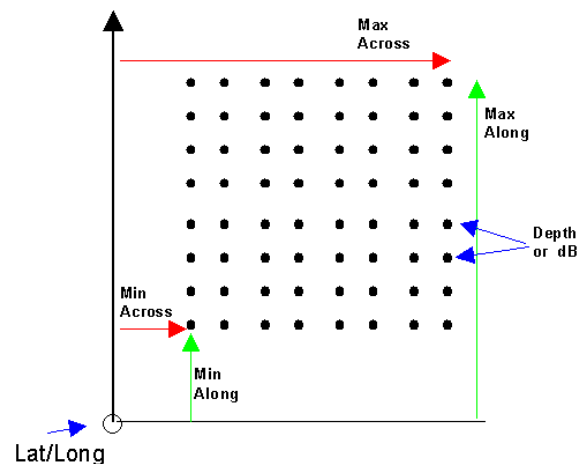

Figure 6. Data placement

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[2]HIPS is a registered trademark of CARIS (Universal Systems Ltd.), Reg. USPTO.

Motion

According to the paper, *A New Approach to High-Resolution Seafloor mapping, published in the Journal of Ocean Technology, 2012 by Callow, Hagen, Hansen, Saebo, and Pedersen*, "Traditional motion compensation used for correcting MBES measurements does not work because multiple pings make up every pixel in SAS bathymetry data, either the SAS processor must apply any improved navigation processing to each ping, or bathymetric post-processing software must be adapted to support the type of data that SAS produces".

There is still work to be done in determining what aspects and techniques for motion compensation need to be handled during data collection and what can be done in post processing.

Total depth calculation

A simple, but essential processing step is the combination of the SAS depth measurements with the AUVs depth, to get a total water column depth rather than a relative one. The AUV depth is usually determined by a pressure sensor. This depth calculation may be done at the time of collection or as a post processing step, in HIPS and SIPS for example, the pressure sensor depth information can be added to the sonar depth via the "Load Delta Draft" function.

Sound velocity

AUVs typically fly at an altitude of between 5 and 20m above the seafloor. In shallow water surveys (<100m), the greater the flying height the more important it is to measure the changes in sound speed as there is more water column available for variations to occur. But how does this apply in deep water? For example, if the AUV is surveying in deep water (2000m) and is flying between 5 and 20m above the seafloor, then how likely is it that there will be significant changes in sound speed that could affect the accuracy of the bathymetric measurements? Is a sound velocity measurement at the transducer face enough to ensure that the seafloor is accurately modelled? Is it okay to use a pre-determined sound speed because equations from *Del Grosso* or *Chen-Millero-Li* suggest that sound speed change becomes a constant beyond certain water depths or does an argument exist for profiling because of the potential for sound speed changes caused by escaping heat from the Earth's crusts for example?

Another aspect relating to sound velocity is the potential for re-application of sound velocity to the SAS data if an incorrect profile was used at time of collection. SAS bathymetry datasets that we have experienced so far have been in XYZ form rather than the raw range and angle data that is required for ray-tracing. Enough information would need to be present if sound velocity correction is to be possible in post processing applications.

Local versus continuous coverage

When mine hunting with AUV mounted SAS it is normal practice to sweep the area looking for targets and then to home-in and conduct a high resolution postage stamp survey around the target in question, but how does this relate to a regional or route survey? See Figure7.
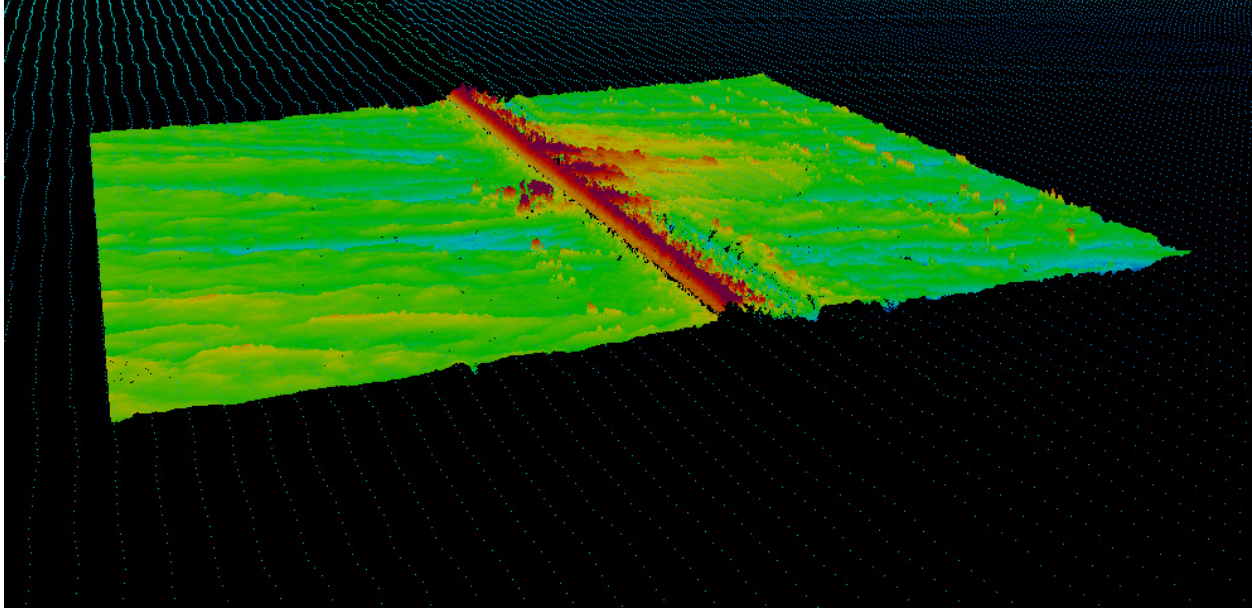
Figure 7. High resolution SAS with lower resolution side scan (data courtesy of Kongsberg Maritime)

This raises two questions: Can the control systems that guide the AUV to the target location be tuned for pipeline survey? In the pipeline case it would be critical to have high resolution data along its entire length. And can the data volumes generated from a large area, high resolution SAS survey be efficiently managed?

Data volumes and storage
As discussed earlier, SAS is capable of capturing very high resolution imagery and bathymetry. These high resolution datasets will demand lots of disk space, which is potentially problematic when considering that the SAS data is collected on an AUV that might be deployed for hours at a time. Add into the mix a gap filling sonar and the disk space requirements would get even more demanding, hydrography is entering the realm of "Big Data". A quick and coarse estimation suggests that 4 TBs of disk space may be required per 24 hours of high resolution data collection (imagery, bathymetry and photography). The time required to transfer this data from AUV disk to ship-based data storage will be greater than the time taken to acquire, therefore swappable drives would seem to be an essential part of the survey setup allowing the data to be read directly. The good news is the disk writing speeds appear to be capable of recording the required amount of data in real time.

Data conversion is a basic first processing step in most workflows; this would likely result in a duplicate file-set at least as large as the raw data itself. This process would also take a lot of time. When dealing with these perceived data volumes the need for onboard near real-time processing becomes quickly apparent; if data could be streamed directly into a batch processor capable of applying some basic processing steps like depth binding, sound velocity correction and was able to auto generate geo-referenced terrain models and image mosaics, then the size of deliverable coming from the AUV could become much more manageable. It would also reduce the amount of post processing time and effort required on the mother ship or in the office.

This batch processing concept was recently prototyped on a project between Liquid Robotics, Teledyne Odom and CARIS. In this experiment a compact multibeam was mounted on a wave glider and the data was collected and processed onboard through the CARIS HIPS batch processor resulting in the auto-generation of a near real-time CUBE surface. See Figure 8 and 9.
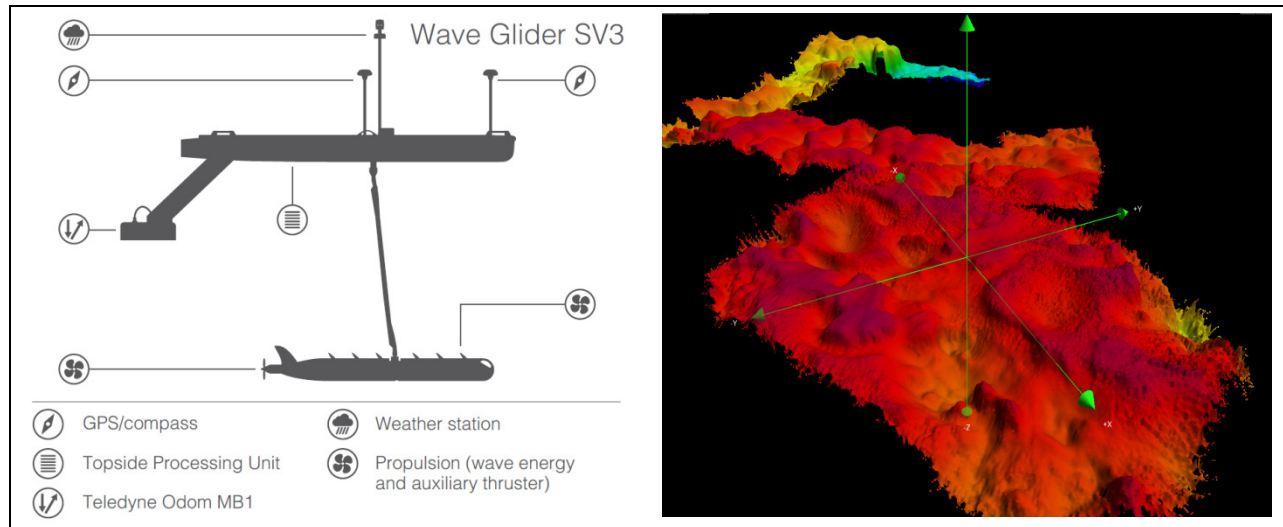

Figure 8. Wave Glider configuration   *Figure 9. Batch processed CUBE surface*

Noise cleaning

The SAS data imported in HIPS and SIPS to date has not required the removal of fliers or noise, this is probably because of the binning methods adopted to derive the bathymetry from the interferometry has essentially had a cleaning effect, also the AUV provides a quiet acoustic platform for collection so there is less noise than a ship or ROV mounted system. See Figure 10. If noisy data did exist in the SAS it will need to be removed in a quick and robust way, as the dataset sizes are going to be too large for manual cleaning. If there is an opportunity for onboard near real-time processing then automated cleaning should be part of the batch process; for regional surveys the creation of a CUBE surface would work well, for pipeline surveys a different process, such as a SCALGO filtering method, may be more appropriate.
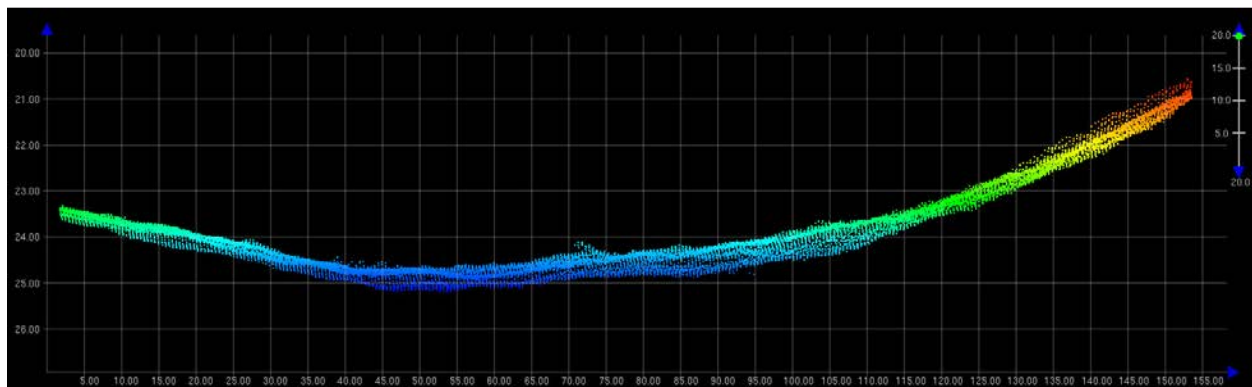

Figure 10. Stacked profiles of SAS bathymetry highlighting limited noise

Combining datasets

A key aspect of using SAS for hydrographic survey will be combining of port and starboard SAS data with data from the gap filling sonar. It is possible that the resolutions of these datasets may be slightly different, or that some areas of the coverage have greater density than others; these would be good candidates for the use of variable resolution gridding techniques, as this would ensure that optimal resolution is maintained in the most critical areas. In a pipeline survey, for example, the variability of resolution may be a function of data density as the pipe and its immediate corridor will be the area with the greatest coverage.

Grids and point clouds

When considering the validity of auto-generating terrains models onboard an AUV and also creating compressed images for real time quality control, the tendency would be to grid the data rather than to load it into a point cloud, largely because of the processing efficiencies of using a regular data structure over a random one. However, when surveying a pipeline it is much more useful to view the pipe as a point cloud rather than a grid. This is because a key part of the survey task is determining when the pipe is in free span. See Figure 11. A gridded representation always joins the pipe to the seafloor making free span detection much more difficult. See Figure 12. A point cloud output of the grid nodes could be one solution to this problem.
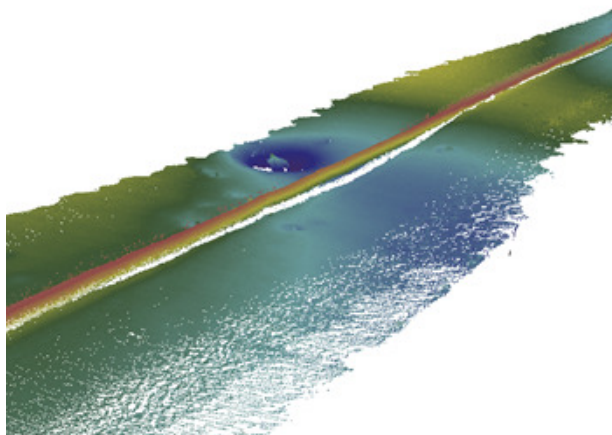

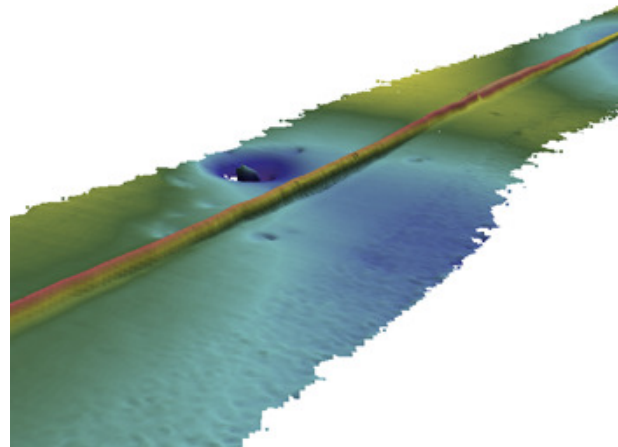*Figure 11. Point cloud of pipe with free span*   *Figure 12. Grid of pipe with free span*

Conclusion

Through the wider use of AUVs, SAS technology seems destined to become a multi-purpose surveying tool. Its ability to combine multiple observations in software provides higher resolution reflectivity and bathymetry that is constant right across the available range. The co-registered nature of the reflectivity and bathymetry data allows for excellent feature detection, paving the way for more intuitive data inspection and quality control.

To use SAS effectively as a hydrographic sensor survey line planning is an important aspect; the use of SAS with a gap filling sonar also highlights the need for sophisticated dataset combination. Typical post

processing activities related to navigation and depth are well understood, but the requirements around motion and sound velocity correction still require further investigation.

Perhaps the biggest challenge on the use of SAS in hydrographic survey will be around data density. This will likely drive the need for onboard near real-time data processing capable of producing datasets that require minimal further human interaction.

When an end user is provided with co-located high resolution bathymetry, reflectivity mosaics and accompanying photography in critical areas, they will be ready to make more informed decisions that are befitting of the Big Data age.