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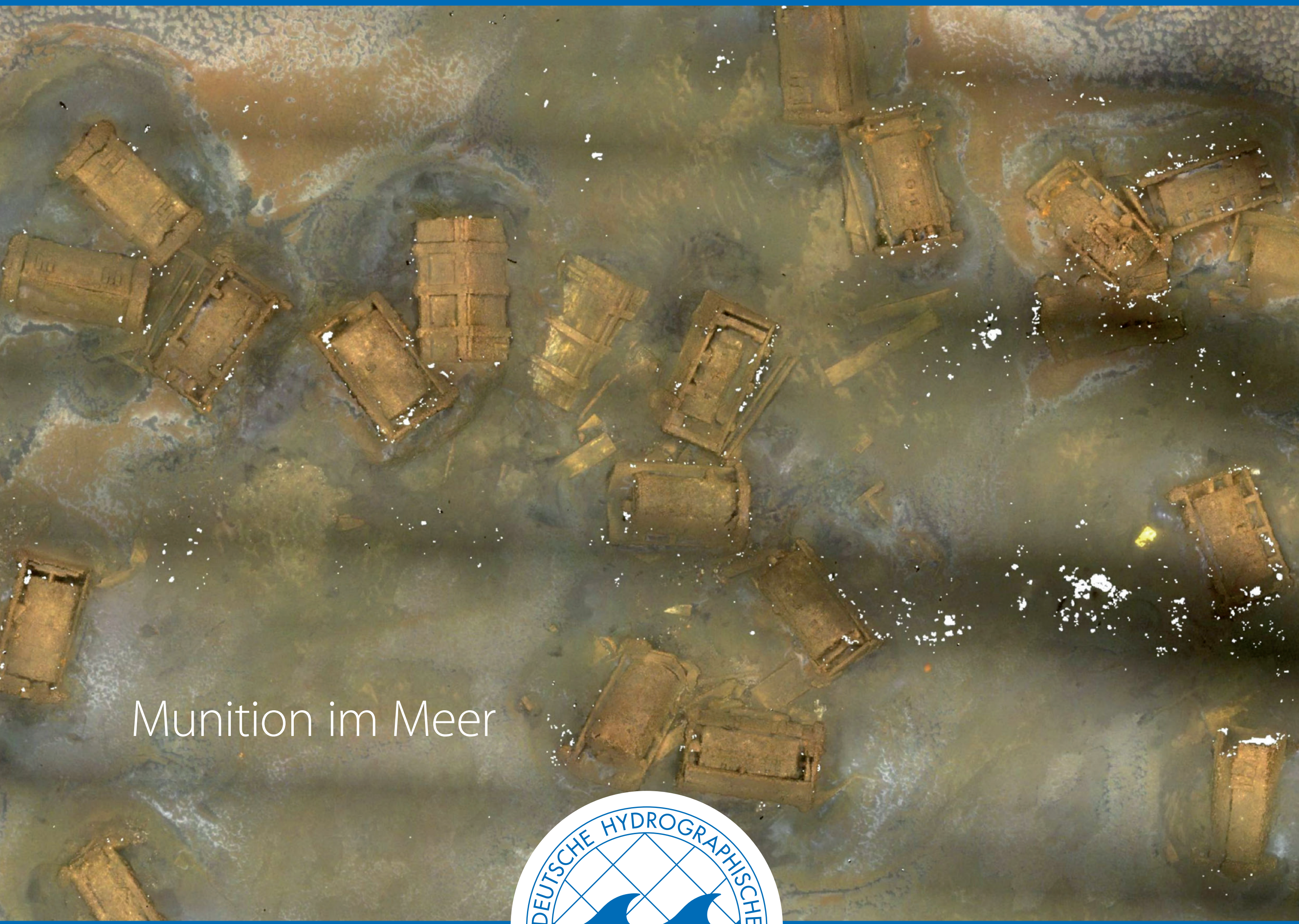

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Marine dumped munition

Example from Lübeck Bay where test clearance will start in 2024

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Substantial amounts of munition have been dumped in coastal areas of the German Baltic Sea. Hydroacoustic methods common for UXO surveys and advanced methodologies including AUV-based optical investigations have been used to support studies that investigate the impact of toxic explosive substances on the marine environment. Multibeam and side-scan sonar, and ROV- and AUV-based optical data sets give a good impression of the occurrence and type of munition in Lübeck Bay. Here, the two munition dump sites Pelzerhaken and Haffkrug were mapped and several thousand munition-like features were identified. Piles of boxes with small calibre munition, isolated torpedoes, scattered cluster-bomb bomblets, as well as clusters of depth charges and aerial bombs could be identified. The combined approach of standard methods and robotic systems such as AUVs allowed detailed insight and scaling of the problem. Several completed and ongoing research projects and the publicity initiated by these projects pushed the German government to start an »Immediate Programme« to test different clearance technologies for munition dump sites and to develop final disposal options that allow industrial upscaling.

Lübeck Bay | marine munition | photogrammetric and hydroacoustic mapping | AUV
Lübecker Bucht | Munition im Meer | photogrammetrische und hydroakustische Kartierung | AUV

In den Küstengebieten der deutschen Ostsee wurden beträchtliche Mengen an Munition versenkt. Hydroakustische Methoden, die für UXO-Untersuchungen üblich sind, aber auch fortschrittliche Methoden, einschließlich AUV-basierter optischer Untersuchungen, wurden eingesetzt, um Untersuchungen zu Auswirkungen der toxischen Explosivstoffe auf die Meeresumwelt zu unterstützen. Fächerlot, Side-Scan-Sonar, ROV- und AUV-basierte optische Datensätze geben einen guten Eindruck über das Vorkommen und die Art der Munition in der Lübecker Bucht. Hier wurden die beiden Munitionsversenkungsgebiete Pelzerhaken und Haffkrug kartiert und mehrere tausend munitionsähnliche Objekte identifiziert. Kistenstapel mit kleinkalibriger Munition, vereinzelte Torpedos, verstreute Bomblets von Streubomben, aber auch Flächen mit Wasser- oder Fliegerbomben wurden identifiziert. Der kombinierte Ansatz von Standardmethoden und robotischen Systemen wie AUVs ermöglichte einen detaillierten Einblick und Abschätzung des Problems. Vergangene und laufende Forschungsprojekte und die durch diese Projekte ausgelöste Öffentlichkeitsarbeit veranlassten die deutsche Regierung, ein »Sofortprogramm« zu starten, um verschiedene Räumtechnologien erstmals in Munitionsversenkungsgebieten zu testen und Vernichtungsmöglichkeiten zu entwickeln, die eine industrielle Hochskalierung erlauben.

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Introduction

Munition in the sea

Below the surface of the German North Sea and Baltic Sea still rest tons of unexploded ordnance (UXO) that were deployed during war activities and a much higher amount of discarded munition material. Dumped munition was originally produced for combat but was not used by the end of the war. As drastic solution to demilitarise Nazi-Germany the Allies decided quickly after the war that unused munition should also be dumped in dedicated dump sites at sea. Such dumping was long regarded as a good method for the disposal of commercial, industrial and military waste. Following the motto »out of sight, out of mind«, dumping at sea was one of the main methods of disposing of old, unwanted or hazardous munition. This was particularly true in Europe after WW I and WW II, when demilitarisation required a quick, inexpensive and safe disposal of stored munition including chemical warfare agents (CWA). Although rather detailed records of the dumping activities were kept, much of this information is still not analysed in depth and is buried in kilometres of files in military archives in e.g. Germany (Federal

Archives in Freiburg) or the UK (National Archives in Kew). Most munition dumping activities at sea took place shortly after the end of WW II, but continued worldwide until the Oslo and London Conventions on the Prevention of Marine Pollution came into force in 1972 and stopped dumping of CWA and only 1996 dumping was generally forbidden. In Germany, dumping ended by 1949.

Already in June 1945, the Allies had selected a number of sites for munition dumping, usually near major coastal munition depots and good infrastructure with harbours and train connection as in Wilhelmshaven, Bremerhaven, Kiel and Lübeck. Areas were indicated by a number of coordinates forming triangles (e.g. Flensburg Triangle offshore Falshöft), rectangles or other shapes (Fig. 1). In the pre-satellite navigation era it was difficult to determine the exact position at sea, with the result that actual dumping locations did not always match the intended dumping area. The motivation to speed up the dumping, e.g. through captains who were paid per load, led to munition also being thrown overboard on the way to and from the official dump sites. This created trails of »en-route« dumped munition on the seafloor. The dumping itself was carried out by military and civilian personnel, the latter also being professional fishermen. The munition was often thrown overboard individually by hand while the ship was kept stationary or was drifting slowly. In other cases, it was loaded into hopper barges that released the entire load by opening doors in the ship's hull, leaving dense piles of munition on the seafloor.

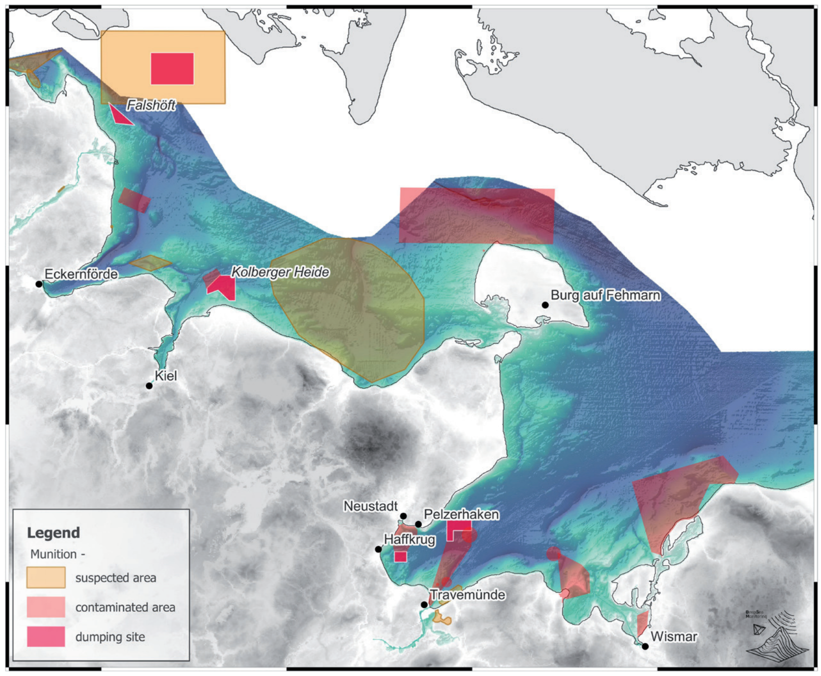

Fig. 1: Map of the south-western Baltic Sea with marked munition suspected, contaminated and dump sites

Munition in the German Baltic Sea

The total amount of munition lying on and in the German seafloor remains an open question. Based on archive investigations, the report by Böttcher et al. (2011) gives a total amount of 1.6 million tonnes in German water, 300,000 tonnes of which were potentially dumped in the German Baltic Sea. These numbers are based on a report by Kulturtechnik GmbH (1990) which give a number ranging from 750,000 tonnes to 1.5 million tonnes; unfortunately, this report is no longer accessible. Rapsch and Fischer (2000) cite the same report and mention that the numbers originate from British sources. To further complicate the generation of a reliable number for munition in German waters, recovery of sea-dumped munition for metal salvage was an active business into the 1950s. Particularly in the North Sea close to Wilhelmshaven, the company Kaus & Steinhausen KG recovered munition until large parts of the disposal site in Wilhelmshaven exploded and safety regulations were tightened considerably (Rapsch and Fischer 2000). Salvaging of dumped munition also took place in the Baltic Sea (Nehring 2009), but to a lesser degree in comparison with the North Sea (e.g. 5,000 tons were cleared from dump site Kolberger Heide by 1953; HELCOM 2024). Today, the balance between what was originally dumped and what was recovered afterwards is not well documented and respective data are not easily accessible. This leaves a large uncertainty on the number of 1.3 million tonnes for the German North Sea and 300,000 tonnes for the German Baltic Sea. Nevertheless, considerable amounts remain on the seafloor, as is shown below.

Next to studying archives and historic reports, detecting, identifying and quantifying the amount and type of munition in the field follow typical UXO survey approaches including multibeam echo sounder, side-scan sonar, sub-bottom surveys, magnetic measurements and visual inspections. Additional methodologies, such as synthetic aperture sonar (SAS), AUV-based magnetic or photogrammetric reconstructions of image and video data become more common and are continuously integrated into existing workflows and approaches. To account for most of the munition, it seems reasonable to start the inventory in dedicated munition dump sites. In the German Baltic Sea, four of those sites are expected to hold most of the munition, or at least have the highest density. These are the dump sites Falshöft, Kolberger Heide, Haffkrug and Pelzerhaken. This paper will focus on Haffkrug and Pelzerhaken, which are two dump sites in the south-western Lübeck Bay with water depths ranging from 12 m to 25 m (Fig. 1). They are to our current knowledge the most contaminated areas. First, dumping of 50,000 tonnes of munition took place in Pelzerhaken, until add-

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ing further material was considered too hazardous. Subsequently, the second area Haffkrug was used. Based on historical records 15,000 tonnes are supposed to be still on and in the ground. In addition to the dumping it should be noted that Lübeck was bombed during WW II, so that unexploded bombs may be present in Lübeck Bay as well. Further, a torpedo research facility existed in Travemünde (HELCOM 2024) and a pilot school was operated in Großenbrode (Böttcher et al. 2011) meaning that practice and live torpedoes could exist in the greater area. Reports according to which CWAs were dumped in Lübeck Bay (Nehring 2009) could never be substantiated. Similar to other areas, munition in Lübeck Bay was salvaged to obtain the valuable materials of the casing. Reportedly, large amounts of munition were cleared in the years from 1953 to 1955 by the private company Eisen und Metall AG. An accident ended further private salvaging activities. They were however continued for another year by the state EOD squad (Böttcher et al. 2011).

As part of a number of research projects, mapping of the dump sites was essential to relate water column chemical analyses with local contamination hotspots on the seafloor. Several studies have shown the accumulation of munition compounds in marine fauna and describe its toxicity (e.g. Appel et al. 2018; Beck et al. 2022). Luckily, concentrations in the environment and in seafood are still low and do not require immediate action. However, ongoing corrosion causes munition objects to leak toxic contaminants, and seafood, such as mussels, placed and collected directly next to chunks of open explosive material (< 2 m) are not fit for consumption anymore. In the following, we report on findings from research cruises with RV *Poseidon* and RV *Alkor* between 2018 and 2024.

Methods for mapping and identification

Several methods exist to map the seafloor for detecting and classifying targets into biogenic, geogenic or anthropogenic objects, and finally identifying them as munition objects of a certain type. Typically, common hydrographic methods (multibeam echo sounder – MBES, side-scan sonar – SSS) and more specific methods for UXO surveying (magnetic gradiometer, ROV and diver inspection) or dedicated military mine counter-measures have been applied. Methods including AUV-based magnetic and photogrammetric reconstructions were applied in Lübeck Bay to verify and elucidate the state of munition inside and outside (!) of the munition dump sites. For effective high-resolution mapping of larger areas, a workflow combining ship-based spatial MBES mapping with detailed AUV-based optical, magnetic and SSS mapping was used. These methods, although very different in resolution and acquisition time, offer a comprehensive approach when used jointly for classification and identification purposes.

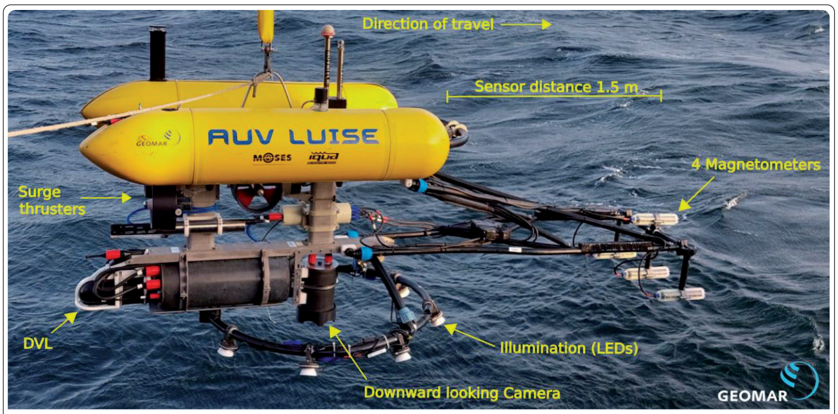

Fig. 2: One of the used Girona 500 AUVs with a downward looking camera and magnetic sensor in front of the AUV (magnetic data are not shown here)

Hydroacoustic mapping

During surveys in Lübeck Bay, a 400-800 kHz T50 and T51 MBES from Reson (0.5° by 0.5° beam opening angle) was mounted in the vessel's moonpool in combination with RTK-supported GNSS navigation (accuracy about ±0.03 m). This high navigational accuracy prevents double detection of objects, as may happen with towed systems and simultaneously allows monitoring object migration. Survey lines were run with 50 % to 100 % overlap. The cell size of the final data products was set to 0.25 m. Over the years and during numerous cruises we completely mapped both munition dump sites in Lübeck Bay covering almost 70 km² in total. Data processing followed the common workflow steps of sensor calibration, sound velocity correction, manual editing and final gridding. The Qimera 2.6.2 (QPS) was used for this purpose. Additional higher resolution acoustic mapping was achieved with two types of SSS. We used a towed EdgeTech 4200 side-scan sonar (tow altitude about 10 m above the seabed), the SSS of a Remus 100 AUV from the German Navy and a Marine Sonic Arc Scout MKII side-scan sonar (900 kHz and 1800 kHz) as part of Geomars Girona AUV (Fig. 2). Using AUVs prevents varying altitude and reduces geo-positioning problems that are common when deploying towed systems. Gradual drifts of the AUV position over time can be compensated during postprocessing. The resulting sonar images provide information about sedimentological changes but also reveal small objects that were not detected in MBES data, e.g. single munition boxes of 40 cm × 40 cm partially sunk into the sediment. SSS data were processed with SonarWiz 7.09.02 applying simple slant range (Auto TVG) and pitch corrections as well as destripe filtering. Manual geo-referencing of generated SSS mosaics was done on basis of previously recorded MBES data.

Fig. 3: Screenshot of the ValidITy software showing munition piles and single objects in Pelzerhaken. The integrated study of several map views in parallel and the very fast computation of derivatives and interactive changes (e.g. radii of the TPI or openness calculation) as well as the auto-aim option for annotation of single targets support easier and faster annotation

Software-supported annotation

Kampmeier et al. (2020) suggests that high-frequency MBESs are a cost- and time-efficient solution for munition monitoring, although their detection capabilities are restricted by data resolution. To detect potential munition targets, bathymetric derivatives (bathymetric positioning index, roughness, openness, real surface area, curvature, etc.) and backscatter analysis can help the manual annotation process by highlighting certain features for close inspection in follow-up investigations. Careful tuning of the derivative representation (colour palette adjustment, semi-transparency with hillshade greyscale image in the back …) support the subsequent annotation.

At Geomar, we are currently developing the ValidITy software to support the process of annotating munition objects and other features in MBES data. The software enables fast derivative processing, user friendly annotation with auto-centre options, export possibilities for annotations and derivative grids, as well as AI training and inference. A typical complaint of data analysts is that recomputing derivatives for each map pixel (i.e. cell in an MBES bathymetry grid) over large surrounding regions can take a long time if done with traditional algorithms and hardware. This is alleviated in ValidITy by harnessing GPU-compute that enables multiple pixels to be computed in parallel, using hardware that is optimised towards image-processing operations. Since this process is much faster, users can interactively modify parameters of geomorphological derivatives, such as the inner and outer radii of the bathymetric positioning index (BPI) and see changes in real time. Another advantage is that the derivatives are only computed on-demand for the region that is currently viewed in the software, meaning that annotation can start before the complete derivative grid is being calculated. Typically, data analysts annotate points which only give information about the occurrence of certain objects in a region. They do not convey information on the area or shape of those objects. Features were built into the ValidITy software that make it easy to mark bounding boxes or even polygons with relatively few interactions. In addition, AI support is given through an implemented You-Only-Look-Once image detection algorithm. Training happens on local computers and is even possible on lower-powered devices like laptops. Only annotations of a sub-set of the entire area are used for training (Fig. 3), and the generated model can be applied to the rest of the area. Continuously training a model improves it and may allow transferring it to other, very different data sets.

As a final step, ValidITy allows experts to review annotations. The software streamlines this process by zooming to each annotated structure and giving the reviewer the opportunity to record a binary accept/reject decision which can be exported and used to generate reports merging different data sets (MBES bathymetry, MBES backscatter, SSS) for each accepted target/object.

Visual investigations

The ultimate identification of munition objects occurs through visual observations with towed camera systems, remotely operated vehicles (ROVs), or imaging systems on an AUV. The quality of the footage depends on good underwater visibility,

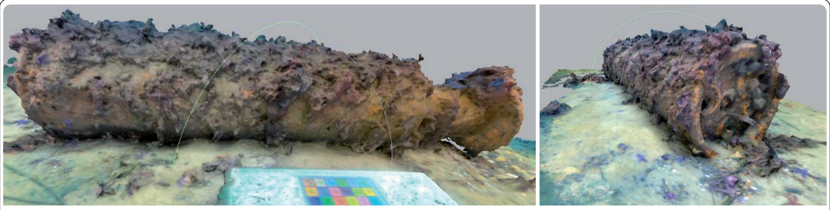

Fig. 4: 3D photogrammetric reconstruction of a sea mine in Kolberger Heide. Web applications even allow to investigate such objects online

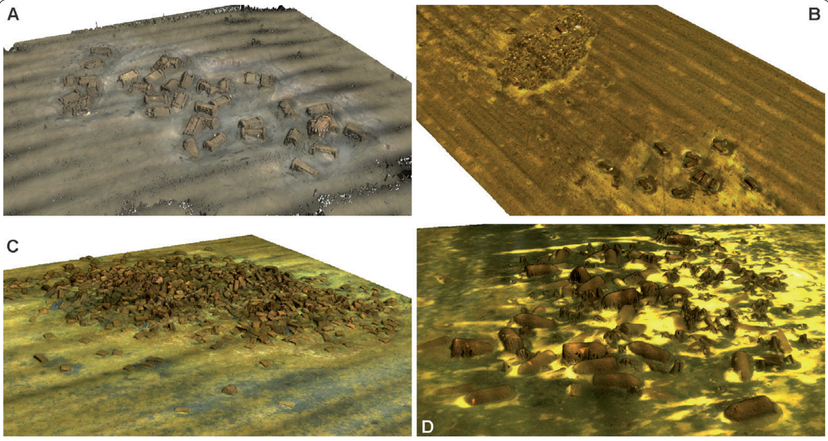

Fig. 5: A: Different munition piles in Lübeck Bay composed of large objects in wooden frames with round ends for an easier transport by rolling (most likely depth charges). B: A pile of boxes with small and medium size calibre grenades next to other large objects. C: Another box pile showing the vertical height difference. D: Scattered torpedo heads and bombs

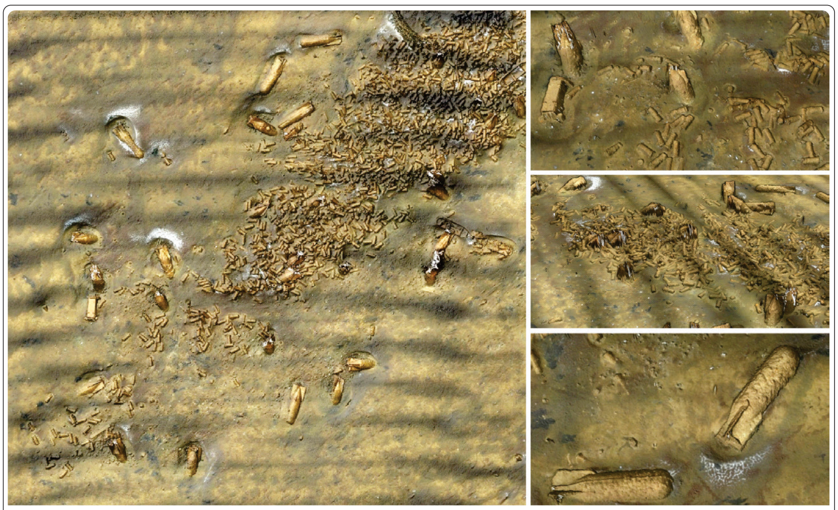

Fig. 6: Another munition pile composed of cluster bomblets and deployment containers. The entire area covered by bomblets is 65 m by 10 m in size with additional large objects scattered around it

which ranged during our investigations from 4 m to 1.5 m. Only once (October 2021; cruise AL567) did we have bad visibility close the seafloor caused by a strong pycnocline that kept turbid water close to the bottom and particles in suspension.

Very good results were achieved with AUV-derived images that were merged in a photogrammetric workflow to derive digital terrain models (DTMs) and photo-orthomosaics in millimetre resolution. For this purpose, a Girona 500 AUV (Fig. 2) was equipped with a downward-looking camera system developed at Geomar (CoraMo MkII). The 12.34 MP camera is held in a pressure housing behind a dome port, which in contrast to a flat port does not introduce additional refractions at the glass-water interface (exact calibration provided; see She et al. 2022). In daytime, surface light can be sufficient to illuminate the sea floor for ROV operations in shallow water environments. During AUV surveys a flash system of circular arranged LEDs around the camera was used. The chosen arrangement reduces light scattering from floating particles (wider distance between camera axis and light source) and illuminates the seafloor homogenously without direction-related shadows. Surveys are conducted in a predefined lawnmower pattern with a linespacing of 1 m and an altitude of about 1.2 m. With a velocity of about 0.4 m/s and an image interval of 1 Hz we achieved 100 % overlap across track lines (each spot on the seafloor is seen in two lines). Along track the image overlap is higher (about 450 %). To reduce navigational errors during the imaging processing, cross lines were added at the beginning or end of the survey in an orthogonal direction.

During acquisition all images are georeferenced which can be considered but is not necessary for the photogrammetric reconstruction that we performed with the Agisoft Metashape (1.8.3) software. The relative orientation between camera positions of neighbouring images is calculated by detecting and matching key features. The key feature position can be projected into 3D space and form a sparse point cloud. By additionally projecting other matching image pixels, a dense point cloud is generated which is the basis for a digital elevation model (DEM) with millimetre resolution. The merged image, composed of several thousands of images, is projected on top of the DTM terrain and an artificial photo-orthomosaic can be generated that shows several hundreds of square metres in one image. Similarly, video footage from ROVs can be used to also generate photogrammetric DTMs. Colour-coding the resulting mesh-grid with representative pixels from the images gives a good 3D representation of specific objects that can be manipulated and viewed in 3D representing software tools (Fig. 4), and supports the decision process on how to proceed with removing the respective object.

One of those tools is the Digital Earth Viewer software developed at Geomar, which can be used to view 4D data (i.e. 3D data and temporal information) in a geospatial and temporal context (Fig. 5). The 2D surface of the photo-orthomosaic is deformed according to the height information stored in the DTM. The result is then displayed using WebGL functionality in a common web browser and can be rotated, moved, lit and exaggerated according to the user's wishes. Temporal information, such as the position of survey vehicles over time can be loaded and shown in concert with static or other temporal data sets. The Digital Earth Viewer reads common formats as CSV or GEO-TIFF to enable a quick display and 3D exploration (Fig. 5 and Fig. 6) and allows easy manipulation of data that are often only explored in 2D.

Lübeck Bay – munition encounters

During our studies, the entire areas of the Haffkrug and Pelzerhaken dump sites in Lübeck Bay were mapped by MBES and the resulting bathymetric grids where used for further analyses (Pelzerhaken 45.3 km²; Haffkrug 23.2 km²; Fig. 7). Through successive and (initially) manual annotations, several thousand potential munition locations were identified, and many subsequently verified by photo or video. These findings were used to evaluate the impact of conventional munition on the environment with particular focus on the release of toxic substances. They were also used to establish differences in fauna composition around munition hotspots/piles of munition and entire dump site areas in comparison to non-contaminated locations and regions.

Although the size of the grid cells does not allow detailed identification of munition objects, the arrangement on the seabed and sedimentary features such as scours allow recognition of anthropogenic objects. In Pelzerhaken, so far, 431 munition piles (defined as areas larger than 20 m²) and 2115 individual targets have been identified using the MBES data set. Of these 2546 targets, 488 are outside of the demarcated dump site (19.2 %). Only 70 targets (piles and individual objects) have been verified so far (2.7 %). For visualisation purposes during target annotation, the hillshade derivative of the bathymetry was predominantly used (Fig. 8).

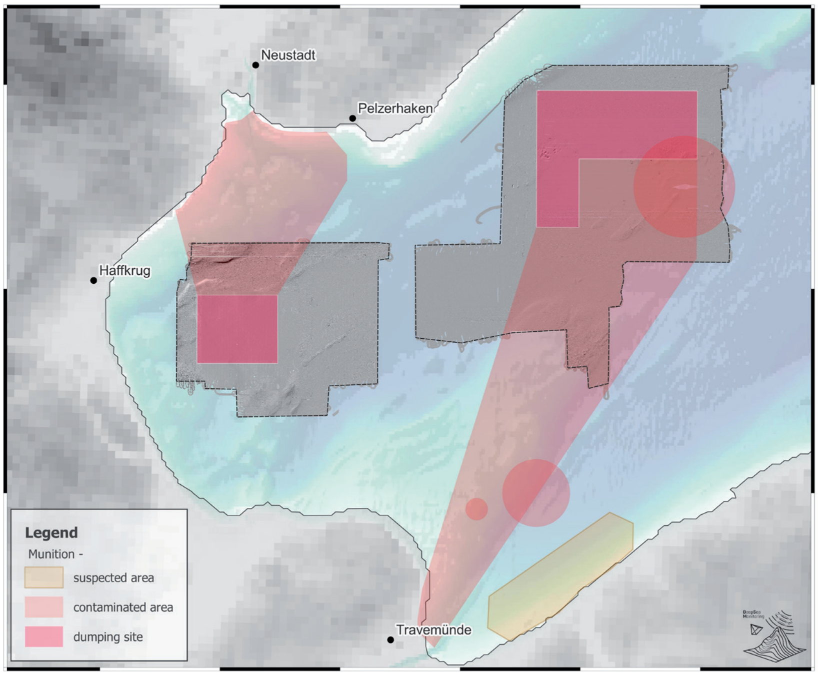

Fig. 7: Overview of the acquired MBES data in Lübeck Bay covering the munition dump sites in offshore Haffkrug (west) and Pelzerhaken (east)

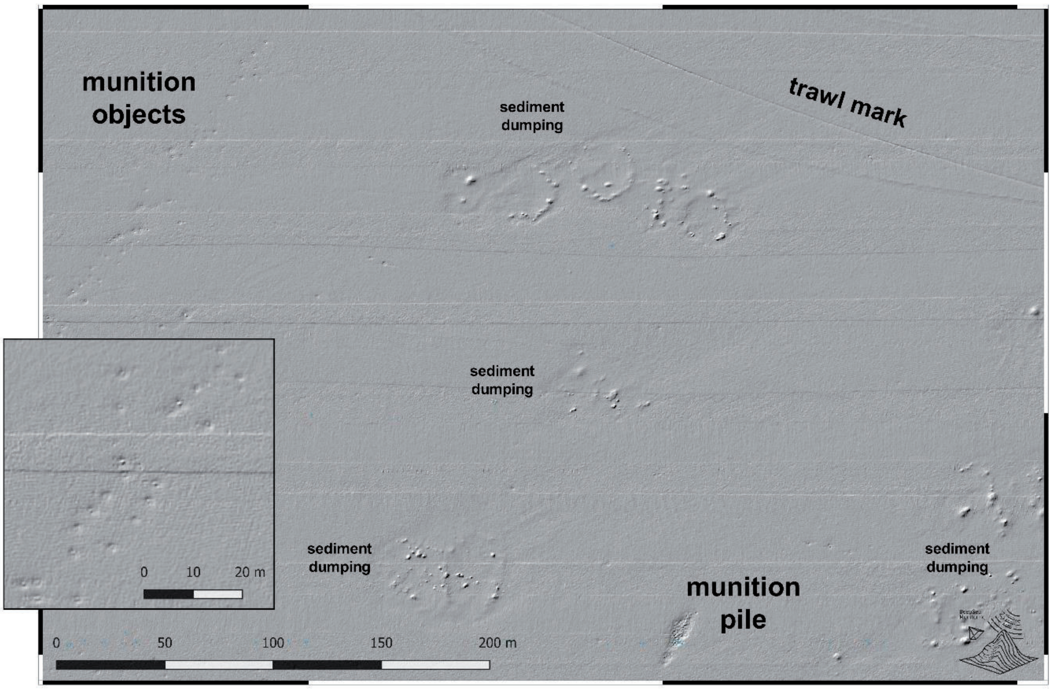

Fig. 8: Example of an area in the Pelzerhaken dump site with sediment dumping locations (circular features), one munition pile creating a small depression, single munition objects with scours and trawl marks. Horizontal lines are caused by minor Z-axis offsets of the neighbouring MBES survey lines despite RTK navigation. Shown is the hillshade of the bathymetry illuminated from the top left

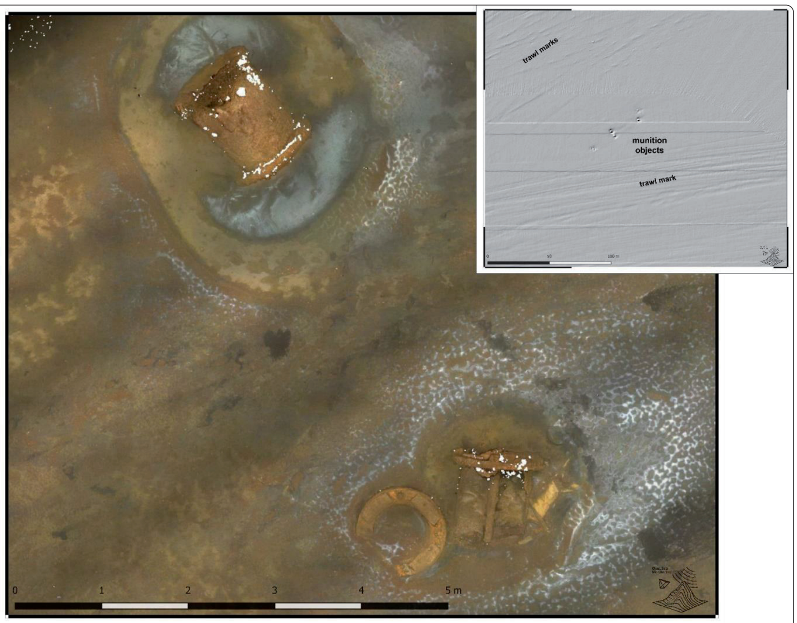

Fig. 9: Example from a number of larger barrel-type objects (depth charges?) between trawl marks outside the munition dump site. Fishermen seem to know exactly where these obstacles exist and avoid them. An alternative explanation could be that the trawl marks are old and are the remnants of munition trawling in the past that missed the observed five objects

In Haffkrug, 245 of 608 targets have been validated (ca. 40 %), and almost all are munition objects. A substantial number of targets is not located in the officially labelled munition dump site, but outside. As in Pelzerhaken, single objects (often boxes) and piles of homogeneous and diverse munition exist in Haffkrug as well. Torpedoes are also typical for Haffkrug, but are not as common in Pelzerhaken. Both mapped areas have natural and anthropogenic features on the seafloor, ranging from glacial ridges and bolder areas to trawl and anchor marks, in addition to munitions as single objects, arranged in lines or in piles.

Single morphologically expressed objects can be detected much more easily in the soft sediments of central Lübeck Bay and the pattern of several objects on the seafloor often helps identify non-natural features. En-route dumping outside the dedicated dump site is more common in Pelzerhaken, with the clear indication that ships left port in Travemünde and started dumping long before reaching the actual dump site. In Haffkrug, it seems that one of the borders of the dump site was missed repeatedly by a few tens to hundred metres. Munition piles were found in both areas, but show a different appearance. In Pelzerhaken, piles are typically surrounded by scour structure and are partially buried (Fig. 9). AUV-based SSS data highlight single boxes, which can be inferred in the hillshade of the bathymetry as well (Fig. 10).

Monitoring marine munition dump sites with optical methods also allows witnessing the dissolution of explosive materials into the water. One of the sites with open explosives consists of a number of barrel-type objects that might be explosive charges of V1-warheads (Fig. 11). One of these objects is strongly corroded and its explosive material is directly exposed to the surrounding water. Between October 2023 and June 2024, the same object was visually inspected four times and a clear degradation of the explosive material could be documented (Fig. 11).

Past, ongoing and starting projects

Although the topic of marine munition has been known since dumping started, little has been done to monitor or further investigate potential environmental contamination. Authorities assumed that munition is safe and will not cause adverse environmental impacts. It was also true until the late 1970s, and subsequently assumed, that necessary technologies for monitoring and clearance do not exist. Around 2010, the first research projects were initiated (MERCW, CHEMSEA, MODUM) that focused on chemical weapons in the sea. After 2015, a number of additional research projects started (UDEMM, BASTA, ExPloTect, ProBaNNt, CONMAR) with the aim of evaluating the environmental impact of conventional marine munition, and to develop and advance technology for monitoring underwater munitions. These projects focused on

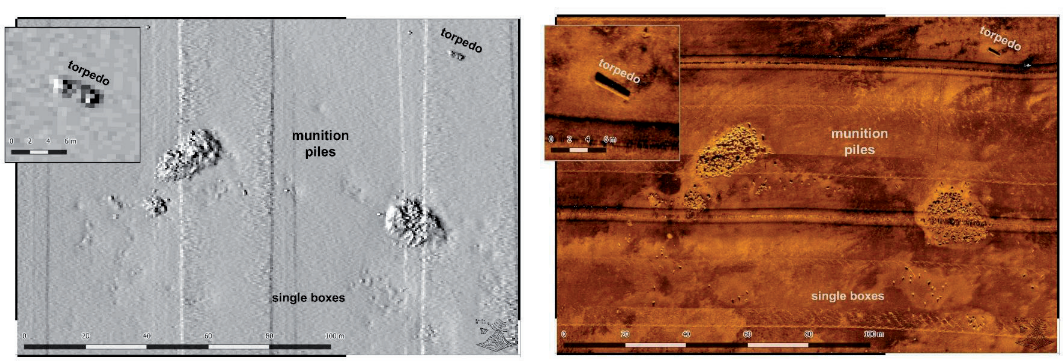

Fig. 10: Bathymetric hillshade of MBES and AUV-based SSS data of two munition piles, scattered small boxes and one torpedo in Haffkrug. The resolution of the bathymetric grid here is only 50 cm. Bathymetric data help to accurately georeference the SSS images

the release of toxic substances from explosive material (e.g. TNT, DNB or RDX), but also pursued technical developments with regards to robotic applications and decision-making (DAIMON I and II). Results from these and other studies focusing on wrecks (North Sea Wrecks, REMARCO) have triggered action on state and federal levels in Germany. Authorities now see the need to increase activities to develop and test technical approaches to recover and dispose of large amounts of munition from the sea in an environmentally friendly and efficient way (safe and fast at low cost).

In late 2022, the German BMUV (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection) initiated the »Immediate Program for Munition Remediation« (Sofortprogramm Munitionsbergung) with a total budget of 100 Million EUR. It is directed towards testing recovery technologies and developing industrial scale disposal capacities for conventional munition at sea. The programme follows an approach with four separate modules that consists of A) munition detection and identification, B) removal and/or wet (underwater) storage of munition, C) munition preparation for disposal and D) final disposal and thermal treatment (BMUV/seascape GmbH). Results from scientific projects that are the basis of the current publication were used to identify sites (munition piles) that are well suited for testing removal technologies and strategies during the first pilot phase of the Sofortprogramm (Sichermann et al. 2024). In summer and autumn of 2024, a total of six munition piles from the two dump sites in Lübeck Bay will be cleared with different removal technologies. The completion of a platform-style disposal facility is planned for end of 2026. Hopefully in 2027, enough data and experience will have been gathered to allow a thorough evaluation of the feasibility and financial implications of clearing more munition from German marine waters on an industrial scale. //

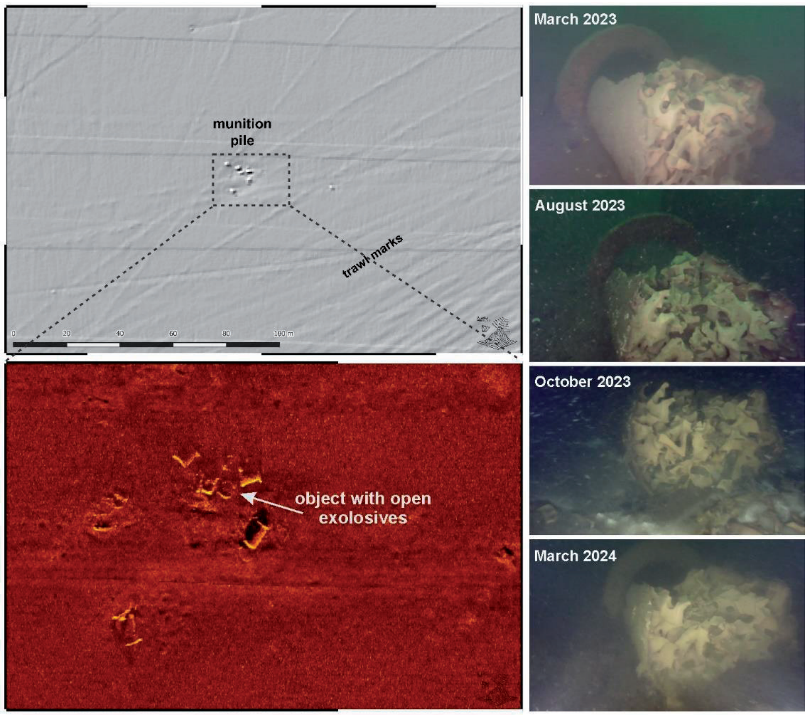

Fig. 11: Area with six similar objects, of which one has solid explosives exposed to the water column. Repeated observations with an ROV show the successive dissolution of the explosives with typical dissolution features and breaking off of small structures

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