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The SENSOTEK Synthetic Aperture Sonar:
Results from HUGIN AUV trials

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Sammendrag

FFI har et samarbeid med Kongsberg Maritime for utvikling av syntetisk aperture sonar (SAS) teknologi for HUGIN autonom undervannsfarkost (AUV). Som en del av dette samarbeidet er en bredbåndet, bredstrålet interferometrisk SAS, kalt SENSOTEK SAS, utviklet. Systemet ble installert på FFIs egen HUGIN I farkost i 2005, og har blitt testet mange ganger under forskjellige forhold og på vanndyp fra 10 m til 200 m.

SENSOTEK SAS har en teoretisk oppløsning i nærheten av 1 cm, noe som er radikalt bedre enn tradisjonell sidescan sonar teknologi. Systemet er også utstyrt med to fullengde mottakerarrayer, noe som gir mulighet for kartlegging i høy oppløsning i samme areal som er dekket av den avbildende sensoren.

Systemet brukes til prototyping av SAS signalbehandlingsprogramvare, sonar design og teknologidemonstrasjoner. Det tjener som prototype i HISAS produktserien fra Kongsberg Maritime. I løpet av 2007 vil Sjøforsvaret motta sin andre HUGIN 1000, utstyrt med et HISAS 1030 SAS system. Dette er andre generasjon SAS-system basert på erfaringer gjort med SENSOTEK-systemet.

Denne rapporten beskriver SAS-systemet i detalj, og viser eksempler på SAS-bilder av forskjellige objekter på havbunnen.

English summary

The Norwegian Defence Research Establishment (FFI) and Kongsberg Maritime have an ongoing programme to develop synthetic aperture sonar (SAS) technology for the HUGIN autonomous underwater vehicle (AUV). As part of this programme, a wideband multi-aspect interferometric SAS, named SENSOTEK, has been developed. The system was installed on FFIs own research vehicle HUGIN I in 2005, and has been tested on numerous trials in various conditions and water depths from 10 m to 200 m.

The SENSOTEK SAS has a theoretical resolution that approaches 1 cm, which is radically better than conventional sidescan sonar technology. The system is also equipped with two full-length receiver antennas, giving the ability of seafloor mapping in the same swath as the high resolution imaging.

The system is used for prototyping of SAS signal processing software, sonar design and technology demonstrations. It is also the prototype in the HISAS product series manufactured by Kongsberg Maritime. In 2007, the Royal Norwegian Navy will receive their second HUGIN 1000, equipped with a HISAS 1030 system. This is a second generation SAS system heavily based on the learnings from the SENSOTEK system.

This report describes the SAS system in detail, and shows example imagery of various targets on the seafloor.

Contents

1 Introduction

1.1 The SENSOTEK project

Figure 1.1: SENSOTEK SAS on the HUGIN I AUV during recovery.

In 2000, the Norwegian Defence Research Establishment (FFI), Kongsberg Simrad AS (now Kongsberg Maritime) and Simrad AS, started a project named SENSOTEK to develop a synthetic aperture sonar (SAS) for the HUGIN autonomous underwater vehicle (AUV). FFI's part of this joint project was performed in FFI Project 808 "Sensorteknologi for AUV-basert minejakt (SENSOTEK)". No funding was exchanged between FFI and Kongsberg; each partner financed their part from internal R&D funding. The main tasks in the project were:

- Interferometric SAS design (KM/FFI)
- Prototype sonar production and AUV integration (KM)
- Development of a complete SAS processing suite (FFI)

Project 808 ended in 2004, and FFI's work was continued in Project 850 "HUGIN MRS, utvikling". In March 2005, the first sea trial was conducted with the prototype sonar, named SENSOTEK SAS. Since then, the system has been tested in numerous sea trials under different configurations and different environmental conditions. Figure 1.1 shows the SENSOTEK SAS on the HUGIN I during recovery on Simrad's test and demonstration vessel Simrad Echo. The sensor was designed specifically to be a high-end system; to serve both as a technology demonstrator and a prototype for reduced-complexity systems.

The end result of the SENSOTEK joint project was (1) a new range of products from Kongsberg Maritime, the HISAS 1000 series of interferometric SAS systems, and (2) the *FOCUS synthetic aperture signal processing toolbox* from FFI. As of today, four HISAS 1030 systems have been sold (to the Norwegian and Finnish navies).

This report describes the prototype system. A wide range of results obtained from several sea trials with the SENSOTEK SAS mounted on the HUGIN I AUV, and processed with the FOCUS toolbox, are included in the report.

1.2 Current Development

The Royal Norwegian Navy (RNoN) has ordered their second HUGIN AUV, to be delivered in 2007. The new vehicle, called HUGIN 1000-MR [13], features a number of enhancements based on 4-5 years of operational experience with HUGIN AUVs in the RNoN. Principal applications for the HUGIN 1000-MR will be mine countermeasures (MCM) and rapid environmental assessment (REA). A new high-resolution interferometric SAS from Kongsberg, the HISAS 1030, will be the main payload of the new vehicle. This is the next generation SAS with a number of improvements over SENSOTEK SAS.

FFI continues to develop key technologies such as automated target recognition (ATR), vehicle autonomy, sensor autonomy and synthetic aperture imaging techniques in general. The SAS research will be directed towards towards specific topics such as image enhancement related to ATR, high resolution bathymetry and robust and fast streaming SAS.

FFI also actively participates in the NATO Undersea Research Centre's joint research program on Mine Detection and Classification, where SAS technology is a primary topic. The SAS development at FFI has been an integrated part of the HUGIN AUV development. Today, the SAS development runs in two different projects: 1075 SENSOTEK II further develops key SAS technology; 1032 AUTOTEK II includes development of sensor autonomy for AUV operations. The SAS team at FFI also collaborates with SAR projects at FFI.

Figure 1.2: HUGIN 1000 on the aft deck of the RNoN mine hunter HNoMS Karmoy in 2005.

1.3 Principle of Synthetic Aperture Sonar

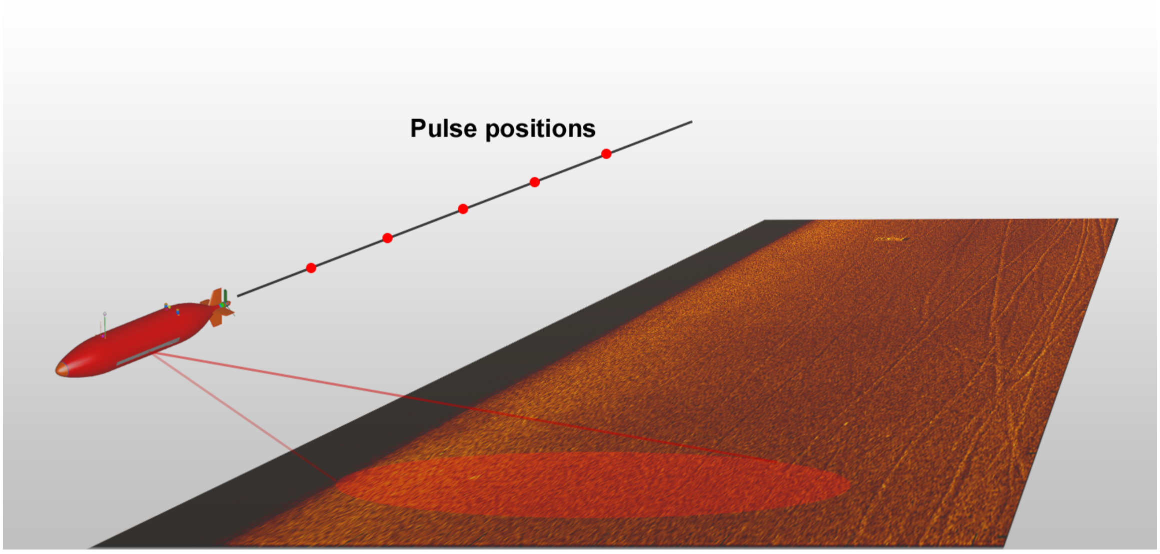


Figure 1.3: Principle of synthetic aperture sonar.

The principle of synthetic aperture sonar is to combine successive pings coherently along a known track, in order to increase the azimuth (along-track) resolution (see Fig. 1.3). Ideally, the synthetic array length increases with range, such that the along-track resolution becomes independent of frequency and range [4]. Thus, SAS technology is not as limited by either range or resolution as practical sized sidescan sonars are. SAS has the potential to produce high resolution images with large area coverage rates, and is therefore very attractive in effective detection and classification of small, man-made objects.

The challenge in SAS imaging is that elements along the synthetic array have to be positioned to within a fraction of a wavelength [18]. For a typical SAS system, this is equivalent to millimetre relative position accuracy within tens of metres flight. In general, such navigation accuracy is very difficult to obtain from an inertial navigation system alone, or from sonar navigation alone. Optimum fusion of inertial navigation and sonar navigation has potential to obtain the required navigation accuracy [16].

A fundamental limitation of SAS is the along-track sampling criterion [5], which leads to the design of multiple-receiver systems. The length of the receiver array gives the area coverage rate (or sonar range for a given speed) [11, 10], while the element size in the receiver array gives the along-track resolution (independent of range) [4].

2 The SENSOTEK System

Figure 2.1: SENSOTEK SAS mounted on the HUGIN I AUV, October 2004.

The SENSOTEK interferometric synthetic aperture sonar is designed to be a flexible high end technology demonstrator. The system is integrated on FFI's research vehicle HUGIN I AUV as shown in Fig. 2.1. Note that the receiver arrays are actually slightly too large to fit well onto the vehicle's double-curved hull. The system has been tested on numerous sea trials since early 2005. Figure 2.2 shows the system and the vehicle during launch from M/S Simrad Echo on the very first sea test March 17, 2005. See section 5 for a complete list of completed missions with the SENSOTEK SAS.

Figure 2.2: HUGIN I AUV with SENSOTEK during launch from M/S Simrad Echo on the very first test March 17, 2005.

2.1 Technical Specifications

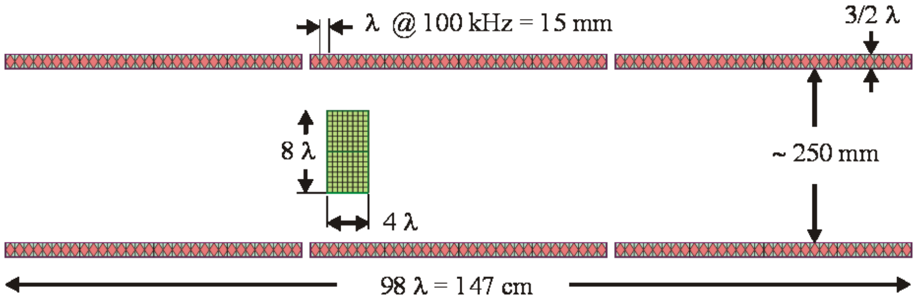


Figure 2.3: Transducer outline of the SENSOTEK interferometric SAS.

The transducer geometry is outlined in Fig. 2.3. The system has the following specifications:

- Two full length receiver arrays with 96 elements each, where each element is one wavelength, λ, at 100 kHz. The receiver arrays have a modular design, where each module consists of 32 channels. The total length is 147 cm. The vertical displacement is approximately 25 cm. The modular design gives flexibility in sonar configurations. It is however suboptimal from a SAS point of view. This was accepted for the prototype as a trade-off between performance and structural complexity.
- The transmitter is a two-dimensional phased array with 8×16 elements of size $\lambda/2$. The individual elements are symmetrical coupled together in the horizontal plane, giving a programmable beamwidth in the horizontal plane, and variable look direction and beamwidth in the vertical plane. The transmitter can defocus the beam both horizontally and vertically, in order to produce high transmit power over large beamwidths.
- The transmitter array has the ability to receive on 64 channels, giving a small, dense, vertical receiver array.
- The frequency band can be selected within 50 - 120 kHz. The system is however limited by the sampling rate in the data acquisition system, which has a maximum around 60 kHz.
- The transmit waveform is fully digitized, such that any waveform can be selected. Preprogrammed waveforms are: gated continuous wave (ping), linear frequency modulation (LFM or chirp) and hyperbolic frequency modulation (HFM). The default setting is LFM upchirp. The pulse length is programmable, and is typically 4 ms or 8 ms. There is a limitation on the duty-cycle, which restricts the pulse length to the ping interval.

These rather high specifications come at a price. Run at maximum bandwidth, the system collects 61 MB/s or 214 GB/hour. Designed as a technology demonstrator and not an operational system, SENSOTEK SAS does not have any real-time wet end processing of data.

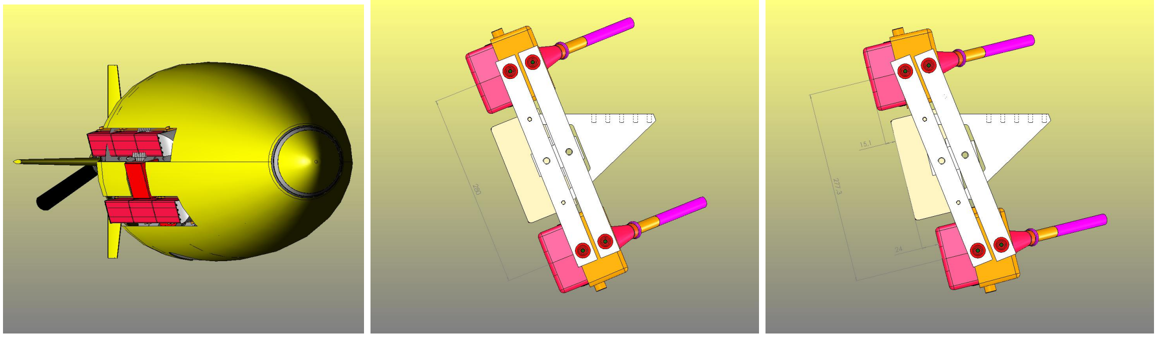


Figure 2.4: Integration of the SENSOTEK system onto HUGIN I. The mechanical tilt angle can be varied.

2.2 Theoretical Performance

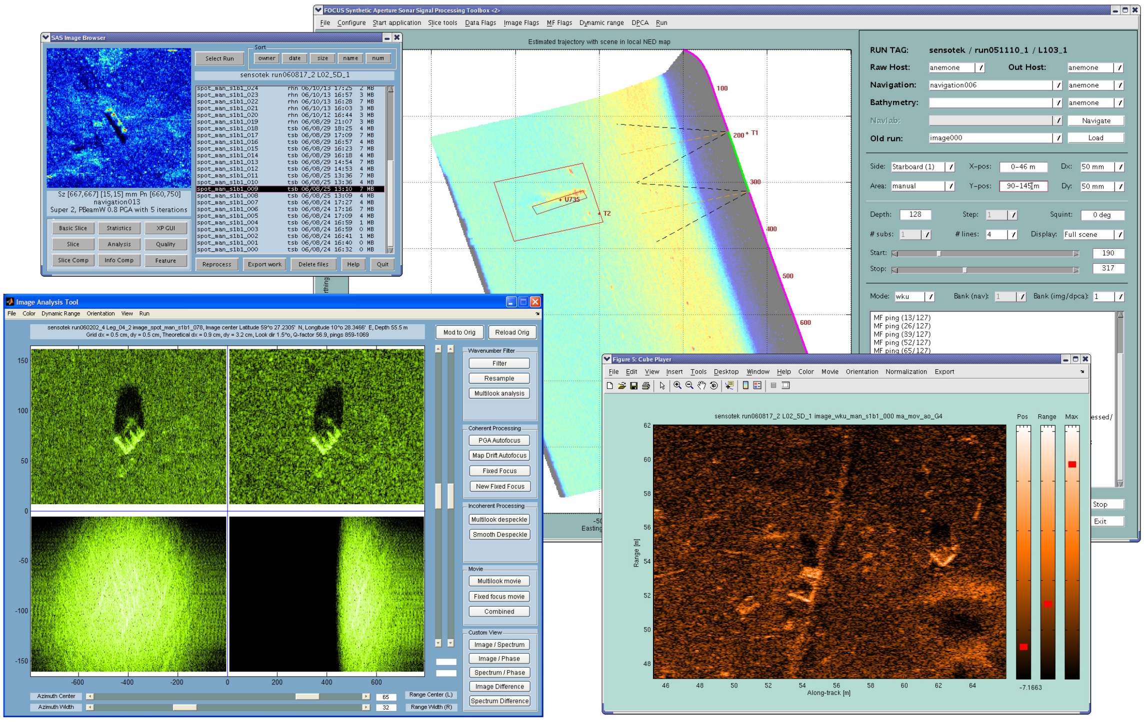
The theoretical performance of the system is:

- 1 cm along-track and 1.5 cm cross-track resolution, independent of range, given sufficient navigation accuracy.
- 60° aspect capability at 100 kHz on the receiver elements.
- 270 m range at 2.0 m/s vehicle velocity. The practical range is, however, currently limited by the self-noise. This has been addressed in the new HISAS system [13].
- Possibility for bathymetric mapping in near full resolution up to full range.

2.3 Mechanical Integration on HUGIN I AUV

The vertical tilt of the receiver arrays and the transmitter array can be mechanically varied 15 degrees around 22 degrees below the horizon, as outlined in Fig. 2.4. Note that the receiver arrays are behind the transmitter at the symmetry angle 22 degrees. The three transducers are never in plane. This was a compromise to fit such a large sonar with such vertical baseline on the HUGIN I AUV.

3 FOCUS SAS Signal Processing Toolbox



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spot_man_s1b1_023    rhn 06/10/13 16:57  3 MB
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Sz [667,667] [15,15] mm Pn [660,750]
navigation013
Super 2, PBeamW 0.8 PGA with 5 iterations

sensotek run060202_4 Leg_04_2 image_spot_man_s1b1_078, Image center Latitude 59^o 27.2305' N, Longitude 10^o 28.3466' E, Depth 55.5 m
Grid dx = 0.5 cm, dy = 0.5 cm, Theoretical dx = 0.9 cm, dy = 3.2 cm, Look dir 1.5^o, Q-factor 56.9, pings 859-1069

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Out Host: anemone
Navigation: navigation006 anemone
Bathymetry: anemone
Navlab:
Old run: image000
Side: Starboard (1)
X-pos: 0–46 m
Dx: 50 mm
Area: manual
Y-pos: 90–145 m
Dy: 50 mm
Depth: 128
Step: 1
Squint: 0 deg
subs: 1
lines: 4
Display: Full scene
Start: 190
Stop: 317
Mode: wku
Bank (nav): 1
Bank (img/dpca): 1

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MF ping (13/127)
MF ping (26/127)
MF ping (39/127)
MF ping (52/127)
MF ping (65/127)
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sensotek run060817_2 L02_5D_1 image_wku_man_s1b1_000 ma_mov_ao_G4

Figure 3.1: Different GUIs in the FOCUS toolbox.

FFI has developed a complete software suite for processing of SAS data, named *FOCUS toolbox* [15]. The toolbox can process data in a variety of different ways, including: Fully automated (with no user interaction) on all raw data; User selected areas with specified quality; Full user control of all the processing details. Figure 3.1 shows different expert level GUIs for operating FOCUS during processing and analysis of SAS data. Note that FOCUS toolbox is not intended to be a post mission analysis (PMA) tool. FOCUS is, however, designed to interface a PMA tool as described in [12].

The toolbox is generic and flexible and can easily be ported to support any SAS/SAR system. Currently FOCUS supports four different systems: 1) The SENSOTEK SAS system described in this report; 2) The Edgetech 4400 SAS for the HUGIN 1000 AUV owned by the RNoN [17]; 3) The InSAS prototype manufactured by DERA (now QinetiQ) used under the InSAS-2000 trials [16]; 4) The E-SAR experimental airborne SAR from DLR.

FOCUS toolbox

FOCUS toolbox is a software package for signal processing of synthetic aperture sonar and synthetic aperture radar data. FOCUS is entirely developed at FFI, and more than 10 man-years has gone into its development. The toolbox serves two purposes: It is a high powered tool for research and development; Parts of the toolbox are integrated into the HISAS product series sold by Kongsberg Maritime. FOCUS toolbox continues to be developed by the SAS team in various FFI projects.

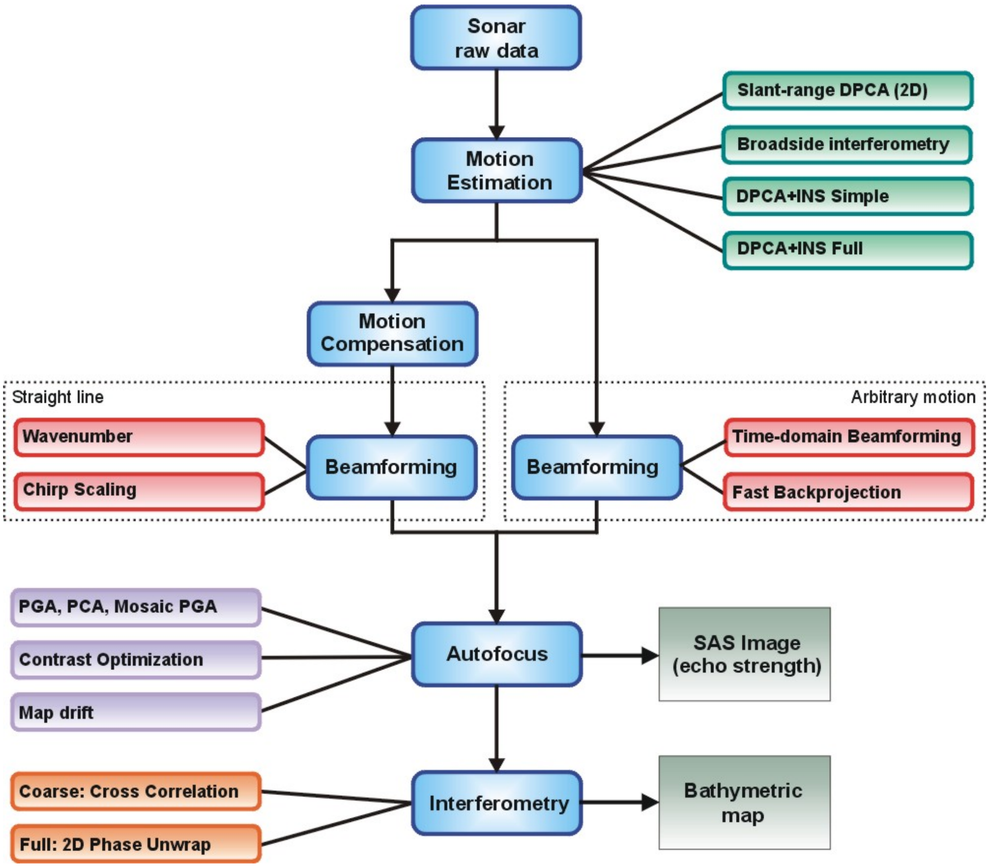


Figure 3.2: Basic signal processing flow in SAS processing.

3.1 Signal Processing Overview

The building blocks for synthetic aperture imaging signal processing outlined in Fig. 3.2 can generally be divided into four main categories:

Motion Estimation or navigation consists of fusion of the aided inertial navigation system [19], with sonar micronavigation [1]. The fusion can be done in a variety of ways [16].

Beamforming or image formation can be done either in time domain (high fidelity for small areas, relatively computationally heavy) and in wavenumber frequency domain (fast, efficient for full swath streaming imagery) [25, 20].

Autofocus is correction of uncompensated motion errors that runs after image formation. Both phase gradient autofocus (PGA) [18, 2] and map-drift autofocus [3] are available in FOCUS.

Interferometry For interferometric systems, relative seafloor height can be estimated, either by interferometry (phase differencing) [4, 18] or by cross-correlation based direction of arrival estimation [23, 22].

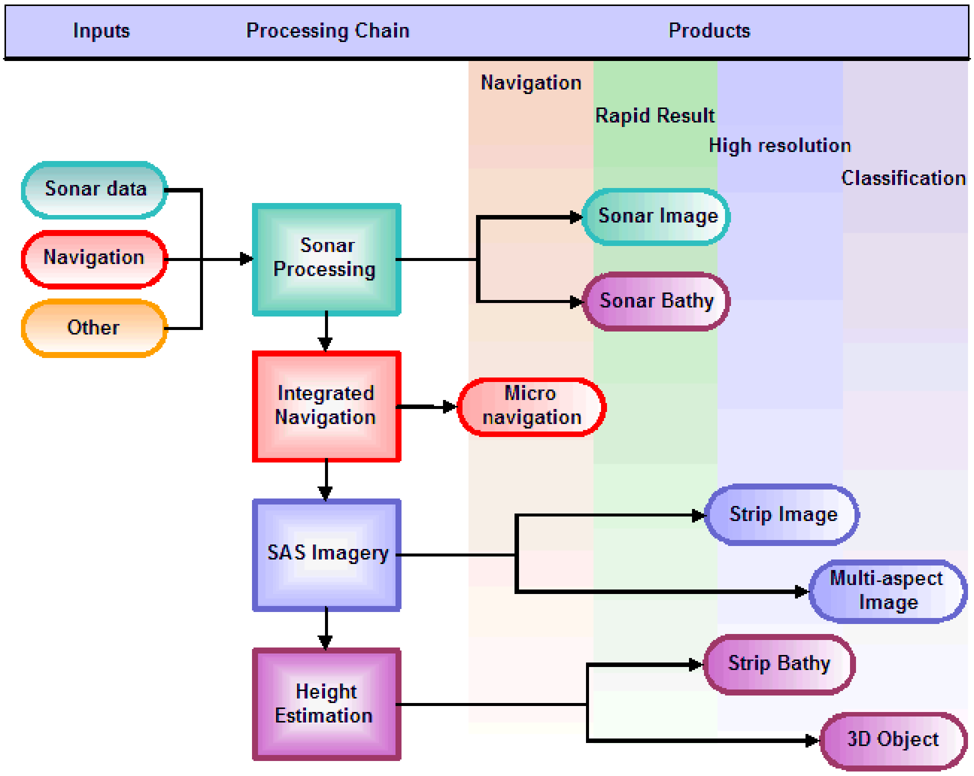


Figure 3.3: Overview of the FOCUS toolbox with emphasis on output products.

3.2 FOCUS Output Products

The FOCUS toolbox can produce several different products at all levels in the processing chain, as outlined in Fig. 3.3. These group into four categories:

Navigation The integrated sonar and inertial navigation produces high fidelity position and attitude with estimated accuracy for synthetic aperture imagery.

Rapid result Sidescan processing produces dynamically focused multibeam sonar images and relative bathymetry. These products can typically be used for rapid environmental assessment (REA).

High resolution Strip mode synthetic aperture processing produces full swath streaming images and relative bathymetry of high resolution. These products are well suited for detection and classification of small targets. This part is the most time consuming part of the signal processing chain.

Classification Spot imaging constitutes synthetic aperture imaging of a small area (i.e. around a mine like object), typically after detection, and as a part of classification. Advanced techniques such as multi-aspect imaging, 3D rendering of objects, fixed focus shadow enhancement and target signature analysis can be run in spot mode.

4 Challenges in Synthetic Aperture Sonar Processing

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 with 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 give. 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.

In this section, we list some of the challenges we have experienced in SAS processing, and how these challenges are addressed in the FOCUS toolbox.

4.1 Topography

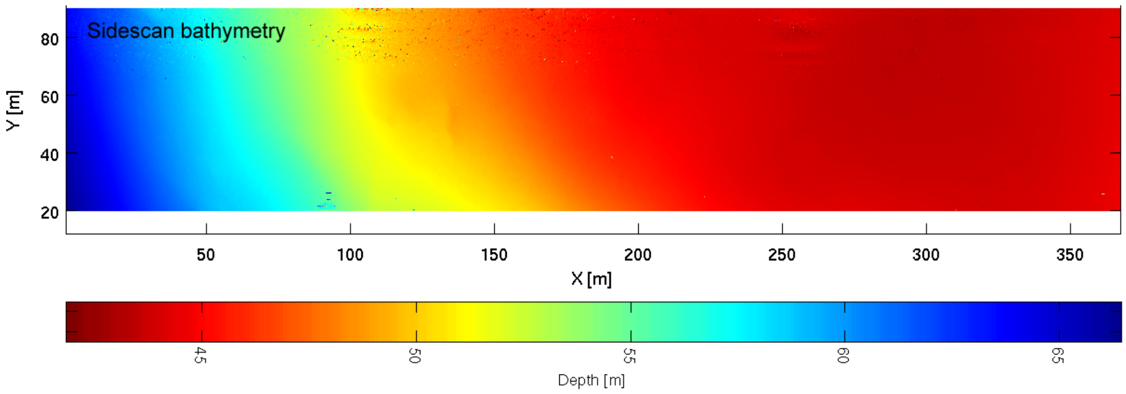


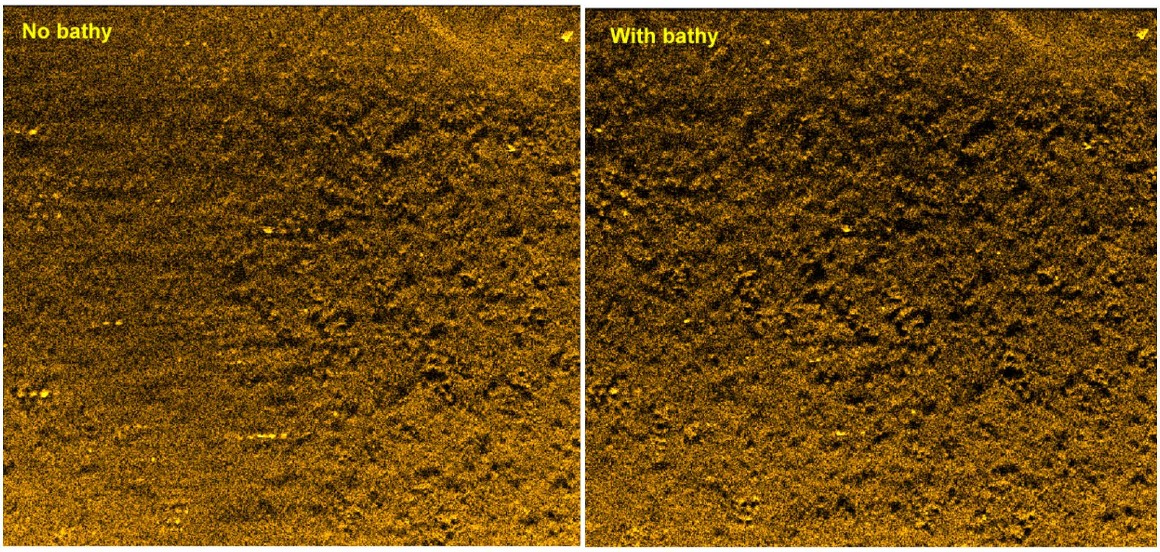
Figure 4.1: Sidescan bathymetry from HUGIN mission run060202_4 from Østøybåen (see Fig. 5.1).

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 [18]. An exception to this is when the sonar travels on a perfectly straight line; symmetry in the imaging process then ensures focused images independently of topography.

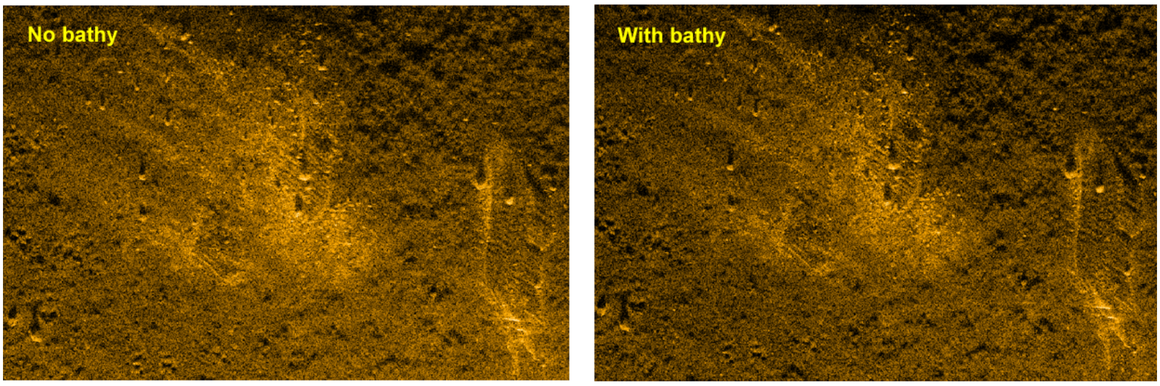
AUVs typically run at a fixed altitude above the seafloor. Thus, when the topography varies, the AUV will exhibit highly nonlinear motion, which again causes strict requirements on the a priori height accuracy [18]. From experimental data we have observed that using the AUV altimeter and depth sensor 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 4.1 shows the estimated sidescan bathymetry from an area with varying topography, and Fig. 4.2 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 images. Note that DPCA micronavigation will potentially reduce the impact of incorrect bathymetry. An integrated navigation solution based on DPCA without bathymetry information can be suitable for SAS imaging, although incorrect. 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.

Area 1: Along-track position: 20 - 55 m. Range 45 - 80 m.



Area 2: Along-track position: 97 - 138 m. Range 41 - 68 m.



Area 3: Along-track position: 345 - 366 m. Range 40 - 60 m.

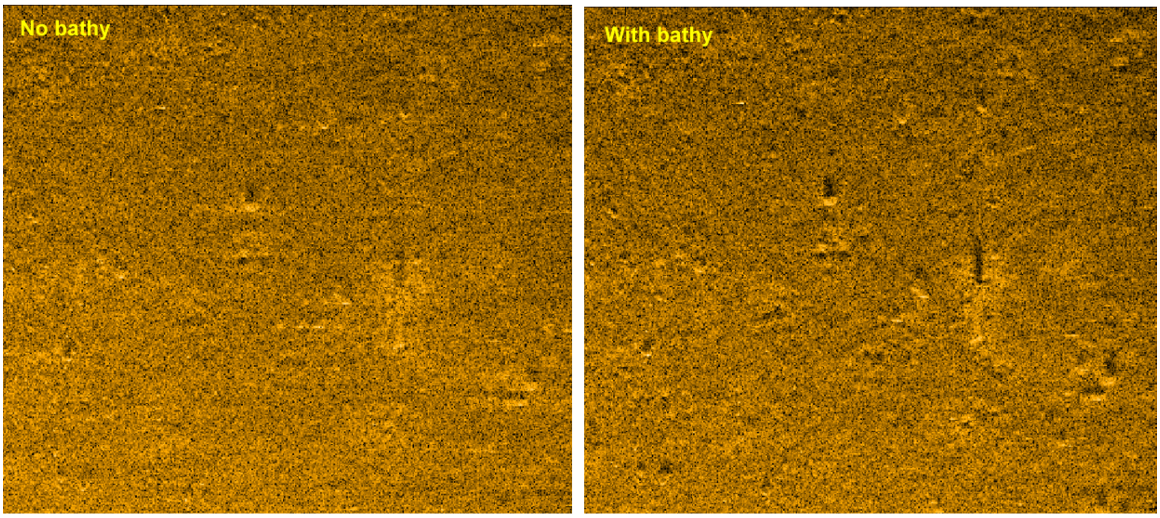


Figure 4.2: Example SAS images without and with using bathymetry information shown in Fig. 4.1.

4.2 Sound Velocity Variatioions

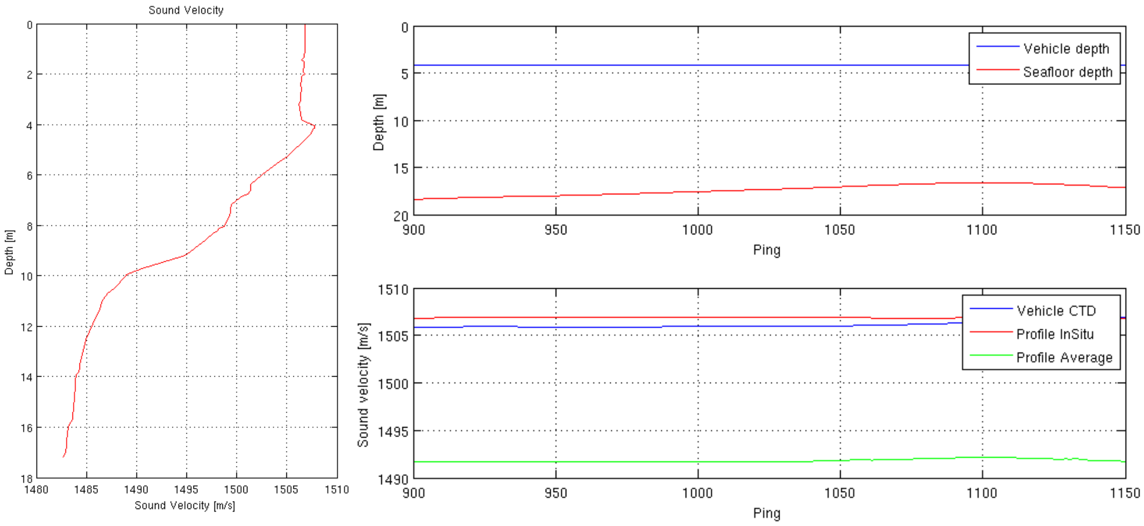


Figure 4.3: Sound velocity profile (left), vehicle depth and seafloor depth (upper right) and sound velocity (lower right) for L_02, run060817_2.

SAS image quality is critically dependent on sub-wavelength navigation accuracy. Inaccuracies and variations in the sound speed causes inaccuracies in the wavelength and thereby possibly reduced image quality. The image degradation will typically be defocusing (blurring). During a HUGIN mission in the inner harbour of Horten (run060817_2), there was a significant sound velocity variation with depth, as shown in the left panel of Fig. 4.3. The HUGIN AUV is carrying a high quality CTD on-board. To a first-order approximation, the sound speed used in imaging should be the average value between sonar and seafloor instead of that measured at the vehicle. The lower right panel of Fig. 4.3 shows the calculated average sound velocity from vehicle to seafloor (green) compared with the vehicle CTD (blue) and the predicted sound velocity at vehicle depth from the profile (red). We see that the sound velocity at vehicle depth is 1507 m/s, while the average sound velocity between vehicle and seafloor is 1492 m/s. This is 15 m/s or 1% in difference.

Figure 4.4 shows a 50×30 m scene from the area where the profiles shown in Fig. 4.3 were collected. The image shows various debris on the seafloor. Figure 4.5 shows 5×5 m snippets of the scene, where different sound velocity has been applied in the SAS processing. In the left image pair, we use the vehicle CTD sound velocity which is 1506.2 m/s. The centre image pair is based on the average sound velocity from vehicle depth to seafloor depth, which is 1491.5 m/s. There is a clear quality degradation by choosing the vehicle CTD sound velocity. Phase gradient autofocus (PGA)[18] performs particularly well in estimating phase variations induced by incorrect sound-speed. Constant errors in sound speed cause along-track invariant defocus and thus closely match the spotlight SAR phase errors PGA is designed to estimate. The right image pair in Fig. 4.5 shows the left image pair after PGA is applied. We see that even though we apply an incorrect sound velocity, the image quality is restored by applying PGA. A by-product of the PGA algorithm is an

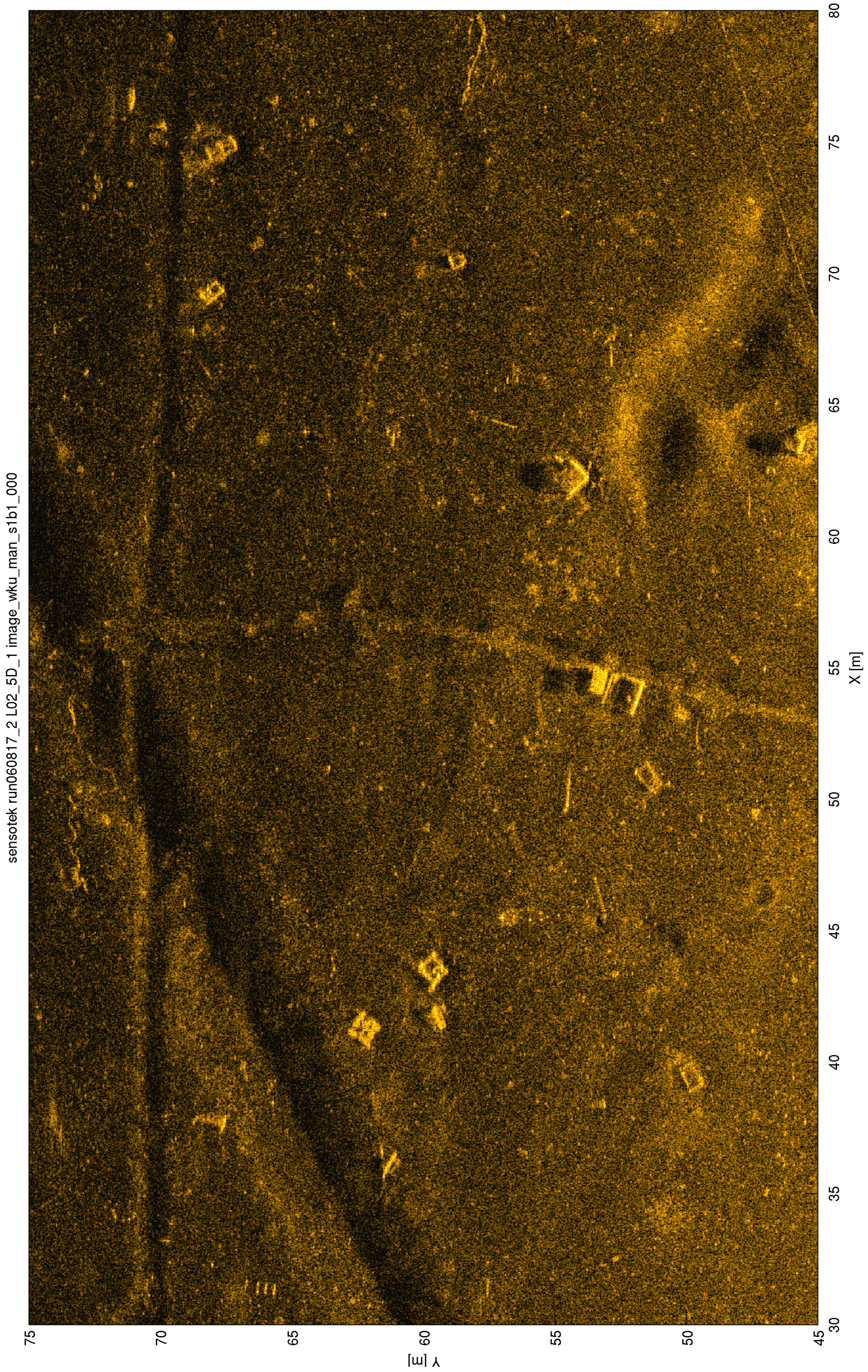


Figure 4.4: SAS image of a 50×30 *m scene from HUGIN mission run060817_2. The image is shown with 70 dB dynamic range.*

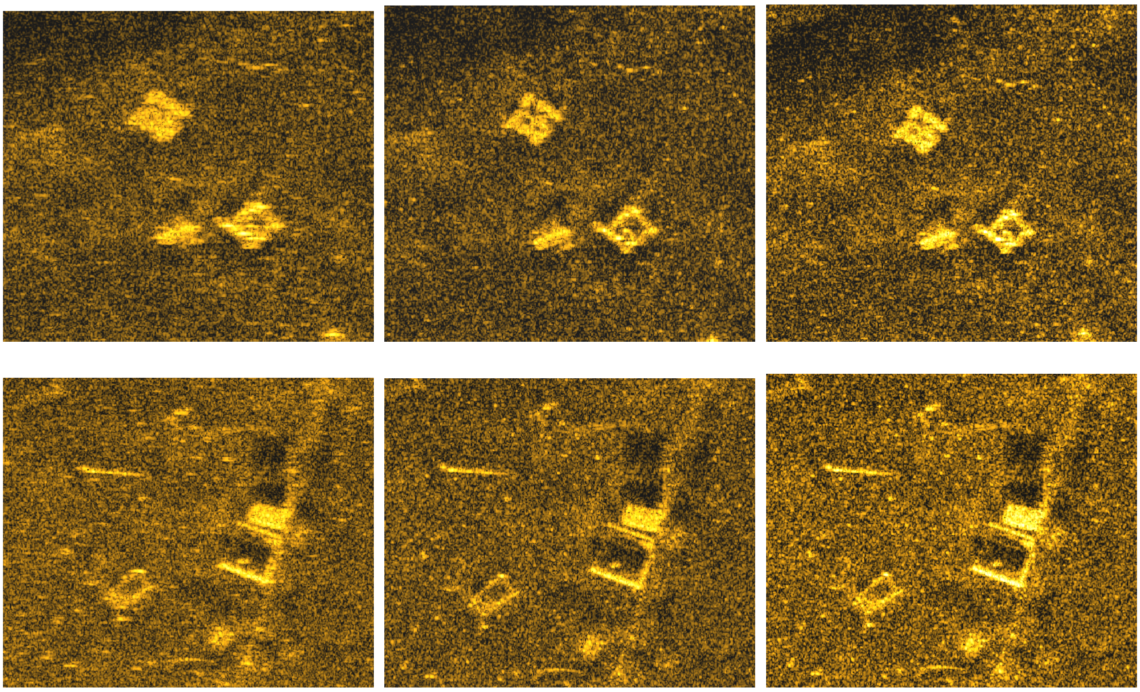


Figure 4.5: 5×5 m snippets of the scene shown in Fig. 4.4. The left image pair uses the sound velocity calculated from the onboard CTD. The centre image pair uses the average sound velocity from vehicle to seafloor. The right image pair shows the left images after autofocusing.

estimate of the corrected sound velocity [14]. In this particular case, the estimate was 1494.3 m/s, which is close, but not identical to the average sound velocity from vehicle depth to seafloor. The reason for this discrepancy is probably the fact that the model in the PGA recalculation of sound velocity is too simple, and also the fact that the SAS image may contain accumulated errors from navigation inaccuracies and not solely sound velocity errors.

4.3 Shallow Water Operations

Imaging at long range in shallow water will always be limited by multipath and direct surface returns. Sonar design choices can limit multipath through beam shaping but some unwanted interference will still exist. Figure 4.6 shows some possible multiple ray paths sound can travel between transmitter, scatterer on the seafloor and receiver. The red line indicates the backscattered signal from the seafloor (without any interactions with the surface). Typically, this is the only wanted signal.

The multipath will affect the SAS image quality in several ways:

1. For a mild degree of multipath, an added noise floor will appear in the SAS images such that the regions of low scattering strength (shadow regions and such) will be polluted.

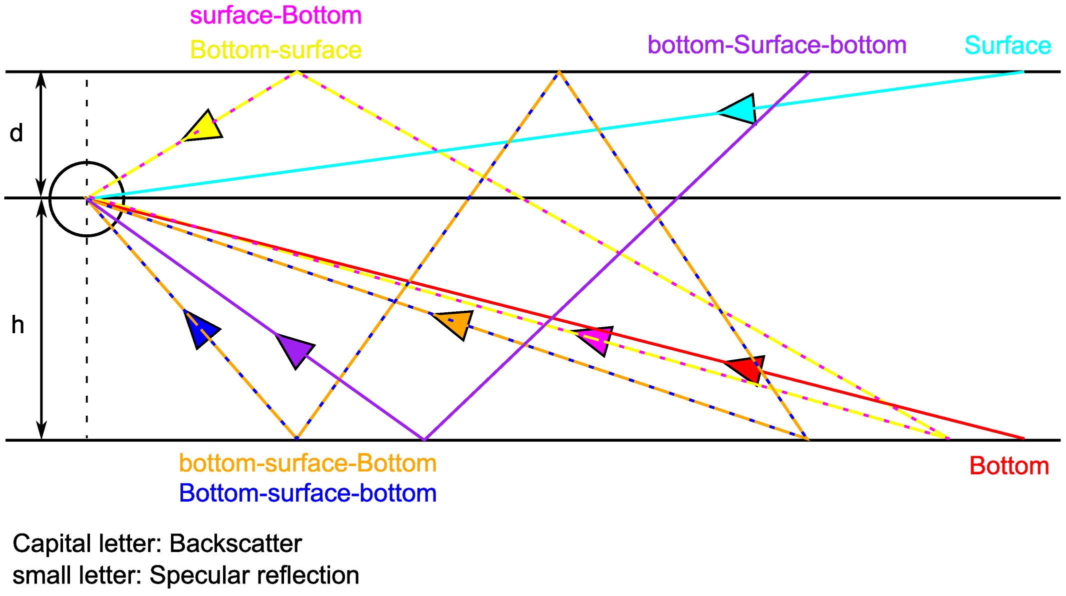


Figure 4.6: Geometrical layout of ray paths between transmitter, seafloor surface and receiver. Capital letter indicates backscatter and small letter indicates specular reflection. The arrow indicates the direction of sound towards receiver. The colours used are the same as the theoretical curves used in Fig. 4.7.

2. For stronger degree of multipath, the sonar navigation might be harmed such that the SAS images becomes defocused (blurred).

3. For strong multipath and, in particular, direct surface return, the echo from the sea surface will be stronger and mask the echo from the seafloor. The images will not contain any usable information from the seafloor at all. This effect is the same for sidescan sonars.

The SENSOTEK SAS has the ability to receive echoes on its dense transmitter array, giving a possibility for assessing the multipaths. Figure 4.7 shows the vertical beampattern from the vertical array, for two different cases. The coloured lines indicate the theoretical prediction of the direction from the different ray paths in Fig. 4.6. The information from this beampattern could be used for autonomous sensor operations (i.e. letting the sensor itself adaptively tune the parameters for the environmental conditions for optimal performance).

The left panel of Fig. 4.7 shows the average beampattern from 20 pings from the inner harbour of Horten, at very shallow waters. The vehicle depth is 1 m, and the vehicle altitude is 10 m. We see the scattered signal from the seafloor as a strong return following the red line. This is the wanted signal without interaction from the sea surface. There is also another signal, arriving above the horizon, following the yellow line. This is the Bottom-surface bounce as illustrated in Fig. 4.6. This signal is of less concern for the SAS receiver arrays, since the receiver antenna has a 3 dB vertical beamwidth of around $40°$, centred around broadside. Note that there is no visible signal around the direct surface return line (cyan) even though the vehicle is only 1 m below the surface. This

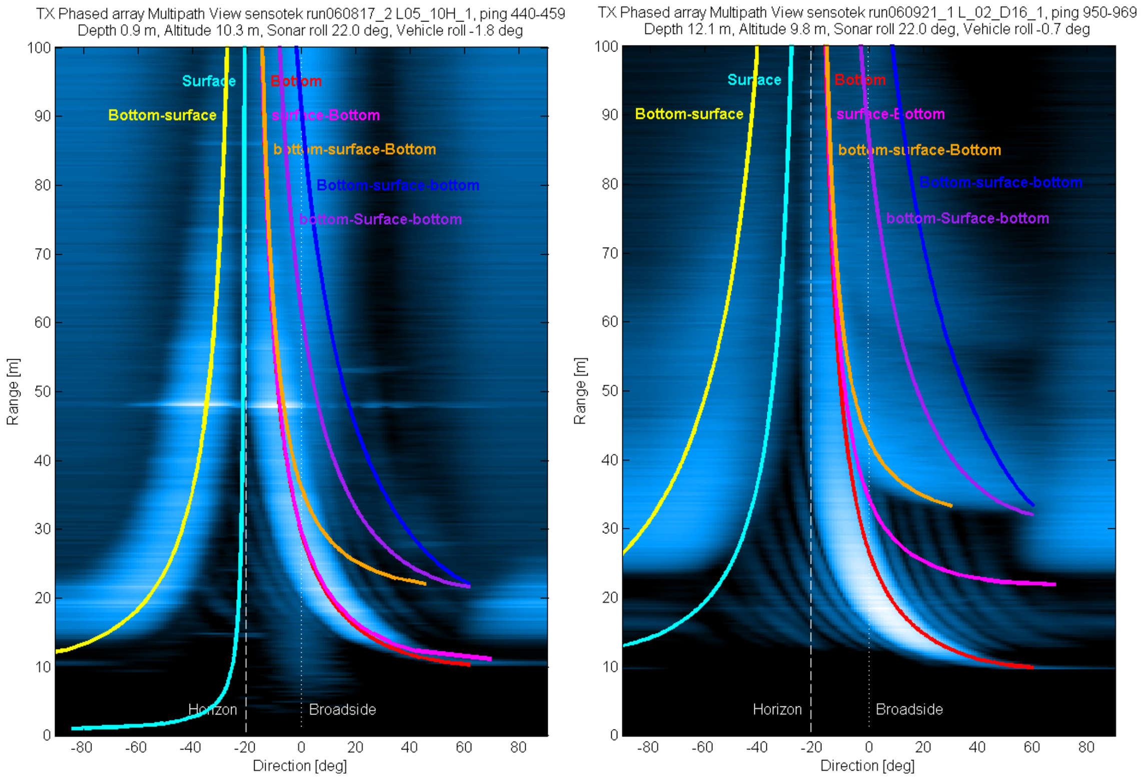


Figure 4.7: Beampattern from the vertical array -90 to 90 degrees from pings in shallow water, with the theoretical multipath echoes based on altitude and depth. Positive angles are downwards. The dynamic range in both beampatterns are 50 dB. See Fig. 4.6 for a description of the described ray paths.

is due to the fact that in this particular run, the vertical transmit beampattern was set to “shallow water mode”. The right panel shows the average beampattern from 20 pings in an area of very high backscatter, also in shallow waters. In addition to the beampattern in the left panel, this beampattern also has a strong multipath return for three bounces in between the orange line, the purple line and the blue line. Note that in calculating the theoretical directions for multipath, we assume a flat seafloor. The seafloor is known to be non-flat from this region, so there will be slight inaccuracies in the predictions. The added multipath is of concern, since it arrives within the main beam of the elements in the SAS receiver arrays.

5 Mission Overview

SENSOTEK SAS has been tested in 11 HUGIN missions listed in Table 5.1. The different areas the missions were conducted in, are outlined in Fig. 5.1. SENSOTEK SAS has been tested in water depths from 10 m to 200 m, over flat sandy seafloor, to soft mud and rocky seafloors. The recorded data amount is more than 1.5 TB. Results from separate missions are documented in more detail in [8, 9].

Name	Area	Depth	Description	Size
run050610_2	1	200 m	Breidangen, sandy seafloor, wrecks	223 GB
run051005_2	1	200 m	Breidangen, sandy seafloor, wrecks	79 GB
run051103_1	1	200 m	Breidangen, sandy seafloor, wrecks	145 GB
run051110_1	1	200 m	Breidangen, sandy seafloor, wrecks	82 GB
run051115_1	1	200 m	Breidangen, sandy seafloor, wrecks	82 GB
run060202_4	2	60 m	Østøybåen, high clutter density	225 GB
run060407_4	3	10-30 m	Bastøyrenna, shallow water, topography	118 GB
run060817_2	4	10-20 m	Horten inner harbour, shallow waters, debries	122 GB
run060921_1	2	10-30 m	Bastøyrenna, shallow water, topography	163 GB
run061018_1	2,1	60-200 m	Østøybåen to Breidangen	254 GB
run061024_1	2,1	60-200 m	Østøybåen to Breidangen	124 GB

Table 5.1: List of HUGIN I / SENSOTEK SAS missions.

A number of different operational modes have been tested on the SENSOTEK system. Table 5 gives a list over the settings used in all missions. The maximum bandwidth tested is 47 kHz around 94 kHz centre frequency, giving 50% relative bandwidth. Note that the system has not always been run in interferometric mode.

Mission	**fc**	**bw**	**fs**	**h type**	**h width**	**v type**	**v width**	**master**	**slave**	**lines**
run050610_2	100	30	40	1	31	1	30	75	72	45
run050610_2	100	30	40	0	0	1	30	6	6	5
run050610_2	90	40	61	1	31	1	30	2	2	1
run051005_2	91	20	26	0	0	1	30	47	1	32
run051005_2	75	20	40	1	30	1	30	2	0	2
run051005_2	93	30	37	1	28	1	30	13	0	6
run051103_1	91	20	26	0	30	1	30	4	4	3
run051103_1	91	20	40	0	30	1	30	7	7	4
run051103_1	100	30	40	0	30	1	30	7	7	5
run051103_1	100	30	40	1	26	1	30	9	9	4
run051103_1	95	30	61	1	26	1	30	6	6	3
run051103_1	95	30	40	1	26	1	30	4	4	1
run051103_1	91	20	26	0	0	1	30	2	2	2
run051103_1	91	20	40	0	0	1	30	2	2	1
run051103_1	100	30	61	0	0	1	30	4	4	2
run051103_1	100	30	40	0	0	1	30	7	7	3
run051110_1	91	20	40	0	0	1	30	2	0	2
run051110_1	91	20	26	0	0	1	30	56	0	33
run051115_1	91	20	26	0	0	1	30	33	33	23
run060202_4	100	30	40	0	0	1	30	41	41	17
run060407_2	100	30	40	0	0	1	26	33	33	8
run060817_2	100	30	40	0	0	1	16	30	30	8
run060817_2	94	47	63	1	50	1	16	6	6	2
run060921_1	100	30	40	0	0	1	16	52	54	22
run061018_1	100	30	40	0	0	1	16	7	7	3
run061018_1	100	30	40	0	0	1	26	37	37	8
run061018_1	81	41	54	1	50	1	26	24	24	7
run061018_1	91	20	26	1	50	1	26	7	7	1
run061024_1	100	30	40	0	0	1	26	34	33	6

Table 5.2: SENSOTEK system setup for all missions. fc *is center frequency in kHz;* bw *is bandwidth in kHz;* fs *is sampling frequency in kHz.* h *represents horisontal;* v *represents vertical;* type *represents beam type where 0 is planar and 1 is defocused.* h width *is related to beamwidth for type = 1. For type = 0, the width is given by the aperture size and the center frequency.* master *and* slave *indicates the number of recorded data files on each setup. 0 in the* slave *field indicates that the system was non-interferometric.* lines *shows the number of mission lines with the specified configuration at that mission. Note that several missions can have the same setup.*

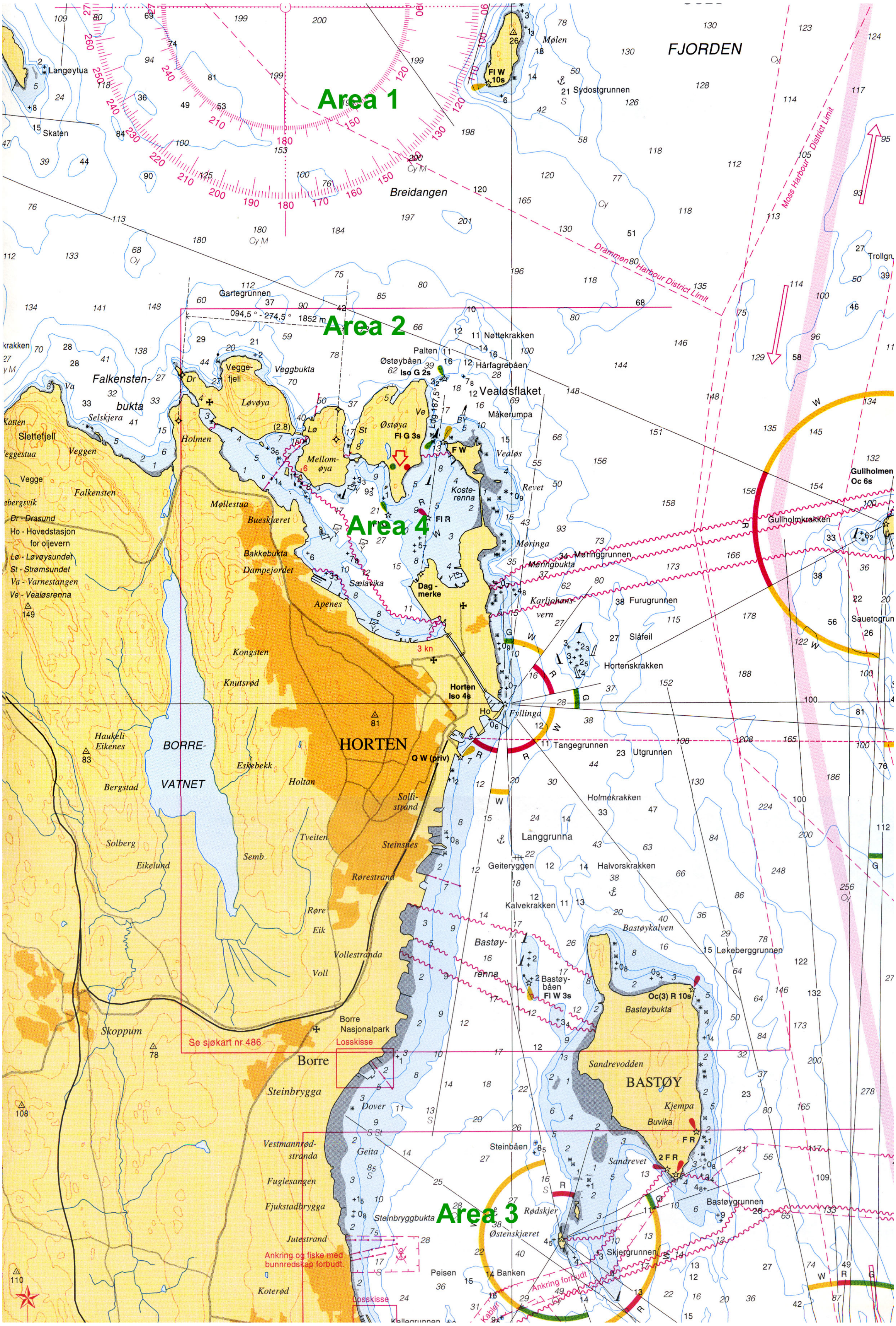


Figure 5.1: Map of the test areas for the HUGIN I / SENSOTEK SAS missions. The area is outside Horten, Norway.

6 SENSOTEK SAS Images

In the following, we show example images of interesting areas and objects to illustrate the capability of the SENSOTEK high resolution SAS system. All the images are processed by the FOCUS toolbox. Some of the images (i.e. the images in section 6.2) are snapshots from *Odin*, a non-commercial sonar data playback and analysis program that contains many of the basic features found in Triton Imaging's *Survey Office*.

6.1 Underwater Archaeology

Synthetic aperture sonar technology is well suited for detecting and imaging underwater ship wrecks and other man made features/objects. One unique feature of SAS technology is the fact that the SAS images have range independent along-track resolution. This is a distinct difference from sidescan sonar. When imaging / documenting large ship wrecks, SAS gives the ability to image the wreck at near and far range with similar quality.

The data in the three following examples are from HUGIN mission run051110_1 at Breidangen at around 190 m water depth. The sonar was run in "low bandwidth" HISAS-1030 mode (see mission run051110_1 in Table 5), and the SAS images were processed to a theoretical resolution of $[dx, dy] = [3.1, 4.8]$ cm.

6.1.1 Submarine

Figure 6.1 shows a SAS image of the German World War II submarine U-735, which was sunk in 1944 outside Horten in area 1 as outlined in Fig. 5.1. The water depth is around 200 m. The forward part of the ship including the conning tower is visible, while the aft body is damaged or buried in the mud.

6.1.2 Fishing Boat

Figure 6.2 shows a SAS image of a 25 m long fishing boat at 25-55 m range. The detail level in the SAS image is very high, and one can for example see ropes from the masts. Figure 6.3 shows the same fishing boat seen from another aspect angle. Note that the ribs can be identified on the inside of the hull, indicating that this is likely a wooden boat.

6.1.3 Barge

In Fig. 6.4, we see a SAS image of an unknown wreck, possibly a barge. The size of the wreck is approximately 10×3 m. The small, well defined, rectangular shadow region on top of the wreck is 50×30 cm. This illustrates the resolution in the image.

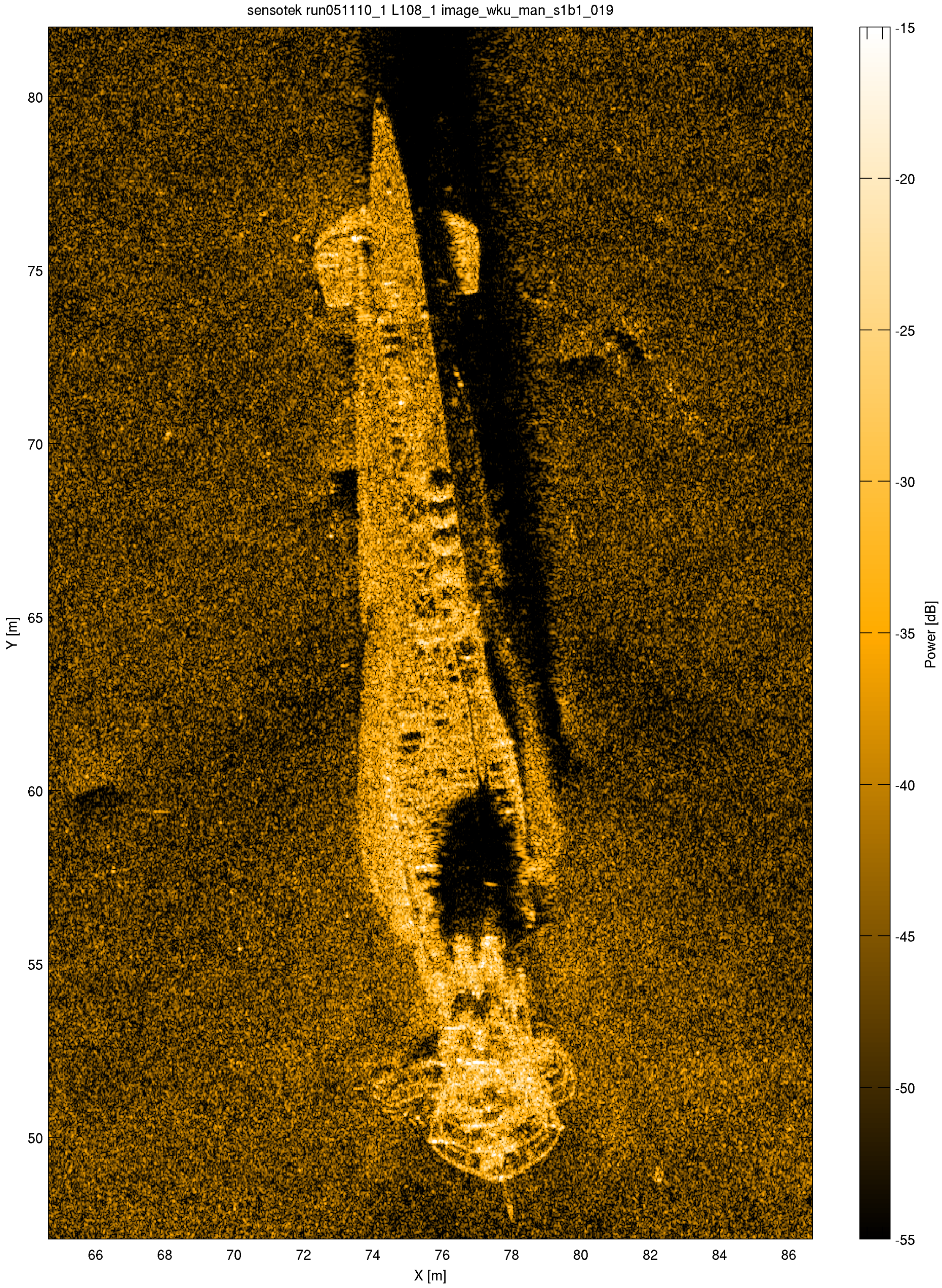


Figure 6.1: SAS image of the sunken German World War II submarine U735, outside Horten, Norway. The vehicle depth is 176.5 m and the altitude is 19.8 m. The theoretical resolution in the image is 3.2 cm along-track and 4.8 cm cross-track. The image is formed using the wavenumber algorithm, and PGA autofocus is applied.

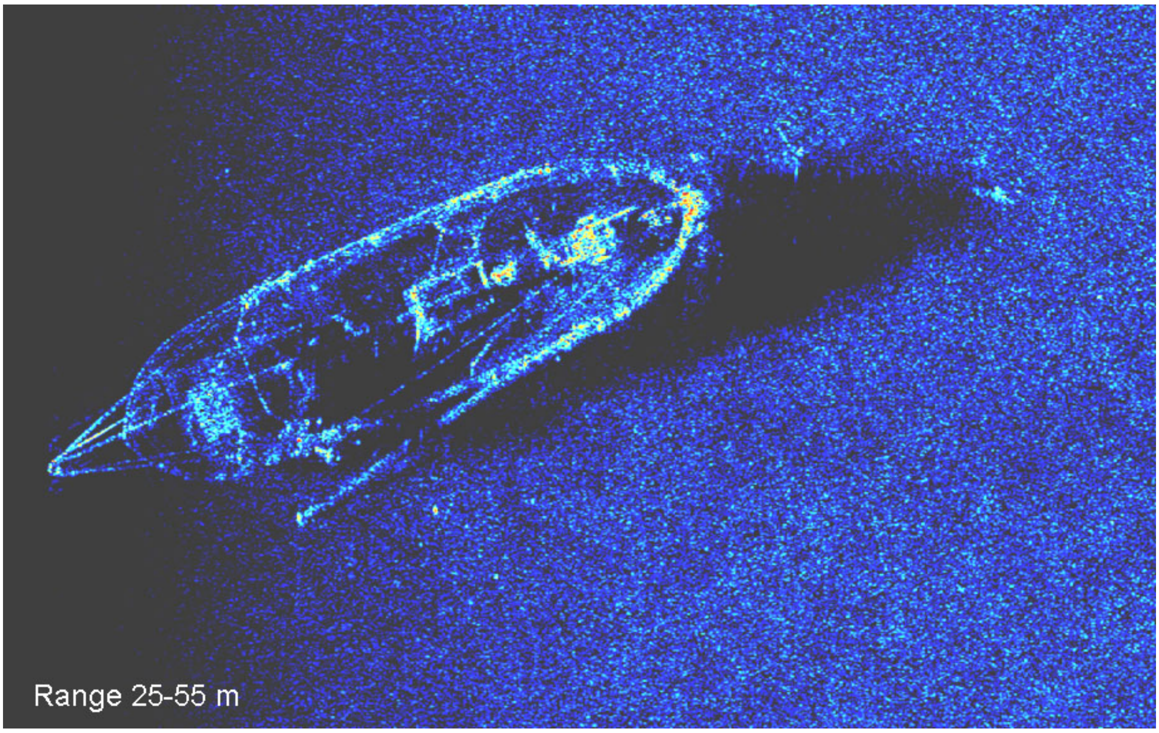


Figure 6.2: SAS image of a small fishing boat at Breidangen. Image range is 25 - 55 m.

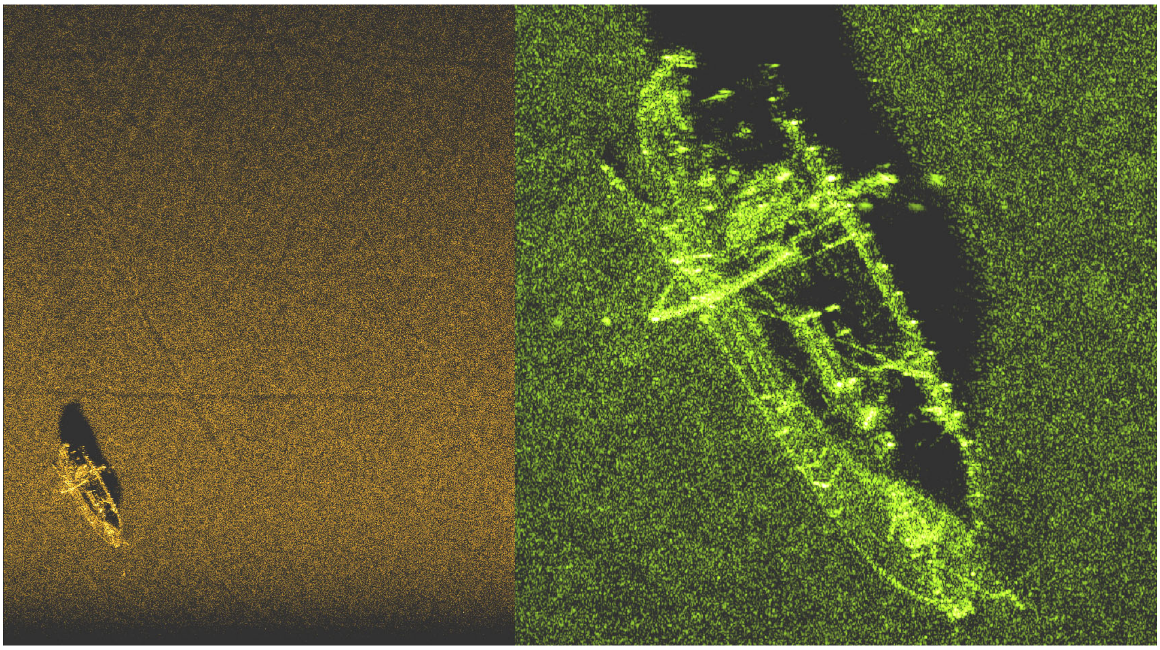


Figure 6.3: SAS image of a small fishing boat at Breidangen. The fishing boat is approximately 25 m long. The left panel shows 40-140 m range, and the right panel shows a zoomed cut out around 53-72 m range.

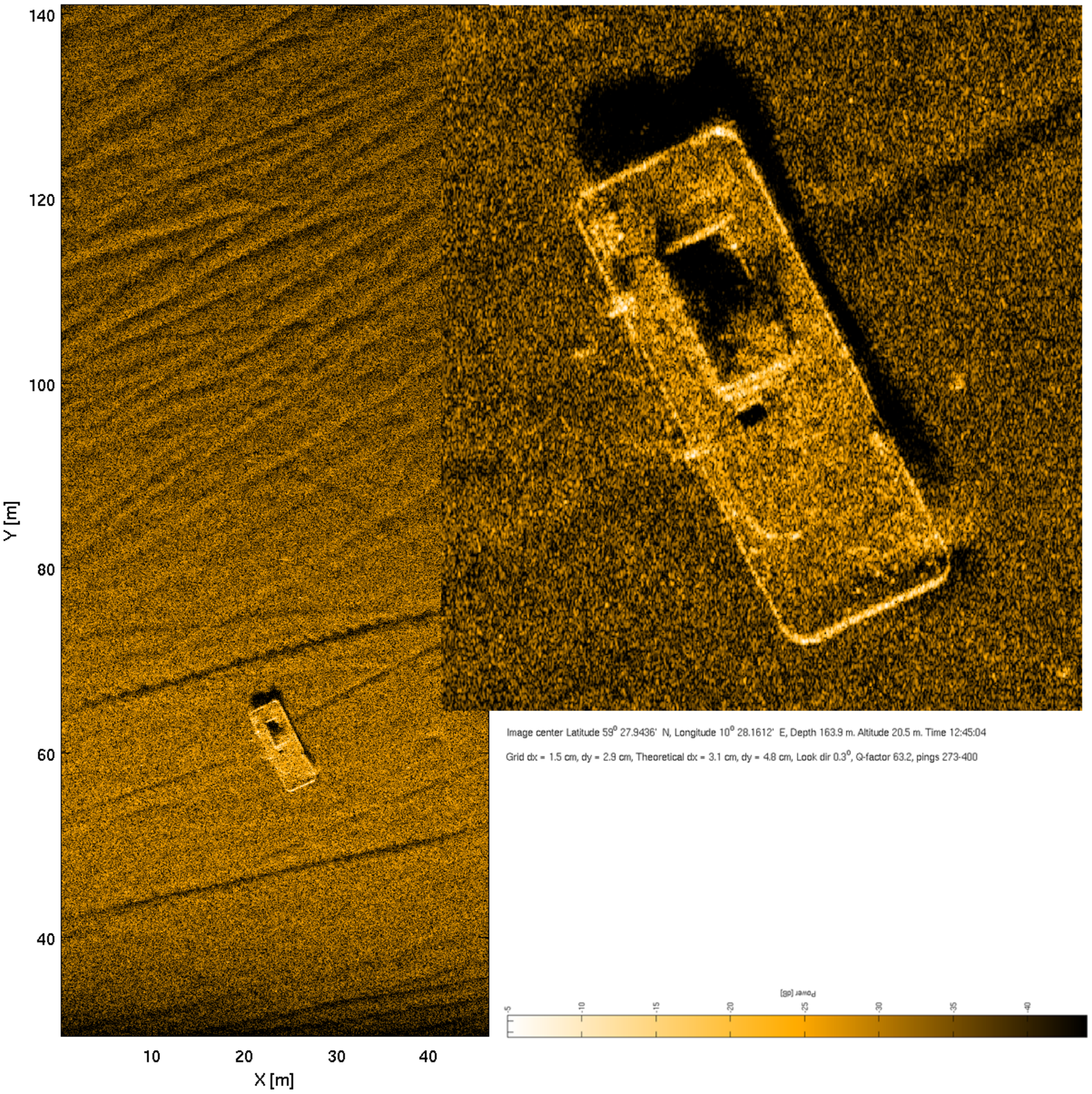
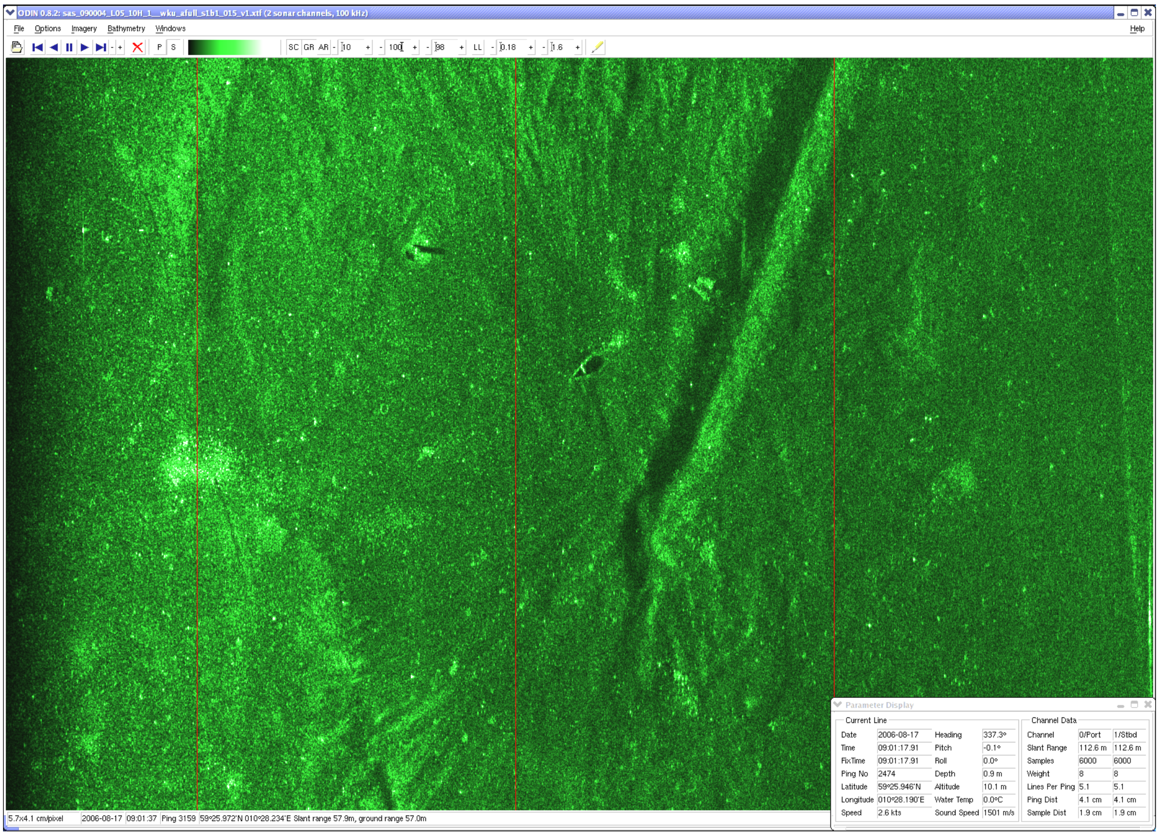


Figure 6.4: SAS image of a barge at Breidangen. The left panel shows 30-140 m range, while the right panel is a zoomed cut out around 55-68 m range.

6.2 Shallow Waters

Figure 6.5 shows a SAS image from Horten inner harbour (indicated as area 4 in Fig. 5.1). The image shows 10-100 m ground range in a total water depth of 11 m. This gives a range equal 9 times the water depth. There is no visible echo from the surface and very little pollution from multipath in the image, even though the vehicle depth is only 1 m. See section 4.3 for a more detailed description on the limitations in shallow waters.

The area has been a harbour for centuries. There are unknown features and debris more or less everywhere in the area. Figure 6.6 shows a SAS image of an unknown geological feature (or possibly man-made) in the harbour. Figure 6.7 shows a SAS image of debris, where we clearly see details such as ropes in the high resolution image.



ODIN 0.8.2: sas_090004_L05_10H_1__wku_afull_s1b1_015_v1.xtf (2 sonar channels, 100 kHz)

Current Line

Date	2006-08-17	Heading	337.3°
Time	09:01:17.91	Pitch	-0.1°
FixTime	09:01:17.91	Roll	0.0°
Ping No	2474	Depth	0.9 m
Latitude	59°25.946'N	Altitude	10.1 m
Longitude	010°28.190'E	Water Temp	0.0°C
Speed	2.6 kts	Sound Speed	1501 m/s

Channel Data

Channel	0/Port	1/Stbd
Slant Range	112.6 m	112.6 m
Samples	6000	6000
Weight	8	8
Lines Per Ping	5.1	5.1
Ping Dist	4.1 cm	4.1 cm
Sample Dist	1.9 cm	1.9 cm

5.7x4.1 cm/pixel | 2006-08-17 | 09:01:37 | Ping 3159 | 59°25.972'N 010°28.234'E Slant range 57.9m, ground range 57.0m

Figure 6.5: SAS image of an area in the inner harbour of Horten showed in the Odin XTF viewer. The image shows 10-100 m ground range. The vehicle depth is 1 m, and the altitude is 10 m.

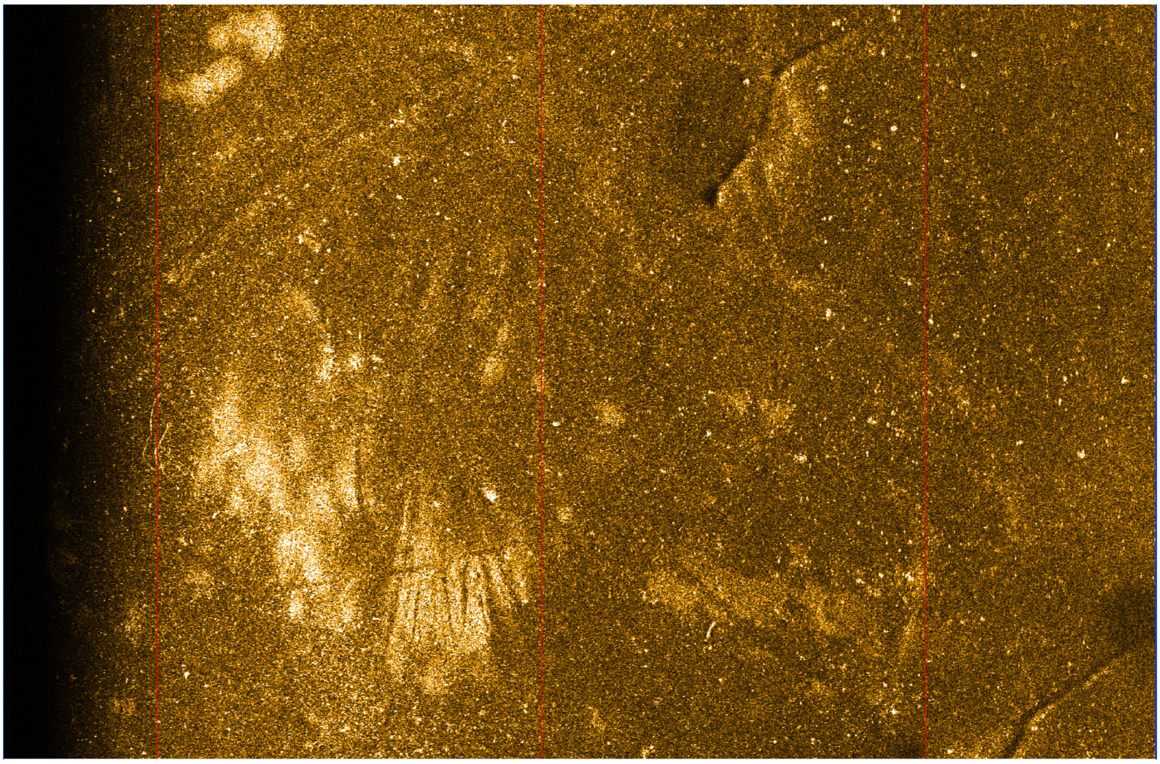


Figure 6.6: SAS image of an area in the inner harbour of Horten. The image shows 15-90 m slant range. The vehicle depth is 4.2 m, and the altitude is 14.2 m.

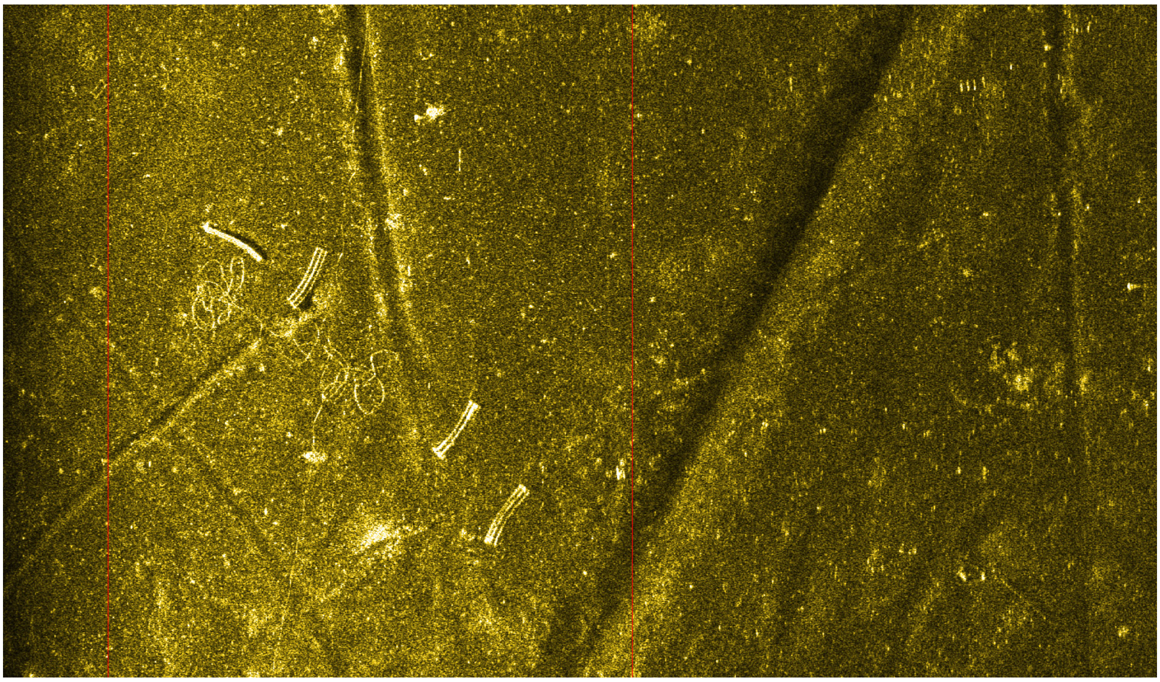


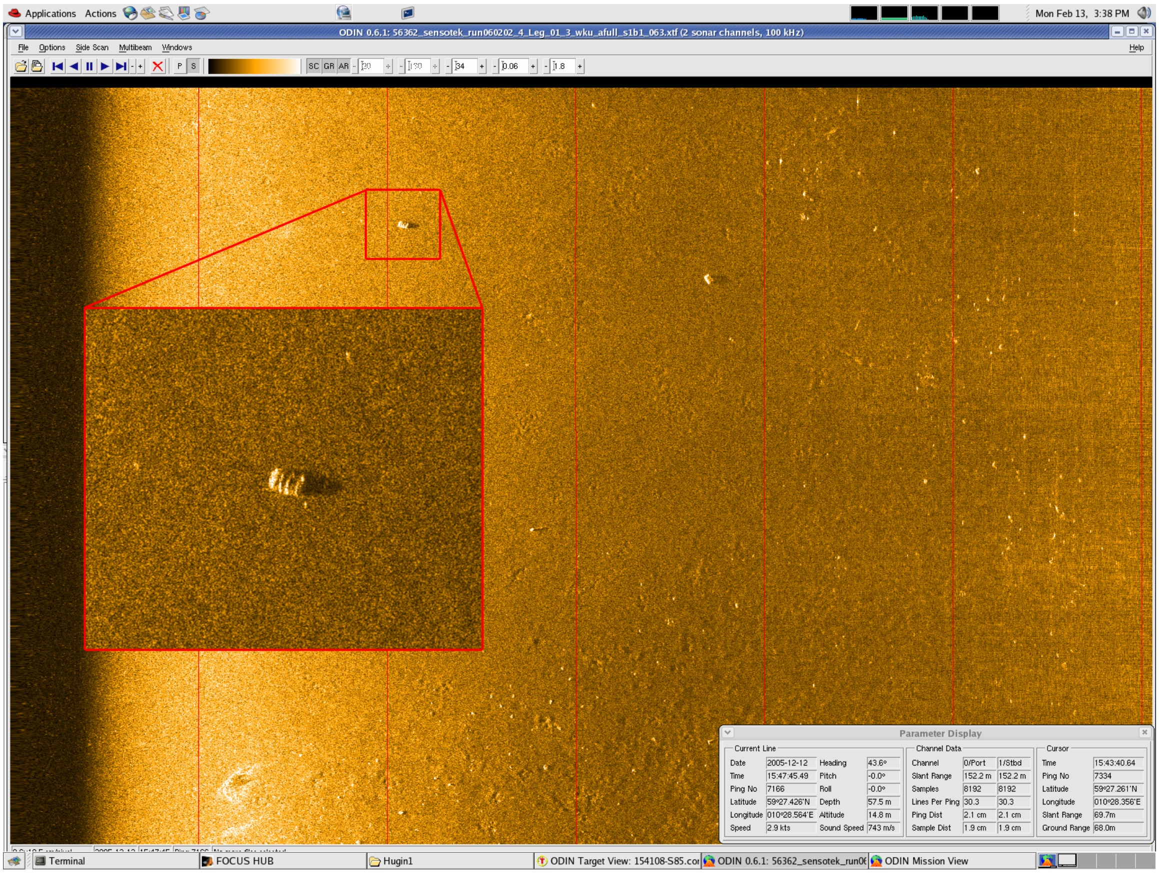
Figure 6.7: SAS image of an area in the inner harbour of Horten. The image shows 20-75 m slant range. The vehicle depth is 4.2 m, and the altitude is 13.7 m.

6.3 Small Targets

Detection and classification of small targets are one of the primary applications of SAS technology. High image resolution and quality are crucial in the target recognition. SAS is the only viable technology that provides long range and high resolution acoustic imagery. In the following, we show examples of small targets of opportunity on the seafloor.

Figure 6.8 shows a SAS image from Østøybåen (area 2 in Fig. 5.1). The water depth is around 50 m, and the area is heavily cluttered with debris. The zoomed area shows an object at around 50 m range that is assumed to be an oil barrel. We clearly see the ribs in the barrel, and the estimated object size matches the size of a classical oil barrel.

In Fig. 6.9, we see another example from area 2, heavily cluttered with debris. Figure 6.10 shows zoomed snippets of three different targets of opportunity from Fig. 6.9.



Parameter Display

Current Line

Date	2005-12-12	Heading	43.6°
Time	15:47:45.49	Pitch	-0.0°
Ping No	7166	Roll	-0.0°
Latitude	59°27.426'N	Depth	57.5 m
Longitude	010°28.564'E	Altitude	14.8 m
Speed	2.9 kts	Sound Speed	743 m/s

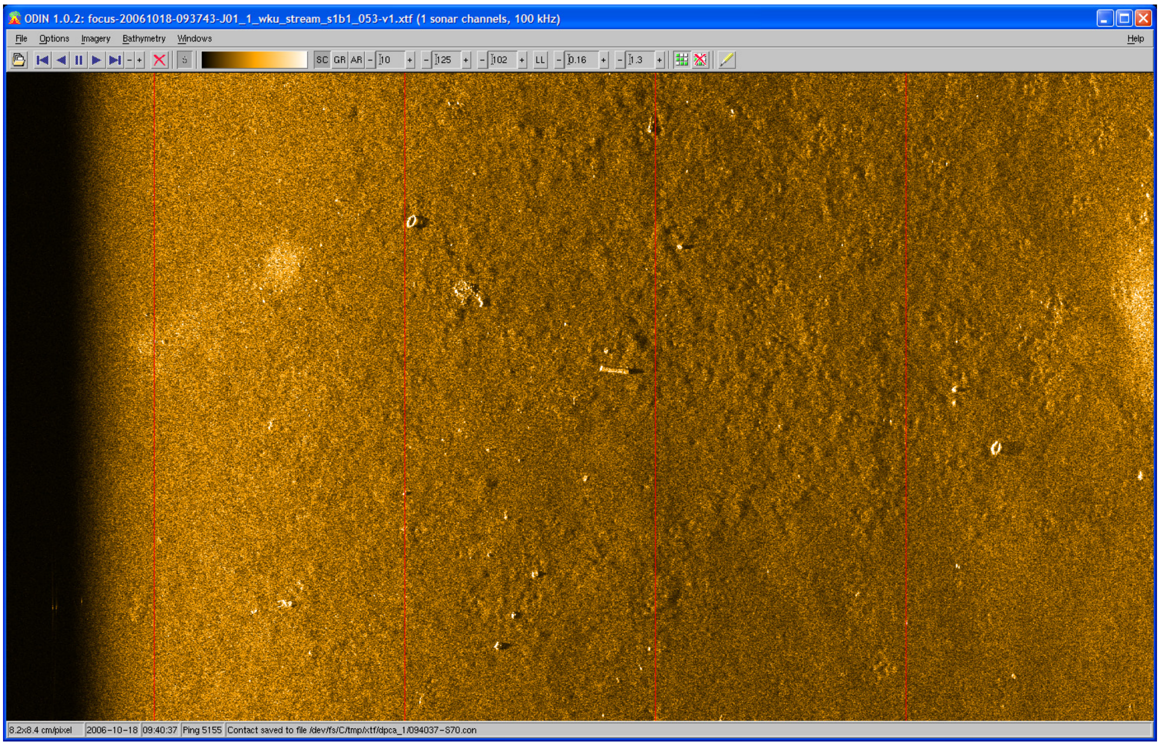
Channel Data

Channel	0/Port	1/Stbd
Slant Range	152.2 m	152.2 m
Samples	8192	8192
Lines Per Ping	30.3	30.3
Ping Dist	2.1 cm	2.1 cm
Sample Dist	1.9 cm	1.9 cm

Cursor

Time	15:43:40.64
Ping No	7334
Latitude	59°27.261'N
Longitude	010°28.356'E
Slant Range	69.7m
Ground Range	68.0m

Figure 6.8: SAS image of an area containing debris outside Horten, Norway. The image is displayed in the Odin XTF viewer. The lower right corner shows the parameter display, containing key parameters about the mission line, the image and the cursor. The zoomed area shows an object that is assumed to be an oil barrel.



ODIN 1.0.2: focus-20061018-093743-J01_1_wku_stream_s1b1_053-v1.xtf (1 sonar channels, 100 kHz)

8.2x8.4 cm/pixel | 2006-10-18 | 09:40:37 | Ping 5155 | Contact saved to file /dev/fs/C/tmp/xtf/dpca_1/094037-S70.con

Figure 6.9: SAS image of an area with debris showed in the Odin XTF viewer. The image shows 10-125 m slant range. The vehicle depth is 54 m, and the altitude is 14 m.

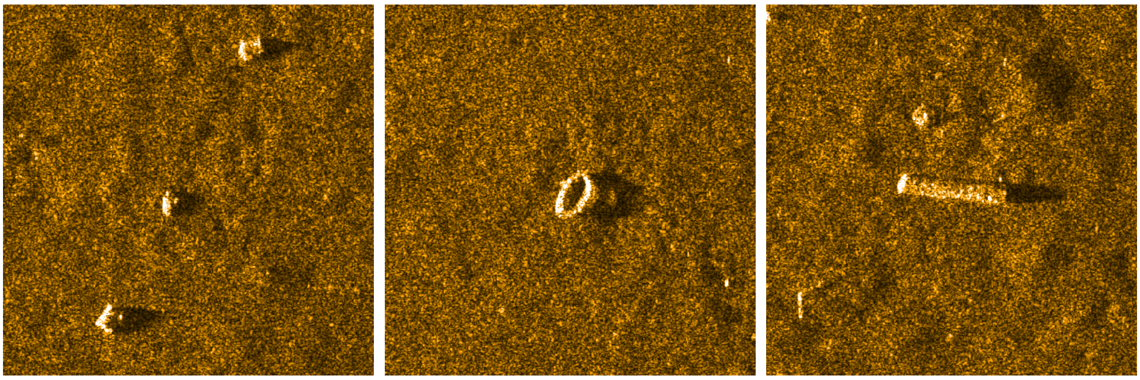


Figure 6.10: SAS image zoomed into 3 different areas in Fig. 6.9. The zoom is 10 x 10 m. The lower box object in the left panel is measured to a size of 60 x 45 cm, with 22 cm height. The ring in the centre panel is measured to 1.3 m in diameter, with a height of 40 cm. The pipe in the right panel is measured to a size of 280 x 42 cm, with 30 cm height.

7 Bathymetric Mapping

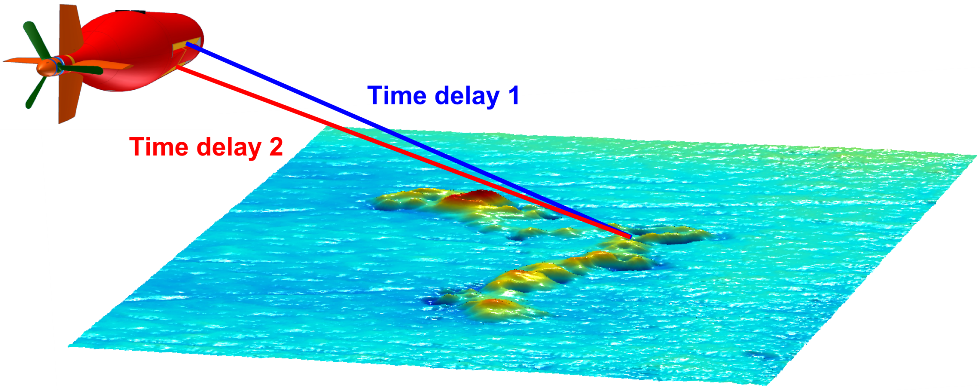


Figure 7.1: Principle of seafloor height estimation with an interferometric sensor.

An interferometric sensor, such as the SENSOTEK SAS, can be used to estimate the relative seafloor height (which again can be processed into bathymetry maps). The principle of height estimation with an interferometric sonar is illustrated in Fig. 7.1. The vertical direction to the seafloor is calculated from the estimated time difference of arrival from the two vertically displaced receiver arrays. This technique can be applied both on sidescan data and on SAS images. Note that this technique is different from the mapping technique used in a multibeam echosounder [21]. In the following, we show examples of maps produced by sidescan bathymetry and SAS bathymetry processing.

7.1 Sidescan Bathymetry

Sidescan bathymetry is performed by cross-correlating range patches from sidescan images [24]. The resolution of the bathymetric map therefore follows the imaging resolution along-track and is filtered with a 2-4 m window across-track. The method is robust and independent of SAS processing, and provides a bathymetric map with detail level especially suited for medium- and large-scale topographical variations.

Figure 7.2 shows a sidescan bathymetry map from area 2 in Fig. 5.1. The estimated seafloor depth varies from 35 m to 80 m. The AUV path is shown in black and illustrates how HUGIN follows the sloping seafloor.

7.2 SAS Interferometry

SAS interferometry estimates the time-delay directly from two SAS images by running a few pixels zero-lag 2D correlator over the images. The bathymetric resolution is therefore only reduced by a

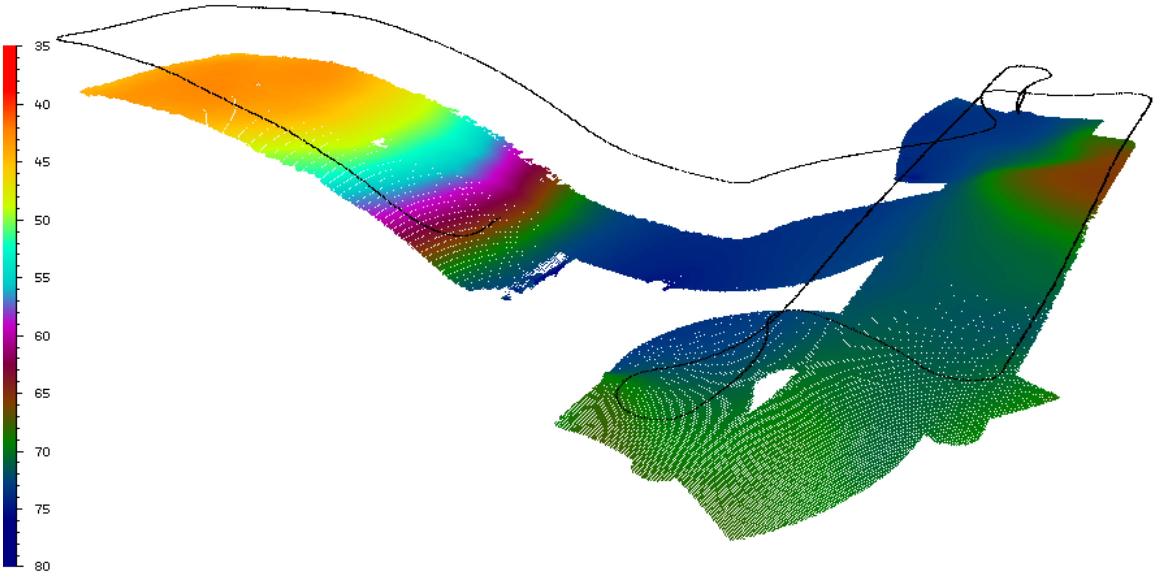


Figure 7.2: Sidescan bathymetry from area 2 as outlined in Fig. 5.1.

factor of 3-9 relative to the input images. The resulting high resolution maps are suited for displaying small, complex features on the seafloor, along with full swath bathymetry.

The upper panel of Fig. 7.3 shows a SAS image of a small rock formation at Breidangen, outside Horten. The data was collected during the run050610_2 mission. The water depth is 198 m, and the vehicle altitude 16 m. The SAS image is based on 320 pings, the grid resolution is 2×2 cm, and the processed theoretical resolution is 1.9×3.2 cm. The lower panel shows the interferometric height map from the same region (mapped in pseudocolour). The white areas are regions of low coherence, where the relative height cannot be estimated. This typically corresponds to the shadow regions in the image. The height map has a grid resolution equal to the image, and a theoretical horizontal resolution of 10×16 cm. Figure 7.4 shows parts of the rock field from other views (and from other missions, with other system parameters).

Figure 7.5 shows a threedimensional rendering of the estimated seafloor map, with the image (scattering strength) rendered on top. The three surfaces, are based on the same map, just rotated in different views. These 3D-views demonstrates one of the major benefits a high resolution interferometric SAS gives, namely high resolution mapping in the same grid as high resolution imaging.

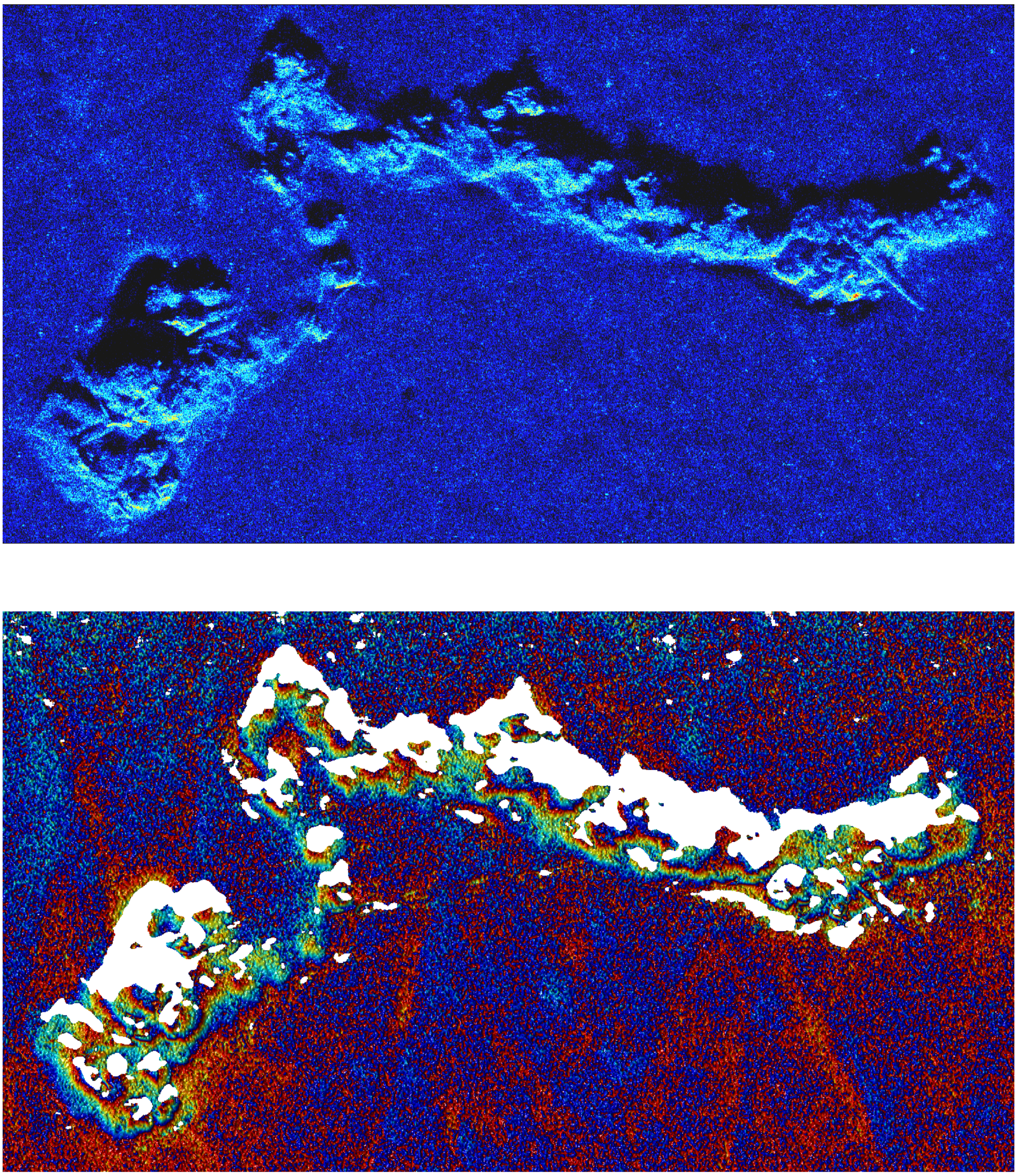


Figure 7.3: SAS image (upper) and bathymetry (lower) of a rock formation at Breiangen outside Horten. The data is from HUGIN mission run050610_2, at 198 m water depth and 16 m altitude. The image size is 48×25 m, and the ground range is 35 to 60 m.

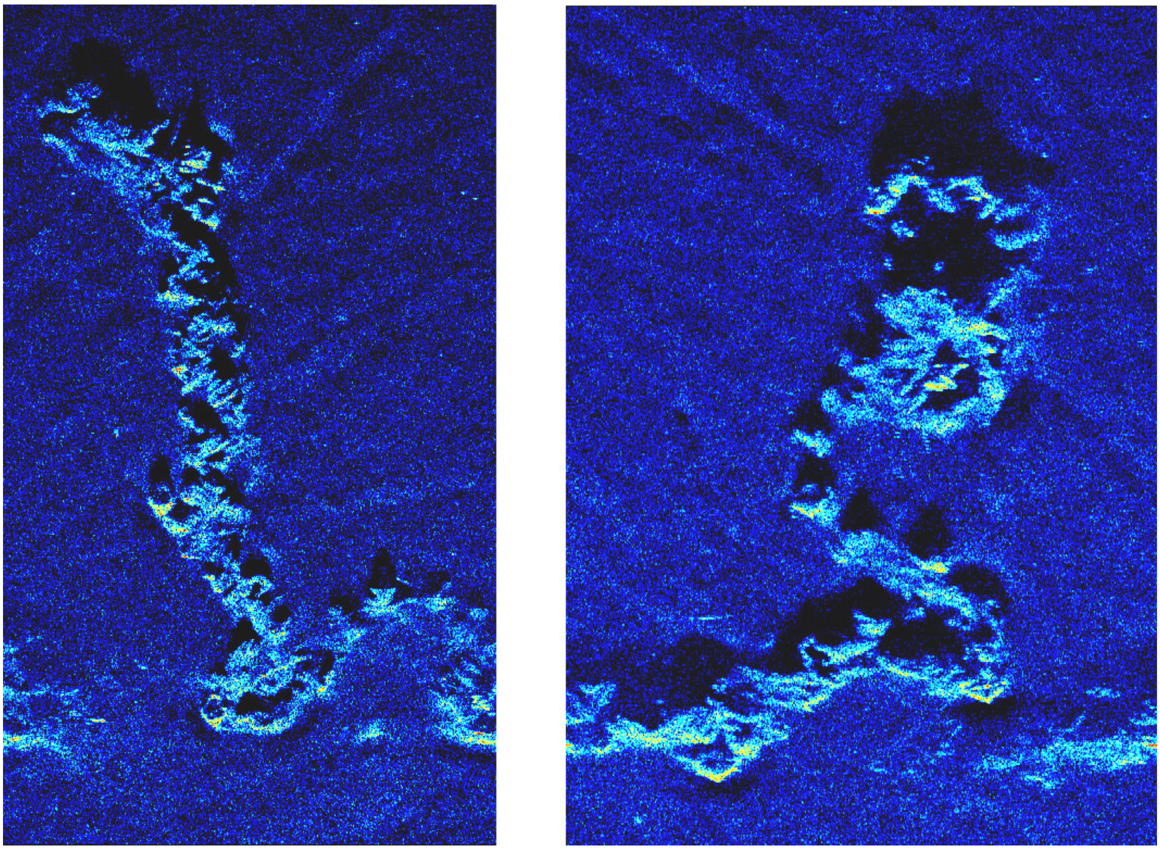


Figure 7.4: Different views from HUGIN mission run051110_1 of parts of the rock field shown in Fig. 7.3. The range is 45 to 85 m in the left image, and 70 to 105 m in the right image.

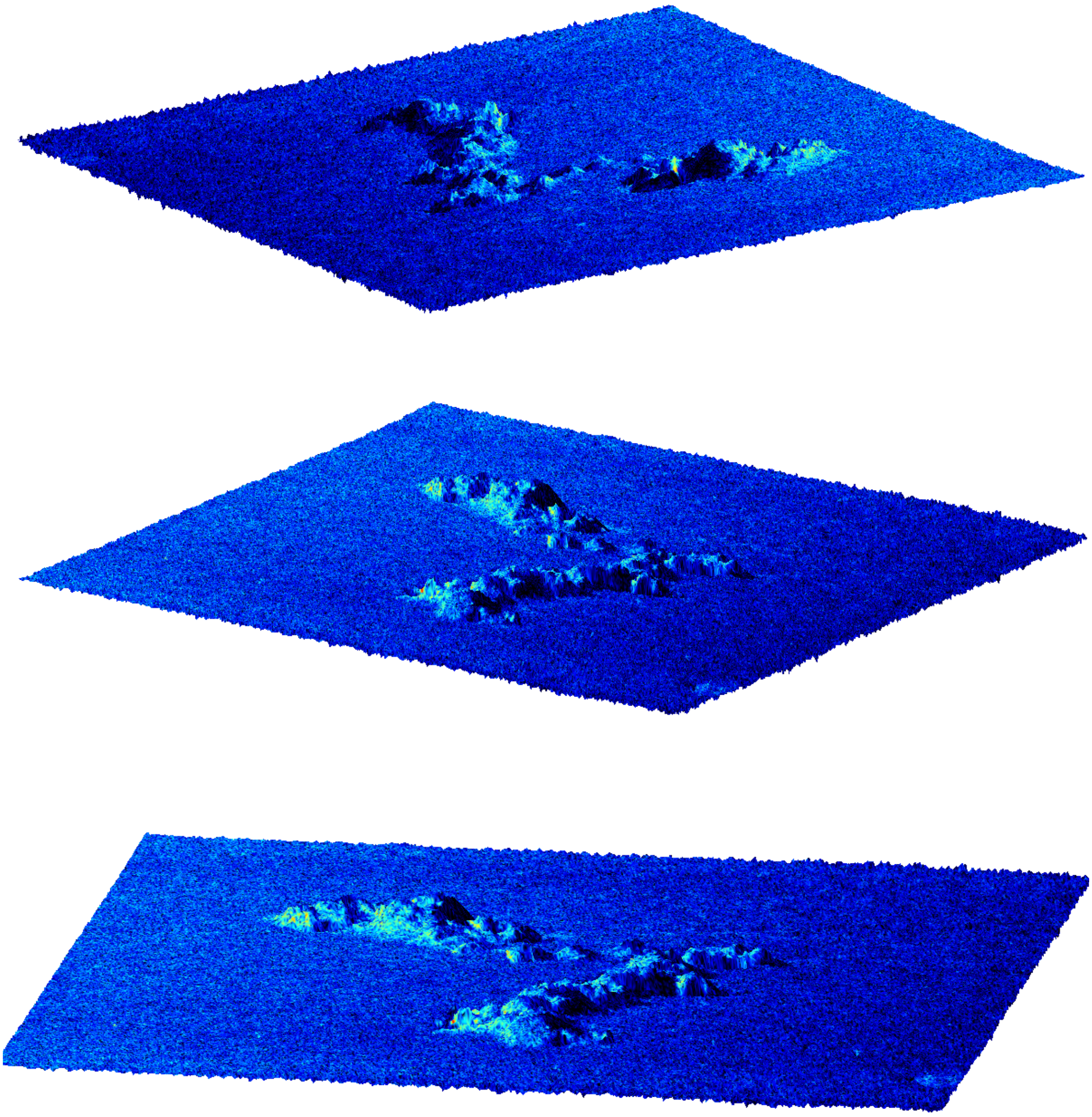


Figure 7.5: Three dimensional renderings of the bathymetry of the rockfield with echo strength on top.

8 Advanced Concepts

Synthetic aperture sonar images are fundamentally different from sidescan sonar (SSS) images in that multiple pulses are coherently combined in each pixel in the image. This coherent combination increases the along-track resolution in the image, such that SAS systems can have substantially better resolution than SSS. An unwanted effect exclusive for SAS, is the accumulation of navigation inaccuracies during the synthetic aperture data collection. This can lead to defocusing (blurring) and production of ghost targets (side lobes/grating lobes) in the SAS images. The aspect-angle variation an object is observed in, is typically larger for SAS than SSS. This leads to more variation and possibly better coverage of angle dependent scattering features, such as glints from cylinders. It also leads to aspect dependent shadow casting, important for traditional shadow classification.

8.1 Target Sharpening by Autofocus

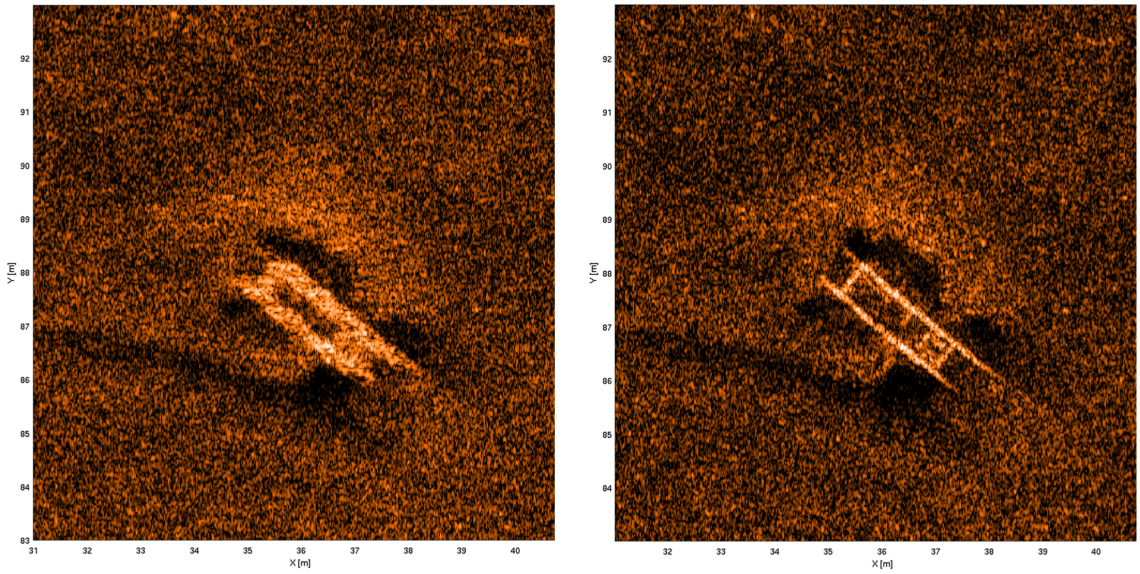


Figure 8.1: SAS image of "ladder" at 87 m range. Left panel: default processing (with inaccurate sound speed). Right panel: image run through PGA.

The SAS image quality is strongly dependent on navigation accuracy, knowledge about the sound velocity and knowledge about the geometry. Inaccuracies can cause geometric distortion, defocusing (or blurring) and grating lobes / side lobes (or artifacts, ghost images) in the images. The PGA [2] algorithm performs blind correction of uncompensated errors, and works best on small areas. Figure 8.1 shows the effect of running PGA on a 3 m object (ladder alike) at 87 m range. In this particular case, the sound velocity was incorrect, causing the image blurring.

8.2 Fixed Focus Shadow Enhancement

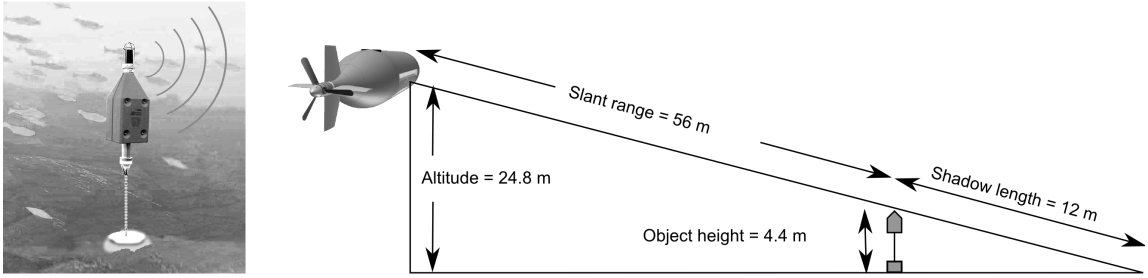


Figure 8.2: Artist impression of the acoustic release transponder (left), and sensor geometry relative to the transponder (right).

Shadows can be of great importance in classification of targets. Synthetic aperture image formation requires that the illumination of the target is spread over a larger angular section. This will again reduce the shadow contrast [6, 7]. The larger angular spread, the less sharp edges between shadow and highlight. The information about both target and shadow are, however, encapsulated in the collected data. By reorganizing the data in a slightly different manner, the shadow can be enhanced (at the cost of less focused surroundings) [7]. This is called “fixed focus shadow enhancement”.

Figure 8.2 shows an acoustic release transponder placed on the seafloor at approximately 200 m water depth during the HUGIN mission run051110_1. The left panel in Fig. 8.3 shows a SAS image with default processing. The right panel shows the same data run through the fixed focus shadow enhancement routine in the FOCUS toolbox. The vehicle altitude is 24.8 m. The suspended target casting the long disconnected shadow is at 56 m range. A sandbag used as sinker is at 58 m and casts a short shadow shadow immediately after the echo.

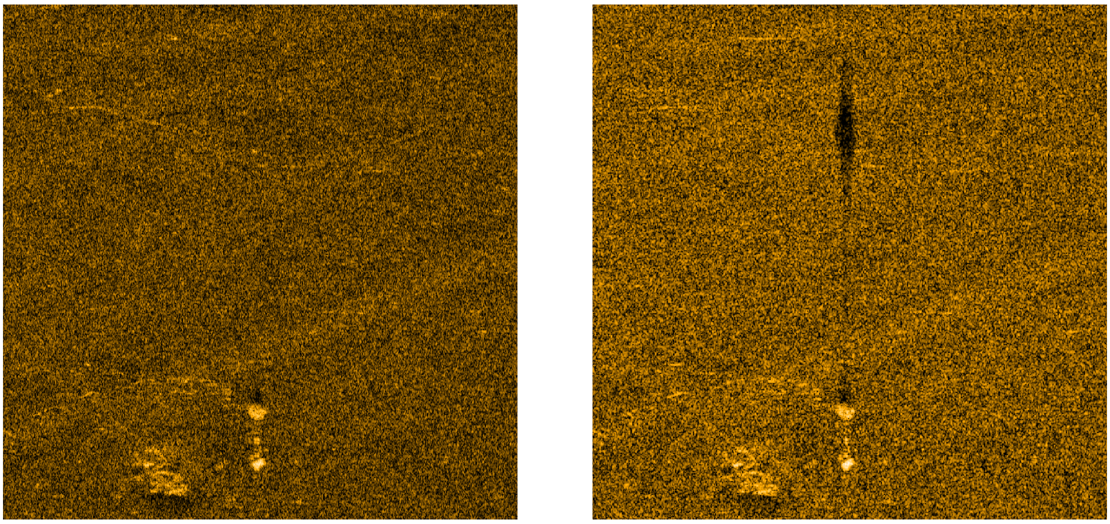


Figure 8.3: SAS image of suspended target at 56 m range. Left panel: default processing. Right panel: fixed focus shadow enhanced image.

8.3 Multi-Aspect View

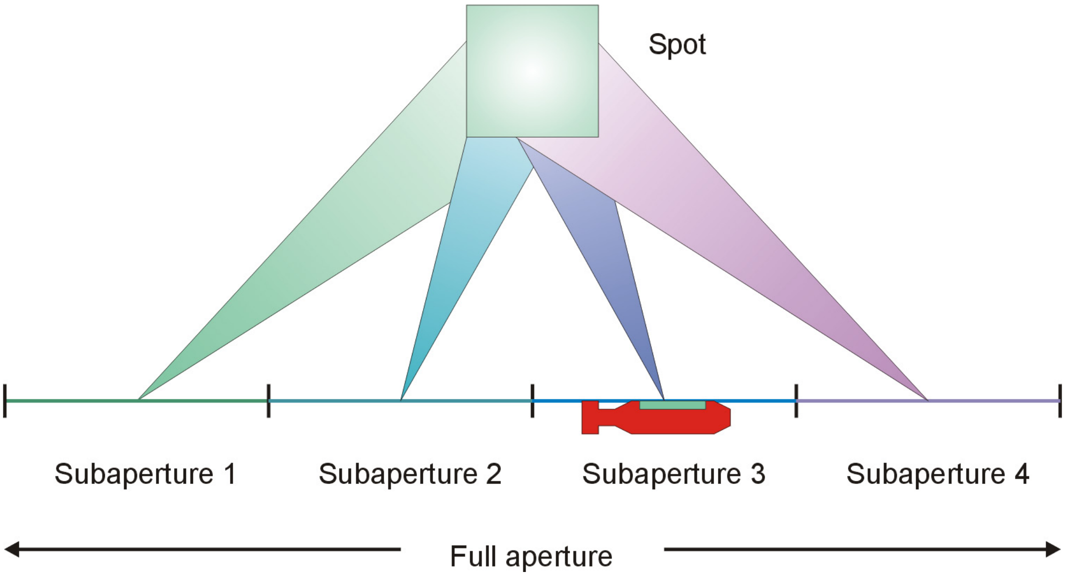


Figure 8.4: Concept of subaperture imagery.

By dividing the full length of the synthetic aperture into subapertures, individual images from each subaperture can be formed. This is illustrated in Fig. 8.4. These images are independent and can contain different information about the aspect dependent highlights and shadows from objects, which again can be valuable information in target recognition. Subaperture processing comes at a price: each individual image is at lower resolution compared to an image processed by the full length synthetic aperture.

Figure 8.5 shows the fishing boat (see Fig. 6.2) subaperture processed in three different aspects. We see that the shadow is cast in slightly different directions. More interestingly, the features on the fore deck and the wheelhouse have aspect dependent scattering strength. Note that the SENSOTEK system was run in “1030” mode (not widebeam mode) in this particular run.

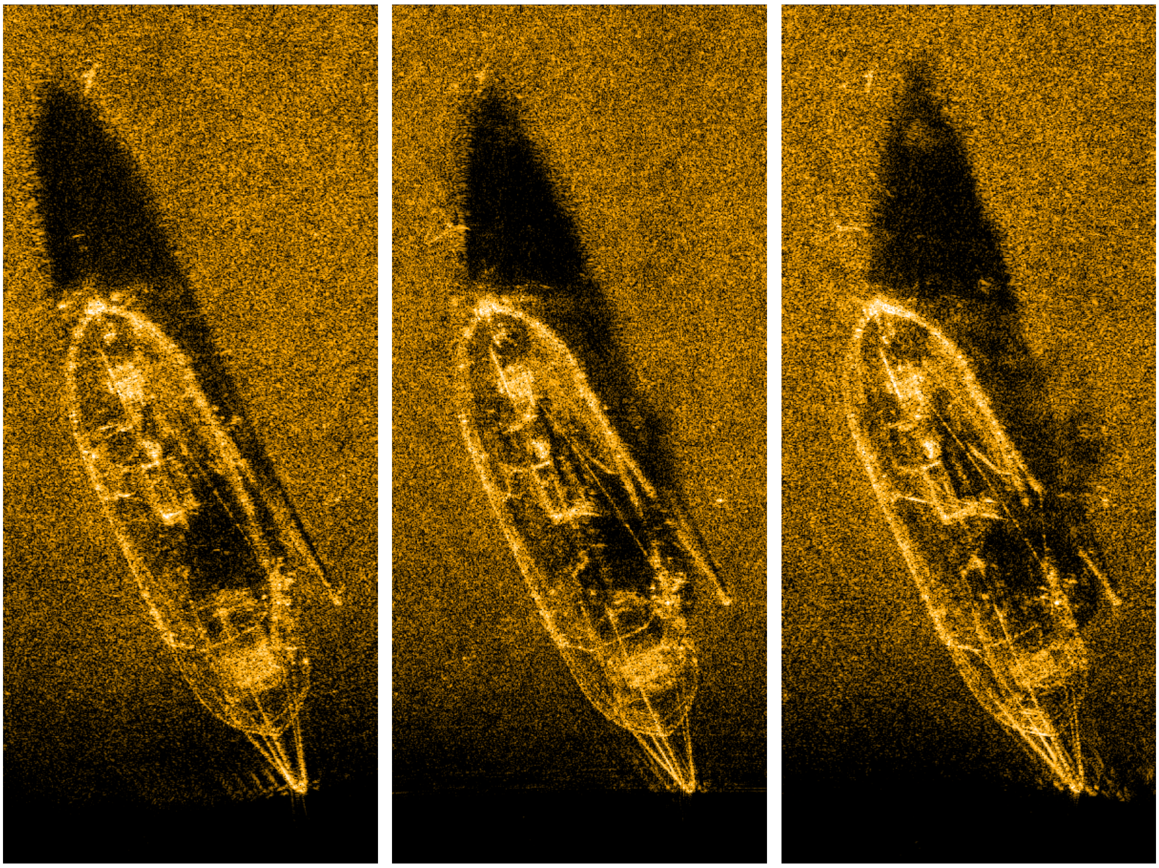


Figure 8.5: Multi-aspect images of fishing boat. Left: -14 degrees; Centre: broadside; Right: +14 degrees. Image range is 24-62 m.

8.4 3D Mapping of Objects

High resolution interferometric SAS such as the SENSOTEK SAS system, can be used to produce images containing information about the target strength, and threedimensional maps of small objects. The map in addition to the image can give clues about the target shape and height, and is as such of interest in target recognition.

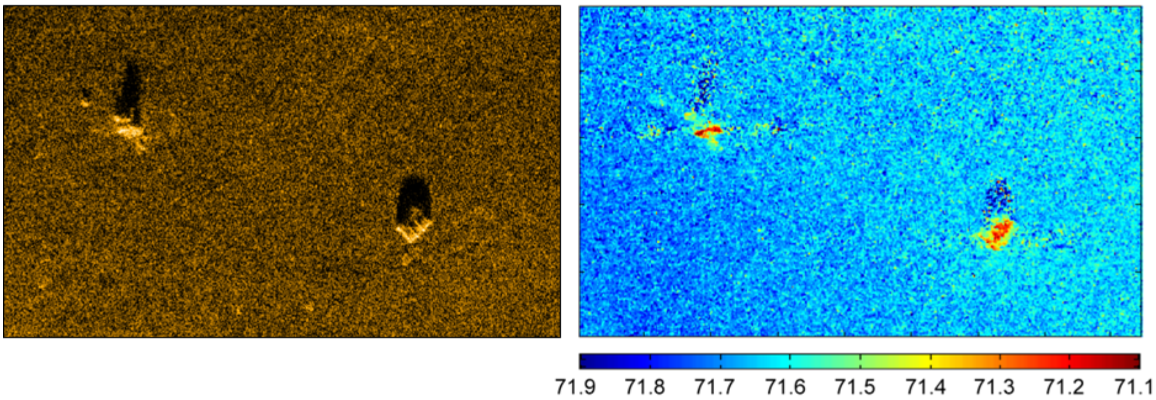


Figure 8.6: SAS image of a rock and a drum (left) with corresponding high resolution bathymetric map (right). The colourbar indicates the depth to the seafloor in metres.

Figure 8.6 shows a SAS image of a barrel and a rock (left), with the corresponding height map (right). The colourbar indicates the depth to the seafloor in metres. The data are collected in area 2 (see Fig. 5.1) at 55 m water depth and 17 m altitude. The range to the drum is 48 m, and the image size is 9 x 16 m. The SAS images are processed with a theoretical resolution of 2 cm along-track, and 3.2 cm cross track. We see that the drum is elevated approximately 50 cm relative to the surrounding seafloor. Note that the height map is invalid in the shadow region.

Figure 8.7 shows a SAS image of the barge (left), with the corresponding height map in pseudo-colourcoded height (right). The vehicle depth is 166 m, and the altitude is 18.7 m. The image size is 15 x 25 m, and the barge is at around 60 m range. The system was run in 1060 mode (widebeam mode), and the image is processed to a theoretical resolution of 1.2 x 2.4 cm. Figure 8.8 shows a 3D representation of the height map of the barge, where colour indicates height.

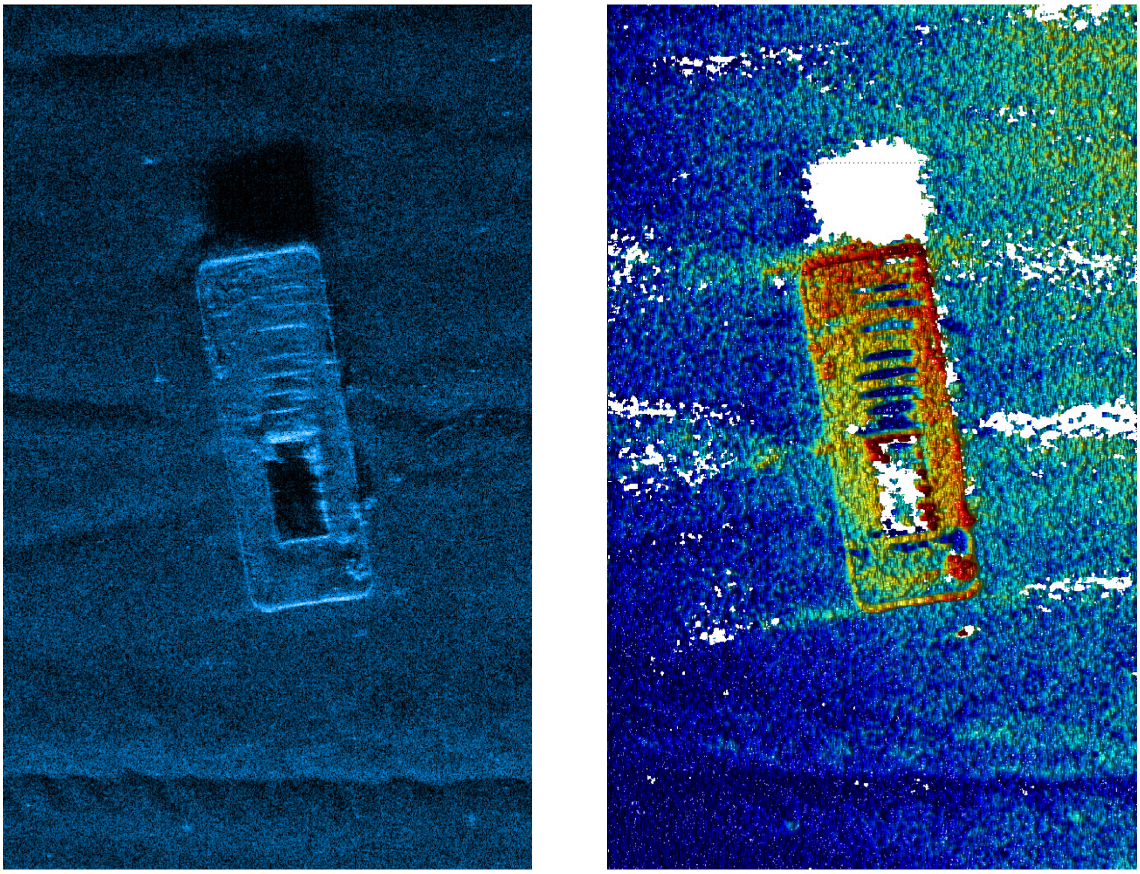


Figure 8.7: SAS image of the barge (left) with the corresponding height map (right) from run061018 in area 1 (see Fig. 5.1).

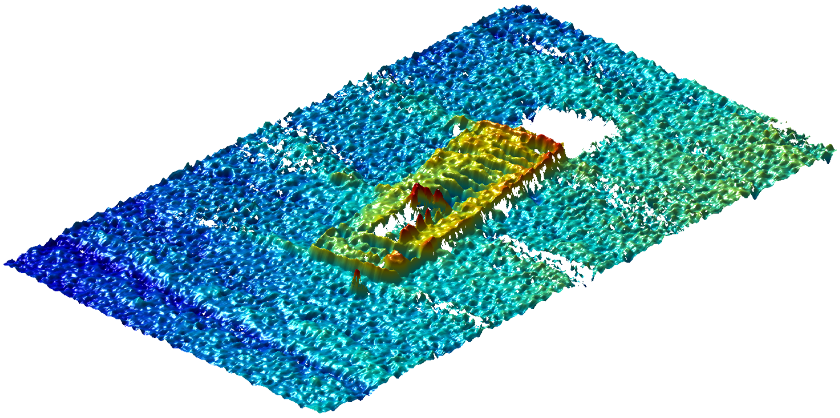


Figure 8.8: 3D view of the bathymetric map of the barge. The colours indicate height (same as in the right panel of Fig. 8.7).

9 Summary

FFI and Kongsberg Maritime have an ongoing program to develop synthetic aperture sonar technology for the HUGIN AUV. In this program, a high end technology demonstrator, named SENSOTEK, has been developed. The system was installed on the HUGIN I AUV March 2005, and has been tested in 11 missions between June 2005 and October 2006. The system has collected more than 1.5 TB of sonar data for development, evaluation and demonstration purposes.

Although being a prototype with several suboptimal solutions, the SENSOTEK system has been invaluable in the research and development of SAS technology at FFI and Kongsberg Maritime. We have successfully demonstrated SAS imagery and interferometric mapping at very high resolution with the SENSOTEK system.

FFI and Kongsberg Maritime continues to develop SAS technology in the next generation SAS system called HISAS 1030. The first commercial delivery in the HISAS series will be part of the HUGIN 1000-MR AUV delivered to the Royal Norwegian Navy in 2007. A number of major improvements are implemented in the HISAS 1030 based on the key learnings from the SENSOTEK system. These improvements include: longer range (lower self noise); more robust sonar design; larger depth rating; real-time processing of dynamic focused sidescan images.

FFI continues the research and development of synthetic aperture technology. New features and applications related to image enhancement, advanced navigation, autonomy, and 3D imaging are under development. The collaboration between the SAS and the SAR group at FFI will be strengthened.

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Abbreviations

AINS	Aided Inertial Navigation System
ATR	Automatic Target Recognition
AUV	Autonomous Underwater Vehicle
CRLB	Cramer-Rao Lower Bound
DPCA	Displaced Phase Center Antenna
DVL	Doppler Velocity Logger
FFBP	Fast Factorised Back-Projection
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
INSAS	Interferometric Synthetic Aperture Sonar
MBE	MultiBeam Echosounder
MCM	mine countermeasures
PGA	Phase Gradient Algorithm
PMA	Post Mission Analysis
REA	Rapid Environmental Assesment
RNoN	Royal Norwegian Navy
SAR	Synthetic Aperture Radar
SAS	Synthetic Aperture Sonar
SNR	Signal to Noise Ratio
SSS	Sidescan Sonar
TDIB	Time Domain Interpolation Beamforming

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