SIGNAL PROCESSING FOR THE SENSOTEK INTERFEROMETRIC SAS: LESSONS LEARNED FROM HUGIN AUV TRIALS

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1 INTRODUCTION

The Norwegian Defence Research Establishment (FFI) and Kongsberg Maritime AS have an ongoing program to develop synthetic aperture sonar (SAS) technology for the HUGIN autonomous underwater vehicle (AUV). The program includes the development of a wideband multi-aspect interferometric SAS, named SENSOTEK[1,2], which was installed on the HUGIN I AUV in March 2005 and has been tested in numerous sea trials (see Figure 1). FFI has developed a full software suite for processing of SAS data, named FOCUS toolbox[3,4]. The toolbox includes integrated sonar and inertial navigation, fast SAS image formation, autofocus and interferometry.

Prior to the deployment of SENSOTEK SAS, the FOCUS toolbox was used with the EdgeTech 4400-SAS sonar on another HUGIN vehicle. The EdgeTech SAS is a quite different and much simpler sonar design. The requirement for FOCUS to handle both these systems (as well as several others) has substantially increased its robustness and flexibility.

In this paper, we list some lessons learned in SAS signal processing on data collected from HUGIN AUV trials.

Figure 1 The SENSOTEK SAS installed on the HUGIN I AUV. From a sea trial in March 2005.

2 SAS SIGNAL PROCESSING

The basic processing flow of SAS data in the FOCUS toolbox is shown in Figure 2. Typically, the processing consists of four stages:

1. Motion estimation by fusion of the aided Inertial Navigation System (INS) on HUGIN[5] and sonar micronavigation by the Displaced Phase Centre Antenna (DPCA) technique[6,7].
2. Image formation by the wavenumber algorithm[8] (also known as the Range Migration Algorithm (RMA), or Stolt migration), or by backprojection[9] (or time-domain interpolation beamforming). The wavenumber algorithm is fast, but assumes the synthetic aperture to be

a straight line with equispaced elements. This is achieved by motion compensating the data onto a straight line.

3. Autofocus is blind correction of uncompensated motion errors (run after image formation), typically by Phase Gradient Autofocus (PGA)[10] or one of its variants[11].
4. Relative seafloor height estimation either by interferometry (phase differencing)[10] or by cross correlation based direction of arrival estimation[12,13].

See[3,4] for more details on the FOCUS toolbox and the integration in HUGIN AUV.

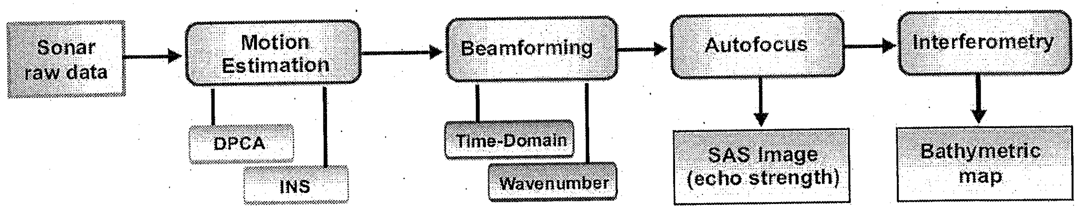

Figure 2 Overview of the basic building blocks in the signal processing of SAS data.

2.1 SAS Image Defects

SAS imagery, in common with SAR, requires accurate sonar position estimation to operate successfully. This requirement is such that there is always some practical positioning error that causes image degradation. SAS differs from typical SAR systems in that an along-track receiver array is necessary to ensure adequate sampling at useful mapping rates. This alters the motion accuracy constraints from those typically discussed in SAR. In particular, the along-track array suffers from rotation misalignments or angle errors. This causes grating lobes at the locations marked in Figure 3. In addition, multiple receiver SAS arrays are insulated somewhat from the high-frequency errors and so tend to have smaller regions of blurring than SAR systems. Other types of motion estimation errors also increase grating lobe levels. Blurring is less commonly seen in our sea-trial experience and appears to be caused primarily by incorrect estimation of sound speed. Both grating lobes caused by incorrect topographic estimation and sound-speed error induced image defects are covered in later sections.

3 LESSONS LEARNED

From the very beginning, an important tenet of the HUGIN AUV program has been to use the sea as our laboratory. New concepts, new techniques and new subsystems are tested at sea early in the development cycle, instead of spending large amounts of time in simulations before the first sea trials. We believe that bringing the systems to the sea, while obviously not completely risk-free, results in a much steeper learning curve and frequently provides new insights that simulations cannot. By going to sea early, lessons learned from sea trials can be fed back to the development process at an early stage, while there is still room for major design changes. Kongsberg Maritime's development and manufacturing facility in Horten, Norway is set up so that HUGIN sea trials can be performed at modest cost and only a few days' notice.

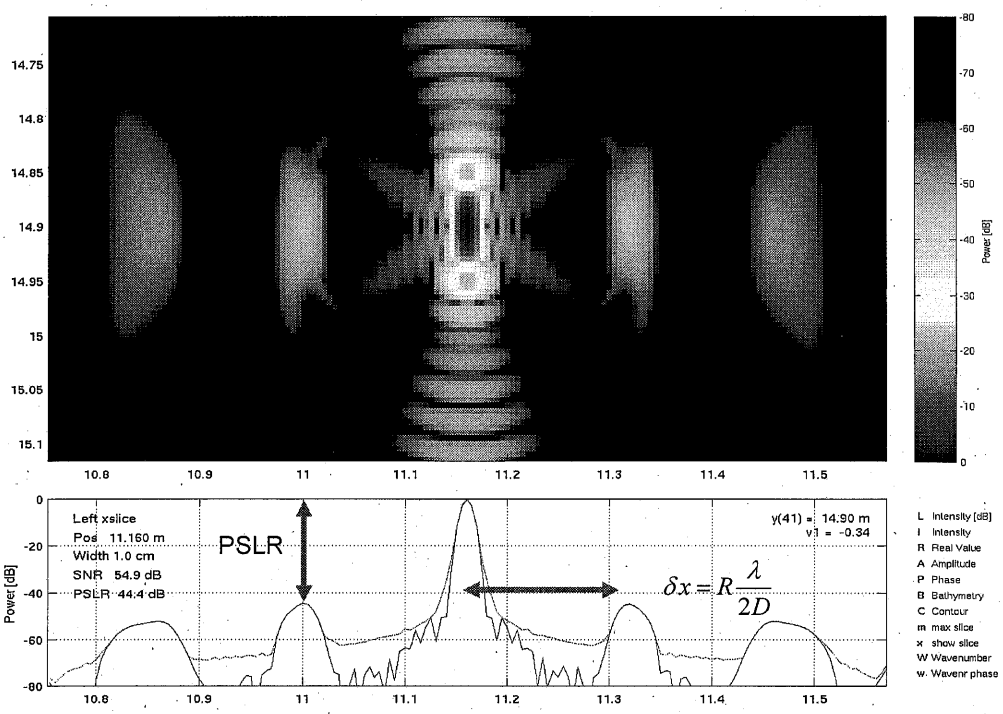

Figure 3 SAS shows artifacts in simulated imagery caused by processing with a constant incorrect yaw value.

3.1 Vehicle Motion

Deviation of the synthetic array from a straight line should be avoided as much as possible in practice. In AUV scenarios this can be difficult, verging on impossible, in some situations. Non-straight motion necessitates more effort in correcting and estimating topography and decreases the likelihood of success in motion estimation.

3.1.1 Crab

Horizontal crabbing is typically caused by transverse currents. Although the platform still moves along a straight line, both relative to the water volume and the seafloor, the direction of travel is not parallel with the platform's fore-aft (x) axis. This can cause image artefacts if not correctly compensated for. Unknown constant crabbing (constant yaw value) is typically caused by insufficient or varying sensor alignment. and can cause grating lobes such as those shown in Figure 3. Even when the crab is known, the synthetic array becomes non-linear, causing other problems. DPCA for example has poorer performance because the redundant phase centres are physically not aligned and biases occur.

Vertical crabbing, typically caused by incorrect vehicle trim or ballasting, causes similar problems.

3.1.2 Attitude Rate

Attitude rates can often become excessive in AUV missions, e.g. when operating close to the surface, in varying currents, when following rough terrain, or due to oscillations in the depth/altitude/heading/speed/roll control loops. This can cause a number of problems for SAS processing with multiple-receiver arrays:

- Signal aliasing and undersampling (same as SAR)

- Uneven illumination
- Uneven synthetic aperture positioning (element displacements)
- Difficulty in interferometric processing

These problems are also exacerbated by large constant attitudes. In general, attitude rates should be kept as low as practically possible when conducting SAS missions.

3.2 Topography

SAS data is collected in a 3D environment where both seafloor and the path of the sonar can vary arbitrarily in space. Coherently reconstructing a SAS image therefore requires knowledge of both the sonar path and the seafloor bathymetry[10]. An exception to this is when the sonar travels on a perfectly straight line, when symmetry in the imaging process ensures focused images independent of topography.

AUVs typically run with a fixed altitude above the seafloor. When the topography varies, the altitude following AUV will exhibit highly nonlinear motion, which again causes strict requirements on the a priori height accuracy[10]. From experimental data we have observed that using the AUV altimeter and depth sensor for seafloor depth estimation is sufficient to focus SAS images when the AUV runs on a straight line (constant depth), while it may be insufficient when the AUV is running with a fixed altitude in topography. In a collaboration between FFI's SAS and AUV developers, novel control strategies are being developed and tested to minimise pitch rates while still maintaining near-optimal altitude above the seabed in rugged terrain.

Figure 4 shows the estimated sidescan bathymetry from an area with varying topography, and Figure 5 shows the improvement attained by estimating and using the seafloor bathymetry in the SAS imaging. The bathymetry in this area is relatively benign, but there is still significant improvement in the final image. Such improvements are only seen however when DPCA is not used for motion estimation. DPCA also corrects some of the errors induced by using the wrong bathymetry in the imaging; DPCA estimates the wrong path but one which makes for better imagery. Equivalently, estimating the bathymetry from SAS images can remove motion errors, since motion errors and bathymetry errors couple in the SAS imaging. But only by knowing both the sonar path and the bathymetry will the images focus in all environments. To decouple the sonar path and the bathymetry, we use sidescan height estimation before DPCA and SAS beamforming.

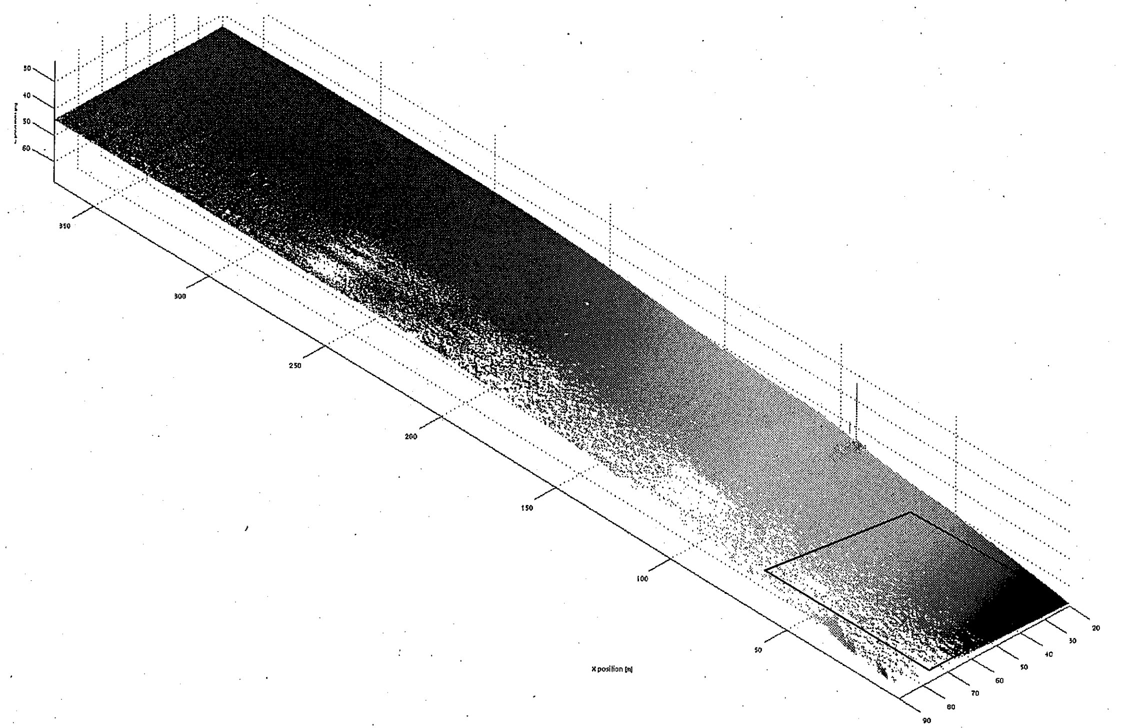

Figure 4 Estimated sidescan bathymetry for a 370 by 70 metres area, where the depth varies from 42 to 62 metres. Figure 5 shows SAS images from the area marked by a black rectangle.

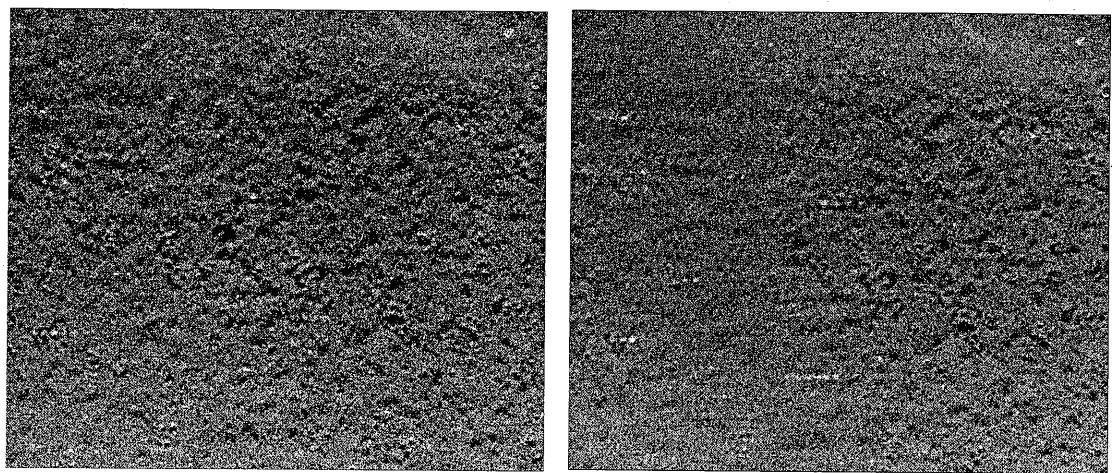

Figure 5 SAS images from the 45 by 40 metre area marked by a black rectangle in Figure 4. The left panel shows the SAS images with the sidescan seafloor depth as a priori input in the beamforming and the right panel shows the corresponding image when using the AUV's altimeter for seafloor depth estimation.

3.3 Sound Velocity Variations

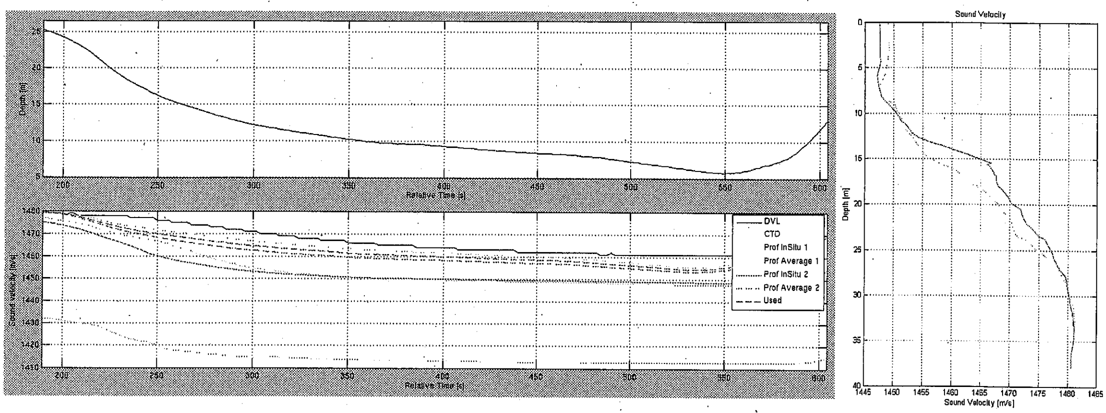

Figure 6 Vehicle depth (upper left) and various logged and calculated sound velocities (lower left). The right panel shows two different CTD profiles taken in the area during the mission. (The large discrepancy between DVL and CTD sound speed estimates are caused by a malfunction in the CTD's conductivity sensor during this mission.)

An important consideration in SAS imaging is motion estimation to sub-wavelength accuracy; variations in the wavelength can also be important. Sound speed variations during imaging can cause various forms of image degradation, the most important being defocus. A recent trial in a region with large quantities of ice-melt freshwater gives an indication of the challenges inherent in shallow-water imaging. As can be seen in Figure 6, sound speed varies sharply with depth. To a first-order approximation, the sound speed used in imaging should be the average value between sonar and sea floor instead of that measured at the sonar.

Three images are shown below having been processed at an average sound speed of 1449, 1459, and 1469 m/s, respectively. The first value is equivalent to using the sound speed measured at the sonar. The second is an integral of averaged CTD profiles between the sonar and the sea floor. The third corresponds to an estimated profile based on DVL sound speed measurements. All images use an identical navigation solution and the only parameter varied is the speed of sound used in the imaging.

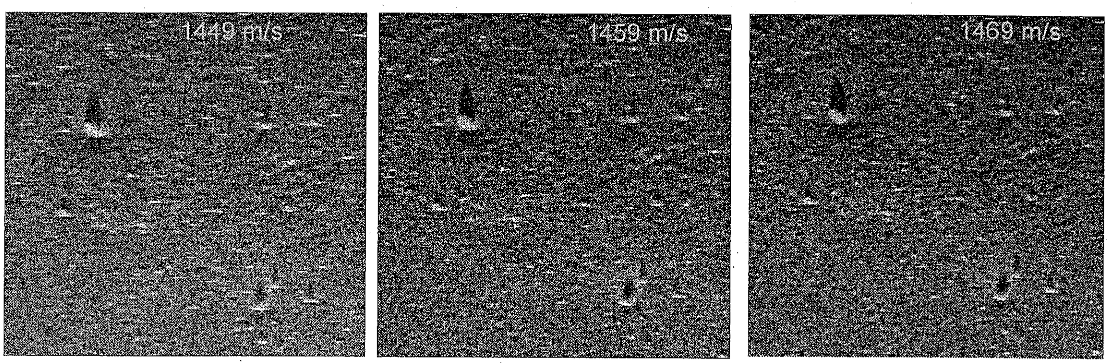

Figure 7 SAS images of a 16 x 16 m scene at the seafloor, with three different sound velocities. Images are created from 400 to 450 seconds after the start of mission line in Figure 6.

Of the images, the qualitative best is the one using an average sound speed of 1469 ms^{-1}. A more quantitative measure is gained by autofocusing the images using PGA and parameter fitting the sound-speed to the error-estimates. From the images above, derived sound-speed estimates were respectively 1466.0, 1469.1, 1475.9. These measures would indicate the third image also is judged to be best by a score based on minimum autofocus phase-error. It should be noted that the post-autofocus images from all three sound speeds have better quality than that in the third image. indicating autofocus is successful at removing this type of imaging error.

PGA in particular performs well in estimating phase variations induced by incorrect sound-speed. Constant errors in sound-speed cause along-track invariant defocus and thus match closely the spotlight SAR phase-errors PGA is designed to estimate. The strip-map system model that makes PGA unsuited for SAS sway estimation is not needed for sound-speed estimation.

Whilst the effect of incorrect sound-speed is highly system dependent, sound-speed estimates will need to be made with errors less than 10 ms^{-1} (1%) if no autofocus is to be used. From these results, it can be seen that use of sound-speed measurements at the sonar height may not be accurate enough to allow imaging without subsequent autofocus.

3.4 Multipath

Imaging at long range in shallow-water will always be limited by multi-path and direct surface returns. Sonar design can limit multi-path through beam shaping but some unwanted interference will still exist.

SAS has been proposed as a method for reducing the effect of multi-path through coherent averaging. The time-varying interference component of the received echo will not combine coherently and thus the coherent sea-floor signal can be enhanced through SAS processing.

As the SENSOTEK SAS has the ability to receive echoes on its dense transmitter array, the amount of multi-path present can be measured along with its effect on SAS image quality.

An example of this effect in 15 m water depth over a highly reverberant sea-floor is given here. Figure 8 shows a traditional unfocused image where the vertical array is beamformed from -90 to 90 degrees, with a guide to interpreting multipath and surface returns. Note that the vertical array is tilted 22 degrees down from the horizontal.

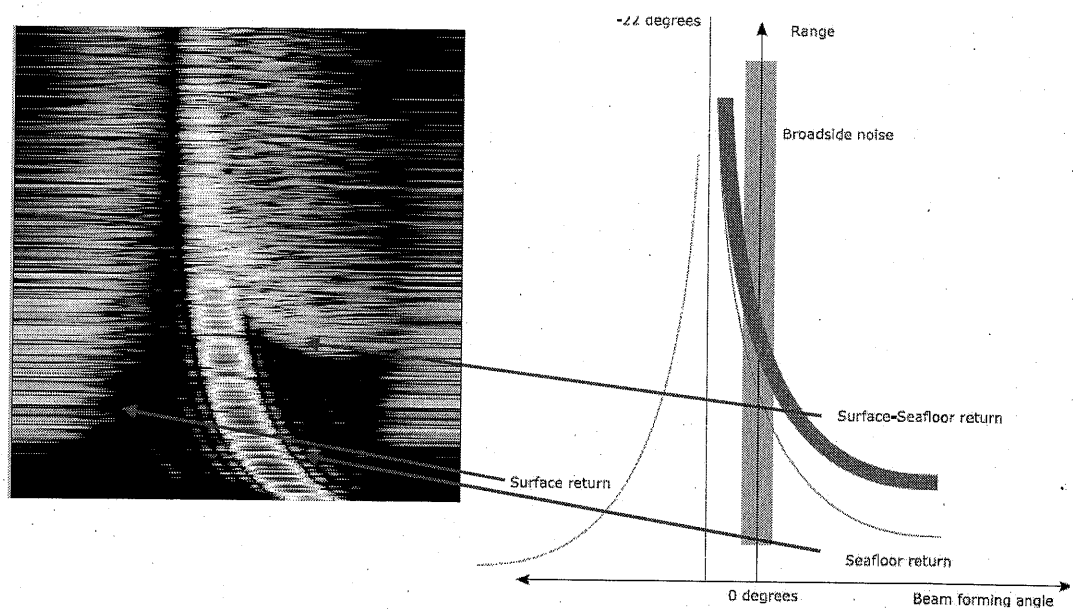

Figure 8 Beam pattern from the vertical array -90 to 90 degrees from a ping in shallow water (left), with a simple interpretation of seafloor echo, surface return and multipath (right).

From these images it is clear that there are large amounts of both direct surface return and surface-seafloor-sonar echoes. The latter noise source reaches the energy level of the direct return at approximately 45m range. As that particular multi-path source is within the receiver's beam pattern it is a directly contributing noise source in SAS imagery.

The effect of this multi-path may be seen in Figure 9. Image contrast is lower than in other images taken on the same survey line and as range increases, contrast decreases through what appears to be an increase in noise-floor level. As multi-path interference is not coherent it will not appear to have structure in SAS images and instead appear as noise floor.

Confirmation of this performance loss may be found in the DPCA coherence estimate for the same image. The coherence is a direct measure of achievable signal to noise on redundant receivers (i.e., receivers that should measure exactly the same seafloor echo with different illumination pings). Coherence levels of 0.5 correspond to an SNR of 0 dB.

From the data shown it is apparent that multi-path coming from the surface-seafloor path causes a decrease in SAS image contrast and SNR. The transmitter configuration should be altered to avoid directly illuminating the surface to improve quality. It is interesting to note that the SAS image SNR is much higher than the (non-SAS) matched filtered echo SNR, this partly confirms the hypothesis that SAS has significant advantages in multipath resistance.

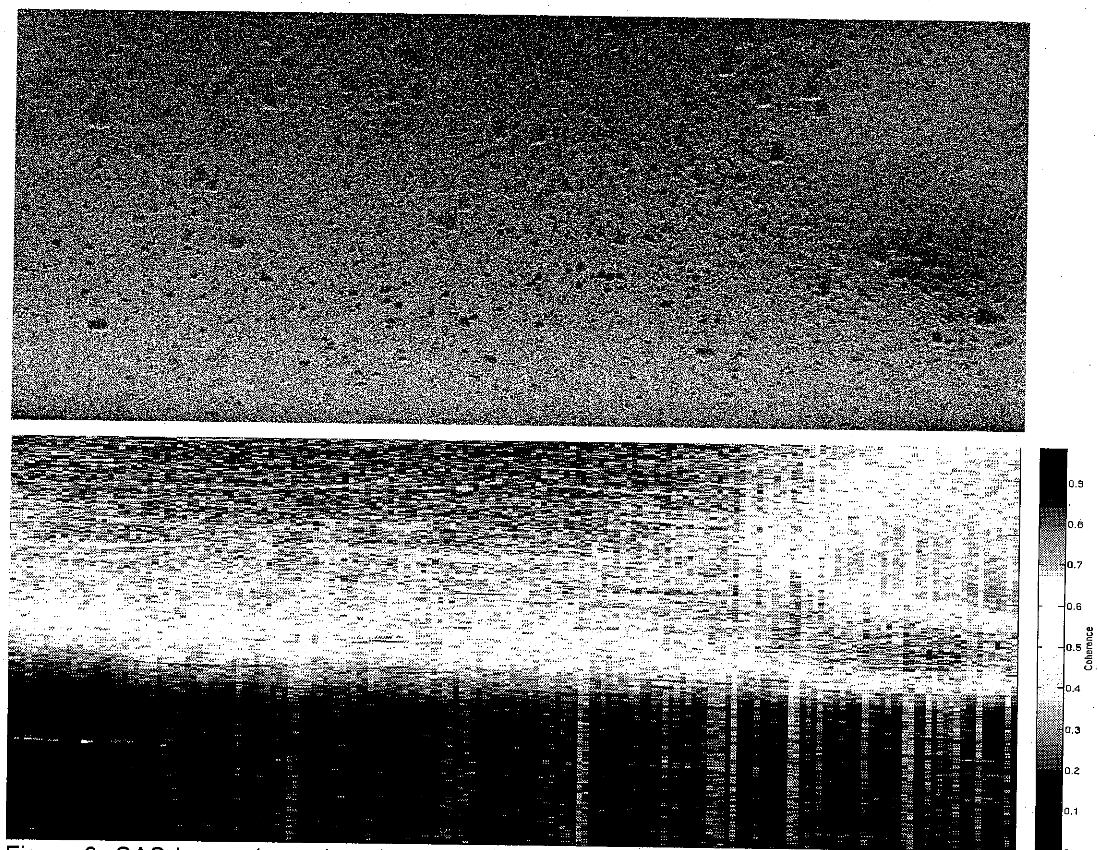

Figure 9 SAS image (upper) and DPCA coherence (lower). Range is from 15 – 65 m, and along-track span is 65 m for 200 pings at shallow waters.

3.5 Other limitations

3.5.1 Acoustic Interference

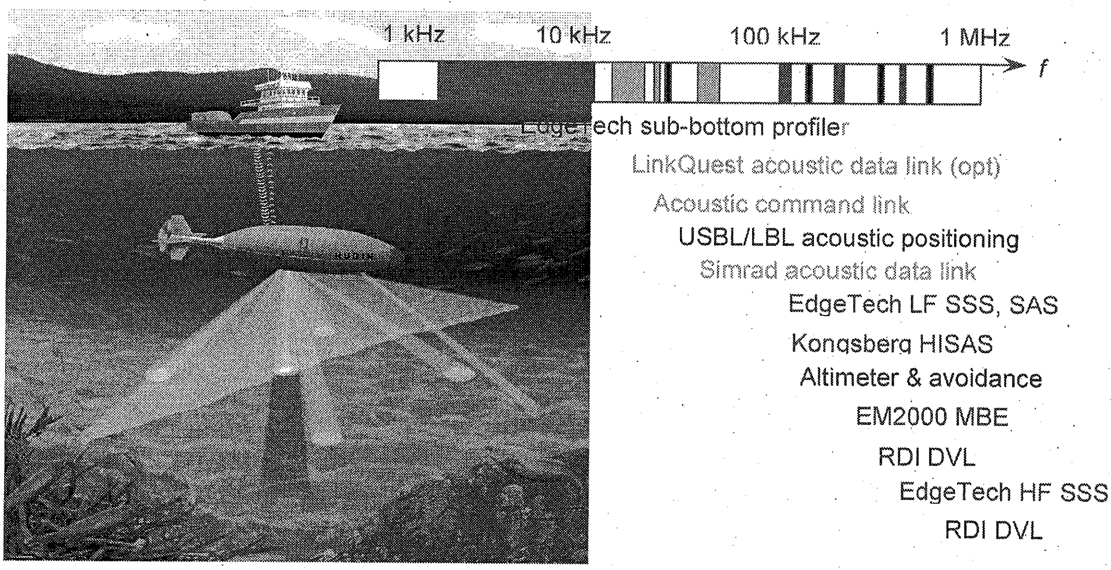

Figure 10 Overview of possible acoustic subsystems on the HUGIN AUV.

HUGIN AUVs are equipped with a multitude of active acoustic devices: Acoustic communication and positioning systems, Doppler velocity log, altimeter(s), obstacle avoidance sonar, various possible payloads – in addition to the SAS system. A substantial effort is made to minimise the possibility of acoustic interference between these systems (frequency band separation, synchronised transmission, etc). Still, with such a saturated frequency spectrum, acoustic interference will occur, e.g. from higher-order harmonics of a low-frequency transmitter.

The fact that SENSOTEK SAS works over a wide frequency band (virtually any range within 60-120 kHz) further increases the probability of interference. On the other hand the wide frequency range also makes the system more robust. Wide beamwidths also help make the system more robust. Short, narrow-band interference pulses can sometimes be seen in single ping imagery from SENSOTEK, but the effect is almost negligible in the final SAS imagery, as the noise is spread out through SAS processing over the entire beamwidth. While this increases the noise-floor there are fewer objectionable image artefacts.

3.5.2 Transmit interval jitter

For good navigation performance, the sonar array should be displaced an integer number of phase centres between each ping. In SENSOTEK, the along-track distance between phase centres is 7.5 mm. At the nominal AUV speed of 4 knots, this corresponds to less than 4 ms of AUV travel time. To achieve a given integer distance within ±10%, a trigger precision of ±0.75 mm or ±400 μs is thus required. (For a simpler design such as the EdgeTech 4400-SAS, the distance between phase centres is 10 cm and the time 50 ms.)

In HUGIN, constant distance triggering is achieved by integrating the velocity estimates from the real-time navigation system (or, as a fallback, directly from the Doppler velocity log). Noise in the DVL measurements, finite resolution in the trigger timer and other effects may cause deviations from the integer phase centre displacement.

The consequences of missing the integer phase centre overlap diminish as element size decreases and receiver beamwidth increases relative to the transmitters beamwidth.

4 SUMMARY

This article has highlighted some of the potential difficulties in producing high-quality imagery from an AUV mounted high end synthetic aperture sonar. The HUGIN team's philosophy of bringing new concepts to sea at an early stage has allowed us to learn what the main issues are, and how to deal with them. The ability to perform AUV sea trials at short notice and moderate cost means that the SENSOTEK and EdgeTech SAS systems have been operated across a wide range of scenarios – very shallow, shallow and deep water; flat, moderate and extreme bathymetry; varying sound speed; and with various sensor and equipment malfunctions.

The close interaction between the AUV and SAS system developers also mean that problems can be dealt with at the appropriate place – where they cause the least amount of work.

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