Challenges in synthetic aperture sonar imaging of shipwrecks for change detection

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Abstract: *After World War II (WWII) large amounts of chemical munitions were dumped in the Skagerrak strait in Norwegian waters. The approach was to fill decommissioned cargo ships with the chemical munitions, and then sink the ships in a designated area. In 2015 and 2016, the Norwegian Defence Research Establishment (FFI) conducted a large area search to detect all shipwrecks part of the dumpsite, and judge their conditions. The equipment was FFIs HUGIN autonomous underwater vehicle (AUV) carrying a HISAS synthetic aperture sonar (SAS). In 2019 and 2022, several of the wrecks were revisited using the same equipment. The condition of each of the shipwrecks is varying, and there is a chance that aging and decay may cause structural changes to the wrecks that again may cause leakage of chemical munitions substances from the cargo bays to the surrounding ocean environment. A potential tool for monitoring the conditions of the shipwrecks over many years is AUV-based SAS in combination with image based Change Detection (CD). For successful use of this technique, the CD must be high resolution, reliable and automated. In this paper, we describe the requirement for track quality, track repeatability, and image quality in order to perform image based CD on shipwrecks. We describe SAS image errors caused by non-straight data collection tracks in combination with large three-dimensional structures on the seafloor, how these may cause false positives in CD, and potential techniques to mitigate these errors. We demonstrate our techniques on data collected by FFIs HUGIN AUV from 2015, 2019 and 2022.*

Keywords: *synthetic aperture sonar, autonomous underwater vehicles, change detection*

1. INTRODUCTION

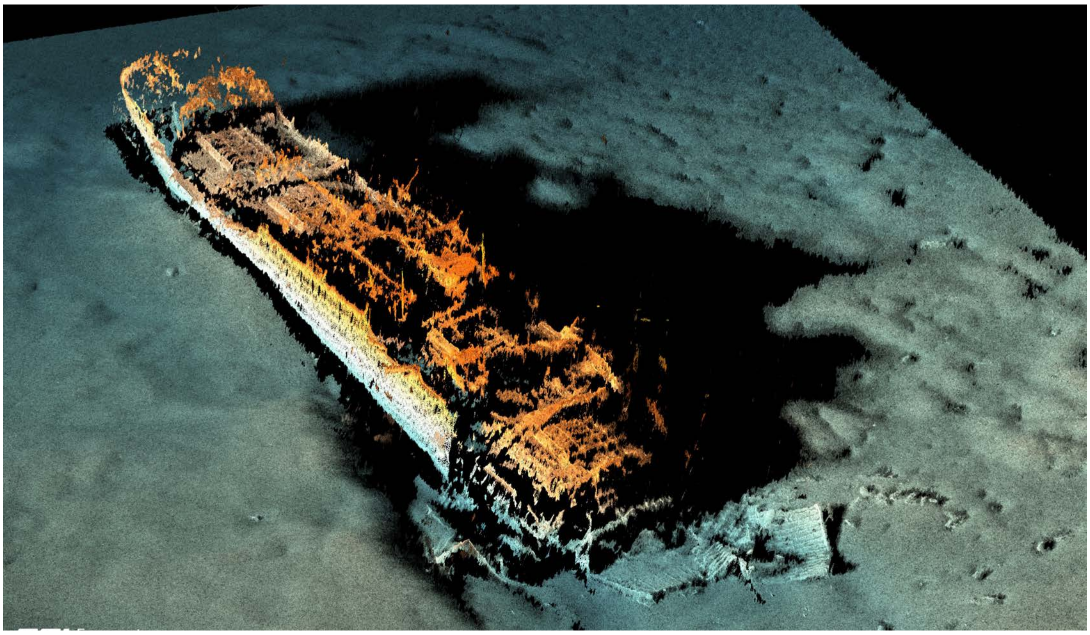

Figure 1: SAS bathymetry 3D render of wreck 13 in the Skagerrak chemical munitions dumpsite. The bow part is damaged. The intact part of the wreck is approximately 100 m long and 17 m wide. The wreck is elevated at least 10 m above the seabed.

Synthetic aperture sonar (SAS) represents state-of-the-art in high resolution acoustic imaging and mapping of the seabed [1]. Change detection (CD) is the comparison of multiple images collected of an area at different times in order to find any changes [2]. Being able to produce images of the seabed in a few centimeter resolution, SAS is a technology well suited for seabed CD [3].

After World War II (WWII) large amounts of chemical munitions were dumped in the Skagerrak strait in Norwegian waters. The approach was to fill decommissioned cargo ships with the chemical munitions, and then sink the ships in a designated area [4]. In 2015 and 2016, the Norwegian Defence Research Establishment (FFI) conducted a large area search to detect all shipwrecks part of the dumpsite, and judge their conditions. The equipment was FFIs HUGIN autonomous underwater vehicle (AUV) carrying a HISAS interferometric SAS [5]. In 2019 and 2022, several of the wrecks were revisited using the same equipment.

The condition of each of the shipwrecks is varying, and there is a chance that aging and decay may cause structural changes to the wrecks that again may cause leakage of chemical munitions substances from the cargo bays to the surrounding ocean environment. A potential tool for monitoring the conditions of the shipwrecks over many years is AUV-based SAS in combination with image based CD [6, 7].

In this paper, we describe the requirement for track quality, track repeatability, and image quality in order to perform image based CD on shipwrecks. We describe SAS image errors caused by non-straight data collection tracks in combination with large three-dimensional structures on the seafloor such as shipwrecks (see Fig. 1), how these errors may cause false positives in CD, and potential techniques to mitigate these errors. We demonstrate our techniques on data collected by FFIs HUGIN AUV from 2015, 2019 and 2022.

2. CONDITIONS FOR SUCCESSFUL DATA COLLECTION AND PROCESSING

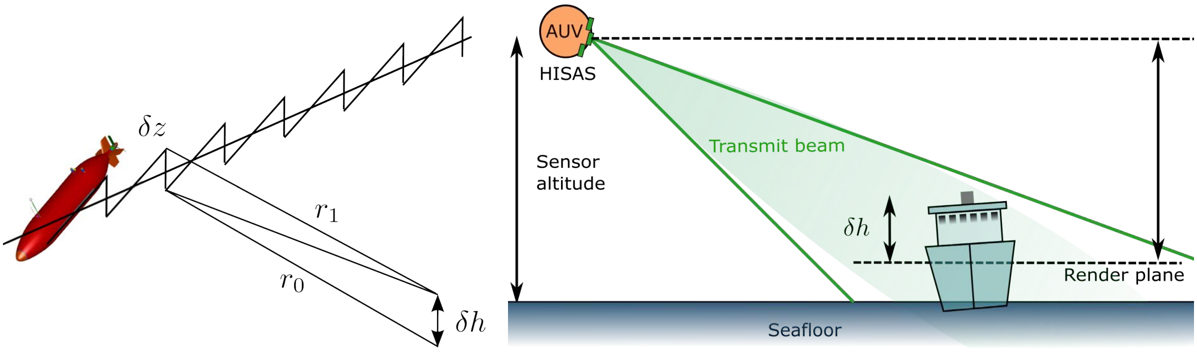

Figure 2: Non-straight synthetic apertures causes potential out-of-plane projection errors.

In order to successfully perform image based CD, there are specific challenges to be overcome related to the data collection of each track, and their similarity.

2.1. TRACK INTEGRITY

Each track must be well suited for SAS imaging of shipwrecks: The data must be collected such that a well functioning synthetic aperture can be formed, and that the relevant parts of the shipwreck is within the view-angle and swath of the sonar [5]. In addition, each element in the synthetic aperture must be locally positioned within a fraction of a wavelength [8]. Larger elevated structuresimpose a specific requirement to track linearity. A non-straigth synthetic aperture leads to an out-of-plane projection error if the chosen imaging plane (or render plane) is chosen incorrectly [9, chapter 3.8]. For a shipwreck with elevated structures such as decks, rails and masts, the correct render plane may be very difficult to determine (see Fig. 2). A requirement for acceptable low out-of-plane projection errors is [8]

$$|\delta z \delta h| \leq r_0 \lambda / 8 \tag{1}$$

where δz is the out-of-plane deviation from a straight line, and δh is the vertical render plane error. r_0 is the range to the scene and λ is the wavelength. For a perfectly straight synthetic aperture $\delta z = 0$, the SAS image quality becomes invariant of the choice of render plane. For $\lambda = 1.5$ cm, $\delta h = 1$ m and $r_0 = 80$ m, we get $\delta z \leq 15$ cm. This is a rather strict requirement that clearly illustrates the importance of this error. Note that the magnitude of the errors in the SAS image also is dependent of the scale and repeatability of the non-straight aperture.

A poorly ballasted (or trimmed) vehicle may have to run with vertical crab to keep constant depth (see Fig. 2, left). This will cause a periodic pattern in the synthetic aperture which again will lead to ghost replicas of real targets in the SAS image, acting as *grating lobes* if an incorrect render plane is chosen [10]. A similar effect may occur for horizontal crab caused by e.g. ocean currents non-parallel with the vehicle track. Fig. 3 shows two local SAS images of a part of the shipwreck. The vehicle was running with both horizontal and vertical crab (see Table 1, 2015b results). In the left image, a render plane close to the seabed is chosen. In the right image the render plane is moved 7.5 m upwards, closer to the actual depth of the scatterers. We see that the ghost targets, especially around x = 45 m, y = 100 m, is reduced by choosing a better render plane. These ghost targets may easily cause false positives in the change detection.

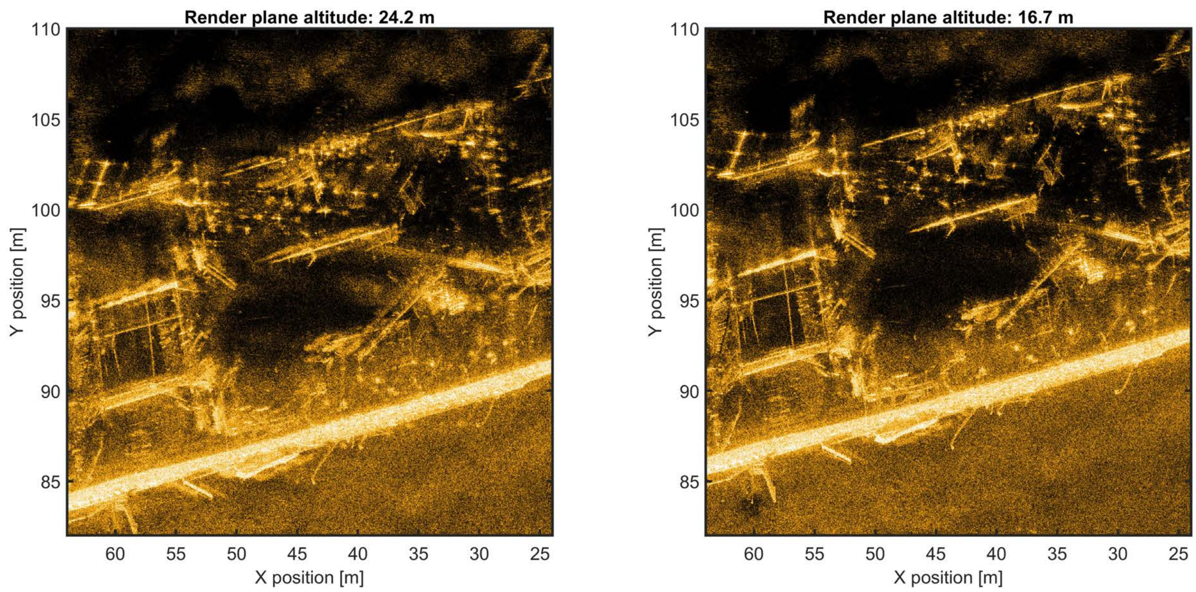

Figure 3: SAS image of wreck 13 from 2015. Left: Render plane near the seabed. Right: Corrected render plane (near deck level).

2.2. TRACK REPEATABILITY

The reference and repeated tracks must be sufficiently similar. A change in the vertical or horizontal observation angle between passes may lead to a different backscattered signal and therefore different information content in the SAS images. This can either be due to different distance, depth or track orientation between passes. Ensuring that the tracks are sufficiently similar includes that the planned missions are similar, that the vehicle guidance and control system is able to execute the plan within bounds, and that the navigational accuracy is sufficient.

Table 1 summarizes the navigational data for three passes on each side of the wreck (B and C-lines). Depth represents depth variation around a nominal giving the desired altitude. Sway is deviation from a straight line cross track in the horizontal plane. There is a depth variation of up to 2.1 m in the C-lines due to the fact that the vehicle was set to run in constant altitude mode. Although being small, the horizontal and vertical crab impose potential problems if the render plane error is large enough. In these data collections, one degree of vertical crab equals approximately $\delta z = 1$ cm. Note also that similar tracks with different horizontal crab causes different sonar view-angles that again may cause changes in the SAS images.

run	Altitude	Depth	Sway	H crab	V crab	Heading	AT offset	CT offset
2015c	24.8 m	1.8 m	27 cm	$4.2°$	$2.0°$	$-32°$	0 m	0 m
2019c	24.8 m	1.9 m	15 cm	$3.3°$	$0.5°$	$-31°$	-0.5 m	0 m
2022c	25.1 m	2.1 m	12 cm	$1.0°$	$-2.0°$	$-29°$	-1.5 m	6.0 m
2015b	24.9 m	0.8 m	19 cm	$-4.5°$	$2.5°$	$156°$	0 m	0 m
2019b	24.9 m	0.7 m	21 cm	$-1.5°$	$-1.5°$	$154°$	-1.5 m	0.2 m
2022b	25.2 m	0.7 m	17 cm	$-4.0°$	$1.0°$	$156°$	-3.5 m	2.5 m

Table 1: Track statistics. 2015 is the reference for the along-track (AT) and cross-track (CT) offsets. B and C-lines are from each side of the wreck.

3. SUGGESTED METHOD FOR AUTOMATED CHANGE DETECTION

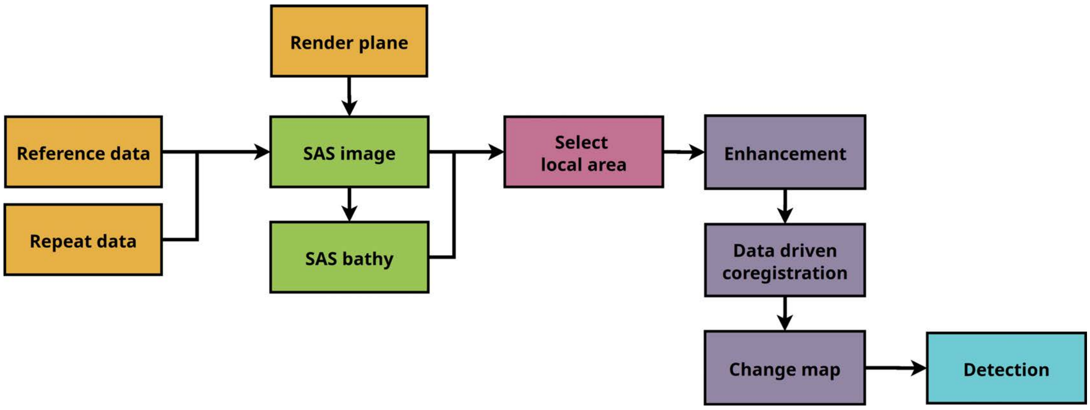

Figure 4: Method for automated change detection.

In order to test whether image based CD may be a viable technique for monitoring shipwreck conditions, we suggest the following simple procedure for automated change detection processing (see Fig. 4):

1. Select a reference dataset and scene. Select a suitable render plane.
2. Produce SAS images and SAS bathymetries of the reference and repeated passes.
3. Select a local area, small enough for simplified data driven coregistration.
4. Run image enhancement if needed. This may be despeckling, adjustment of render plane, adjustment of view-angle or other.
5. Run data driven coregistration to estimate horizontal shift only. This can be done by minimizing log intensity image difference.
6. Produce a log intensity difference image (a change map).
7. Run detection on the change map.

Repeat 3 – 7 until the entire shipwreck is covered. For this simplified algorithm to succeed, the rotational error and the scaling error must be negligible. This can be tuned by choosing local area size.

A fully automated algorithm should also include a *track integrity* and *track repeatability* check, where the data collected are checked for their suitability to form SAS images without significant errors (such as grating lobes), and that the tracks are repeated with sufficient similarity. This can be done based on the track data themselves, and the output of the coregistration (the shift estimates).

4. CHANGE DETECTION RESULTS

Fig. 5 shows a SAS image of wreck 13 with indications of 5 different local areas for investigation. Fig. 6 shows the SAS image of each local area for two selected passes in addition to the difference image. Averaging and downsampling with a factor of 2 in each dimension was conducted before coregistration. The data driven coregistation worked satisfactory for all 5 areas. Area 0 is an area outside the shipwreck with larger cargo objects. There are no changes in these images. Area 1 is on the shipwreck. There is an apparent change visible in the difference map - a part of the railing or similar (a white line). This line is present in the 2015 image but not in

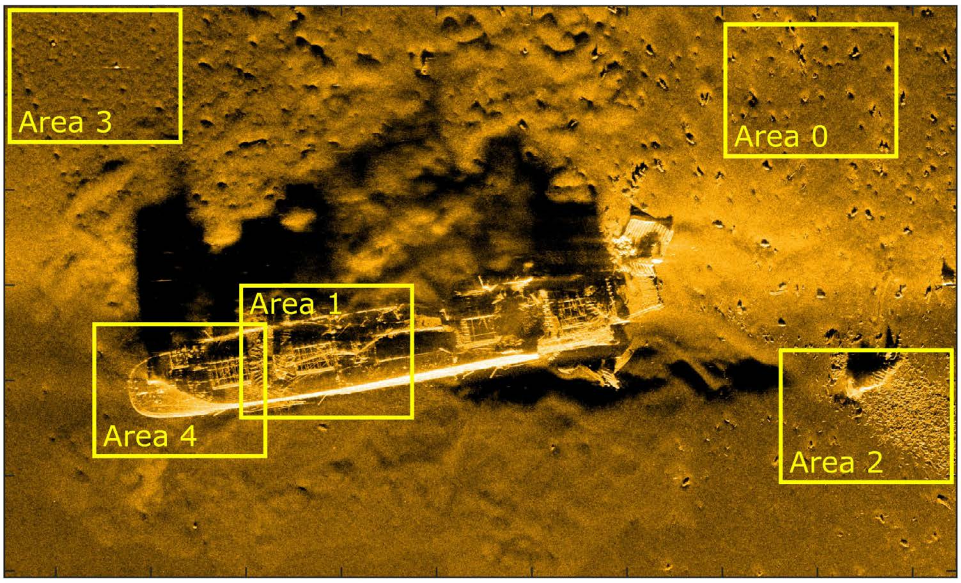

Figure 5: Overview of the areas to be investigated. Wreck 13, pass C, 2022 data.

the 2019 image. Area 2 shows parts of the wreck that is broken off in addition to a pile of cargo. There is a black circular region in the difference image indicating that an object has appeared in the 2019 image, that wasn't there in the 2015 image. This may be a part that has fallen off the larger structure. Area 3 is outside the shipwreck, where two black regions in the difference image are associated with objects present in the 2019 image but not in the 2015 image. These are likely sandbags that has been placed in the area some time between 2015 and 2019. Area 4 shows the aft part of the shipwreck. A white area is present in the difference image indicating something present in the 2019 image but not in the 2022 image. This is, however, from the shadow part of the SAS image, and should therefore be ignored.

The results indicate that it is possible to perform successful coregistration and production of change maps where a detection algorithm may find changes in the scene. This also holds on the shipwreck itself. There are residual errors (or rather differences) that cause variability in the change maps caused by differences in the data collection geometries and variations in the image consistency per pass. If these errors are large enough, they may cause false positives in the detection algorithm. A specific challenge is any acoustic pollution in the non-valid regions of the images, e.g. the shadows behind the shipwrecks. Any changes in the images from repeated passes will cause a signal in the change map. A solution to this issue is to form a *validity map* per pass where the shadow regions are flagged as invalid.

5. SUMMARY

Synthetic aperture sonar (SAS) is an excellent tool for high resolution imaging and mapping of the seabed. Carried on an AUV, it may be a suitable tool for monitoring the conditions of shipwrecks and detecting larger changes over time. Successful image based change detection (CD) is, however, related to the ability to repeat the tracks and the quality of the SAS images per pass. In this paper, we have done a data investigation of a selected shipwreck in the Skagerrak WWII chemical munitions dumpsite. We have demonstrated the ability to produce change maps where small and relevant changes can be detected.

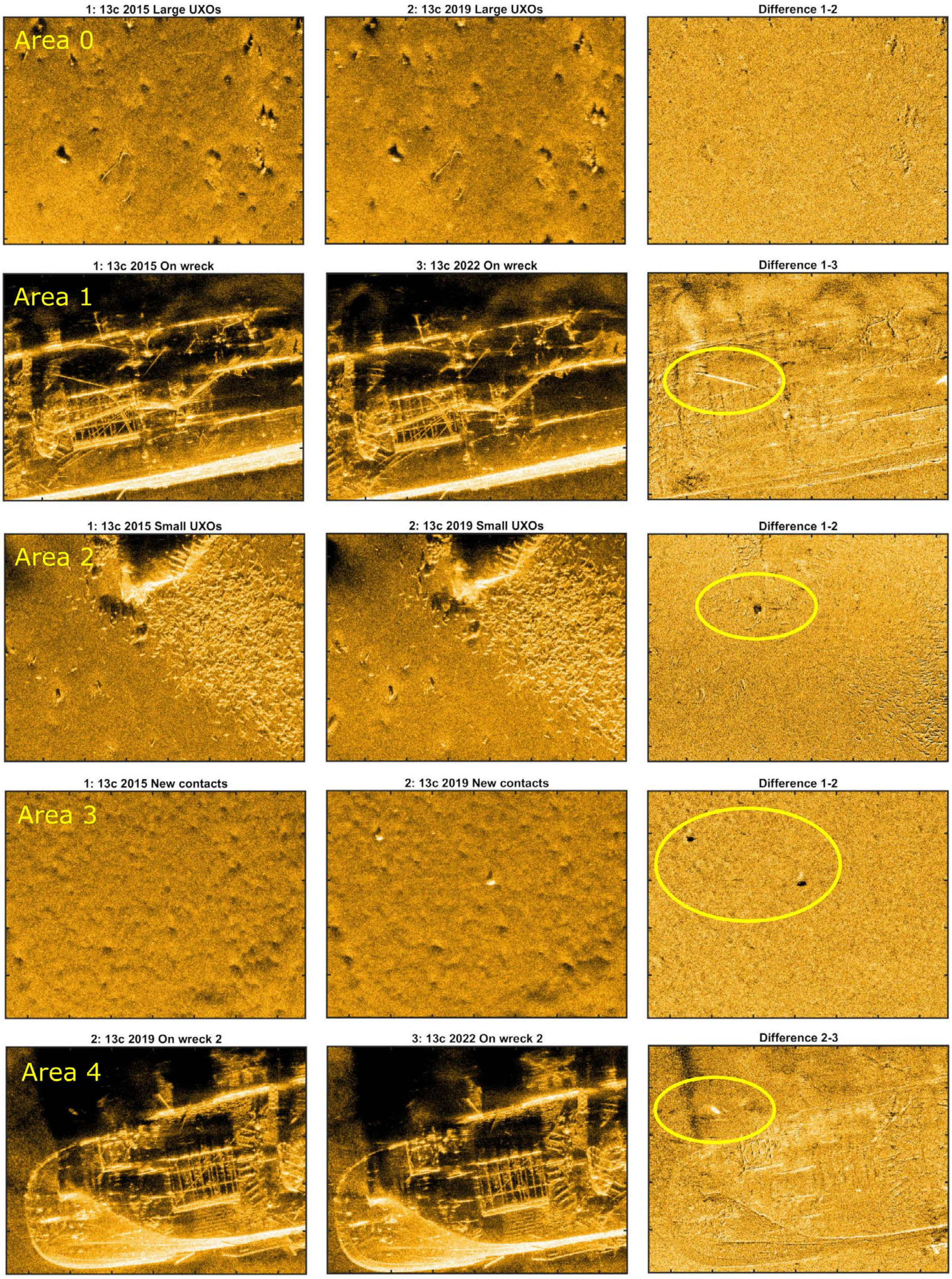

Figure 6: Change detection results from area 0–4 as shown in Fig. 5. The scene size is 35×25 *m. Left column: before image. Middle column: after image. Right column: difference image. The yellow ellipses indicates the changes.*

6. ACKNOWLEDGEMENTS

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