COMPARISON OF SYNTHETIC APERTURE SONAR IMAGES AND OPTICAL IMAGES OF UXOS FROM THE SKAGERRAK CHEMICAL MUNITIONS DUMPSITE

Roy Edgar Hansen, Marc Geilhufe, Erik Makino Bakken, Torstein Olsmo Sæbø

Norwegian Defence Research Establishment (FFI), P O Box 25, NO-2027 Kjeller, Norway

Contact author: Roy Edgar Hansen
Norwegian Defence Research Establishment (FFI) P O Box 25, NO-2027 Kjeller, Norway
Fax: +47 63 80 75 09, E-mail: Roy-Edgar.Hansen@ffi.no

Abstract: *After World War II chemical munitions were loaded onto large ships and sunk in the Skagerrak Strait in the Norwegian trench, in deep waters between Norway and Denmark. In collaboration with the Norwegian Coastal Administration, Norwegian Defence Research Establishment (FFI) conducted two separate missions in 2015 and 2016, where around 450 square kilometers were mapped using a HUGIN autonomous underwater vehicle (AUV) equipped with a HISAS interferometric synthetic aperture sonar (SAS). 54 wrecks were found, and 36 of these are believed to be part of the chemical munitions dumpsite. Many shipwrecks have suffered severe damage, and their cargo is spread out around the shipwrecks. In January 2019, FFI revisited the Skagerrak dumpsite for additional data collection using the HUGIN AUV with SAS and an optical camera. Multiple wrecks were revisited, and SAS images and optical images of unexploded ordnances (UXO) were gathered. In this paper, we compare SAS images with optical images of UXOs. We assess the retrievable information present in high resolution large area coverage rate SAS images by comparing separate objects and their conditions as seen with optical camera.*

Keywords: *Synthetic aperture sonar, Optical Imaging, Unexploded Ordnance*

1. INTRODUCTION

After World War II, a substantial amount of chemical munitions were loaded onto large ships and sunk in the Skagerrak Strait in the Norwegian trench, in deep waters between Norway and Denmark [1]. In collaboration with the Norwegian Coastal Administration, Norwegian Defence Research Establishment (FFI) conducted two separate missions in 2015 and 2016, using FFI's HUGIN autonomous underwater vehicle (AUV) equipped with the HISAS interferometric synthetic aperture sonar (SAS) [2, 3]. This was a continuation of cruises done in 1989, 2002 (without AUV) [4], and 2009 (with AUV but without SAS) [5, 6]. The main goal of the 2015-2016 mission was to search the largest possible area with SAS, find the ship wrecks, judge their conditions, as well as to search for objects, debris, and UXOs. Approximately 450 km^2 were mapped in 4 cm$\times$4 cm resolution, and 54 wrecks were found, 36 of these are believed to be part of the chemical munitions dumpsite. An indication of the wreck locations is shown in Fig. 1. The boxes indicate the recommended no fish zone as of 1947, 1990, and 2018. The zone was substantially expanded after the 2015-2016 HUGIN missions due to the newly discovered wrecks found using AUV with SAS. More details about the missions and the technology can be found in [7].

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In this paper, we compare SAS images with optical images of UXOs. We assess the retrievable information present in high resolution large area coverage rate SAS images by comparing separate objects and their conditions as seen with optical camera.

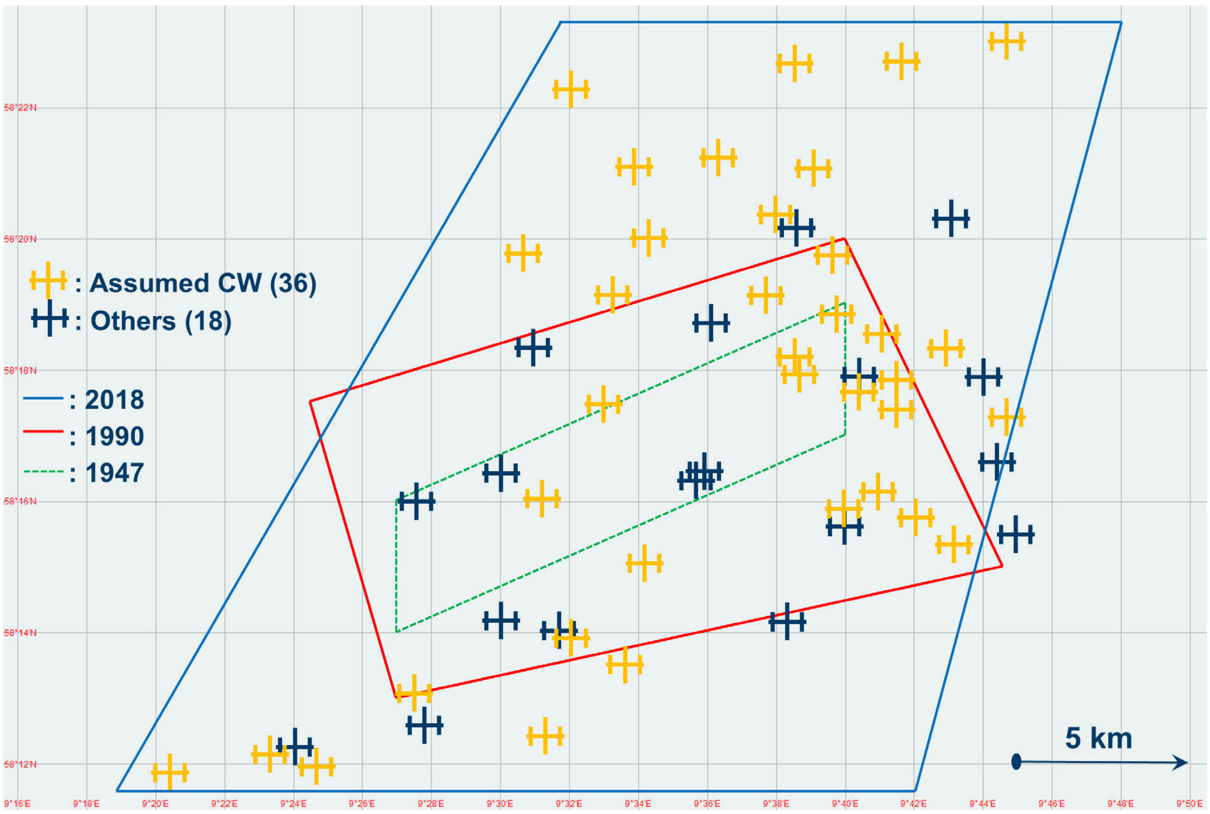

Fig. 1: Wreck positions in the Skagerrak dumpsite.

2. HUGIN AUV AND ITS SENSORS

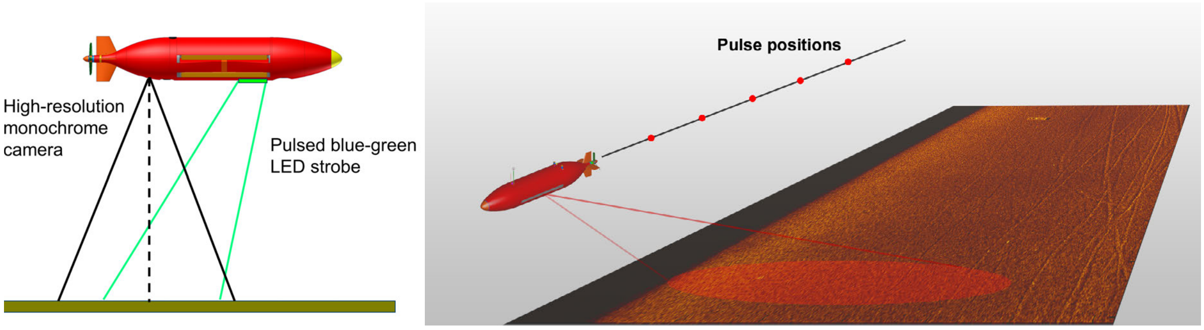

Fig. 2: Sensor geometry for the optical camera (left) and the SAS (right) on HUGIN AUV

The HUGIN AUV is a medium sized autonomous underwater vehicle developed by Kongsberg Maritime and FFI [8]. A typical operation is that the vehicle dives to the operational depth close to the seabed, and images or maps the seabed when running in a lawnmower pattern or in a dedicated pattern. The vehicle can be equipped with high performance imaging and mapping sensors such as the HISAS interferometric SAS, the EM2040 multibeam echosounder, flash based optical camera, and laser 3D profiler. Other sensors commonly used are subbottom profiler, magnetometer, turbidity sensor, CTD, and chemical sniffers. In this work, we only consider the optical camera and the SAS system.

2.1 Camera

FFIs HUGIN AUV is equipped with a TileCam optical camera and a synchronized pulsed LED strobe. The camera and strobe are mounted with maximal distance from each other (see Fig. 2) to reduce backscattering. The typical range (vehicle altitude) is between 3 m and 10 m, dependent on the water clarity. The swath width is approximately equivalent to the altitude. For a vehicle operating at 2 m/s and 5 m altitude, the area coverage becomes 10 m^2/s. TileCam has earlier been used for several missions [9, 10], but this is the first time we are using it for UXOs.

Each image has varying illumination with typically more light in the middle and less around the edges. In order to make the transition between the images in the mosaic smoother, the illumination is evened out with a height dependent model, similarly to what is done in [11]. The image quality also varies throughout the image, and is worse where there is little light or a large amount of backscattering. The seam between the images is optimized such that the higher quality image is used for each part of the mosaic. A mosaic based on 10 individual images showing several UXOs can be seen in Fig. 3.

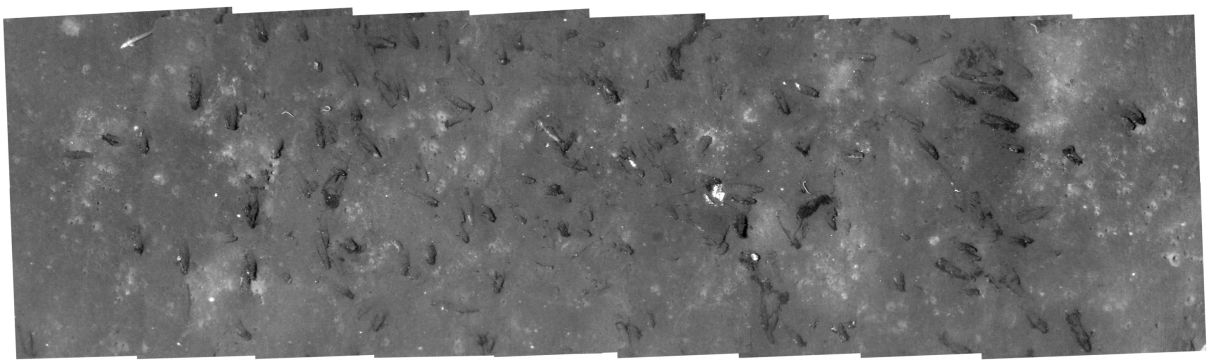

Fig. 3: Camera mosaic of 10 images of an area of ~6 m×20 m with high density of UXOs.

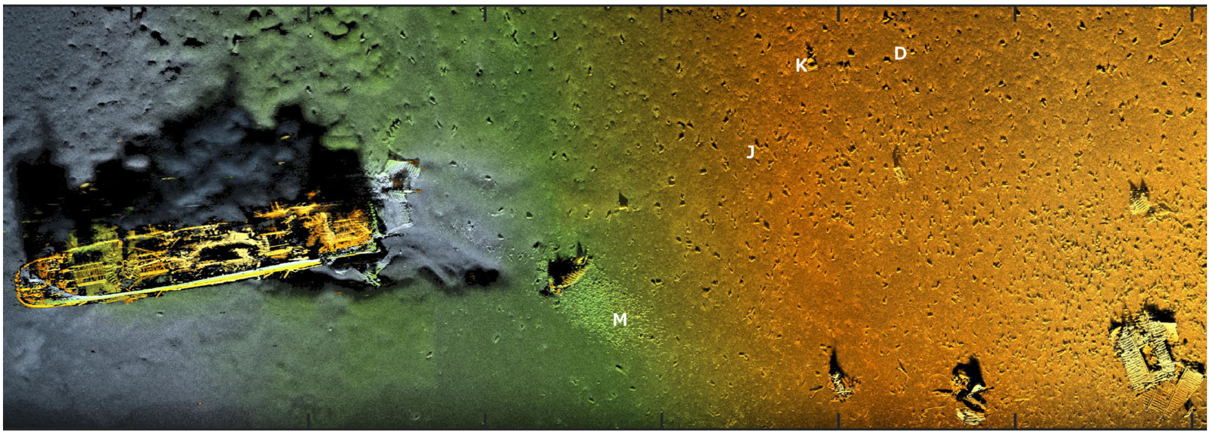

Fig. 4: SAS image fusioned with SAS bathymetry of wreck 13. The image size is 330 m×120 m, and the depth variation is 10 m in the color mapping. We have marked the positions of area M (Fig. 3), J (Fig. 5), D (Fig. 6, upper row) and K (Fig. 7). E and F (Fig. 6, middle and bottom row) are not covered in this image.

2.2 SAS

SAS is a sonar imaging technology that allows for high resolution and large area coverage rate at the same time [12]. The basic principle is based on coherent combination of sonar data from multiple pings when moving in order to improve along-track resolution (see Fig. 2). The HISAS 1032 has a theoretical resolution of around 3 cm×3 cm, and an instantaneous area coverage rate of approximately $400\,\mathrm{m}^2/\mathrm{s}$. Note that the area coverage rate is reduced if the SAS sensor is used as the gap-filler (covering the blind-zone for the SAS itself). See [2, 13] for details. Fig. 4 shows an example SAS image fusioned with SAS bathymetry from the Skagerrak dumpsite. The SAS image is despeckled using a multitaper despeckler [14]. The image shows wreck 13 where parts of the cargo is spread over a large area surrounding the wreck. This area forms the basis of our study in this manuscript.

3. COMPARISON OF CAMERA AND SAS

FFI performed a new HUGIN AUV survey of the Skagerrak dumpsite in January 2019 revisiting chosen wreckages. For the first time, we have gathered information of UXO on the Skagerrak site with HUGIN's optical camera. Each UXO or other wreckage part covered in the camera swath is also covered multiple times by SAS data, in up to four different orthogonal directions and at varying ranges. This makes it possible to co-register optical and sonar data for visual comparison purposes, see Figs. 5 – 7. All SAS images in this section is processed using the product version of the SAS processor, where we have selected to use backprojection for spot images, autofocus based on Phase Gradient Autofocus (PGA) [15], and despeckling using a median filter.

Fig. 5 shows three UXOs of approximate size 1.6 m×0.4 m that are cleary damaged and torn into pieces. From the optical images it is not unlikely to expect that their chemical munition is discharged into the water, though this would need to be evaluted with e.g. core sampling. The UXOs are well visible in the three displayed SAS images independent of look angle. However, from the SAS images it is only possible to determine the general object shape, not the UXO's integrity. SAS is well suited for covering large areas with high resolution, while an optical camera is better suited for a more detailed look at single object for identification purposes.

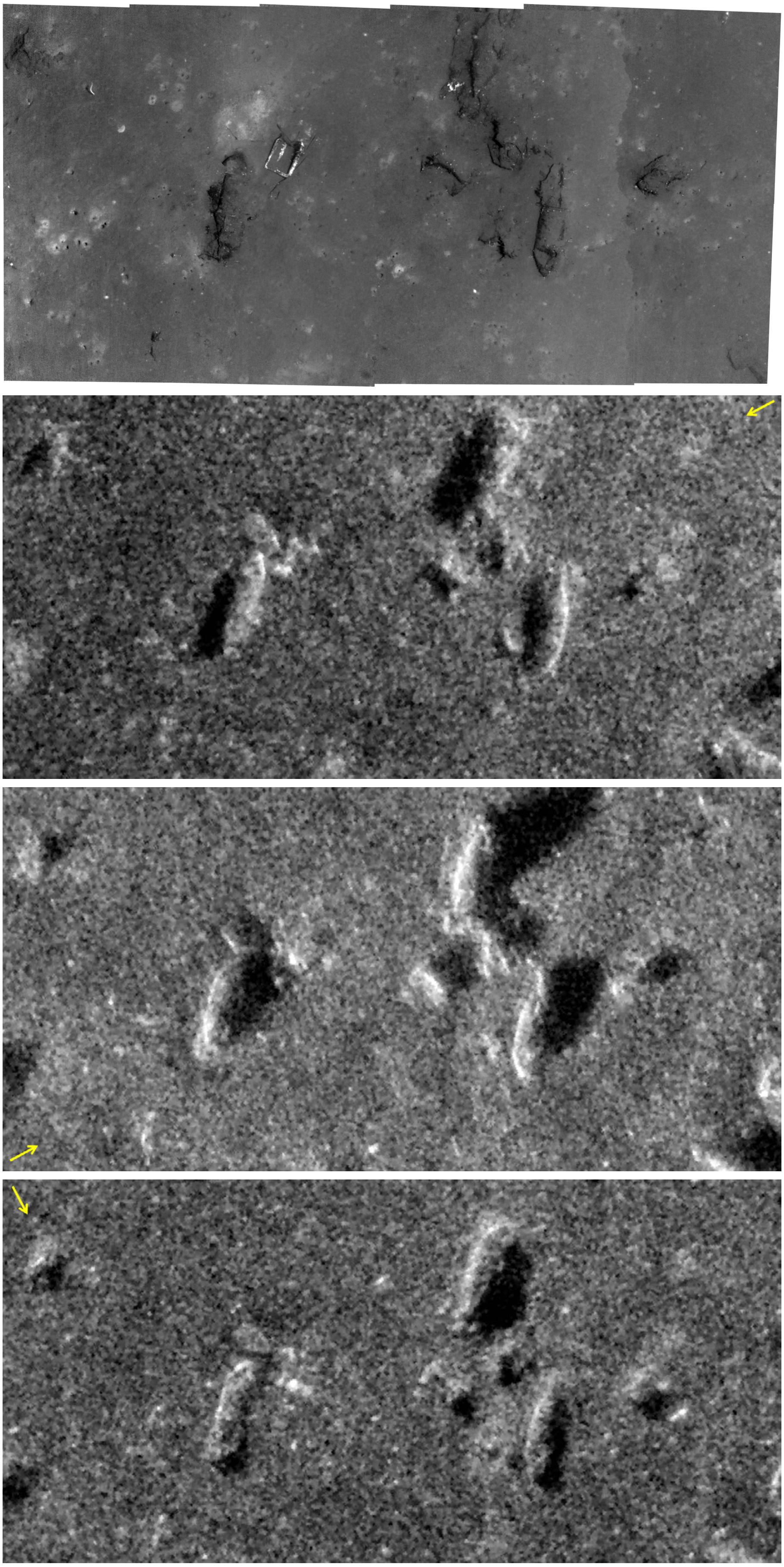

Fig. 5: Camera mosaic of six optical images covering ~6 m × 12 m (top) compared with SAS images taken at ranges 70 m (second from the top), 111 m (second from the bottom) and 63 m (bottom). The yellow arrow in each SAS image indicates the sonar look direction.

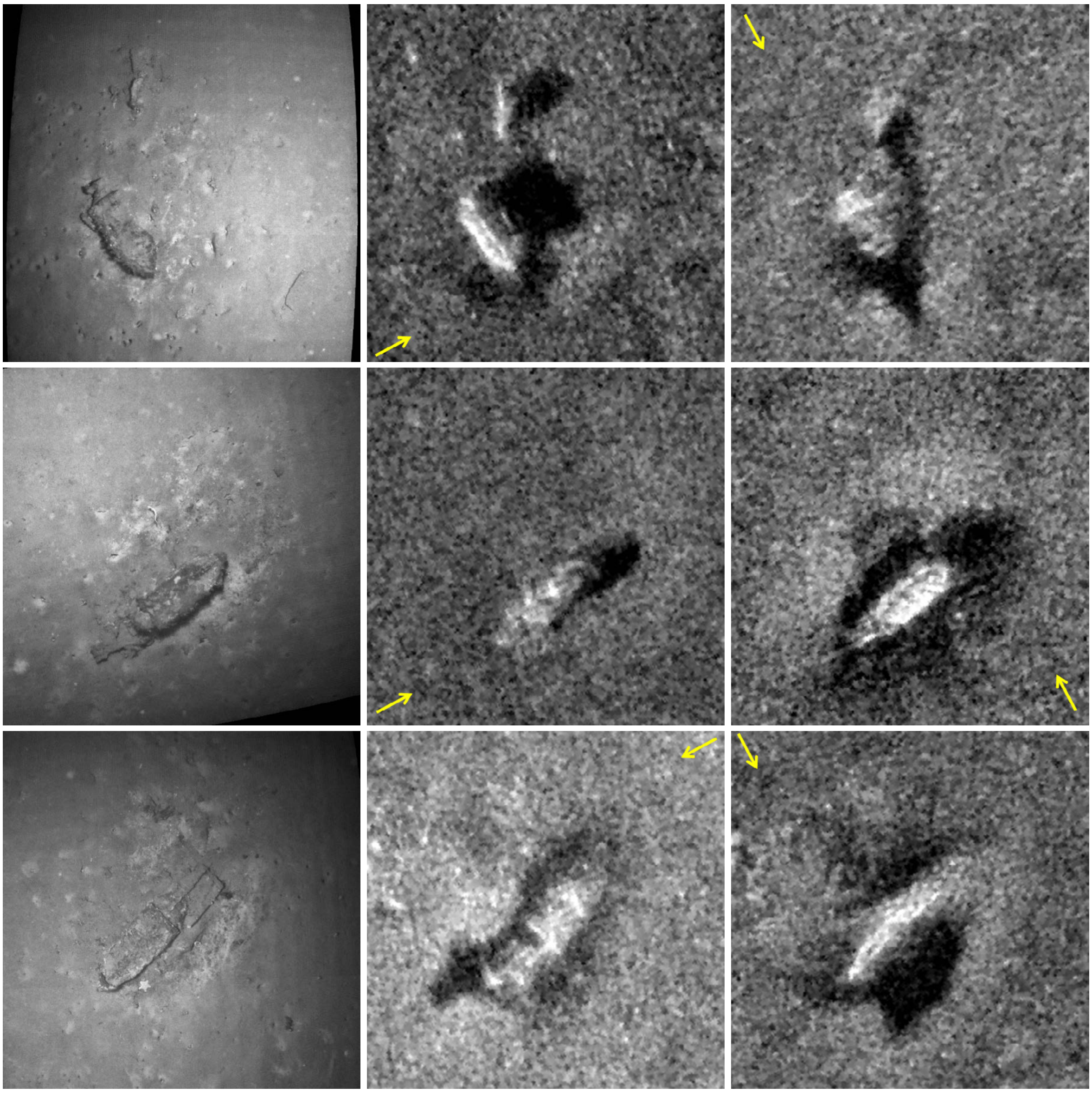

Fig. 6: Camera images (left) compared with two SAS images for each scene taken at ranges 140 m, 107 m (top row), 50 m, 128 m (middle) and 121 m, 115 m (bottom). The sonar look angle is indicated by the yellow arrow in each SAS image. UXO sizes vary from ~1.2 m× 0.45 m (top) to 1.65 m×0.4 m (middle and bottom).

Three further UXOs are visible in Fig. 6. They seem more intact than those in Fig. 5, however not undamaged either. The upper row object is around 40 cm shorter than the two others, which could be an indication that some part of the tail section is missing.

Operating an AUV with an optical camera is somewhat more risky than with SAS, as the typical AUV height for good optical images is around 5 m, while we usually perform SAS surveys at 20–25 m altitude. The risk of low altitude is that the AUV crashes into an object or the seafloor, especially if there is lots of terrain (which was not the case in our example), or that it gets stuck in e.g. fishing trawl. In Fig. 7, the optical image indicates that there is trawl in the upper right part of this unknown man-made wreckage object.

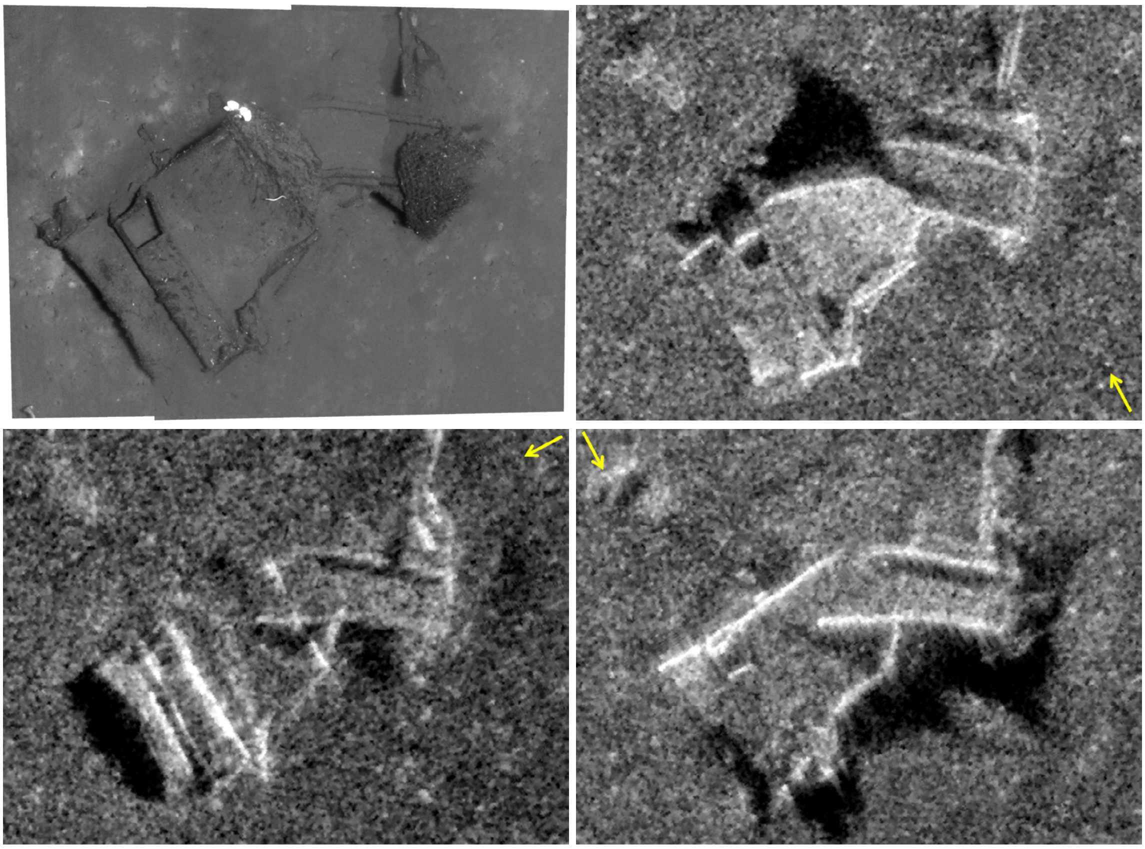

Fig. 7: Camera mosaic covering ~6 m×8 m (top left) compared with three SAS images at ranges 41 m (top right), 44 m (bottom left) and 79 m (bottom right). The look sonar angle is indicated by a yellow arrow.

In Fig. 7 we show a larger object, which is not a UXO, but potentially a part of the ship wreckage partly buried into the seafloor. Here we clearly see strong specular reflections that vary with the sonar look angle. Each SAS image thus contributes with different information, though the general object shape is evident in any of the SAS images.

4. SUMMARY

In this paper, we have examined the suitability of SAS and optical imagery for finding and judging the conditions of UXOs in the Skagerrak chemical munitions dumpsite. SAS is well suited for searching after small and large objects over large areas. This includes detection and classification of objects. As we have found here in our small study, SAS is less suitable for judging the conditions of UXOs. The optical camera is well suited for identification and judging of the conditions of individual UXOs. Camera is less suited for searching over large areas due to the limited area coverage rate. It is also of limited use when operated from HUGIN type AUVs in mapping and imaging large structures such as ship wrecks. This is due to the limited range in water. In such cases, a high frequency multibeam echosounder may be a good choice.

In our experience, the SAS and a flash based optical camera on an AUV is a very powerful combination. This allows for searching over large areas for detection and localization of UXOs with SAS, and identification and judging of the conditions with the camera.

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