Archaeological use of Synthetic Aperture Sonar on Deepwater Wreck Sites in Skagerrak

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Abstract

Marine archaeological surveying in deep waters has so far been challenging, mainly due to operational and technological constraints. The standard tool has been Side Scan Sonar (SSS) towed behind a surface vessel. Synthetic Aperture Sonar (SAS) technology is not subject to the traditional range/resolution trade-off, and produces results of considerably higher quality than traditional SSS. In 2015 and 2016 a comprehensive mapping of wrecks in Skagerrak, a large deepwater area off the south coast of Norway was undertaken, using an interferometric SAS system deployed on an Autonomous Underwater Vehicle (AUV). By examining data from two passes of one of the many historical wrecks that were detected in the survey area, we demonstrate how SAS can be used to produce very high resolution imagery and bathymetry of wreck sites. Furthermore, post processing techniques are applied to exploit the high information content inherent in SAS data, enhancing aspects of the data for relevant archaeological analysis and interpretation. We show in this paper how SAS technology represents significant improvements in our abilities to conduct high quality and high resolution seabed mapping. The adoption of this technology will both benefit archaeological research and provide knowledge for better decision making in underwater cultural heritage management.

Keywords

Synthetic Aperture Sonar, Archaeology, Deepwater wrecks, High resolution, Seabed mapping
1. Introduction and background

There are practical and physiological constraints limiting the use of human divers for seabed surveying beyond very shallow depths. To explore, investigate, map and monitor in deeper waters we must rely on remote sensing technologies to provide data. Due to the inherent optical properties of water, light has limited range, and acoustic sensing has been the technology of choice for most marine sciences for larger area seabed mapping (Singh et al., 2007). Marine archaeology was an early adaptor of such technology, and has used Side Scan Sonar (SSS), Multi Beam Echo Sounders (MBES) and Sub Bottom Penetrating Sonars to detect, map and monitor cultural heritage on the seabed for decades (Bates et al., 2011). As acoustic sensors have developed over the years, data quality has improved significantly. However, the range-resolution tradeoff has always been a matter of fact, and applicants of underwater acoustics for seabed mapping have always had to make compromises best suiting their particular needs (Quinn et al., 2005). With the advent of SAS technology, this no longer is the case. The resolution of SAS imagery does not depend on wavelength (frequency), and SAS can therefore operate at long range (several hundreds of meters) and at the same time retain a consistently high resolution (centimeters) (R. E. Hansen, 2011).

The sophisticated technology comprising the sensor, the strict requirements for precise platform navigation and the computer intensive and complex post processing needed to produce high quality SAS data has so far curbed widespread use of the technology in marine archaeology. The rapidly advancing developments within underwater robotics and computer technologies are likely to change this within the coming years, as the technology becomes more commercially available and easier to use (P. E. Hagen et al., 2008; Roy Edgar Hansen, 2013). The few published examples of SAS used in marine archaeology have mainly showcased the potential (R. E. Hansen et al., 2009; Lawrence, 2011; Roman et al., 2010; Ødegård et al., 2013).

After WWII stockpiles of chemical weapons and munitions were a safety issue on the allied agenda. The disposal of huge amounts of highly dangerous materials was a problem, and the corresponding to the period unlikely solution was to dump it in the ocean. Convoys of discarded ships were filled with munitions, and in various manners sunk more or less within designated deepwater areas. Today this historical idiocy poses huge environmental and health safety problems many places around the globe, and the need for detailed information of locations and states is crucial for making good and safe management decisions (Long, 2009). In 2009, 2015 and 2016 the Norwegian Defense Research Establishment (FFI) and the Norwegian Coastal Administration have cooperated on detailed mapping of dumping fields just off the Norwegian coast in the Skagerrak Strait (C. M. Hansen et al., 2009; Torstein Olso Sæbø et al., 2015). In addition to finding many of the wrecks from the post WWII dumping, the survey also discovered a number of other wrecks that appeared to be much older (fig.1).
Fig. 1 Map showing Skagerrak with survey area. (Source bathymetry: EMODnet)
The Skagerrak strait links the Baltic Sea to the North Sea, and thus the rest of the world. It lies between Norway, Sweden and Denmark, and is today one of the most heavily trafficked sea routes in the world. We can assume that it has seen human seafaring since the Mesolithic era (Gaffney et al., 2007), and we know that it has been a very important commercial and political seaway since at least the Viking age. The Øresund Sound Toll was a tax the Danish king levied on all ships passing the narrow strait leading into the Baltic just south of Skagerrak in the period 1497-1857 (Gøbel, 2010). The records are accessible for online search and show that a total of 1.8 million passages were registered for the whole period (east- and west-bound). For the period 1634-1700 an average of 3146 passages each year, for the following periods respectively; 1701-1750: 3365 passages; 1751-1800: 8013 passages; 1801-1857: 12563 passages (http://dietrich.soundtoll.nl/public/stats.php?stat=py). The weather in this area can be rough (Lamb et al., 1991), and a considerable number of vessels have been lost in the open seas of Skagerrak. An estimation by Willard Bascom (1976, 72) that about 10 % of all ships that ever sailed sunk in open seas, has been corroborated for the region by analysis of databases from modern times by Gundersen et al. (2008). The latter also conservatively estimates that at least 10,000 ships have sunk in the Norwegian sector of the North Sea alone. We do not have information of how many ships have gone down in the adjacent Skagerrak area, but given the high sailing frequency and that losses at open seas were common, we can safely assume that the total number must be very high – at least several hundreds. The underwater cultural heritage deposited on the Skagerrak seabed represents invaluable sources for knowledge of our history for the last few thousand years. Most of Skagerrak is considered a shallow sea, with depths around 90 m. The exception is the Norwegian trench that extends down to around 700 m, and this includes the surveyed area. The seabed geology in the deepest parts is characterized by meters thick fine grained sediments deposited over the last 13000 years (Gyllencreutz et al., 2006), potentially very benign environments for preservation of shipwrecks. As for deeper waters all over the world, depth has been a methodological barrier for high resolution seabed surveying and mapping.

This paper briefly describes the principles behind SAS and how it differs from traditional SSS in terms of data acquisition, processing and products. We argue that SAS technology deployed on AUVs represents great methodological progress in our abilities to detect and record underwater cultural heritage. The paper aims to substantiate this claim by presenting and discussing data from deepwater wreck sites in Skagerrak, and by demonstrating post processing techniques for enhanced archaeological interpretations.

2. Method and materials

2.1 Sensor and platform

Traditional (real aperture) sidescan sonar systems produce imagery where mainly wavelength and array length determine along-track resolution, and pulse bandwidth determine across-track resolution (Blondel, 2009). It follows that a high frequency system will give high resolution both across and along track for short ranges, but with increased range the along-track resolution is impaired by wider beam and longer pulse repetition intervals. Acoustic absorption in seawater depends on frequency, such that...
higher frequency signals have shorter range than lower frequency signals. Therefore, you can lower the frequency can be lowered to gain longer ranges, but at the cost of lower resolution (Lurton, 2010). In contrast, along-track resolution for a SAS system is determined by the false length of the array (i.e. synthetic aperture) – which is a function of range (Massonnet et al., 2008). It is thus independent of frequency - which is a notable difference from real aperture sidescan sonar. By creating a ‘false’ array, even longer than the platform carrying it (fig. 2), the signal can be refined by using multiple echoes to focus on very small areas on the seabed, enabling much smaller pixels in the produced seabed imagery (fig. 3). By arranging an array consisting of multiple receivers, the SAS system uses beamforming to focus the received signal in particular directions. Furthermore, by processing phase coded transmit signals from consecutive pings the SAS system can benefit from high energy signals (i.e. longer range), while retaining large bandwidth. Delaying the signal from each receiver for every ensonified pixel, and then summing the signals in each pixel, will result in SAS imagery that have rich data basis providing a high signal to noise ratio (SNR). For a thorough overview of SAS principles see R. E. Hansen (2011).

Fig. 2 Synthetic array longer than the real array (R. E. Hansen, 2011).

Fig. 3 Sonar imaging concepts (R. E. Hansen, 2011).

SAS image quality depends on both navigational and environmental factors. To ensure a consistent along-track resolution, the length of the synthetic array increases with range. Hence the quality of longer range SAS depends heavily on accurate measurements of platform velocity and attitudes, in addition to sound velocity. The performance of the platform is of vital importance for the quality of the SAS data. Not surprisingly AUVs with high end aided inertial navigation systems are the commonly preferred platforms for this sensor, although there are examples of towed platforms as well. Main issues regarding AUV as instrument carrier for SAS for this kind of survey are: vehicle stability, attitude compared to direction of survey line (i.e. crab) and trim (Torstein Olsmo Sæbø et al., 2015). Also navigation with a set altitude above seabed could cause the vehicle to do frequent pitching if the bathymetry is uneven (Roy E
The 2015 and 2016 Skagerrak surveys were conducted with a HiSAS 1030 interferometric sensor deployed on HUGIN HUS, a Kongsberg Maritime HUGIN 1000 AUV operated from the surface vessel H.U. Sverdrup II. A range of other sensors were also deployed on the AUV. A short summary of HiSAS 1030 properties is presented in table 1, for an overview of HUGIN 1000 see P. E. Hagen et al. (2003).

Table 1

<table>
<thead>
<tr>
<th>HiSAS 1030 properties</th>
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<tr>
<td>Centre frequency (range)</td>
<td>100 kHz (85-115 kHz)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1,5 cm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>30 kHz</td>
</tr>
<tr>
<td>Resolution</td>
<td>3 cm x 3 cm</td>
</tr>
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</table>

2.2 Post processing

After download the initial processing step is to use a wavenumber algorithm (frequency domain) to transform raw data (low resolution, real aperture sidescan data), together with navigational data, into high resolution SAS imagery (Roy Edgar Hansen et al., 2005). As with traditional SSS data post mission analysis is usually performed by reviewing the data in suitable software with a waterfall view. A first analysis of the data is to reduce the number of false positives by separating actual Objects of Interest (OOI) from “wreck like” natural features. Finding methods to objectify and automate such processes is a research target (Ødegård, in prep.), but is not the subject of the present contribution. A second review of the remaining OOI aims at being interpretively to determine what the object is likely to be.

Detection and classification of Underwater Cultural Heritage (UCH) depends on three main factors: The data quality in terms of resolution and SNR, the state of the UCH and its distinguishability from the surrounding seabed environment and geology, and finally; the analyst’s knowledge and hence ability to recognize UCH in all its various forms and shapes as it is represented in the data (cf. Maarleveld, 2010). For selected areas containing possible OOI, relevant blocks of data can be reprocessed using a back-projection (time domain beamforming) method. This latter method is more computer intensive and time consuming, but yields imagery with higher resolution and quality. Back projection processing also allows for some interesting manipulation of variables for enhancing certain aspects of the images – potentially well suited for detailed studies of particular features typically found on wreck sites (Roy E Hansen et al., 2008). The processing chain from raw data to high fidelity SAS products is shown in fig 4. Low resolution data are used to compute precise navigation data, that are required to produce high resolution data products. Iterations can improve navigation data, and hence higher quality products. While back projection processing as the final stage is done post mission – the other processes leading from raw data to high resolution products can currently be performed online, an important condition for robust decision autonomy based on payload data deliberation (Krogstad et al., 2014).
Fig. 4 SAS Processing chain showing sequential steps in SAS processing (dark blue boxes) and respective products (light blue boxes).

SAS raw data comprises a much higher potential for information than just imagery. Special software for processing SAS data, FOCUS toolbox, has for the last decade been developed by FFI (R. E. Hansen et al., 2005), and can deliver the following data sets:

- **Intensity** image is similar to backscatter plots typical for SSS or MBES, hence pixel values correspond to echo strength. The pixel size is 2 cm x 2 cm, and the theoretical resolution is typically 3 x 3 cm. The pixel values do not represent calibrated echo strengths. To obtain this, the hardware and software must be calibrated and energy preserving, and all geometry factors must be compensated for. This is very similar to the equivalent problem in sidescan sonar (Clarke, 2004).

- **Bathymetry** data is derived by means of interferometry, a well-known principle in underwater acoustics (Lurton 2010). The HiSAS 1030 system described here has two parallel arrays with vertical baselines on each side of the AUV to measure time delay (phase difference) from the same ping, and calculate bathymetry (Torstein Olsmo Sæbø et al., 2013). For swath bathymetry there is a tradeoff between vertical accuracy and horizontal resolution. When phase differences between images from each array are translated to depth, errors due to noise and wrapping ambiguities occur, especially at long ranges. An **averaging of a number of pixels** is therefore **averaged used** to compute each depth measurement. The more pixels are used for each measurement, the higher accuracy is obtained but at lower resolution. In HiSAS 1030 bathymetry a resolution of 18 cm x 18 cm is typical. For wreck 3 a higher resolution...
bathymetry raster was processed using a 9 cm x 9 cm Kaiser Window, but it proved to have more noise and thus correlated less with the intensity plots.

Coherence in addition to intensity and bathymetry is another third descriptor for data product from interferometric systems. The coherence is the similarity between the two images used in the interferometry-processing. It is calculated as the normalized cross-correlation per bathymetry pixel, and gives a direct assessment of the quality of the measurement.

2.2.1 Despeckling

Speckling is a phenomenon that occurs in sonar imaging as well as all remote sensing that uses coherent radiation for illumination (Blondel, 2009). Echoes from different scatterers are not in phase, and can result in positive or negative interferences (high or low returns) manifested in dark or bright pixels in the image. Applying despeckling filters to SAS imagery has ambivalent effects. They reduce variance in pixel values, and can make subtle features easier to perceive. However, they always reduce the geometric resolution (Oliver et al., 2004). Comparison of despeckled and non-despeckled images of the Skagerrak wrecks indicates that both have their merits. Despeckled images seem to be better suited for general interpretation and establishing boundaries of objects and features, while non-despeckled images could possibly provide details for closer studies and investigations (see fig. 5). A more exact evaluation of despeckling would require ground truthing, i.e. photo images of wreck site features or objects as a reference for SAS-image interpretation and measurements.
2.2.2 Fusion of image, bathymetry and coherence

Combining high resolution SAS imagery with bathymetry allows for a more comprehensive interpretation of areas or objects of interest (Roy E Hansen et al., 2008; Torstein Olso Sæbø et al., 2015). The term “Fusion imagery” is used when intensity, bathymetry and coherence (SNR) plots are merged. The resulting image is a monochromatic intensity plot for backscatter overlaid by a bathymetry plot with color ramps best presenting variations in elevation values for each pixel. A chosen threshold value for coherence is used to mask pixels with low SNR, depending on the elevation gridding (size of each depth cell). As the SAS imagery has a higher resolution than the bathymetry, a careful study of shadows can reveal protruding objects that are not evident in the bathymetry plot—in this category typical features for historic shipwrecks could be stem or stern posts, futtocks, top timbers, masts etc.

2.2.3 Multi view fusion

Ensonifying a wreck with many uneven surfaces and structures from different angles and directions will generate different representations in terms of highlights (reflections) and shadows. Multiple aspects could therefore complement each other and yield a better basis for interpretation and higher confidence in classification. For sites with very elevated structures many important features could be “obscured” by relatively large shadows. Multi view fusion of an area or object of interest can be obtained by blending images from multiple passes at different aspects as layers in an image processor (animation 1). A precise comparison of multiple aspect images would require accurately data driven co-registration of images from the different passes, a problem which is non-trivial (Torstein O Sæbø et al., 2011).

3. Results

3.1 Total area

The survey area measured 450 km² and was mapped in 24 dives at a total survey time of 254 hours. 36 wrecks from the chemical dumping were found and in addition 18 other, potentially historical wrecks. A summary of the 2015 and 2016 surveys is presented in table 2.

<table>
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<th>Table 2</th>
<th>Summary of 2015 and 2016 surveys.</th>
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<tr>
<td>Mapped area in km²</td>
<td>450</td>
</tr>
<tr>
<td>Total dive time for HUGIN AUV (hours)</td>
<td>254</td>
</tr>
<tr>
<td>Distance covered by HUGIN AUV (km)</td>
<td>1600</td>
</tr>
<tr>
<td>Estimated total size of SAS raw data (Tb)</td>
<td>17</td>
</tr>
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The historical wrecks were in varying stages of decomposition, from highly intact structural integrity to completely flat and disintegrated sites (fig. 6). Since the wrecks found in this area likely went down without hull crushing mechanical impacts [Bascom, 1976], we could assume that at the beginning of the
site formation processes they would have relatively similar starting points. Further assuming that the biological, mechanical and physical environmental variables would likely be similar for all through the survey area, the differences in appearance of the wrecks were mainly a function of time (decomposition and sedimentation). In plain words: the most intact and proud were probably younger. In (Ødegård et al., 2016) SAS imagery and bathymetry were juxtaposed with photogrammetry models with sub cm accuracy. It demonstrated that SAS is very well suited for detecting even much decomposed wreck sites with low vertical profile and few visible structural elements. However, we cannot know how long it will take for a wooden wreck to completely disappear in these waters. The wreck site density, based on the current list, indicated a frequency of 0.036 wrecks pr. km$^2$. Since Skagerrak has been part of a much trafficked deep sea area through history, we cannot assume that the wreck distribution here is generally representative. Still, it could be indicative for the density in deep sea sailing routes in relatively confined straits. Density would be higher in shallow harbor approaches (Deeben et al., 2002) and lower in less confined areas.
Fig. 6 Three historical wrecks in various stages of disintegration found during the Skagerrak SAS surveys. Grey images are intensity plots. The coloured images are the same intensity plots merged with bathymetry plots - fusion imagery.

Since parts of the survey area have been mapped both with SSS and SAS, it was possible to compare quality and resolution directly (fig. 7). In 2009 the HUGIN HUS AUV was fitted with an Edgetech 2200 SSS system with dual frequencies of 120 kHz and 410 kHz. The SSS images of the wreck (fig. 7.1 is 120 kHz and fig. 7.2 is 410 kHz) were acquired at 77-89 m range from broadside. The AUV had an altitude of 30 m and held a speed of 3.7 kn. The SAS image of wreck 3 (fig. 7.3) was acquired at 70 m range from broadside. Altitude was 24.8 m, and speed 3.7 kn. The difference in level of detail and image quality between the SSS and SAS images was evident. While the wreck was detected and classified as a probable historic wreck site based on SSS images, the details of the SAS imagery leaves no doubt. Shadows in the SSS images alluded to elevated bathymetric features in relation to the wrecks, but a more specific interpretation would have a low degree of confidence. Compared to traditional SSS imagery, SAS technology typically represents a factor of 10-100 in resolution improvement along track (P.E. Hagen et al., 2007; Roy Edgar Hansen, 2013).
Fig. 7. SSS and SAS images of wreck 3. 1) SSS 120 kHz, range 77-89 m; 2) SSS 410 kHz, range 77-89 m; 3) SAS, range 70 m.
3.2 Wreck 3

On April 13th 2015 two passes were made of the wreck site nine minutes apart, providing data sets 3a and 3b from broadside directions with 180 degrees difference (fig. 8). Since a relatively low grazing angle produces acoustic shadows, data sets from opposite directions could complement each other and provide fuller coverage of the site. Data sets from the two passes were coregistered based on intensity plots georeferenced using a first order polynomial transformation in ArcGIS. Edges of two anchors in the bow area, five frame tops along both sides of the wreck and the feature assumed to be the stern rudder post were used to shift rotate and scale the 3b data set to match 3a. Total residual RMS error was 0.25 cm. When comparing the coregistered intensity plots a 20-25 cm parallel displacement of the starboard side was evident, making the wreck in the 3a dataset appear “wider” (an animation of images with varying blending of the two datasets can be found in supplemental material). Beyond that the two data sets appeared to be remarkably geometrically consistent. There are several ways geometrical errors can be introduced into SSS and SAS imagery. Typical sources are inaccuracies in sound velocity, vehicle speed, slant-to-ground correction and SAS-processing (R.E. Hansen et al., 2014).

Fig. 8 Despeckled intensity plots from two passes on opposite sides of wreck 3. Data set 3a to the left and 3b to the right.
The coherence raster sets (fig. 9) were used to mask bathymetry where the coherence was below a threshold value set to 0.66. The combined coverage of the two bathymetry raster sets (fig. 10) was almost 100% (0.09 m² below SNR threshold). Overlaying the two coregistered bathymetric data sets, and compensating for a 26 cm offset in 3b’s vertical plane, the bathymetry matched very well with a mean difference of only 1.5 cm (fig. 11).

Fig. 9 Coherence plots of data sets 3a (left) and 3b (right).
Fig. 10 Bathymetry plots of data sets 3a (left) and 3b (right).
A single comprehensive 2D plan presenting all relevant information from all datasets was not feasible, but a clearly set out site plan could serve as a basis for analysis and interpretation for management and research purposes. The site plan drawing (fig. 12) was based on manually drawn outlines of features identified by reviewing backscatter intensity, shadows and bathymetry as layers with varying opacities in ArcGIS (fig. 13). In addition a point cloud representation of the wreck could be viewed and rendered in Fledermaus 3D software to enhance the spatial comprehension of the site (fig. 14). The outline of the
wreck's hull shape was drawn by merging high-pass filtered intensity plots (>50%) from both passes. Color-coded elevations were used as a background for the site plan. A 2 m x 2 m window with a dynamic color ramp was moved systematically over the wreck site enabling detection of local variations in elevation, e.g. frames protruding at regular intervals along a ship side (fig. 15). This method revealed features that were not clearly visible in the intensity plot, hence complementing the site plan.

Fig. 12 Plan drawing of wreck site with bathymetry overlay.
Fig. 13 Fusion of intensity and bathymetry (coherence used to mask bathymetry).
Fig. 14. Examples of 3D viewing and rendering of wreck site in QPS Fledermaus software.
Fig. 15 Local elevations interpreted as timbers or frames.
3.2.1 Interpretation

As our knowledge of the wreck except for the present data was very limited, an interpretation had to find support in general assumptions of the wreck’s properties. The wreck appeared to be naturally stabilized. No recent mechanical impacts seemed to have taken place. Degradation was due to long-term biological, physical and chemical processes. This indicated that the ship was built of wood and that it was probably several hundred years old. The general size and shape does not, however, support a medieval or earlier date. Nor does it suggest a fishing vessel or short-distance craft. An ocean-going ship of the postmedieval period would comprise framing in the form of floor timbers and futtocks, covered with more-or-less horizontal planking on the outside and similarly a ceiling on the inside. The continuous high intensity reflection along each shipside suggested the presence of outer planking, or overlapping timbers (typically occurring at the turn of the bilge). In either case it was assumed that the wreck was preserved to above the turn of the bilge, but probably quite a bit higher. The position of the anchor(s) and the characteristic “tail end” consistent with a post for a rudder confirmed the orientation of the wreck, with the bow oriented towards NW. The foremost section of the ship was less intact than the rest, possibly indicating that the ship impacted the seabed at a forward pitching angle, thus causing more damage to this area. While the observable length of the wreck was 27.3 m, the original length of the ship could not be established accurately. The maximum observable width of the wreck was at least 6.8 m. This resulted in a length-width ratio of 4 : 1. This is a very reasonable proportion for cargo and multi-purpose ships of the post-medieval period, and suggested that the lower hull was more-or-less complete. The sides of the wreck presented themselves as very straight, running nearly parallel, with a slight tapering towards the aft. This suggested that the hull stood fully upright, without any noticeable list or pitch. The abrupt form change toward the aft deadwood and rudderpost confirmed this, in being representing a virtually symmetrical, section at a level higher than the load-waterline. This meant that a considerable part of the hull was preserved under the sediments. Depending on the ship’s designed draft, this could be at least 2.5 or more than 3 or 3.5 m.

Furthermore, the images showed part of an upright standing mast. This suggested that at least part of the deck-construction was preserved, as the stump would have fallen over if this was not the case. The distance from the sternpost to the center of the mast was measured as 13.6 m. Since the center of gravity (COG) in sailing ships usually lies before the middle of their length, and the COG of the sails should be before the ship’s COG, we should conclude that the ship had more than one mast.

In the intensity plots it was clear that there were at least two anchors present on the wreck site. The anchor outside the starboard bow had a measured shaft length of 3.3 m and displaying rounded arms it seemed to correspond well to anchors of the 18th century (Sadania, 2015, pp. 360-361). Studies on large stock anchor typology, however, are rare, and an earlier date could not be excluded. Inside the wreck in the bow area a complex feature with multiple parts was visible in both passes, possibly a windlass. Along the starboard side of the wreck a number of shadows appeared at regular distances – an indication of frames protruding above the top strakes of planking. Near the bow on the port side the high intensity line in the imagery (planking/ceiling) corresponded to a narrow line of 20-30
cm depression in the bathymetry data (fig. 16). A likely explanation was that the low frequency SAS system penetrated soft sediments, and could have revealed features or objects that were buried. The seabed reflectivity indicated a change from homogenous muddy sediments inside most of the wreck (similar to the surrounding seabed), to a coarser more uneven surface towards the stern area. This coincided with more pronounced shadows that could indicate a structure or conglomeration of objects that were not covered by sediments. The apparent extension of this aggregation outside the hull on both sides of the stern rudder indicated that the features were objects rather than a fixed structure. The bathymetry showed a marked elevation in this area.
Fig. 16 Depression in bathymetry (light blue line) corresponding to ships side in intensity plot.
The bathymetry of the site clearly showed that there has been considerable sediment movement, with scouring areas around both stem and stern. The symmetric distribution suggested that the direction of the current has been athwartships, and probably predominantly from northeast.

Beyond its length-width ratio, its sharply flared lower hull at the stern, and its straight sides it was difficult to say anything specific from the overall shape of the wrecked ship. No evidence of cannon could be observed on the site, indicating that the vessel was commercial: a cargo vessel moving through the Skagerrak from the Baltic to the North Sea or vice versa. The cargo was most probably still present. With regard to dating, it was hard to be specific. An 18th century date would fit the present data. Considering the level of deterioration in relation to the geographic context the wreck a 17th century date could not be excluded either. In that case, a flute, a pinnace, or a similar type of vessel comes to mind. These ships are normally associated with Dutch trade that was responsible for a large proportion of the transport between the Baltic or Southern Norway and the ports in the southern North Sea during the 17th and 18th centuries. But an English, Danish-Norwegian or other nationality could not be excluded either. The end of the 18th century or the period just after the Napoleonic wars was conceivable as well, but it is clear that the wreck occurred long before the 100 year cut-off date for heritage protection that is employed as a rule of thumb both in Norway and internationally (Maarleveld et al., 2013).

4. Discussion and Conclusion

Marine archaeology has for decades used available seabed mapping technologies for detection and surveying underwater cultural heritage in deep waters, both for management and research purposes (B. Foley et al., 2002; Singh et al., 2000; Søreide, 2011). An operational constraint for such activities has been the requirement for navigating a surface vessel closely to the survey area, either towing a sensor platform or remotely controlling it via a cable (Blondel, 2009; Newman et al., 2008). The advent of AUVs has allowed us to bring relevant sensors close to areas of interest, performing complex missions independent of surface vehicle navigation (Bingham et al., 2010; B. P. Foley et al., 2009). An additional constraint has been the range-resolution tradeoff coupled to use of acoustic sensors for surveying larger areas efficiently. Quinn et al. (2005) found that for reconnaissance surveys using SSS to locate submerged archaeological sites, maximum swath width should be no more than 80 m, and for site specific research they recommend a lane spacing of 5-10 m. SAS high resolution intensity plots give consistently detailed presentations of small features and objects on the wreck at swaths up to 400 m, while coregistered bathymetry data complement them providing elevations enhancing interpretations of the wreck’s structural properties. SAS fusion imagery allows for careful interpretations of even disintegrated wreck sites with better accuracy and confidence than traditional SSS or MBES data (Bates et al., 2011). The high dynamic range enhances the perception of subtle differences in reflection, mitigating the need for low grazing angle induced shadows for interpretation, typically desired when using SSS. High resolution bathymetric data of the surrounding seabed can also provide visual and statistical clues to understanding and monitoring of scouring and sedimentation on the site (Quinn 2006), providing insight into the site formation processes. In addition to surveying for wrecks, the
combination of efficient coverage and high resolution could also make SAS a suitable tool for mapping submerged prehistoric landscapes, currently a methodological challenge increasing with depth (Missiaen et al., 2017).

As acoustic sensors produce ever higher resolution images, it is important to emphasize the possibility for errors that are typical for these technologies. Comparing data from the two passes, it is clear that the width of the wreck is inaccurate in at least one of the data sets. The difference is not great, only a few decimeters, but serves as a caution not to take seemingly photo-like images at face value. Also, backscatter responses of different materials may vary for SAS as for SSS (Quinn et al., 2005), rendering interpretation and classification subject to uncertainties. Archaeological inferences must be seen in light of the limitations inherit in the information at hand, i.e. the capabilities of the sensor technology. Although not discussed in this paper, it is worth mentioning that processing techniques for studying echo structures in widebeam SAS data could extract information on facet lengths, supporting estimations of material roughness (Synnes et al., 2015).

The Skagerrak mapping survey was specifically targeted towards wrecks containing chemical munitions from WWII (C. M. Hansen et al., 2009; Torstein Olsmo Sæbø et al., 2015). Such wrecks and other similar dumping sites constitute substantial threats to the environment worldwide, and knowledge of the state of these wrecks is of great importance for managing potential risks (Missiaen et al., 2002). At the same time, the historical significance of many of these wrecks merit interest from archaeologists (Hanson, 2016). This duality could represent potential management challenges in the years to come, especially as many of these wrecks become old enough to attain legislative protection as historical monuments. The older wooden wrecks found during the survey were an unintended bonus, so to speak, and shows that multiple stakeholders could benefit from the same data sets. The high level of seabed detail provided by SAS can reduce the number of false positives, and also serve as basemaps to confidently delimit areas for closer inspection with HD cameras, sub bottom profiling, multibeam echosounders or other relevant sensors. The versatility of underwater robots as carriers for sophisticated sensors can help survey managers to better decide what to deploy adaptively (Nilssen et al., 2015), a methodological approach that reduces the need for repeated surveys. Recent experiences from collaborations in seabed mapping across scientific disciplines, also including industrial partners, indicate that such ventures can be of mutual benefit (Holmlund et al., 2017; Ludvigsen et al., 2014).

The results presented in this paper clearly demonstrate that data sets from multiple passes can be advantageous for interpretation and analysis of wreck sites. In a future perspective, the ability to online classify objects or areas of interest and re-plan survey lines to get multiple passes at different aspects or even deploy additional sensors, would significantly increase the information value of such seabed mapping surveys. Research into automated detection and classification of historical wrecks in SAS data could advance the utilization of the potential for autonomy that lies in intelligent robotics (Ødegård, Nornes, et al. 2016).

In summary, this study (one of the first to look at SAS applied to UCH) shows the potential of high-resolution seabed mapping using SAS and AUV for marine archaeological surveys in deep waters. We have described procedures for archaeological analysis and interpretation of SAS data to draw inferences
of state, vessel type and even possible age for a selected wreck site. The advantages of SAS compared to SSS have been emphasized, and advocates a transition to this new technology for seabed mapping surveys. We propose that this will be a valuable new method for both management and research applications.

Acknowledgements

We are grateful to the Norwegian Coastal Administration and the Norwegian Defence Research Establishment for access to data. Parts of this work have been carried out at the Centre for Autonomous Marine Operations and Systems (AMOS). The Norwegian Research Council is acknowledged as the main sponsor of AMOS through the Centres of Excellence funding scheme, Project number 223254.

References

Deeben, J., Hallewas, D., & Maarleveld, T. J. (2002). *Predictive modelling in archaeological heritage management of the Netherlands: the indicative map of archaeological values (2nd generation)*: ROB.


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Appendix A. Supplementary data

Animation 1

https://1drv.ms/v/s!At1pp9BK3HePua5xFqmE6h7_SWn9yw

Animation made in Photoshop and Blender to illustrate multi view fusion. Best viewed in looped mode.