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Toward monitoring and estimating the size of the HFO-contaminated seabed around a shipwreck using MBES backscatter data

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ABSTRACT

Despite a progressive reduction of oil spills caused by the activity of maritime transportation, the latent sources of pollution still exist. Although the harmful impact of heavy fuel oil (HFO) on the marine environment is widely known, many shipwrecks cause contamination of the surrounding areas. In this paper, an approach to monitor the area of the HFO spill around a shipwreck is made using a bottom backscattering strength (BBS) obtained by a multibeam echosounder (MBES). As a case study, the s/s Stuttgart wreck located in the Gulf of Gdansk (Poland) is verified. Two different measurement campaigns have been carried out in shallow waters using low (190 kHz) and high (420 kHz) MBES frequency. The results indicate that the polluted area around s/s Stuttgart was estimated at 49.1 ha, which is around 18.3% more in comparison to the geological surveys made four years earlier.

1. Introduction

For decades oil spills caused by human activity in the maritime industry have been one of the biggest threats to the marine ecosystem. Their damaging impact is very extensive and it is not only limited to the deficiency of the biodiversity in the region of an accident. Besides their direct and indirect harmful influence on wildlife (Bejarano and Michel, 2016; Beyer et al., 2016; Perez et al., 2017; Soares et al., 2020), there are also many negative effects concerning human health (Chen et al., 2020; Simon-Friedt et al., 2016), as well as socio-economic (Albert et al., 2018; Cirer-Costa, 2015; Simon-Friedt et al., 2016) impacts on the communities affected. Moreover, the range of pollution often spreads far out of its initial area causing even more ecological losses (Thyng, 2019).

Despite a positive trend related to the reduction of oil spills in maritime transportation (ITOPF Limited, 2020), a significant and latent source of sea pollutants still exists. Meanwhile, the shipwrecks lying on the seafloor from one year to another are increasingly corroded. The chemicals or heavy fuel oil (HFO) not only transported as cargo but also used to propel the ships, are still located in their tanks, and have been sporadically released to the marine environment causing its inevitable pollution (Amir-Heidari et al., 2019; Landquist et al., 2014, 2017). One of the most exposed areas to this kind of danger is the Baltic Sea. It is estimated that the total number of all shipwrecks lying on its bottom may even exceed 100,000 (Balazy et al., 2019). Many of the Baltic wrecks are classified as potentially polluting ones (PPW), as they probably still contain fuel and other environmentally harmful materials inside their tanks. Only in Swedish waters, the total amount of bunker oil residing in the shipwrecks' tanks may vary from 1000 up to 15,000 tons (Hac and Sarna, 2021). Concerning the number of PPW, it can be estimated that such objects in the Baltic Sea may be around 1000 (Hac and Sarna, 2021), or even more, as only a few countries of the Baltic region provide a specific classification of the identified shipwrecks (HELCOM, 2018). Additionally, this value can be much higher, as not all of the detected wrecks have been confirmed in terms of carrying hazardous materials to date.

The Baltic Sea was also one of the main areas of fighting during World War II (WWII). Hence, there are numerous wrecks of ships engaged formerly in military operations (HELCOM, 2018; Rogowska et al., 2015). It is however very difficult to provide their precise number, as new wrecks are still being discovered, even after half a century (Grządziel, 2020). Besides a slow leakage of harmful substances to the marine environment, there may also exist a high risk of their rapid release caused by progressive wrecks corrosion, which could lead to a hull split-off or stability loss in the near future. A prediction of the current state of structural integrity is generally challenging due to many factors influencing the corrosion process (eg. pH, temperature, salinity,

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water depth, etc.) (MacLeod, 2016; North and MacLeod, 1987). Therefore, the presence of oil inside shipwreck tanks also affects this phenomenon and hampers the corrosion activity (Russell and Murphy, 2010; US NPS-SRC, 2008).

Nevertheless, it could be assumed that structures of the Baltic WWII warship wrecks being on the sea bottom for more than 70 years are partly exposed and afflicted by this kind of phenomenon. The flagship examples of the PPW are two German vessels sunk in the Southern Baltic (Gulf of Gdansk, Poland - see Fig. 1). These are the hospital ship Stuttgart (1943) (Rogowska et al., 2010, 2015) and the supply ship Franken (1945) (Hac, 2018b; Zaborska et al., 2019). Both shipwrecks have been recognized as high-priority objects (Hac, 2018a; HELCOM, 2015), as they contain a large amount of oil residing in the tanks (approx. up to 500 m^3 in case of m/v Franken) (Hac, 2018b) or have already heavily polluted the surrounding area (approx. up to 800 tons of HFO has leaked in case of s/s Stuttgart) (Hac and Sarna, 2021).

The nature and location of the Baltic Sea, as well as the positions of the aforementioned shipwrecks (near the Tricity metropolitan area) also favor the adverse effects of the potential oil spill. As the Baltic is an inland sea, the distance to the shoreline is relatively small, while the seawater circulation with open ocean waters is very limited because of Danish straits. Thus, a potential oil spill can cause a disaster for the ecosystems of the coastal countries. Therefore, a constant monitoring of potentially polluting shipwrecks located in this region, as well as effective estimation of the current oil pollution size are crucial for the decision-makers concerning e.g. wreck removal operations.

There are numerous detection methods of sunken oil differing in their efficiency, time consumption, cost, or limitations (IMO, 2014; Michel, 2008). Among others, visual observations (carried out by divers, *Remotely Operated Vehicles (ROVs)*, or aircrafts), (Michel, 2011); bottom trawling, sampling of sediment cores (Michel, 2008), chemical analysis (mass spectrometry, fluorometry), (Camilli et al., 2009; Fingas and Brown, 2014); as well as utilization of acoustic systems (side-scan sonar, multibeam echosounder), (Fingas and Brown, 2013; Weber et al., 2012) can be distinguished. Amid these, acoustic surveying is considered the most advantageous technique, especially because of its cost-effectiveness and high-coverage capabilities (IMO, 2014; Michel, 2011). In general, it relies on utilizing the backscatter strength of the sound wave (Medialdea et al., 2008). The acoustic response of any object is determined by its physical characteristics. Therefore, the dependencies between bottom backscattering strength (BBS) and seafloor properties have been studied over the past decades (Brown and Blondel, 2009; Tegowski et al., 2018; Trzcinska et al., 2020). It has been proven that the intensity of the signal returning from a seabed is related to the properties of its surface, so it can be used for data (e.g. seabed sediment) classification and segmentation (GeoHab Backscatter Working Group, 2015). Due to the improvement of the multibeam echosounder (MBES) backscatter imagery parameters (Brown and Blondel, 2009), it can be nowadays utilized, for instance, in benthic habitat (Trzcinska et al., 2020) or seafloor mapping (Brown and Blondel, 2009; Janowski et al., 2018). The research also revealed that based on the data collected, it is possible to determine types of sediments, while using the strength of the backscatter, the graininess of the seafloor can be obtained. Afterward, a search for other backscatter applications has been commenced, including the confirmation of the shipwreck location and determination of its shape (Masetti and Calder, 2012). In 2004, the same method was used to detect an oil located on the seabed (Parthiot et al., 2004). One of the first experiments in which patches containing different types of heavy fuel oils were placed on the sandy bottom of a seawater tank is described in Parthiot et al. (2004). Meanwhile, it was confirmed that in laboratory conditions, high-frequency sonar systems, such as side-scan sonar or MBES enable the detection of oils located on the seafloor (Parthiot et al., 2004; Wendelboe et al., 2009). Medialdea et al. in 2008 utilized MBES backscatter in the identification of the heavy oil spill or submerged oil from the tanker *Prestige* wreck that is located in Galicia Bank at an approximate depth of 3700 m. To correlate the intensity of the MBES backscatter with sediment types, as well as their physical properties, the geological samples were collected using a gravity corer (Medialdea et al., 2008). As aforementioned, there are a few studies utilizing MBES backscatter for identification of submerged oil. Nevertheless, the research verifying a usefulness of this method in shallow waters, as well as using various frequencies of the MBES in real conditions, is still missing.

Therefore, to bridge this gap, the scope of this paper is threefold. Firstly, it is an elaboration on a potential application of the MBES BBS as a method of periodic monitoring of an oil spill from a shipwreck. Secondly, it is a comparative analysis and verification of the MBES frequencies utilized for submerged HFO monitoring in shallow waters. Finally, it is a determination of a current contamination area, as well as an estimation of its spreading caused by the leakage from s/s Stuttgart shipwreck selected as a case study.

Fig. 1. The location of the Stuttgart and Franken shipwrecks in the Gulf of Gdansk.

2. Methods and materials

2.1. Hydrographic background

Bathymetric measurements dominate among hydrographic surveys. The main device used for that purpose is a multibeam echosounder, as it enables high accuracy visualization of the seabed. It is a type of sonar system that transmits an acoustic signal at a known time with specific characteristics, i.e., one that is narrow along the track and broad across it (IHO, 2005). As the impulse reaches the seabed, it creates an echo that returns through the water column to the MBES receiver. The echosounder measures two main values, which are used for further computations (GeoHab Backscatter Working Group, 2015; Tegowski et al., 2018). The first is the time of delay T between transmission and reception of the signal. The result of the calculations is a dense point cloud that can be depicted as a bathymetric map, which is made with respect to the ensonified areas of a seabed called *footprints* (IHO, 2005). The second value measured by MBES is the strength of the signal received, which provides basic information about the seafloor nature (GeoHab Backscatter Working Group, 2015). It might be indicated intuitively that soft seafloor sediments cause a lower intensity of the returned echo than the hard ones. However, the characteristics of the seabed based on the reflected signal strength are more complex. Therefore, it requires more additional information to be taken into account, among others (GeoHab Backscatter Working Group, 2015):

- initial acoustic wave characteristics (frequency, signal energy, etc.);
- transmission loss caused by spreading and absorption;
- the fluctuation of the signal and noise caused by other sound sources;
- water column characteristics – salinity, temperature, turbidity, etc.;
- target strength – the parameter describing the dependency between the intensity of the sound wave when reaching the target and the scattered intensity;
- incidence angle and roughness of the seafloor.

Signal reflects or scatters after reaching the seafloor, experiencing the same losses resulting from spreading and absorption as the transmitted signal. Assuming a perfectly smooth surface, the reflected signal would be a copy of the incident wave, except for the signal losses. However, because of the seabed roughness, the wave is scattered around the surface, which also produces backscatter as shown in Fig. 2. The strength and direction depend on the roughness characteristics, i.e., for its high irregularity, the intensity of the wave is scattered in all directions. Contrary, for smoother surfaces, most of the scattered wave is concentrated in one direction.

The backscatter strength received by the MBES after signal reflection is usually much lower than the wave intensity directly sent to the seafloor. Nevertheless, the generated echo is still measurable and can be then analyzed. However, the same values of received intensity may be a result of different operational and environmental factors. Thus, BBS cannot be the sole source of information.

For this reason, various methods including geological ones are involved for backscattering data complement. So far, side-scan sonar data were utilized for the determination of the location of future geological samples. Their aim was to classify the types of sediments that were specified on a sonar image. Today's backscatter data can be adapted in the same way as side-scan sonar data, which allows for survey optimization.

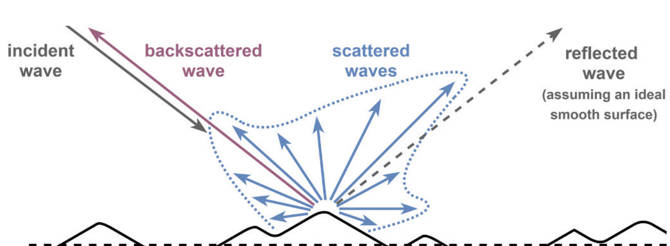

Fig. 2. The principle of the acoustic wave (back)scattering phenomenon. Adapted from GeoHab Backscatter Working Group (2015).

In terms of HFO detection, the previous studies carried out in lab or real conditions proved that BBS can be a useful tool for the characteristics of sediments determination (Medialdea et al., 2008; Tegowski et al., 2018; Trzcinska et al., 2020). It was assumed that the presence of the HFO will change seabed characteristics, hence also its acoustic response. In order to verify if the difference in signal strength is sufficiently meaningful, it was decided to perform a survey using a known shipwreck and survey site as a case study. This allows some crucial pieces of information to be used (e.g. level of the area contamination), which were obtained from previous research by other methods like geological sampling.

2.2. Materials and resources

For the purpose of this paper, analysis of the surface sediments was taken as reference data from the report of the *Maritime Institute in Gdansk* (MIG), which was prepared in 2016 for the *Ministry of Environment of Poland* (Maritime Institute in Gdansk, 2016). The probes were collected by Van Veen grab (surface sampling) and vibrocorer (core sampling). The main objective of this research was to assess the current environmental impact of the s/s Stuttgart shipwreck, as well as verify the prospective possibilities of hull removal. Therein, information about geological samples of the sediments obtained in 2016, which were presented in the abovementioned report, has been utilized. Geological, biological, and chemical analyses were performed after sampling. During chemical analysis calcination loss, the concentration of petroleum hydrocarbons, and polycyclic aromatic hydrocarbons (PAHs) were determined (Maritime Institute in Gdansk, 2016). The interpolation of the calcination loss values complied with the classification of the seabed surface was made during conducted observations and sampling (Maritime Institute in Gdansk, 2016). The content of compounds from the PAHs detected during the abovementioned analysis indicated considerable contamination of the area. Moreover, previous chemical analysis conducted by other researchers revealed the occurrence of several heavy metals in the vicinity of s/s Stuttgart shipwreck (Rogowska et al., 2015).

Herein, the MIG report (Maritime Institute in Gdansk, 2016) served as a reference for an analysis of the backscatter data gathered during a hydrographic survey made in 2020. To achieve this, the BBS values have been linked to the locations of the clean and oiled samples, which were evaluated organoleptically and classified during the geological surveys in 2016. Based on this collation, specific ranges of the backscatter strength were determined for the contaminated seabed. The map with the locations of the sediment samples from 2016 is presented in Fig. 3.

2.3. Study site and technical equipment

The study site of the hydrographic survey was located in the Gulf of Gdansk, approximately 2.5 NM from the approach fairway to the port of Gdynia. The wreck of *s/s Stuttgart* lies at an estimated depth of 22 m in the position $\phi = 54^\circ\ 33'\ 33.11''$ N, $\lambda = 018^\circ\ 37'\ 0.54''$ E. In 2016, it was assessed after conducting geophysical and geological surveys (including shallow marine seismic surveys) that the area contaminated by the HFO was around 41.5 ha (Maritime Institute in Gdansk, 2016). In this paper, the entire survey area is approximately 260 ha. Its main part is situated northeast of *s/s Stuttgart* where moraine with sandy banks is located. Its ridges are situated obliquely to the shore and thereby forming in the central part a valley between them (Fig. 4). It is assumed that the topography of the Gulf of Gdansk has a major impact on the direction of the HFO spreading. In terms of water flow at bottom layers, the environment is rather stable, so the impact of water mass movement on the spread's direction is rather negligible (Hac, 2018b; Maritime Institute in Gdansk, 2016).

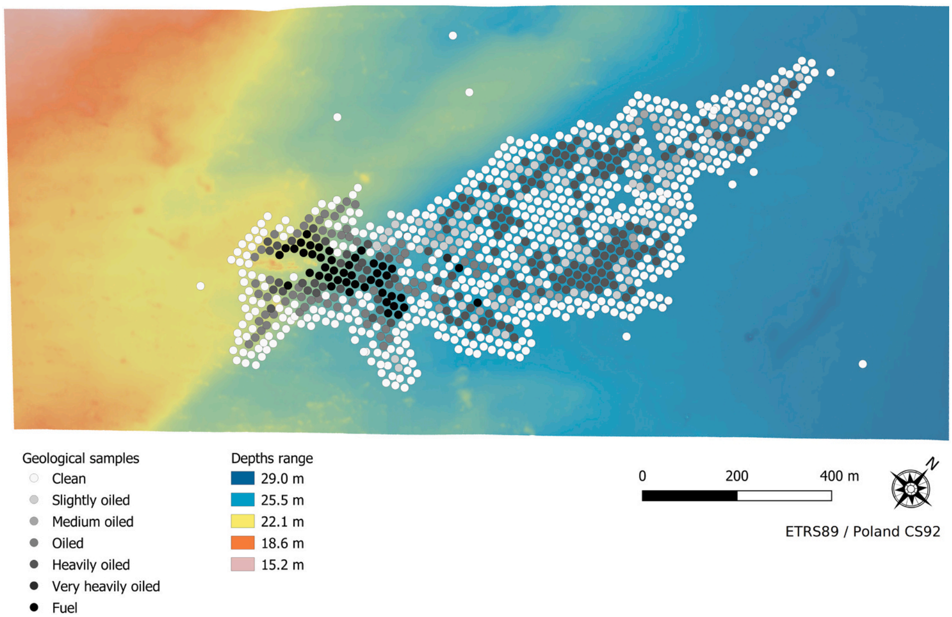

Fig. 3. The map of the sediment samples in the vicinity of s/s Stuttgart. Adapted from Maritime Institute in Gdansk (2016).

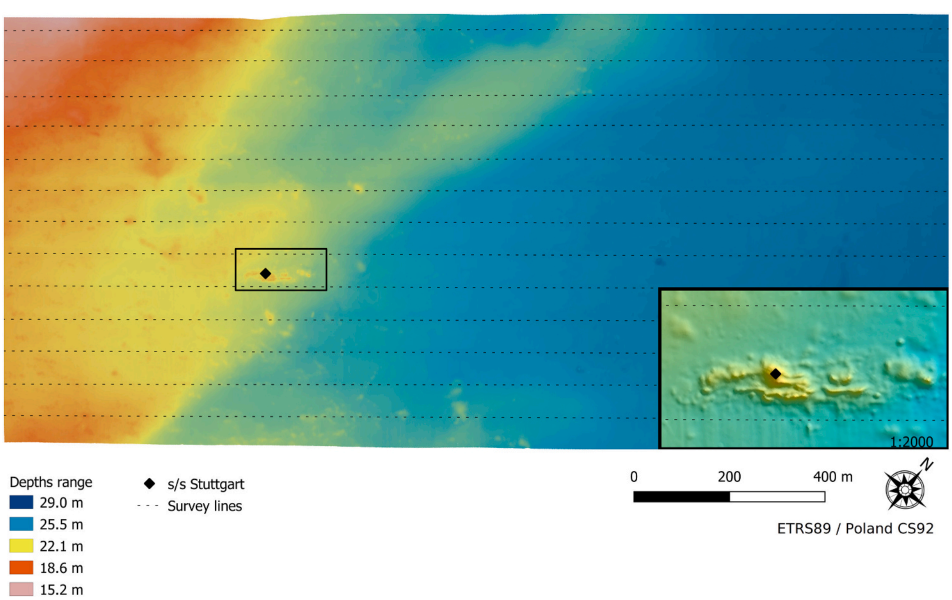

Fig. 4. Bathymetric map with the survey lines used during the second measurement campaign.

Due to the need of verifying the influence of the MBES frequency on submerged oil detection in shallow waters, two independent measurement campaigns have been conducted. During the first one, a total of 11 survey lines with a length of 1800 m were planned every 70 m and run in both directions. During the second attempt, two additional lines were outlined, so the surveyed areas differ from each other with regard to the size. The survey lines utilized during the 2nd campaign are presented on the bathymetric map in Fig. 4 along with the shipwreck position.

To conduct the survey, the *Reson SeaBat T50* MBES was mounted in the moonpool (special opening in the ship hull that gives access to the water) of the research vessel at a fixed depth of 2 m. This MBES is able to operate at frequencies from 190 kHz to 420 kHz (Teledyne RESON, 2018). The maximum operational depth range is from 250 m to 475 m and depends on the frequency set by the operator. The construction of *SeaBat T50* allows for receiving up to 1024 beams (Teledyne RESON, 2018). The angular coverage of the swath was approximately 120°. The properties of the MBES footprints at 20 m depth are given in Table 1. The accuracy of the positioning systems was up to 0.1 m during the measurements. For planning the surveys, acquisition of the data, as well as post-processing the *QPS Qinsy* software was used.

Table 1
The dimensions of the footprints at 190 kHz and 420 kHz frequencies.

Frequency	190 kHz	420 kHz
Nadir	0.35 m × 0.70 m	0.17 m × 0.35 m
Marginal beam	1.40 m × 1.40 m	0.70 m × 0.70 m

2.4. Data acquisition and processing

The hydrographic surveys were conducted in two separate campaigns in June and August 2020. In the first survey, 190 kHz frequency was applied for data gathering. The second campaign was performed using the 420 kHz frequency for better detection of the seabed structure (Trzcinska et al., 2020). The goal was to verify if there is a difference in data accuracy and its unambiguity between both frequencies (the highest and the lowest ones from available frequencies in the utilized MBES model). Prior to data collection, a sound velocity profile was made and included in the data files.

Additionally, a high-resolution *Digital Terrain Model* (DTM) was created based on the bathymetric data gathered during the second measurement campaign. This has been done to allow later interpretation of the BBS results in comparison to the up-to-date survey site profile. It was necessary as valid bathymetric data are essential for the proper backscatter intensity analysis, thus the oil spill size estimation. They allow for indicating the areas that are naturally protected from the impact of potential contamination because of the sea bottom relief. Therefore, even if the BBS data are ambiguous, DTM allows for excluding the areas that cannot be affected by HFO.

A backscatter normalization process (Wendelboe, 2018) has been automatically applied to each snippet of the record using an algorithm built in the MBES software. The reliability of the gathered backscatter data was assessed based on Gaussian distribution at the 95% confidence level. The data which did not comply with the three-sigma criteria were excluded from the collection. The last stage of backscatter data processing was their interpolation to depict the entire survey area. Finally, the bathymetric data had been processed utilizing cleaning algorithms and refraction corrections.

Despite the best efforts made to plan and conduct the surveys as reliable as possible, as every field study, this also is burdened by some limitations. The main issues identified during the study include i) different sizes of the survey areas in both campaigns; ii) a lack of comparative data from similar studies; iii) geological samples used as reference data that are not up-to-date. All these limitations are discussed in detail in Section 4.2.

3. Results and analysis

As the BBS has been collected in two different measurement campaigns, the results are presented separately with respect to the MBES frequency. Each of the areas has been estimated in terms of their extent and compared with the results of the geological sampling performed in 2016. Finally, potentially HFO-contaminated areas determined using various frequencies have been overlaid and compared with each other.

3.1. Low-frequency campaign (190 kHz)

The area surveyed during the first campaign at low frequency (190 kHz) had approximately 156 ha. The noted MBES backscatter intensity was within the range from −43.53 dB up to −21.96 dB. According to the spatial analysis of the data and structure of the seabed, the area with lower values of the BBS was classified as contaminated. As presented in Fig. 5, where the gridded backscatter data is given, the oil deposition is spreading toward the northeast direction. It is because of the smooth slope located in the vicinity of s/s Stuttgart shipwreck. The estimated area of the oil spill based on the data gathered at 190 kHz frequency is approximately 42.5 ha. Thus, it can be assessed that the contaminated area is larger by about 2.4% compared to the surveys made in 2016 using different methods.

3.2. High-frequency campaign (420 kHz)

In the second campaign, the survey area increased to 184 ha to the north. MBES frequency was changed to 420 kHz to verify the influence of this parameter on the accuracy of the oil detectability in shallow waters. The observed magnitude of the filtered and processed MBES backscatter intensity was within the range from −40.02 dB to −18.56 dB. The gridded backscatter data from August 2020 are presented in Fig. 6. In this campaign, the estimated area of the oil deposition based on the data gathered using high frequency is about 49.1 ha. The second survey revealed that the oiled area is larger when 420 kHz frequency has been used for HFO detection. Moreover, the area that is potentially contaminated has increased by around 18.3% compared to the previous measurements made in 2016. All information concerning the comparison of the extents of oil pollution obtained during various measurement campaigns is included in Table 2.

3.3. Comparison of the results

To verify the validity of the oil spill location, the backscatter data from both campaigns were combined with more than 1000 geological samples obtained at the shipwreck site in 2016 (see Fig. 3), which were determined approximately every 20 m (Maritime Institute in Gdansk, 2016). The comparison of the backscatter information collected with the

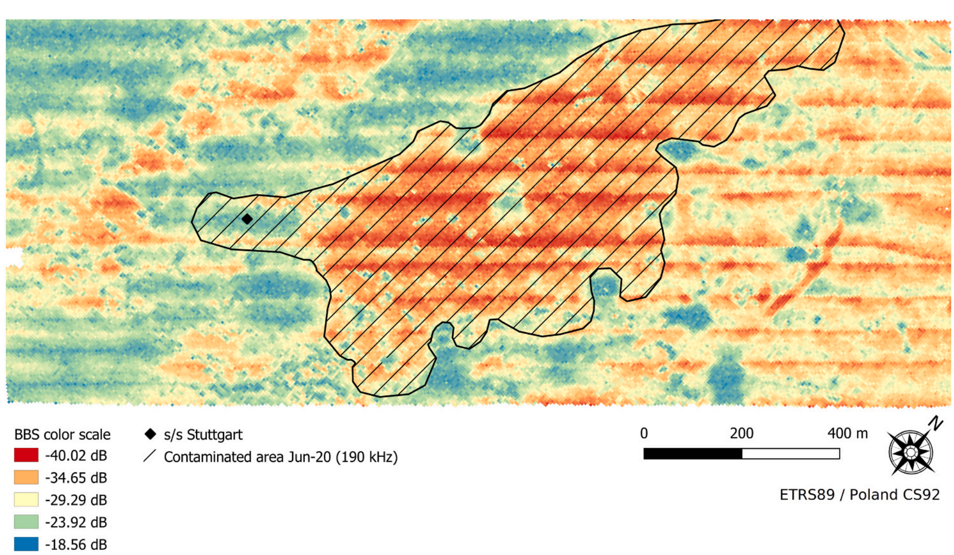

Fig. 5. The values of the BBS collected in June 2020 and potentially contaminated area determined by 190 kHz MBES frequency.

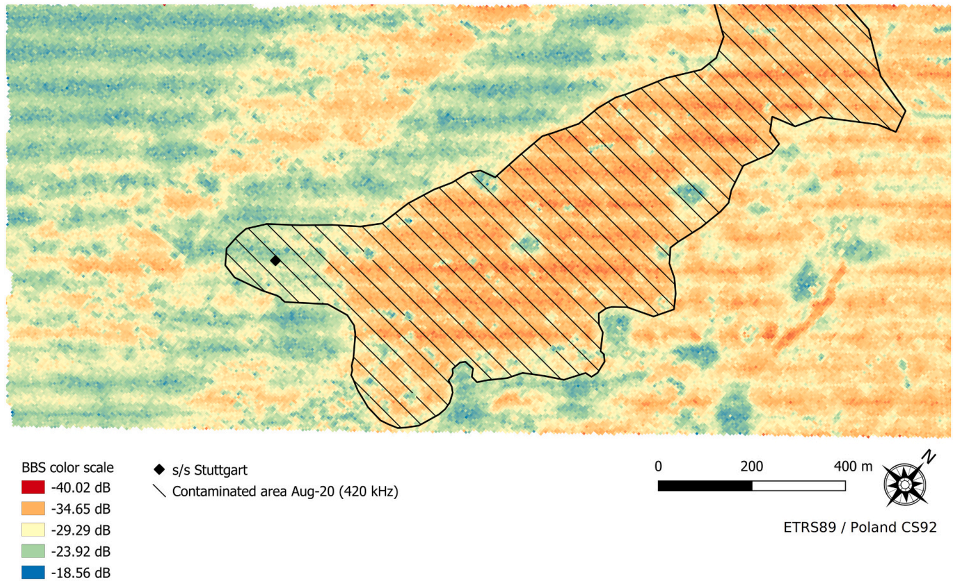

Fig. 6. The values of the BBS collected in August 2020 and potentially contaminated area determined by 420 kHz MBES frequency.

Table 2
Differences in estimations of the contaminated area size with respect to the MIG report.

	Potentially contaminated area [ha]	Increase of the area [%]
MIG report from 2016 (Maritime Institute in Gdansk, 2016)	41.5	N/A
Based on the LF campaign	42.5	2.4
Based on the HF campaign	49.1	18.3

reference data confirms the contamination area. As mentioned in Section 2.2, the classification of the samples in the MIG report was related to the level of their oiling (Maritime Institute in Gdansk, 2016). For the purpose of this study, the geological probes are simply divided into two groups regardless of the level of their contamination, i.e., *clean* and *oiled*. A total of 566 of them were classified as *clean* in 2016. Most of the area previously classified as *clean* has been presently categorized as contaminated using the MBES BBS method. Therefore, based on the reference data and especially the geological samples, the total size of the HFO contamination from s/s Stuttgart cannot be clearly stated. To confirm that the backscatter intensity of the received signal is different on the contaminated sea bottom, the values of backscatter intensity were determined all over the surveyed area, with a division into two groups: potentially contaminated (*oiled*) and not oiled (*clean*). The backscatter ranges were computed based on data distribution for the high and low frequencies, respectively. As shown in Fig. 7, the clean area has mainly a higher range of the backscatter intensity in both low and high frequencies.

The values of the backscatter intensity in the area of spillage are slightly higher (approximately 12.6%) from the campaign performed in June. The information gathered with the 420 kHz frequency depicted in Fig. 6 is more readable and meaningful, thus easier to interpret. It is possible to determine different sediment fractures more accurately based on this data set. Nevertheless, the difference between the MBES BBS in two conducted campaigns is still not sufficiently unambiguous to consider it separately as an independent data set. The estimated areas of the HFO contamination determined using both frequencies (190 kHz and 420 kHz) and overlaid on a common bathymetric chart are presented in Fig. 8.

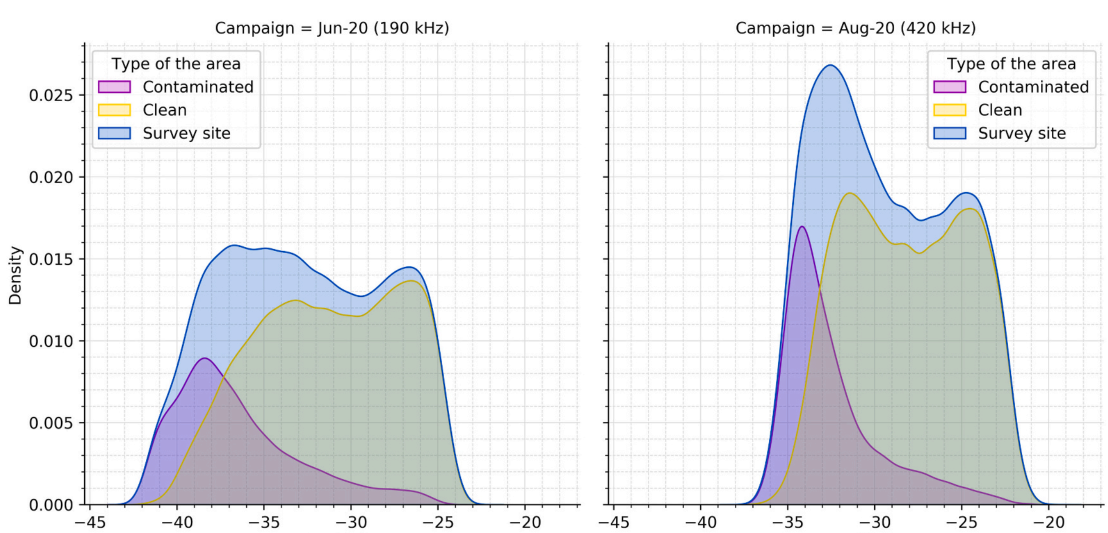

Fig. 7. The distributions of the BBS in contaminated and clean areas collected during the two measurement campaigns.

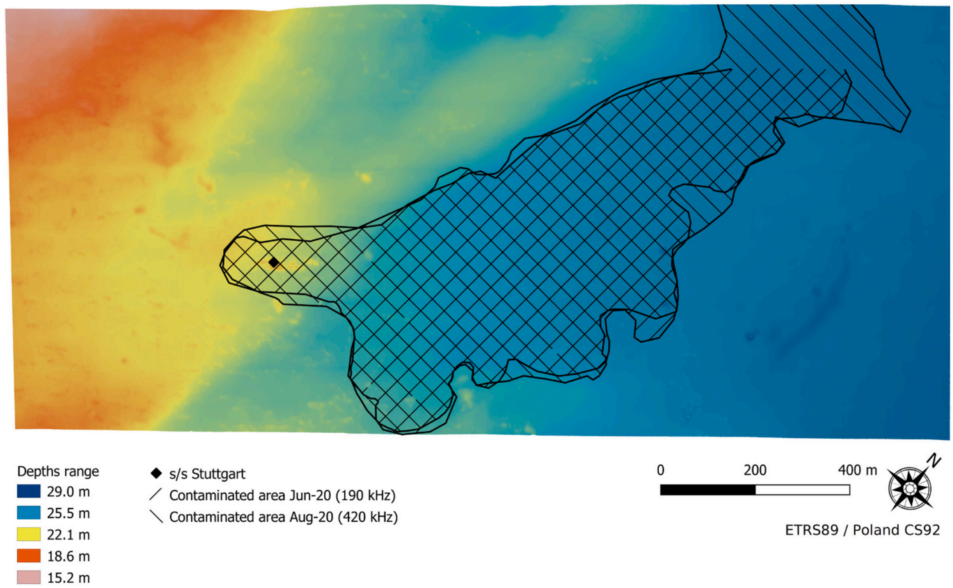

Fig. 8. The overlapped areas of estimated HFO contamination derived from both measurement campaigns.

4. Discussion

4.1. Main findings

Firstly, it has been confirmed that using MBES backscatter intensity it is possible to monitor and estimate the size of the area contaminated by the HFO coming from the shipwreck. It was presented that at low depths where the occurrence of contamination is located, the collected data are readable and can be interpreted.

Secondly, to specify the optimal MBES frequency in environmental surveys conducted in shallow waters, two measurement campaigns (using low and high frequency) were carried out. Regarding the quality and accuracy of both datasets, the difference between the measurements taken at 190 kHz and 420 kHz was generally assessed as negligible on the surveyed depths in the shipwreck location. Furthermore, the analysis of the survey both on high and low frequencies revealed that it is possible to utilize both frequencies for the acquisition of the backscatter intensity in the HFO-contaminated area, while the higher one is more convenient for further data analysis.

Lastly, based on the geological samples, the area to the south of the s/s Stuttgart wreck was classified as highly oiled, but backscattering data provided ambiguous results. The reason could be the principle of the MBES operation as different types of sediments on the sea bottom affect the backscatter intensity. Therefore, as per data from 2016, the sediments in the deeper part where oil was found are soft and muddy, so contaminants attach easier to the fine particles. This, in turn, increases the absorption of the signal and reduces the bottom backscattering strength.

Concerning the pros and cons of the presented method, the main advantage of the BBS utilization in the periodic monitoring of the HFO contamination from a shipwreck is a reduction of necessary geological sampling. It is especially important, as typically the latter is more time-consuming. If the MBES backscatter is involved, the number of samples, thus the required time/cost can be significantly reduced. This is possible, as the geological probes are used only as a reference for the determination of the BBS ranges. These are needed only to take into account the sediments present in the survey site, as well as the level of their contamination. In addition, there is usually a problem to find a company dealing with waste collection and management that would accept geological samples contaminated with the HFO. It might be challenging to dispose of a large number of samples remaining after geological surveys, while the usage of the MBES BBS also partly or completely solves this issue.

4.2. Limitations and uncertainties

After obtaining the preliminary results from the first survey at low frequency, a decision was made to enlarge the study site during the second attempt carried out in August 2020. This has been made due to a suspicion that nowadays, the contaminated area can spread up more than to the limits of the June campaign. Based on the comparative analysis of their common parts, the differences in the dimensions of the contaminated areas are relatively small and may probably result from the individual assessment of the data processor. However, the areas determined during both measurement campaigns are similar with respect to their shape and direction of the HFO spill spreading. Because of the various sizes of the survey areas, the obtained results collected using low and high frequency cannot be directly compared.

The application of the backscatter data for assessing the size of the HFO-contaminated area is not developed enough to create a universal intensity scale that will fit every sea bottom type and, additionally, its potential contamination. As shown in Fig. 7, clean and contaminated BBS ranges overlap both in high and low frequency. It results from many factors influencing the strength of the scattered acoustic signal, like the type and granularity of the sediment. Therefore, it seems to be important to perform a larger number of tests on various types of subsoil to examine this factor. Moreover, heavy fuel can partially mix with fractions of the seabed. This process can result in a change of the initial characteristics of the bottom acoustic response. It is possible that areas with high sediment mixing will be excluded from the utilization of this method. This is due to the probability of sediment unification, thus the backscatter strength in the contaminated areas will not sufficiently stand out. However, this assumption requires confirmation with additional tests. That is why the validation of the BBS acquired on the same sediment type but with different content of oil should be performed.

The main method to confirm the consistency of the obtained BBS results with the initial assumptions is to compare them with valid geological samples. The probes that were used for this purpose were taken in 2016. Although they generally confirmed the location of the oil spill, the data are not up-to-date enough to collate them directly with the backscatter results obtained this year. Regarding the BBS results, the HFO-contaminated area is larger than assessed during the survey made by Maritime Institute in Gdansk (2016) and covers the main surface sampled then. Despite the high resolution of the geological samples (approximately 20 m), the level of uncertainties when using BBS for the oil spill monitoring is not known and cannot be precisely assessed.

4.3. Future work

Further work concerning the utilization of the MBES backscatter information in monitoring and estimating the size of the HFO-contaminated area should be focused mainly on the removal of the currently identified limitations of the study. However, the improvements are not only narrowed to the aforementioned imperfections but also comprise the following ideas:

1. Increasing the reliability of the obtained results.

It is necessary to perform research on a different area affected by the oil spill. It is important to confirm that a pollutant with other sediment types or with different retention times will be still detectable. Therefore, the next analysis should be performed on a similar range of depths (probably up to 50 m), and with the same MBES parameters maintained. In future work, it should be crucial to confirm the BBS results with recently collected geological samples to provide the baseline. These should be probed in the positions formerly indicated by the backscatter intensity data gathered.

2. Unifying the research method.

The study presented in this paper reveals that one of the most crucial issues for further development of the method proposed is the unification of the BBS scales for different sediment types and their level of mixing. Each scale could comprise various backscatter intensity ranges for different types of both clean and contaminated sediments. It is essential to validate the impact of the pollutant presence on its mixture with a subsoil. As the BBS for the same type of sediments could differ when these are contaminated, it seems to be possible to detect and classify them in separate ranges. The first step toward solving this issue could be confirmation of the relation between the BBS and contaminated sediments in lab conditions.

3. Developing post-processing methods and procedures.

The foundation of all estimations and interpretation of the BBS is a visual evaluation of the results made by the data processor. For this research, the backscatter intensity was post-processed only on a basic level. It is possible to refine the procedure and post-processing method to get more meaningful data, for instance, by *Principal Component Analysis* (PCA), using data segmentation like in the BRESS (*Bathymetry- and Reflectivity-Based Approach for Seafloor Segmentation*) algorithm (Masetti et al., 2018), or classification methods using *Neural Network Algorithms* (NNA). Such improvements could allow for a more accurate interpretation of the results, thus for better determination of contaminated areas.

5. Conclusions

This study set out to determine if the MBES BBS could be a useful tool to monitor oil presence and the HFO extent around a known shipwreck. As a case study, the s/s Stuttgart located in shallow waters of the Gulf of Gdansk (Poland) was selected, where the contamination was confirmed and assessed in the past using other survey methods. Presently, the survey was performed in two campaigns with different MBES frequencies (190 kHz and 420 kHz).

Based on the conducted research, it was confirmed that it is possible to detect and estimate the size of the oil pollution coming from a shipwreck using the MBES backscatter intensity. It is a time-effective solution for the periodic monitoring of an HFO-contaminated area. Due to several factors affecting backscatter intensity strength, the BBS cannot be a sole source of information. Hence, it is required to confirm the contamination also by an additional method like chemical analysis of geological probes. Nonetheless, usage of this technique allows for the reduction of the number of necessary geological samples, thus also a cost. Additionally, the MBES BBS can be used as a reference for the determination of the sediment sampling stations.

It is challenging to explicitly confirm the actual size of the HFO-contaminated area near the shipwreck of s/s Stuttgart. Given the fact that the survey area was slightly larger during the second measurement campaign made in August, the estimated surface of the fuel contamination is approximately 49.1 ha. This means that the polluted area determined in 2020 by 420 kHz MBES BBS is larger by almost one-fifth (18.3%) than using different survey methods in 2016.

The results of conducted research may be found relevant by decision- and policy-makers of seaside countries, especially of the Baltic Sea Region states. The proposed application of the MBES BBS for detecting and assessing the HFO-contaminated area from a shipwreck can be found interesting by maritime administrations and salvage companies as well.

CRediT authorship contribution statement

Marta Szafrańska: Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Mateusz Gil:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Jarosław Nowak:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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