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Change detection on shipwrecks using synthetic aperture sonar

– North Sea Wrecks Task 3.5 Deep Water Case Study

Roy Edgar Hansen

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Summary

During the last 15 years, synthetic aperture sonar (SAS) technology has matured substantially. Today SAS represents state-of-the-art in seabed imaging and mapping when used on autonomous underwater vehicles (AUV). SAS provides high resolution and large area coverage rate, and is well suited for a number of different applications in marine research, offshore survey mapping and monitoring, search for objects, wrecks and dumpsites, and military applications such as naval mine countermeasures and intelligence, surveillance and reconnaissance, and seabed warfare.

The Norwegian Defence Research Establishment (FFI) has a long-standing collaboration with the Norwegian company Kongsberg Maritime (KM) to develop AUV-technology and SAS-technology. Today, there are multiple products in the HUGIN family of AUVs and the HISAS family of SAS systems available from KM, partly developed at FFI.

Change detection (CD) is a technique to find relevant changes in data products collected in repeated passes. SAS, providing high resolution and large area coverage rate, is well suited for image based CD.

In this feasibility study, we consider the suitability of using AUV with SAS for detecting structural changes on shipwrecks, with years of time separation. The potential application is monitoring of shipwrecks and their conditions in dumpsites. We describe the specific challenges related to both SAS imaging, mapping and CD of shipwrecks. We consider three data sets from 2015, 2019 and 2022 collected by FFIs HUGIN AUV carrying a HISAS 1032 interferometric SAS of wreck 13 in the Skagerrak World War II chemical munitions dumpsite.

Summarized, using our approach, we are able to successfully coregistrate local images, produce difference images and detect small changes. To verify that the detected changes are real changes, the similarity in the imaging geometry for the repeated passes must be investigated. Shadow regions should be flagged and ignored in the change maps.

Our conclusion is that AUV with SAS can be used for long term monitoring of shipwrecks if requirements are met regarding the similarity in the data collection and the sensor, and the choice of processing.

This study is sponsored by the EU Interreg project North Sea Wrecks.

Sammendrag

De siste 15 årene har syntetisk-apertur sonar (SAS) modnet som teknologi. SAS representerer i dag det mest moderne innenfor avbildning og kartlegging av havbunnen gjort fra autonome undervannsfarkoster (AUV). SAS gir høy oppløsning og stor arealdekning per tidsenhet. Derfor er teknologien godt egnet til bruk i marin forskning, offshore-kartlegging og monitorering. Den er også velegnet for søk etter objekter, vrak og dumpefelt, samt en rekke militære anvendelser. Blant disse er mottiltak mot miner, overvåkning og krigføring på havbunnen.

Forsvarets forskningsinstitutt (FFI) har et langvarig samarbeid med Kongsberg Maritime (KM) innenfor utvikling av AUV-teknologi og SAS-teknologi. Flere verdensledende produkter finnes i HUGIN-familien av AUV-er. Det samme gjelder HISAS-sensorene fra Kongsberg Maritime, sensorer som er delvis utviklet ved FFI.

Endringsdeteksjon er en teknikk for å finne relevante endringer i data, samlet inn fra repeterte passeringer. Syntetisk-apertur sonar gir høy oppløsning og stor arealdekning per tidsenhet. Derfor er teknologien godt egnet til bruk i bildebasert endringsdeteksjon.

I denne mulighetsstudien ser vi på hvor egnet det er å bruke AUV med SAS for detektere strukturelle endringer av skipsvrak, med års mellomrom mellom passeringer. En mulig anvendelse er monitorering av tilstanden til skipsvrak i dumpefelt. Vi beskriver de spesifikke utfordringene som må løses. Det gjelder både for SAS-avbildning av skipsvrak, og for SAS-bilder til bruk i endringsdeteksjon. Vi studerer tre datasett. De er samlet inn i 2015, 2019 og 2022. Innsamlingen ble gjort med FFIs HUGIN AUV. Den var utstyrt med en HISAS 1032 interferometrisk syntetisk-apertur sonar. Dataene er av vrak 13. Vraket ligger i dumpefeltet med kjemiske stridsmidler, dumpet etter andre verdenskrig i Skagerrak.

Ved å bruke vår fremgangsmetode er det mulig å koregistrere lokale bilder, konstruere differensbilder og detektere små endringer. For å verifisere at endringene som er detektert er faktiske endringer på et vrak, må en inspisere likhet i målegeometri for de repeterte passeringene. Skyggeområder bør flagges og ignoreres i differenskartet.

Vår konklusjon er at AUV med syntetisk-apertur sonar kan brukes til monitorering av skipsvrak over mange år. Det forutsetter at det er likhet i avbildningsgeometri og sensorsystem, og at prosesseringen er riktig.

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1 Introduction

During the last 15 years synthetic aperture sonar (SAS) technology has gone through a significant development, and represents today state-of-the-art in high resolution seabed imaging and mapping (Hansen 2013; Hansen 2019). SAS is well suited for autonomous underwater vehicles (AUV), which are stable submerged platforms. Modern AUV-based SAS-systems are typically interferometric such that both an acoustic image and the estimated depth can be made of the seabed. The Norwegian Defence Research Establishment (FFI) has a long-standing collaboration with Kongsberg Maritime (KM) to develop the HUGIN family of AUVs and the HISAS family of SAS systems.

Change detection (CD) is the technique to observe differences in data collected from the same area repeatedly (Ban and Yousif 2016; Radke et al. 2005). FFI has an ongoing activity to develop CD technology for AUV-based SAS, especially for route surveys and naval Mine Countermeasures (NMCM) (Midtgaard et al. 2011; Midtgaard 2013; Midtgaard 2018). FFI also collaborates with Naval Surface Warfare Center (NSWC) Panama-City Division, USA, and Defence Research and Development Canada (DRDC), Halifax, Canada, in the Coalition Underwater Mine and Improvised Explosive Device (IED) Defeat (CUMID) to advance automated CD techniques and architect operator tools and decision aids for NMCM (Sternlicht et al. 2018; Crawford et al. 2022).

After World War II (WWII) chemical munitions were deposited in the Skagerrak strait, in the Norwegian trench, in a large scale. The procedure was to load the munitions onto cargo ships and sink the ships in a designated dump field (Arison III, 2013; Tørnes et al. 2015). The Norwegian Coastal Administration tasked FFI to search a large area to find all wrecks part of the dumpsite, and judge their conditions. In 2015 and 2016, FFI conducted a series of missions using FFIs HUGIN AUV carrying a HISAS 1032 interferometric SAS. Approximately 450 square kilometers were searched, and 54 shipwrecks were found (Sæbø and Lorentzen 2016; Sæbø et al. 2015; Hansen et al. 2019). In addition, a few areas were revisited in 2019 and 2022 with the same vehicle and sensors.

In this report, we do a feasibility study on using AUV-based SAS for monitoring the conditions of shipwrecks over years. Specifically, we investigate if image based CD can be performed to detect relevant structural changes on shipwrecks. We suggest a simple procedure well suited for automated image based CD on shipwrecks. We select wreck 13 in the Skagerrak dumpsite as a test-case for our study (Sæbø and Lorentzen 2016). This is a wreck where we have collected SAS-data in 2015, 2019 and 2022 using the same SAS system.

2 Seabed change detection using SAS

SAS is a technique based on coherent combination of multiple pulses in order to improve image resolution (Hayes and Gough 2009; Hansen 2011). Similar to Synthetic Aperture Radar (SAR) (Massonnet and Souyris 2008), the technology has the unique property of providing very high resolution and large area coverage simultaneously.

SAS interferometry is the technique to estimate the seabed depth using two or more vertically spaced receiver arrays (Griffiths et al. 1997; Sæbø 2010; Sæbø et al. 2013). Similar to SAR interferometry (Hanssen 2001), SAS interferometry provides a bathymetric estimate in the full swath of the SAS. The horizontal resolution in the SAS bathymetry is, however, lower than in the SAS image, since many imaging pixels are used in the estimation of vertical direction. The estimated depth accuracy is dependent on the Signal-to-Noise Ratio (SNR) and thereby the echo strength. This means that the depth accuracy typically varies over a scene.

Figure 2.1 show an example SAS image fusioned with SAS bathymetry of wreck 07 in the Skagerrak WWII dumpsite (Sæbø and Lorentzen 2016). The fusion technique is described in Hansen et al. (2017). The image resolution is approximately 3x3 cm before despeckling and 9x9 cm after despeckling (Austeng et al. 2013). The bathymetric resolution is 18x18 cm. The shipwreck is more than 130 m long, intact and placed standing on the seabed. Most of the cargo is therefore believed to still be inside the shipwreck.

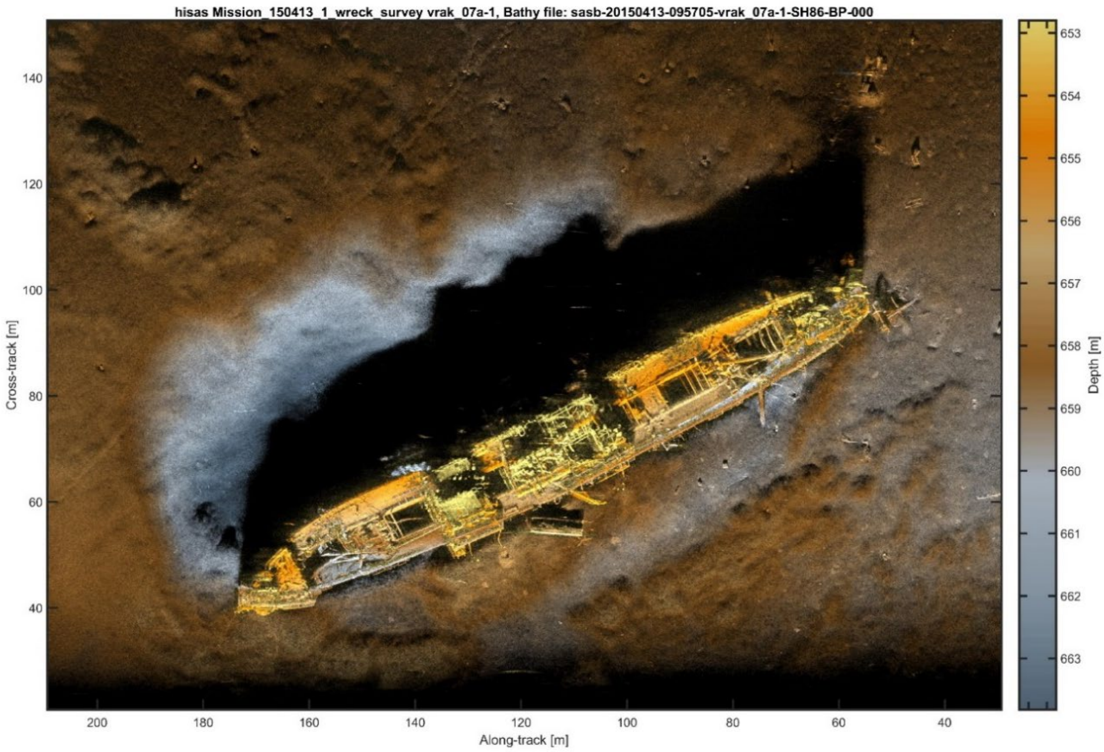


Figure 2.1 Fusion of SAS image and bathymetry of wreck 07 in the Skagerrak WWII dumpsite.

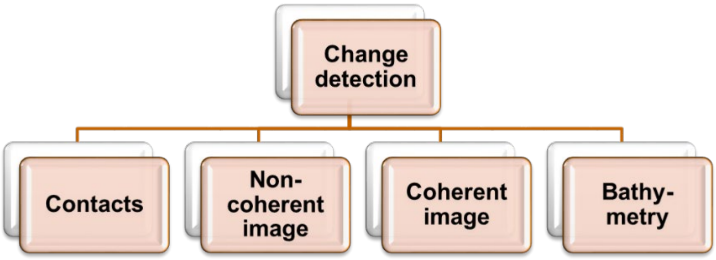


Figure 2.2 Overview of different change detection alternatives.

Change detection (CD) is the technique of finding relevant changes in images and bathymetries collected of the same seabed scene at different times. The technique has many applications of interest such as route surveys, NMCM, harbor protection, and monitoring. There are essentially four data products from an interferometric SAS that can be used for CD (Figure 2.2):

- **Contact based**: Differences in produced contact lists after detection and classification. This is most suited and may be the only choice when image based techniques does not or cannot work properly. Reasons for this can be that the scene is non-stationary, e.g. the seabed changes too much in time for image based techniques to work, or that the look angle of the sonar during data collection is significantly different per pass.

- **Coherent image based**: Calculation of the magnitude and phase difference between passes. Typically, a detection is flagged if the repeat-pass coherence is low. Can detect very small changes that may be invincible in the log intensity images. Requires sub-wavelength accuracy in the coregistration and very similar imaging geometry (Sæbø et al. 2011).

- **Non-coherent image based**: Direct calculation of a difference image by placing the repeated image grid onto the reference image grid. Typically, the log intensity difference image is constructed. Requires fine data driven coregistration of the data (but not sub-wavelength) and similar imaging geometry (Midtgaard 2013), (Midtgaard 2018).

- **Bathymetry based**: Direct calculation of the difference in estimated seabed depth. In principle invariant of sonar look-angle and track angle. Poorer resolution than image based techniques since each bathymetric estimate requires a group of imaging pixels. Requires that the bathymetric estimate is valid (the coherence must be high enough).

For the shipwreck application, it is not meaningful to form a contact-list. Coherent image based techniques requires the scene to be stationary within a fraction of a wavelength, which is unrealistic over years. Coherent CD also requires the imaging geometry to be very similar. For the application of detecting relevant changes on a shipwreck, we therefore only consider non-coherent image based, and bathymetry based techniques.

2.1 Challenges in SAS

There are numerous challenges to overcome to make SAS images successfully (Hansen et al. 2011; Geilhufe et al. 2019), and specific challenges related to SAS imaging and mapping of shipwrecks (Sæbø et al. 2015). Table 2.1 summarizes the challenges related to SAS.

Challenge	Description
Multipath	In shallow waters, unwanted multiple reflections from the sea surface and seabed occurs. This will cause loss of contrast and interferometric coherence.
Ocean current	Ocean cross-currents relative to the platform trajectory, causes horizontal crab which again causes loss of micronavigation performance and non-straight synthetic apertures. There are different SAS imaging strategies that may handle crab well or poorly.
Trim	A poorly ballasted or trimmed vehicle will run with vertical crab which again causes loss of micronavigation performance and non-straight synthetic apertures.
Rough terrain	Rough terrain may cause vertically nonlinear tracks along a synthetic aperture. It becomes more demanding to produce a perfectly sharp SAS image.
Autopilot	The guidance and control system may induce nonlinear tracks. Any deviation from a straight line, either in the horizontal or vertical plane, will cause less favorable conditions for successful SAS processing.
Navigation	Unknown and uncompensated navigational errors in the Inertial Navigation System (INS) and in the sonar micronavigation, may cause several types of error in the SAS data products.
Sound speed	Incorrect average sound speed along the acoustic paths may cause nearfield defocusing and loss of image quality. A sound speed depth gradient will lead to a bias in the interferometric depth estimate, if not corrected for.
Multiple scattering	Large structures, such as shipwrecks, impose specific challenges for SAS imaging. The acoustic waves may be reflected or scattered two or more times. This breakdown of the single scattering approach may cause misplaced and degraded signals in the images, or acoustic pollution.

Table 2.1 Challenges in SAS imaging and mapping.

2.2 Challenges in CD using SAS

Our basic concept of using AUV-based SAS for image based CD is to run repeated tracks as close to identical as possible using the same sensor and processing (Midtgaard 2013). There are specific challenges in the CD data collection that are related to the ability to produce images repeatedly. Any change in the ocean environment, error in the vehicle global navigation accuracy or insufficient ability to repeat the tracks will potentially cause issues in image based CD. Table 2.2 summarizes the potential CD challenges and their consequences.

It should be noted that a critical step for image based CD is successful coregistration. That is, the ability to use the SAS images themselves to estimate any residual shift, rotation, scaling and higher order warping between passes. For further reading and more details see (Midtgaard 2013; Hansen et al. 2014; Hansen et al. 2018).

Challenge	Description
Horizontal position offset	GPS does not work underwater. AUVs use INS with aiding. The error is in the order of meters or hundreds of pixels.
Depth offset	The vehicle depth is estimated using a pressure sensor and ranging to surface positioning unit if available. This is susceptible to tidal variations and ocean swell. Error in the order of meters for large temporal baselines.
Horizontal rotation error	The INS on modern advanced AUVs, have very accurate attitude estimates. The error is typically better than 0.1 degrees.
Range scaling	The sound speed in the ocean varies with up to 3 - 4 % mainly with depth. Typically less than 1 % within a scene. Errors in the order of decimeters.
Along-track scaling	The INS depends on Doppler velocity logging aiding. The accuracy is in the order of 0.1 – 0.2 % of distance travelled. Errors in the order of decimeters in a scene.
Range dependent depth error	Roll error, sonar mounting error, sound speed gradient error. May cause seabed depth estimation error in the order of meters, but is in principle possible to calibrate and compensate for.
Nonlinear local errors	Induced by terrain variations, terrain errors, navigational errors, and nonideal and different tracks. This may cause non-linear higher order warping of the imaging grid between passes.
Vertical geometry and crab difference	A difference in the vertical geometry (baseline) and/or horizontal look angle will potentially cause different highlight and shadow regions between the repeated passes.

Table 2.2 Data gathering issues and their potential consequences for SAS based change detection.

3 Data gathering

Figure 3.1 shows the 2022 track lines with corresponding sidescan sonar (SSS) images of the seabed surrounding wreck 13. We have collected data from both sides of the wreck, the C-lines run North-West, and the B-lines run South-East. The vehicle followed the same mission plan in 2015, 2019 and 2022, such that track lines should be identical. Note that we only used the starboard SAS system for the images of the wreck. The approximate distance from track to wreck at closest point is 100 m, and the vehicle altitude was 25 m.

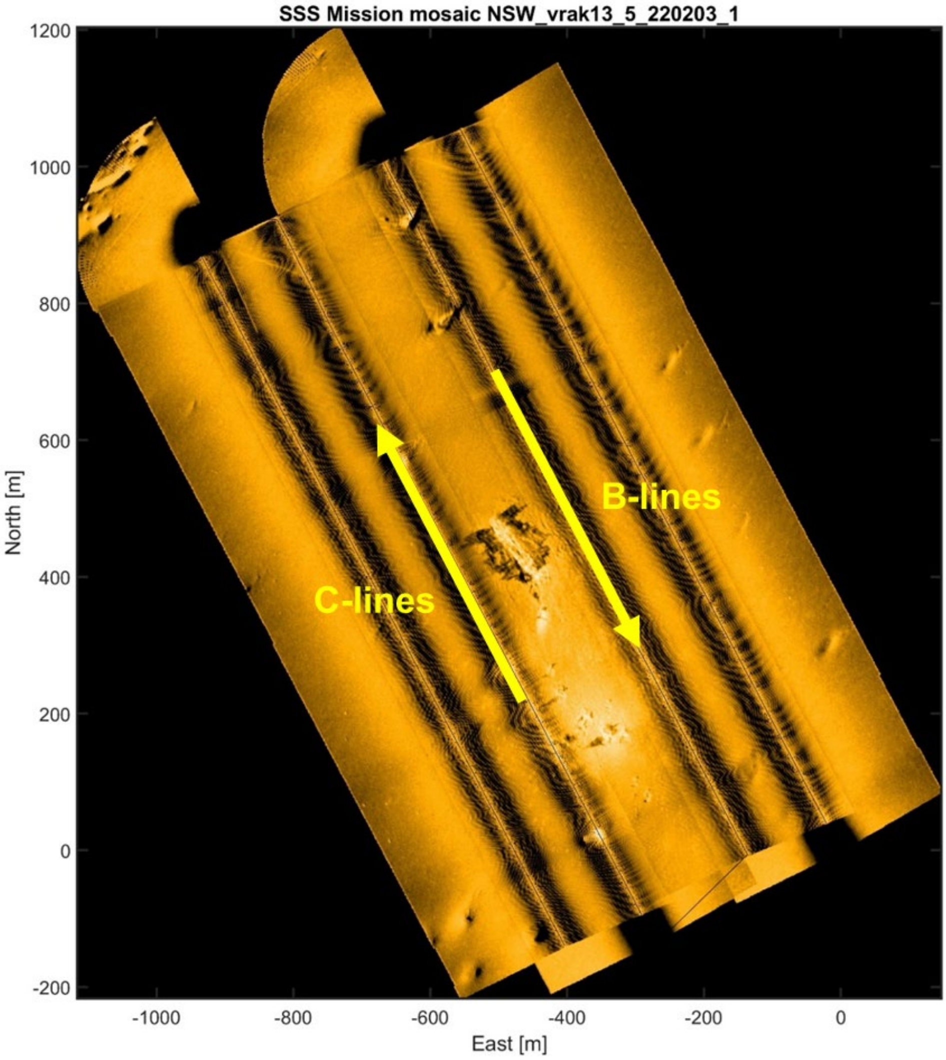


Figure 3.1 Track lines and sidescan sonar (SSS) images for the wreck 13 data collection.

3.1 SAS images

Figure 3.2 shows the SAS images of the shipwreck seen from both sides, from all three years. The imaging scene is 200x120 m, the images have been despeckled (Austeng et al. 2013) and range-intensity compensated (data driven). The SAS images are constructed using the backprojection algorithm and choosing a flat render plane approximately at the surrounding seabed depth (Hansen et al. 2011). The intact part of the wreck is approximately 100 m long. A part of the bow is broken off and the surrounding area contains a large amount of debris and cargo. Further details are provided in Hansen et al. 2017 and Bryan et al. 2022 regarding the UXOs surrounding wreck 13. We observe clear similarities within the B-lines and within the C-lines. The main differences between the B- and C-lines are caused by the horizontal look angle dependence. It is clear from these images that CD using opposite horizontal look angle will work poorly or not work at all. In the shadow of the wreck, there is a rather large area of acoustic pollution (unwanted signals most likely caused by multiple scattering). This may also cause problems for automated CD if not handled properly.

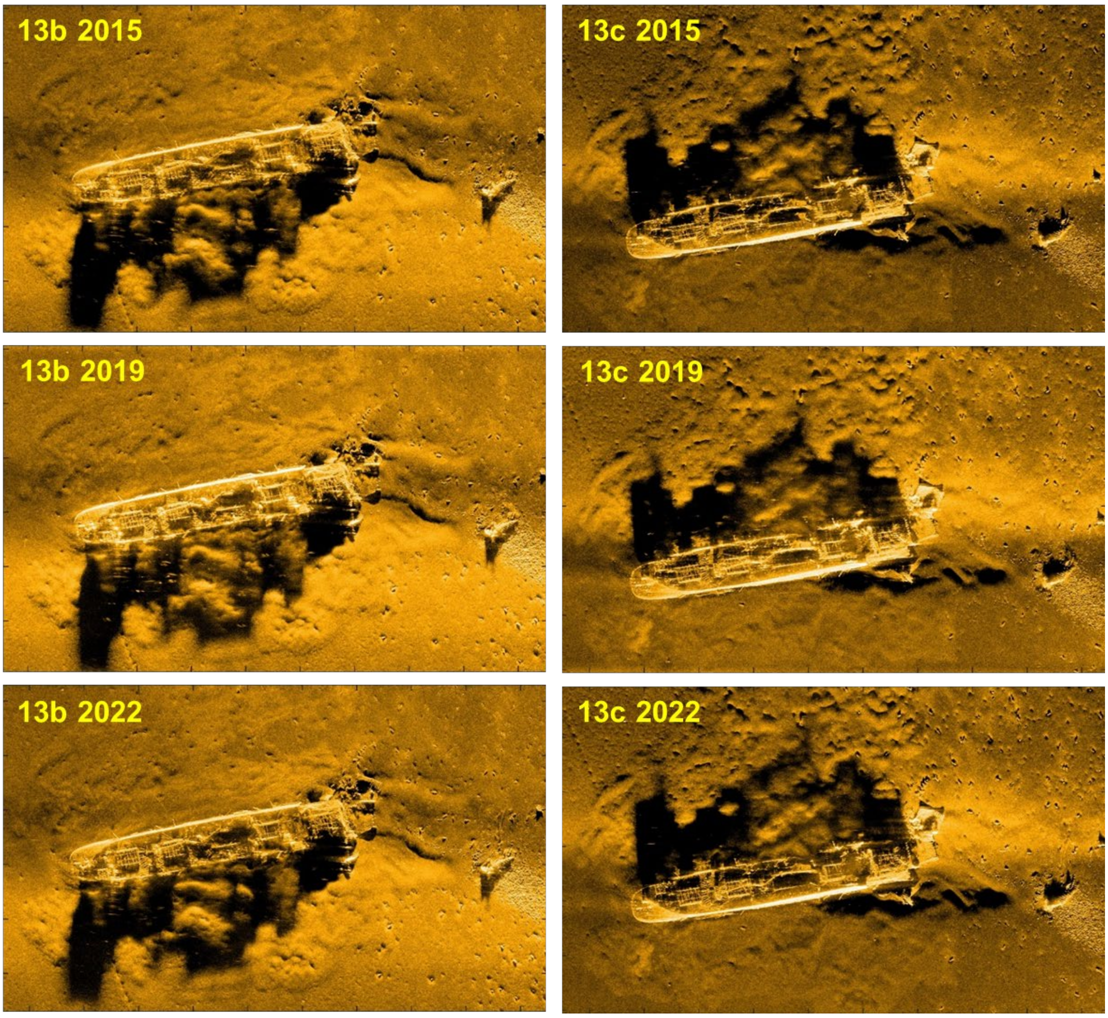


Figure 3.2 SAS images from all the passes.

3.2 Track repeatability

In order to assess the suitability of the SAS images for image based CD, we must investigate the track data. Our approach to CD is based on the following:

- The tracks must be repeated as similar as possible. Any large deviation in the track line, vertical geometry and horizontal geometry may cause systematic differences in the images that again affect the ability to coregistrate the images and successfully forming difference images.

- Each track must be suitable for SAS for imaging of shipwrecks. This includes that the track must be sufficiently linear, and that the vertical/horizontal crab is small enough. Any non-straight aperture causes a render plane dependency that may be difficult to solve in the imaging, especially on an elevated structure such as a large shipwreck.

- The tracks must be chosen such that the entire shipwreck is visible (or at least the important parts of the wreck must be visible). This includes choosing sonar range, track angle relative to the shipwreck, and a sensible vehicle altitude. Note that this cannot directly be evaluated using the track data alone. A-priori knowledge about the wreck is needed (e.g. from an earlier survey or other sensors).

Figure 3.3 and Figure 3.4 shows the navigation data for the B-lines and the C-lines, for all three passes, as function of local SAS image ping number. 530 pings correspond approximately to 260 m along-track. The vehicle was running in constant altitude mode, giving a depth variation of 0.8 m for the B-lines and 2 m for the C-lines. We observe that the sway variation (horizontal cross-track) is very small. The vertical crab varies a few degrees between passes. This is probably due to slight differences in the ballasting of the vehicle between passes. There is a small but significant difference in the horizontal crab and vehicle heading between passes, indicating different ocean currents between passes. The crab will cause a non-straight synthetic aperture with periodicity with the potential to construct grating lobes or ghost targets.

The horizontal track offset estimated by relocation of small objects surrounding the shipwreck in each image is shown in Table 3.1. Note the rather large offset between the 2015 and the 2022 lines. This error may be reduced by running navigation post-processing using NavLab (Gade 2005).

	2015-2019 along-track	2015-2019 cross-track	2015-2022 along-track	2015-2022 cross-track
B-lines	-1.5 m	0.2 m	-3.5 m	2.5 m
C-lines	-0.5 m	0 m	-1.5 m	6.0 m

Table 3.1 Estimated horizontal track offset along-track and cross-track.

We conclude that the track repeatability is good, and should be within bounds for image based CD to work. The vertical and horizontal crab variation may cause some differences in the production of grating lobes. A more thorough analysis can be done based on the theoretical constraints for SAS imaging and CD. This is outside the scope of this feasibility study.

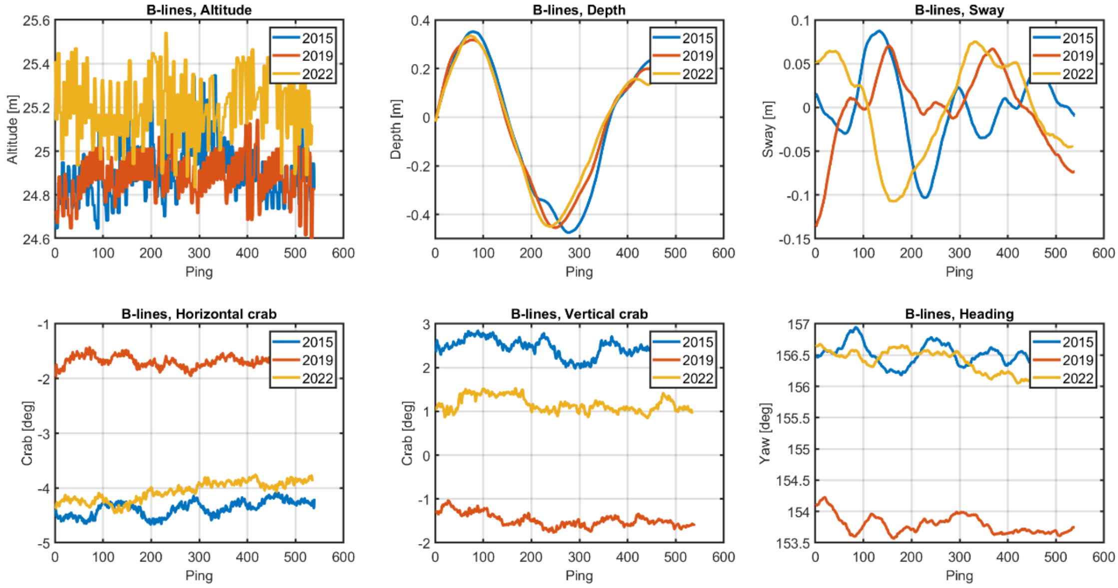


Figure 3.3 Navigation data for the B-lines as function of sonar ping number. The travelled distance between pings is approximately 0.5 m.

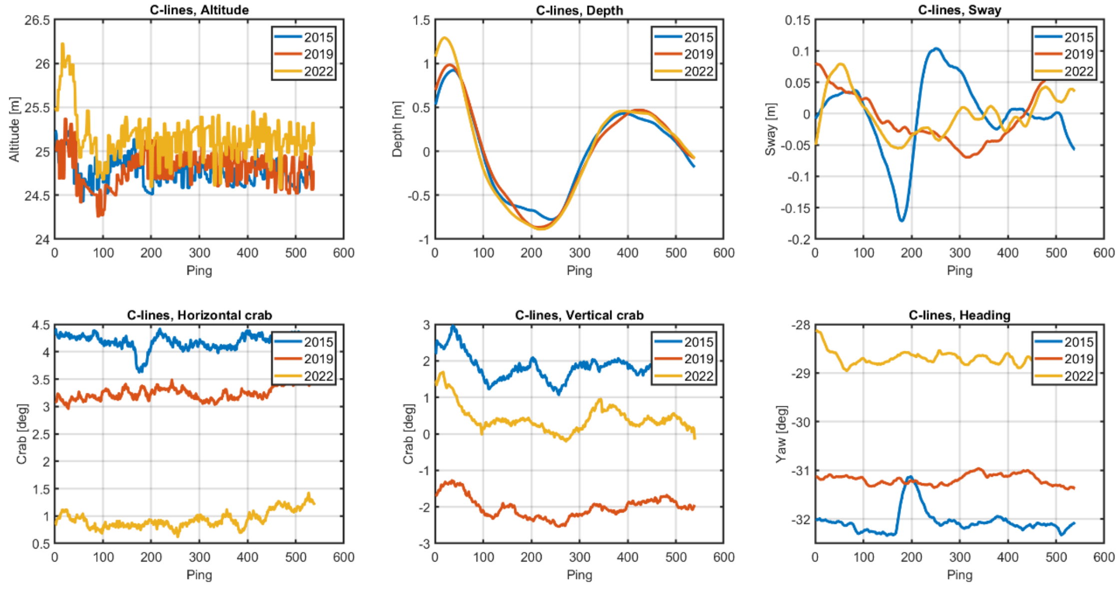


Figure 3.4 Navigation data for the C-lines as function of sonar ping number. The travelled distance between pings is approximately 0.5 m.

4 Data representation

Interferometric SAS imaging and mapping of shipwrecks gives us at least three different data representations that may be used in CD. Table 4.1 illustrates three alternatives, with increasing level of information. A fundamental question related to coregistration and the calculation of difference products, is whether the data are 2D or 3D. For the SAS bathymetry, this is a choice. The 3D point cloud is a better representation for full 3D understanding and visualization of the wreck. It is, however, more complex to handle, since there are no trivial way of calculating the difference between two point clouds. Potential depth errors in the SAS bathymetry, e.g. from tidal variations, can be removed by using reference areas surrounding the wreck. In the following, we study the SAS image only. This is the starting point, and should always be used (if possible) for coregistration, given the fact that the image has higher resolution than the bathymetric map. After successful coregistration, a non-coherent difference image and a 2D map can be made.

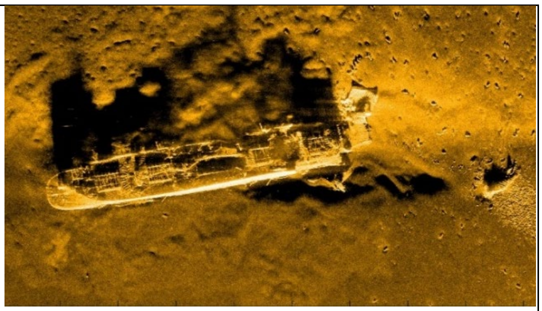
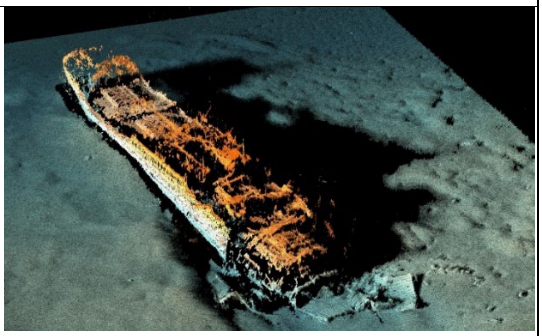
SAS image 2D representation of the relative acoustic reflectivity. The choice of render plane is critical for the information content and correctness of the data. The image has higher resolution than the map. Shadowing, layover and multiple scattering cause potential false echoes that may be misinterpreted as changes.	
SAS bathymetry in 2D Seabed depth measured in a 2D grid combined with the SAS image and the SAS coherence. As for the image, layover and multiple scattering complicates the use of the data. Coherence values below a threshold leads to disqualification of the data.	
SAS bathymetry in 3D Seabed depth measured as a 3D point cloud. Each point contains the (x,y,z) estimated position of the seafloor. The representation may also contain information about the acoustic backscatter level (as shown). 3D point clouds is a better representation in layover-regions and complex parts of the shipwreck.	

Table 4.1 Interferometric SAS data products.

5 Method for Automated Change Detection

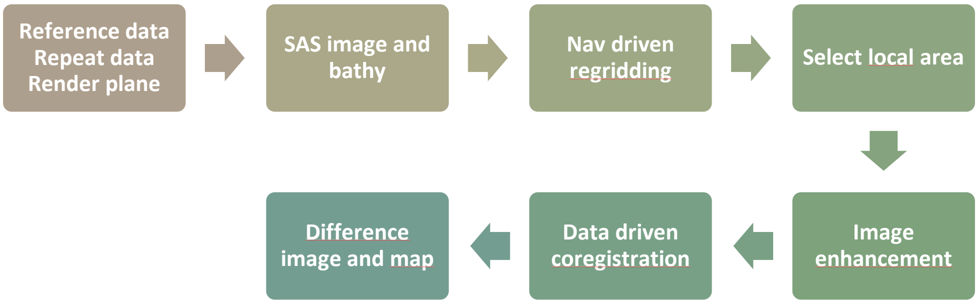


Figure 5.1 Suggested method for local image based change detection on shipwrecks.

With reference to Figure 5.1, we suggest the following data driven approach suitable for automated coregistration and CD on SAS images collected using repeated and similar tracks:

1. Choose a scene covering the wreck and use a flat render plane.

2. Make the SAS image and SAS bathy of the reference and repeated pass.

3. Regrid the repeated pass onto the reference grid using navigation data only.

4. Select a local area small enough such that the data may be coregistered using a horizontal shift only.

5. Enhance the local area image per pass if needed. We have omitted this in our study.

6. Run a simple shift estimation by minimizing of the absolute value of the log intensity difference between passes. Note that the mean value in each local image should be removed to reduce potential intensity-driven bias in the estimate.

7. Calculate the log intensity difference image and detect relevant changes. Calculate the SAS bathy difference and investigate if needed.

Then loop through and repeat 4 – 8 until the entire shipwreck and its surroundings is covered. For this simple procedure to succeed, the regridding (3) must remove any orientation error. This is typically fulfilled for modern high precision AUVs (section 2.2).

5.1 Choice of render plane

In pulse-echo imaging such as SAS, non-straight apertures implies a dependence on the choice of render plane in order to do successful imaging. This is described in detail in (Jakowatz et al. 1996). For SAS imaging of shipwrecks, this may be problematic due to the elevated nature of the shipwreck (Figure 5.2).

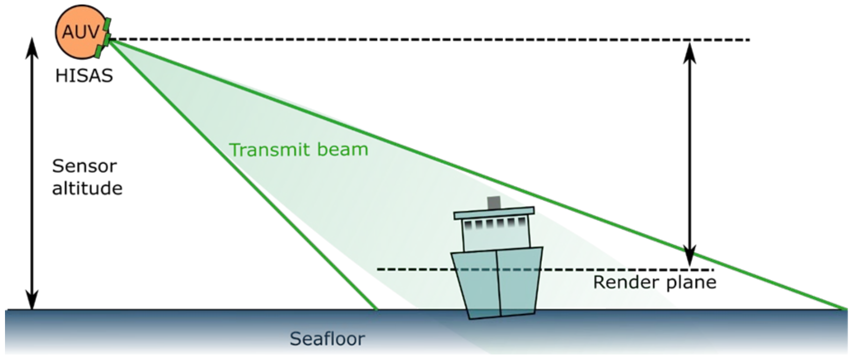


Figure 5.2 Choice of render plane in SAS imaging.

There are two types of problems caused by non-straight apertures:

- For slow depth variations in smooth curves (e.g. depth in Figure 3.4), incorrect render planes will cause defocus (smearing) along-track.
- For vertical and/or horizontal crab (e.g. crab-plots in Figure 3.3 and Figure 3.4), incorrect render planes will induce periodic errors in the synthetic aperture and thereby grating lobes in the image.

We have illustrated the latter point in Figure 5.3. A render plane altitude of 24.2 m was automatically chosen in the left image. This causes repeated ghost replicas (or grating lobes) of some of the objects in the scene. In the right image, we have chosen a render plane of 16.7 m. We see clear reduction of the grating lobes. Grating lobes may impose a significant problem for image based change detection, since a grating lobe very well can be misinterpreted as a target (or a change).

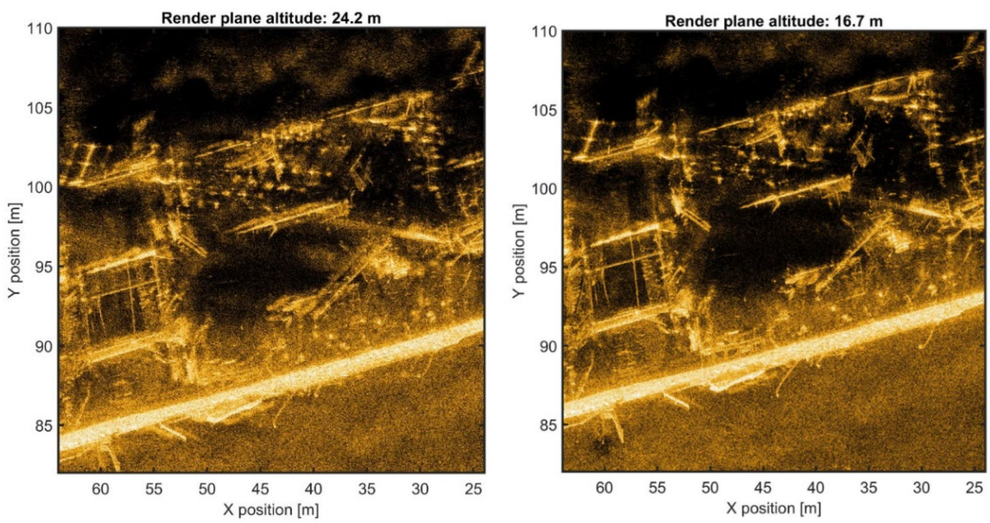


Figure 5.3 Example choice of render plane and its effect on grating lobes.

5.2 Misregistration

Incorrect registration (or misregistration) may occur if the data driven coregistration algorithm does not find the correct shift, or if the model is incorrect. The latter may occur if only a shift is assumed but the transform of putting the repeated image onto the reference grid requires a higher order transform. Such transforms are typically rotation, scaling and non-linear warpings (Jakowatz et al. 1996, chapter 5). In our case, we assume a shift only for data driven coregistration (that is, after regridding the repeated data onto the reference grid using navigation data only).

In order to judge the quality of our coregistration, we consider the example of simple misregistration in Figure 5.4. A misregistration of 5 pixels along-track (lower left) and cross-track (lower right) gives significantly more pollution in the difference image compared to the (assumed) correctly coregistered difference image (upper right). Note that a homogeneous difference image (with constant values or the same color over the entire scene) would be the perfect result if the scene does not contain any changes and the imaging geometry is identical.

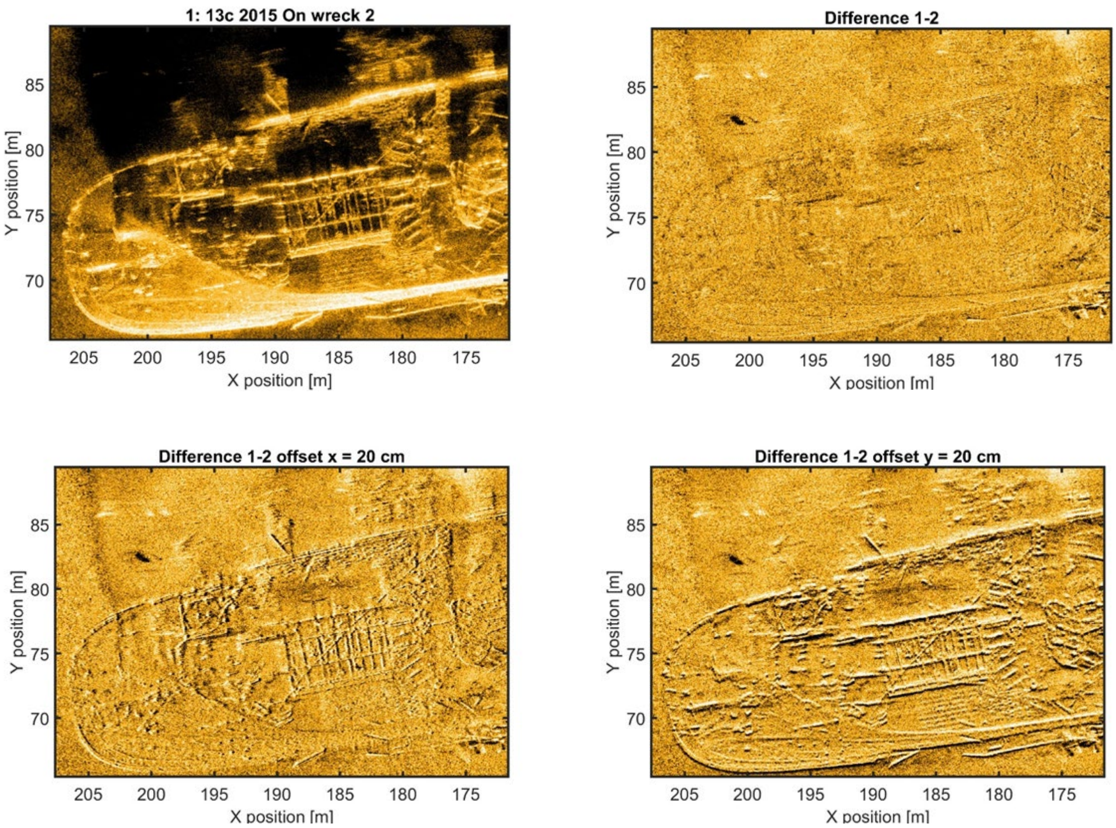


Figure 5.4 Misregistration examples. Upper left: Local image from the 2015 pass. Upper right: difference image using the assumed correct shift in x and y. Lower left and right: misregistered difference image with 20 cm error (5 pixels) along-track (left) and cross-track (right). The dynamic range in the difference images is 30 dB.

6 Change detection results

In this chapter, we present local difference images of five different areas, as shown in Figure 6.1. We only consider the C-lines, and the log intensity difference images between all three years, where we have used the coregistration approach and model as described in chapter 5. We also only consider the log intensity difference images. These serve as a starting point for automated change detection, and are sufficient for a feasibility study.

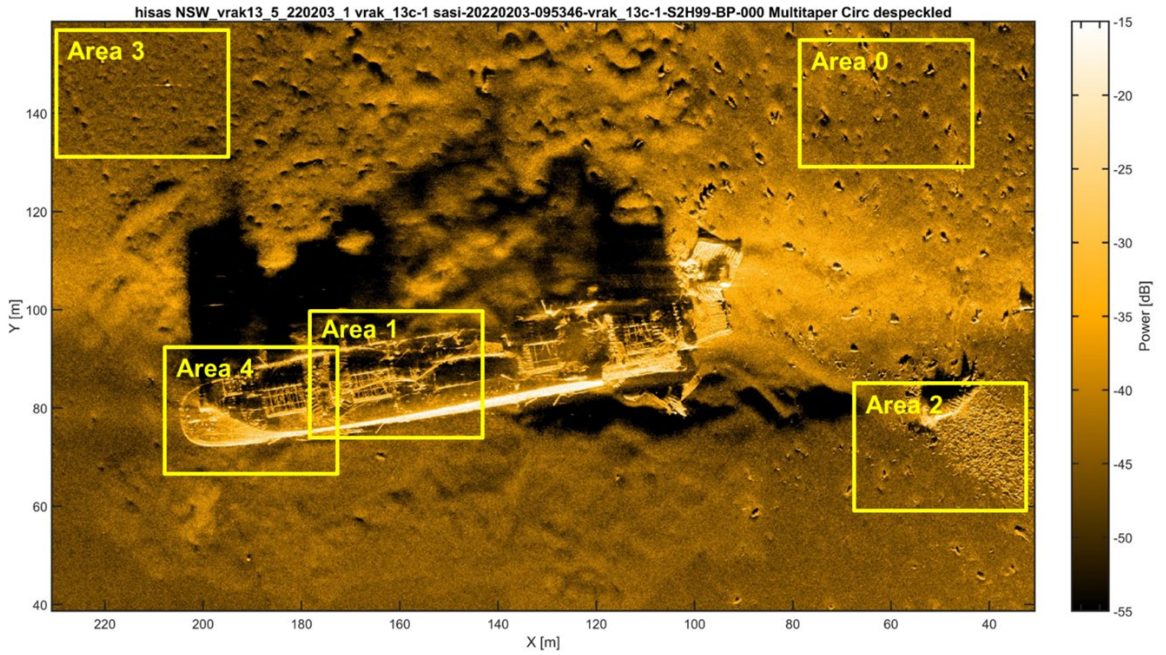


Figure 6.1 Selected areas for C-lines.

Figure 6.2 - Figure 6.6 show the individual local images and all the difference images from each area. The dynamic range for the images are 40 dB, and 30 dB for the difference images. The yellow curves highlight changes. Results show the following:

- Area 0 contains relatively large UXOs or objects, assumed cargo from the shipwreck. We observe no signal in the difference image that can be assumed to be significant changes on the scene. The apparent lighter and darker areas in the right part of the lower right change image are likely to be caused by small changes in the shadows of the objects due to slight changes in the imaging geometry.

- Area 1 is from the middle part of the shipwreck. There is one significant signal in the difference images, highlighted with yellow curves. A rod or similar is visible in the 2015 and 2019 images, and disappeared in the 2022 image. This could either be from railings or part of a mast. In order to verify that this is an actual change in the scene, the effect of different imaging geometry per pass must be checked. This can be done by using the estimated SAS bathymetry and the differences in tracks to calculate the vertical and horizontal look angle differences, and thereby conclude if the imaging geometry is similar enough. In addition, the opposite looks could be investigated (the B-lines).

- Area 2 contains lots of small cargo and a larger piece of debris. There is one significant change in the images. In the 2019 and 2022 images, an object is visible in the shadow region of the debris. This object was not visible in 2015. This apparent object could be caused by a change in the debris. Again, in order to verify that this is an actual change in the scene, the imaging geometry should be investigated. Note that the difference images from the patch of small cargo (lower right corner) show little signal, indicating high quality coregistration.

- Area 3 is outside the shipwreck and contains no objects in the 2015 pass. In 2019 and 2022, two new objects are present. Given the sub-meter size and shape with highlight and shadow of these objects, they are likely to be weights used as part of Remotely Operated Vehicle (ROV) operations conducted at some time between 2015 and 2019.

- Area 4 is from the aft part of the shipwreck. In the 2019 image there is an apparent object that is missing in the 2015 and 2022 images, highlighted with yellow curves. Note the negative difference (darker spot) in the *Difference 1-2* image, and the corresponding positive difference (brighter spot) in the *Difference 2-3* image. This apparent change is likely not a real change in the scene. The apparent object present in the 2019 data is in the shadow region and most likely a grating lobe.

Summarized, using our rather simplistic approach, we are able to successfully coregistrate local images, produce difference images and detect small changes. To verify that the detected changes are real changes, the similarity in the imaging geometry for the repeated passes must be investigated. Shadow regions should be flagged and ignored in the change maps.

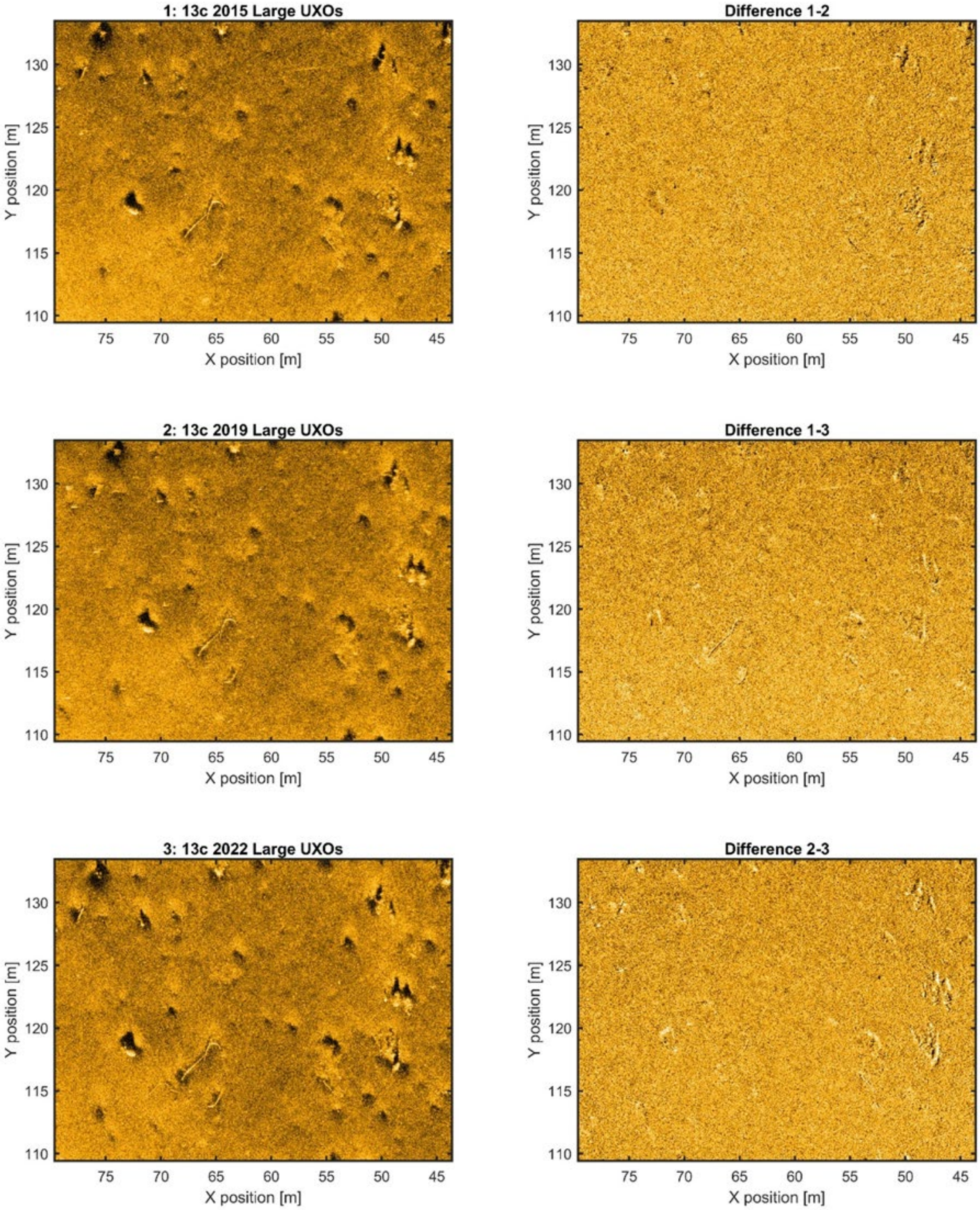


Figure 6.2 Area 0: Large UXOs outside the shipwreck.

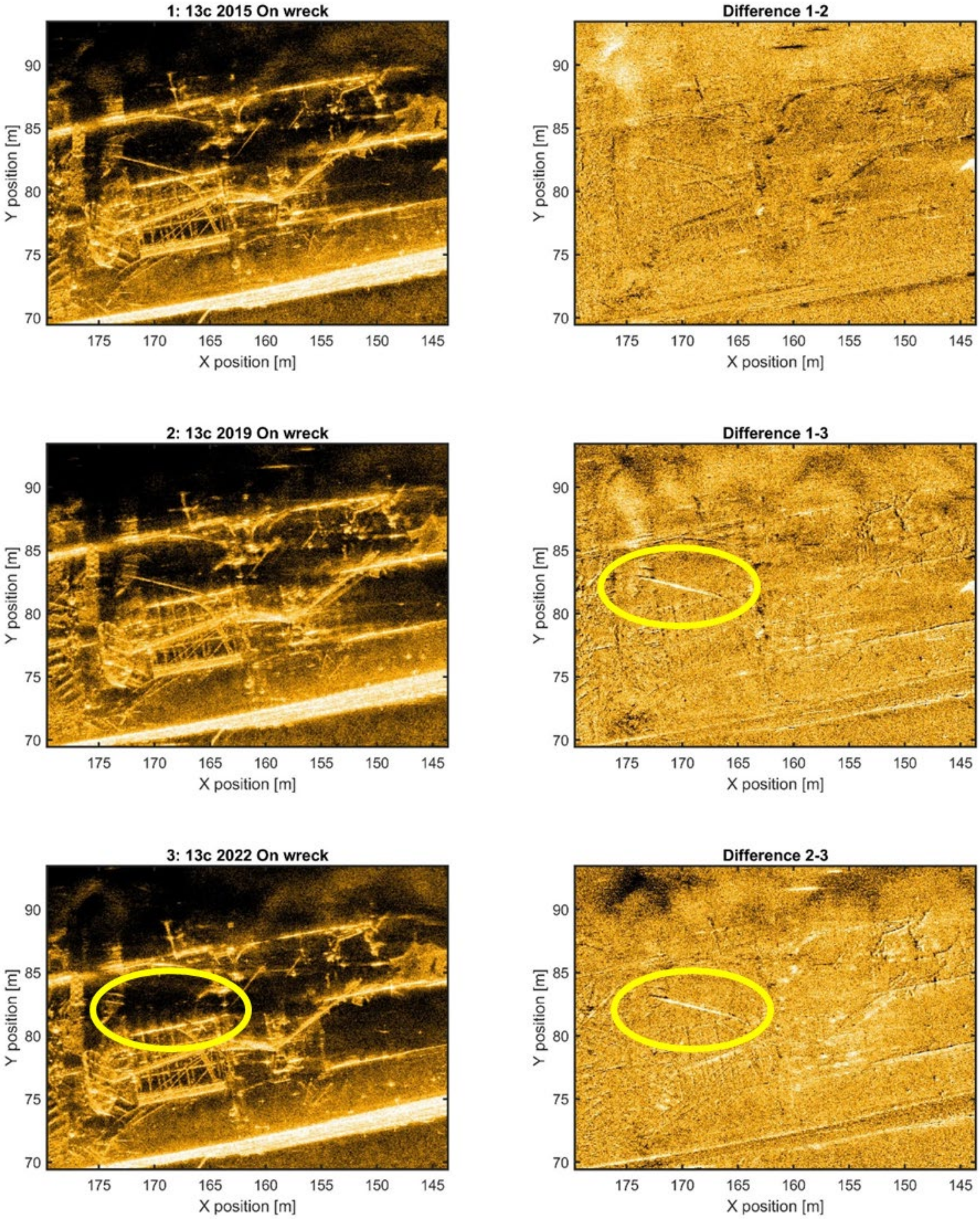


Figure 6.3 Area 1: The middle of the shipwreck.

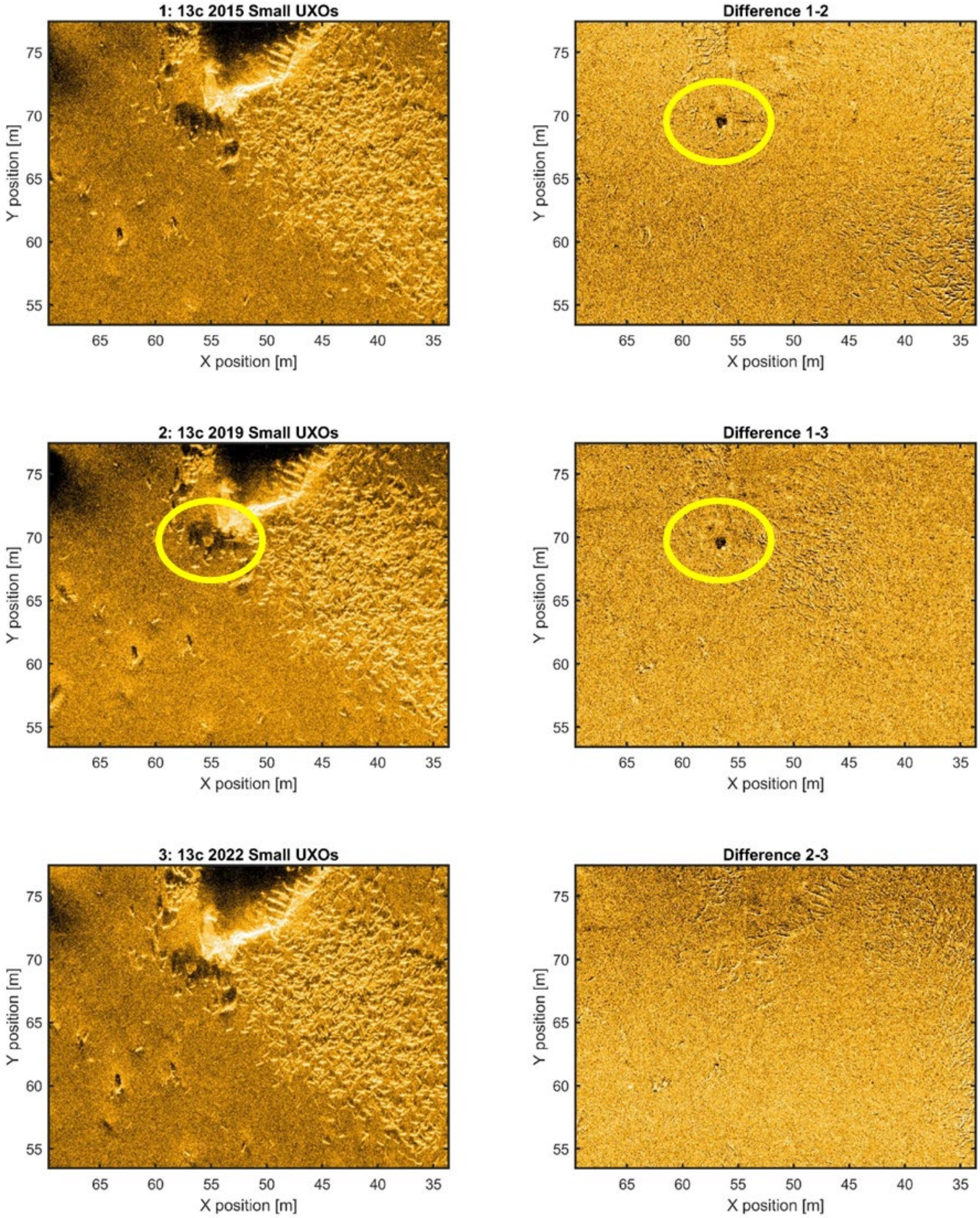


Figure 6.4 Area 2: Small cargo and debris outside the shipwreck.

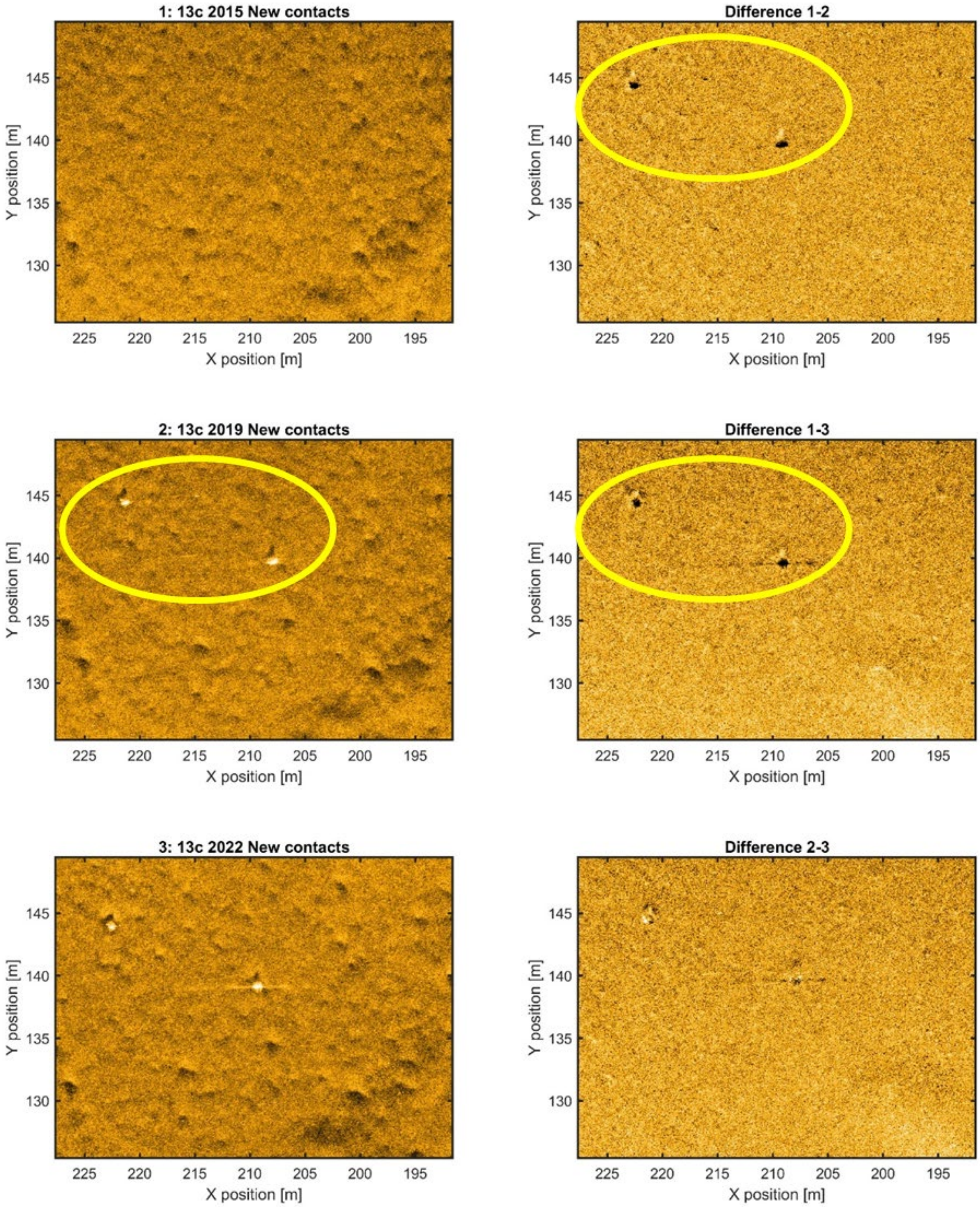


Figure 6.5   Area 3: Outside the shipwreck.

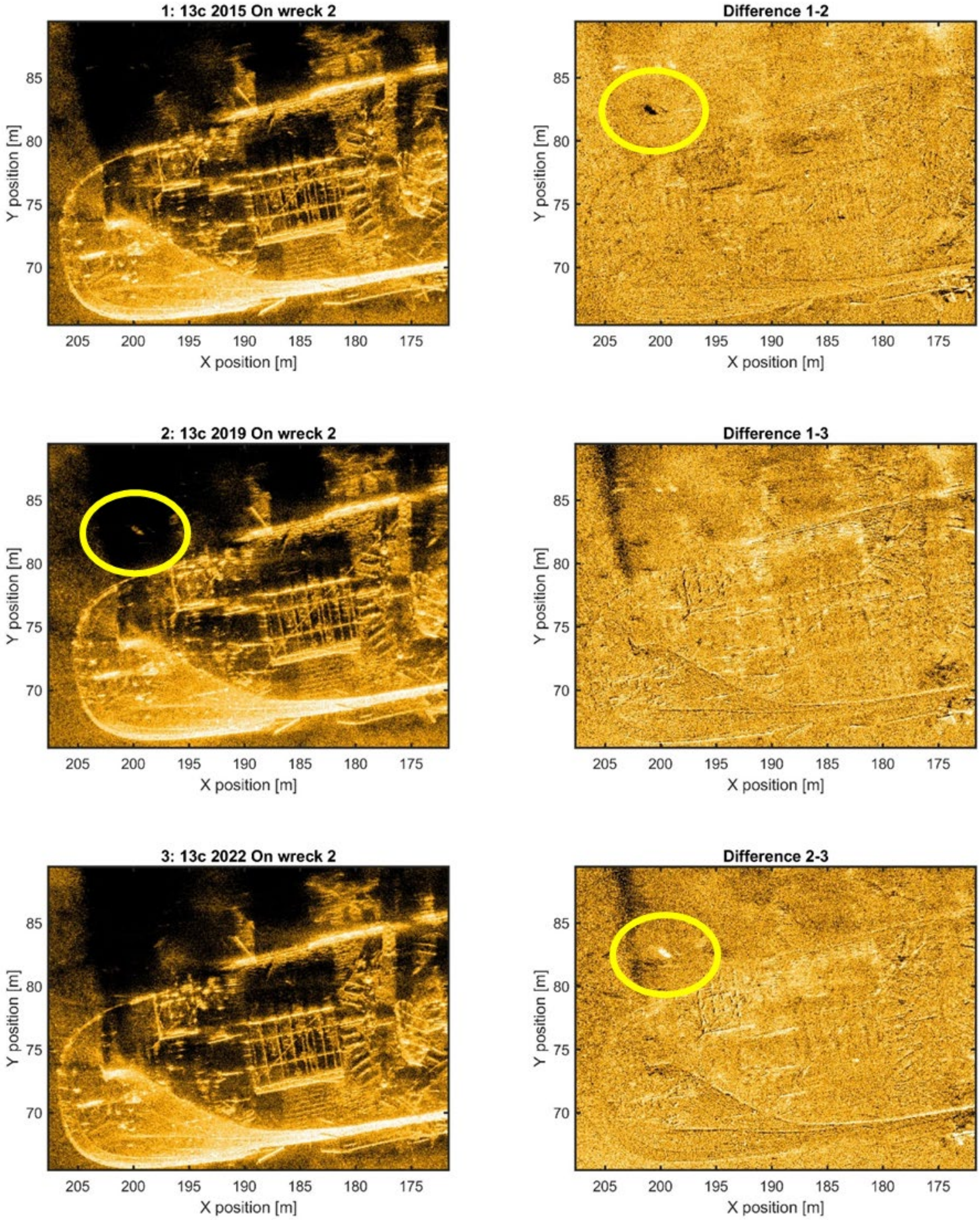


Figure 6.6   Area 4: The aft part of the shipwreck.

7 Summary and recommendation

In this feasibility study, we have considered using AUV with SAS for detection of relevant changes on shipwrecks. We have investigated one shipwreck in the Skagerrak WWII chemical munitions dumpsite, wreck 13, where data was collected during various periods in 2015, 2019 and 2022. We have developed a simple scheme for automated local change detection in the SAS images and demonstrated that we are able to detect changes if the imaging geometry for the repeated passes are sufficiently similar.

Our conclusion is therefore that AUV with SAS can be used for long term monitoring of shipwrecks by using image based CD if certain requirements are met regarding the data collection, the sensor, and the processing.

For successful use of AUV with SAS in image based change detection on shipwrecks over large time intervals, we suggest the following approach:

1. Carefully choose reference track lines that are optimally placed relative to the shipwreck. Get all views of the shipwreck (2 or more).
2. Run repeated track lines, as similar as possible.
3. Qualify reference and repeat runs by inspecting track quality including position offset and crab.
4. Choose render plane carefully.
5. Make SAS image and SAS bathy.
6. Regrid globally using navigation data. Optional if the tracks are very similar.
7. Select a local region of suitable size.
8. Run local image quality improvement (adapt render plane) if needed.
9. Coregistrate locally based on the image.
10. Do per pass difference local calculation of the log-intensity image.
11. Do per pass difference local calculation of the bathymetry.
12. Detect significant changes.
13. Repeat 7-12 until the entire shipwreck is covered.

7.1 Future work

In this feasibility study, we have considered AUV with SAS for detection of relevant changes on shipwrecks. In order to do fully automated and reliable CD, either during a CD mission, or in post-processing, the technology must be further developed. We suggest further work in the following topics:

- Automated qualification of AUV track data before imaging and CD.
- Automated labelling of relevant areas in the scene, e.g. drawing bounding-boxes on the shipwreck.
- Automated filtering of multiple scattering, non-valid data, and acoustic shadow.
- Better coregistration including using a scoring metric.
- Investigation into the suitability of using SAS bathymetry in addition to SAS images.
- Automated interpretation of the difference images.

The latter is a larger and wider topic where multiple alternatives should be investigated.

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Acronyms

ATR	Automated Target Recognition
AUV	Autonomous Underwater Vehicle
CD	Change Detection
CTD	Conductivity, Temperature, Depth
CUMID	Coalition Underwater Mine and IED Defeat
CW	Chemical Warfare
DRDC	Defence Research and Development Canada
DVL	Doppler Velocity Logger
FFI	Norwegian Defence Research Establishment
ID	Identification
IED	Improvised Explosive Device
INS	Inertial Navigation System
KM	Kongsberg Maritime
MBES	Multibeam Echosounder
NMCM	Naval Mine Countermeasures
NSWC	Naval Surface Warfare Center
ROV	Remotely Operated Vehicle
SAS	Synthetic Aperture Sonar
SAR	Synthetic Aperture Radar
SSS	Sidescan Sonar
SNR	Signal-to-Noise Ratio
UXO	Unexploded Ordnance
WWII	World War II

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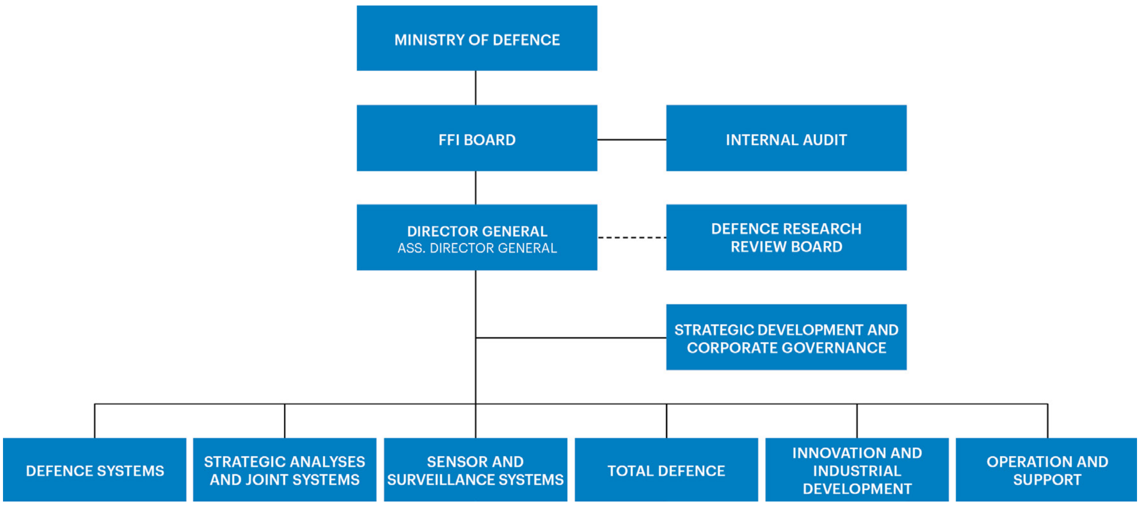

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