Optimal sidescan sonar and subbottom profiler surveying of ancient wrecks: The ‘Fiskardo’ wreck, Kefallinia Island, Ionian Sea

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ABSTRACT

Marine geophysical data collected during an underwater natural and cultural heritage assessment survey along the coastal zone of Kefallinia Island in the Ionian Sea, Greece, showed among other seafloor features, the presence of a Roman shipwreck and its amphorae cargo on the seafloor. The study and analysis of the collected data demonstrated that: (i) sidescan sonar and chirp sub-bottom profiling systems, can successfully detect ancient shipwrecks and their amphorae cargo on the seafloor, (ii) the use of objective computer vision techniques in processing sidescan sonar seafloor images, is a valuable tool for the separation of potential ancient shipwreck targets from other seafloor features with similar acoustic signatures. Furthermore, a guideline for the data acquisition parameters that should be used to obtain optimal seafloor sonar images to maximize the separation of potential shipwreck targets from other seafloor features, is provided. The underwater sonar remote sensing techniques may also provide adequate indication regarding the amphorae hull stowage and its vulnerability to human activity in the area. The shipwreck is dated between 1st century BC and 1st century AD and is one of the largest found so far in the Mediterranean Sea, for that period. It is estimated that it was carrying about 6,000 amphorae. The amphorae cargo, visible on the seafloor, is in very good state of preservation and the shipwreck has the potential to yield a wealth of information about the shipping routes, trading, amphorae hull stowage and ship construction during the relevant period and is therefore considered to be of significant archaeological importance.

1. Introduction

In July 2013 and November 2014, an underwater natural and cultural heritage assessment survey was carried out, within the “Interreg GR-IT 2007–2013” framework, around the coastal zone of Kefallinia Island in the Ionian Sea, using underwater sonar remote sensing techniques to identify areas of natural and archaeological potential. The survey focused on four areas which are listed as NATURA sites and there was information about the presence of wrecks on the seafloor (Fig. 1a). During the survey, three almost intact WWII wrecks were found lying on the seafloor two ships and a plane as well as a Roman shipwreck and its amphorae cargo. The latter, named ‘Fiscardo’, was found at the north-easter tip of Kefallinia Island at about 2 km from the entrance of the Fiskardo embayment (Fig. 1a,c).

This paper focuses on the Roman shipwreck and describes: (i) the data acquisition strategies used for imaging ancient seafloor shipwrecks and their amphorae cargo and (ii) the data processing procedure used to separate potential ancient shipwrecks among other seafloor features and outline their characteristics. Furthermore, the archaeological significance of the wreck and its cargo as well as its vulnerability to human activity in the area, is evaluated. Ancient shipwrecks and their amphorae cargo usually appear as low elevation - high texture seafloor features, such as many other small seafloor features (e.g. scattered rocky outcrops and coralligenous communities, Posidonia and sea-grass prairies etc). Thus, detecting ancient shipwrecks among other seafloor features using sidescan sonar, is not a straightforward procedure unless the shipwreck outline is unchanged (Quinn et al., 1998, 2002, 2005; Bates et al., 2011).

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2. Methodology

To achieve the overall objectives of the project, the survey was carried out in two phases: the “reconnaissance survey” and the “site specific survey”, using the coastal survey vessel “Socrates” and a variety of sonar equipment and data acquisition parameters in each phase. The “reconnaissance survey” was a fast, high density one, aimed at specifying the overall seascape of the study area and detecting potential seafloor targets, which might correspond to ancient shipwrecks. The “site specific survey” aimed at the detailed surveying of selected areas where...
potential targets were detected. The positioning and navigation of the survey vessel were carried out using a GPS Hemisphere VS101 system, providing an accuracy of less than 0.2 m.

2.1. Reconnaissance survey

During the “Reconnaissance Survey” in July 2013 the following high resolution acoustic systems were used: (a) an ELAC Nautik Seabeam 185 multi-beam echo-sounder for establishing the overall bathymetry of the coastal zone around Kefallinia Island, (b) an Edge-Tech 4200 sidescan sonar (SSS), which provides perspective sonar images of the seafloor (Fig. 2a and b), operated at 100 and 400 kHz for establishing the backscatter texture of the seafloor and identifying potential targets of archaeological importance and (c) a Geopulse Chirp sub-bottom profiler system (Chirp SBP), which provides vertical plane section sonar images of the seabed (Fig. 2a, c), for establishing the seafloor stratigraphy and identifying submerged and/or buried targets. The SSS data collected in the “Reconnaissance Survey” were acquired with the vehicle towed at about 40 m above the seabed at a speed of 3 knots (1.5 m/s), slant range of 100 m and transmitting at 100 kHz and 400 kHz frequency. The Discover (Edge Tech) software was used for recording the data, while the raw SSS records underwent radiometric and geometric corrections using the ISIS Sonar (Triton Imaging Inc) software. Beam-pattern correction and ping energy level normalization were followed with slant range correction using the flat seabed assumption. No absolute dB values are given in the backscatter images, as recommended by the GeoHab community, e.g. (Lamarche and Lurton, 2018).

Geo-rectification and mosaicking of the SSS data were realized through the Triton Map software (Triton Imaging Inc), producing 8-bit grey-scale images with 10 cm × 10 cm pixel size.

2.1.1. SSS seafloor image quantification and “automated target detection”

The collected sonar images were processed with an image-based automatic classification procedure with the use of the “Sonar Class” (Fakiris and Papatheodorou, 2007, 2009, 2012), a Matlab software package that has recently been used with success in various benthic habitat mapping and target detection works (Papatheodorou et al., 2012; Fakiris et al., 2012, 2016; 2018, 2019). Sonar Class performs image quantification through a range of seafloor imaged features, that describe the local image texture and applies well documented classification algorithms to them. Image texture is compared to the relative level of the grey scale in the collected seafloor sonar image, and describes the roughness or the smoothness, the variability or the homogeneity and the repeatability or the randomness of different areas on the SSS records (Blondel et al., 1998). More precisely, the “Sonar Class” uses 3 feature extraction algorithms, namely first order grey-level statistics, grey level co-occurrence matrices (GLCMs) and 2D power spectrum specifications, forming a feature vector (FV) of 11 textural descriptors, described by Fakiris and Papatheodorou (2007, 2012). For this target’s automatic detection, the “automated target detection” (ATD) procedure described in Fakiris et al. (2016) was used. According to Fakiris et al. (2016), Independent Component Analysis (ICA) is applied to the textural derivatives of the SSS images to transform the FVs into a few meaningful Independent Components (ICs) that maximize the difference and therefore the separation among any potential targets e.g. ancient shipwrecks and other seafloor features e.g. scattered rocky outcrops and coralligenous communities, Posidonia and sea-grass prairies etc. To identify which ICs are more likely to emphasize seabed irregularities (e.g. targets), the ‘kurtosis’ criterion was used. Kurtosis, is considered an outlier indicator (related to the tailedness of the distribution), it is much higher for ICs that emphasize small targets than for those reflecting larger scale seafloor characteristics (e.g., seafloor dynamics, morphology or sedimentology) or systematic ambient and self-noises (e.g., caused by the sea column stratification, internal waves or SSS platform movements).

Two sets of SSS seafloor images acquired by two different sets of data acquisition parameters during the reconnaissance survey (Fig. 3 and Table 1) were mosaicked with a 10 cm resolution and the textural features were extracted from each one utilizing 5 × 5 m (50 × 50 pixels) image patches (windows), with a 2.5 m (25 × 25 pixels) sliding step, leading to 11 feature maps per SSS record, of 2.5 cm spatial resolution. Each of the SSS images was first quantified and then targets of potential interest were automatically highlighted, using the above described procedure.

Fig. 2. Schematic presentation showing the SSS and Chirp SBP basic operation principal. The SSS transmits high frequency sound pulses in a vertically wide fan shape from a moving vessel, which scans the seafloor (a). The reflected pulses from the seafloor (backscatter) are recorded and processed to produce a perspective image of the seafloor (b). The Chirp SBP emits a narrow acoustic beam, which penetrates the layers beneath the seafloor (a). The reflected acoustic pulses from the seabed and the deeper layers are recorded and processed to produce a vertical plane seismic section of the seabed along the vessel’s trajectory (c).
Fig. 3. The dual-frequency 100 kHz (a) and 400 kHz (b) SSS seafloor sonar images (Edge Tech 1L and 1H, see Table 1) collected during the reconnaissance survey and their respective highest kurtosis Independent Components (IC) along with the shipwreck separation level “S”. Arrows indicate the target with the overall highest IC values.

Table 1
List of the SSS systems used (vertical column) in the collection of the sonar images during the “Reconnaissance” and “Site Specific” surveys along with the data acquisition parameters (height above the ground, frequency, ground range and incidence angle), and the estimated wreck separation level (S).

<table>
<thead>
<tr>
<th>Equipment Line</th>
<th>Height above the ground (m)</th>
<th>Frequency (kHz)</th>
<th>Ground Range to the wreck (m)</th>
<th>Incidence angle (la)</th>
<th>Wreck separation level (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Reconnaissance Survey”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EdgeTech 1L</td>
<td>41.4</td>
<td>100</td>
<td>22.0</td>
<td>27.9</td>
<td>24.1%</td>
</tr>
<tr>
<td>EdgeTech 1H</td>
<td>41.4</td>
<td>400</td>
<td>22.0</td>
<td>27.9</td>
<td>34.2%</td>
</tr>
<tr>
<td>“Site Specific Survey”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EdgeTech 2L</td>
<td>15.6</td>
<td>100</td>
<td>24.5</td>
<td>57.5</td>
<td>63.0%</td>
</tr>
<tr>
<td>EdgeTech 2H</td>
<td>15.6</td>
<td>400</td>
<td>24.5</td>
<td>57.5</td>
<td>70.1%</td>
</tr>
<tr>
<td>EdgeTech 3L</td>
<td>18.2</td>
<td>100</td>
<td>14.5</td>
<td>38.5</td>
<td>32.8%</td>
</tr>
<tr>
<td>EdgeTech 3H</td>
<td>18.2</td>
<td>400</td>
<td>14.5</td>
<td>38.5</td>
<td>49.3%</td>
</tr>
<tr>
<td>EG&amp;G 1</td>
<td>44.8</td>
<td>500</td>
<td>13.0</td>
<td>16.2</td>
<td>14.2%</td>
</tr>
<tr>
<td>EG&amp;G 2</td>
<td>48.3</td>
<td>500</td>
<td>24.5</td>
<td>26.9</td>
<td>21.8%</td>
</tr>
<tr>
<td>Klein 1</td>
<td>7.5</td>
<td>900</td>
<td>26.0</td>
<td>73.9</td>
<td>70.2%</td>
</tr>
<tr>
<td>Klein 2</td>
<td>12.6</td>
<td>900</td>
<td>6.0</td>
<td>25.5</td>
<td>26.9%</td>
</tr>
<tr>
<td>Klein 3</td>
<td>3.4</td>
<td>900</td>
<td>31.5</td>
<td>83.8</td>
<td>96.6%</td>
</tr>
</tbody>
</table>

2.2. Site specific survey

The aim of this survey was three fold: (i) to provide detailed visual and sonar images of the highlighted targets in the reconnaissance survey, (ii) to study the SSS data acquisition parameters to obtain the optimal perspective seafloor sonar images for maximizing the separation between potential ancient shipwreck targets and other seafloor features such as scattered outcropping rocks and coralligenous communities, Posidonia and sea-grass prairies, which may have similar acoustic signature in the records, and (iii) to provide guidelines regarding the SSS data acquisition parameters that should be used when surveying for ancient shipwrecks and their cargo. The visual inspection of the target was carried out using an ROV and divers for taking photographs to provide a detailed orthophoto mosaic of the target. The detailed sound imaging of the target was carried out with (a) a Klein 3900 side scan sonar operated at 900 kHz with a horizontal angle of 0.21º, transmitting with a pulse length of 0.1 ms, a pulse repetition rate of 15 per sec. for a slant range of 50 m and moving at speed of 3knots (1.5 m/s) and (b) the Kongsberg Geopulse (GeoAcoustics Universal) Chirp sub-bottom profiler (Chirp SBP) system, for the detailed vertical plane imaging of the identified target, operated at 1.5–11.5 kHz, with a pulse length of 30 ms, offering a vertical resolution of about 15 cm. Acquisition of the SSS data was carried out using the Discover (EdgeTech) software while data processing was done through the Isis Sonar (Triton Imaging Inc) software, as described in paragraph 2.1. Acquisition of the “Chirp SBP” data was realized through Sonarwiz (Chesapeake Technology Inc) software while data processing used the SB-Interpreter (Triton Imaging Inc) software. The survey-lines for imaging the seafloor around the shipwreck had a total length of 13.9 km (Fig. 1c) and the collected data were geo-referenced using Hypack and ArcGIS softwares.

2.2.1. Evaluating optimal SSS acquisition parameters for maximising wreck separation

The SSS data acquisition parameters to acquire the optimal perspective seafloor sonar images for maximizing the separation between potential ancient shipwreck targets and other seafloor features, were studied with the use of eleven sets of SSS seafloor images, acquired by three different SSS models over the site-specific area (Table 1). The following SSS data acquisition parameters were examined: (i) the altitude of the vehicle above the seafloor, (ii) the beam incidence angle, (iii) the ground range, that is the distance of the seafloor target from the shipline plotted on the seafloor and (iv) the transmitted acoustic frequency, to investigate their effect on the potential wreck target separation. To avoid subjective criteria in assessing the separation level, hereafter called “wreck separation level” (S), between shipwrecks and other seafloor features objective computer vision criteria were used. For this, the three ICs with the highest kurtosis values were used to apply supervised classification to the acquired images and examine the accuracy with which the classifier can accurately manage to identify the wreck-site among the other seabed features. The naive Bayes classifier (John and Langley, 1995) was chosen to avoid over-fitting of the Euclidean feature space and to extract simple decision rules. Training of the classifier was performed using imaged patches (5 × 5 m each) located within the wreck’s outline (assigned to the “wreck” class) and others randomly picked from the rest of the site (assigned to the “other” class). The latter
among others includes scattered outcropping rocks and coralligenous communities, Posidonia and sea-grass prairies etc. The above situates a binary classification problem (1 = “wreck” and 0 = “other”) and the wreck classification accuracy can be directly used as a proxy for the wreck separation level (S) among other seabed features in the SSS images. The wreck classification accuracy was estimated using the “precision” metric, such as \( S = \frac{tp}{tp + fp} \times 100\% \), where tp is the number of true positive (expected) predictions and fp the number of false positive (unexpected) ones. The above formula implies that when the wreck interior has been correctly classified as “wreck” and no other imaged features (e.g. scattered outcropping rocks etc) have been classified as such, (S) takes 100% value.

3. Interpretation-results

3.1. Acoustic characteristics of the “Fiscardo” shipwreck and its amphorae cargo

The study of the SSS data collected during the “Reconnaissance Survey” showed that the coastal zone around Kefallinia Island up to a depth of 80 m, has a complex seafloor consisting of muddy sand sediments, scattered patches of low relief bedrock and various benthic habitats such as Posidonia Prairies and coralligenous communities (APtEH Partners Final Report, 2015; Fakiris et al., 2018). Furthermore, in the SSS records WWII wrecks (two ships and a plane) were identified. The WWII wrecks were easily detected as they had kept their initial frame. No other wrecks were discernible on the SSS records. A careful visual analysis of the SSS records collected during the reconnaissance survey, showed, that at the entrance to the Fiscardo embayment at the northeastern tip of Kefallinia Island, there is a relatively distinctive acoustic signature slightly different to the acoustic signatures produced by other seafloor features (Fig. 3a and b).

The highest kurtosis ICs of the FVs extracted from the dual-frequency SSS records EdgeTech 1L (Figs. 3a) and 1H (Fig. 3b)(Table 1) collected during the “Reconnaissance Survey”, separated this relatively distinct target but also other seafloor features such as scattered rock outcrops and coralligenous communities in the surrounding area by rather low wreck separation levels “S” equal to 24% and 34%, respectively (Fig. 3a and b). The target with the overall highest IC value of all the targets, combined with the target’s shape and dimensions, was selected for detailed surveying, as a potential shipwreck site.

For comparison purposes a Klein 3900 sonar image, collected over the selected shipwreck target (Fig. 4a) during the site specific survey, shows the increase achieved in the “wreck separation level (S) from 24.1 to 34.2% (Fig. 3a and b) to 96.6% (Fig. 4b) thus maximizing the separation among the shipwreck target and the other seafloor features.

The high resolution “site specific survey”, using the Klein 3900 sidescan sonar operating with the settings described above, displays clearly on the sonar image an oval shaped pile of the ship’s amphorae...
cargo and the individual amphorae lying on the seafloor (Fig. 5a). The amphorae pile is about 30 m long, 12 m wide and about 1.3 m high on the seafloor.

Similarly, the orthophoto mosaic shows the oval shaped pile of amphorae surrounded by a whithis rim composed of carbonate sand (Fig. 5b). Furthermore, the detailed study of the orthophoto mosaic allowed the amphora’s dimensions and their total number lying on the cargo surficial layer, to be estimated. The amphora’s length was at between 0.80 and 0.90 m and the max. width at 0.40 m (Fig. 6a). The number of amphorae lying on the cargo surficial layer was 1,200, based on the detailed counting of the intact amphorae (Fig. 6b). The aforementioned number of amphorae agrees very well with the number ex-

The general stratigraphic sequence around the wreck is interpreted as a 3.5 m thick, homogeneous, muddy sand layer, as indicated by the surficial prolonged (high amplitude) continuous reflector and the absence of internal reflectors, overlying the hard substrate (Fig. 7a and b). Over the area that is spatially covered by the cargo, the above described acoustic character in the upper part of the sedimentary layer is interrupted by highly irregular reflectors with an overall elliptical shape (Fig. 7a and b). The reflectors inside the ellipsis are highly jagged (denticulate) and are in shades of light and dark grey (Fig. 7a and b). This acoustic pattern apparently arises from the reflection of the sound on the amphorae (clayey) surfaces that are apparently stacked in layers and from the voids between them. Therefore, the upper and lower edges of the ellipsis are considered to be the outlines of the wreck with the length of the minor and major axis of the ellipsis corresponding to the maximum height and length of the wreck/amphorae cargo, respectively. The height is 3.3 m of which 1.3 m is above the seafloor and 2.0 m below, whilst the length is 30 m (Fig. 7b). Furthermore, the absence of the hard substrate reflector directly below the highly jagged irregular reflectors (Fig. 7a and b) indicates that the emitted acoustic energy is reflected and/or absorbed by the denser amphorae cargo.

To define the optimal SSS data acquisition parameters for imaging the seafloor texture to obtain the maximum separation among a would-be ancient shipwreck target and other sea-bed features, using objective computer vision criteria, eleven seafloor sonar images were taken over the “site specific” survey area. The sonar images were acquired by three different SSS models transmitting at different data acquisition parameters (Table 1) and they were analyzed according to the procedure described above (Figs. 8 and 9).

The wreck separation level value “S” vs SSS data acquisition parameters shown in the correlation diagrams in Fig. 8, demonstrates (i) a clear positive correlation ($R^2 = 0.9381$) between the sound beam incidence angle (Fig. 8a) (the angle between the sound-beam and that normal to the seafloor) and the wreck separation level ($S$) (i.e. high $S$ value ($S > 90\%$) for $\theta_a > 80^\circ$ and low $S$ value ($S < 20\%$) for $\theta_a < 20^\circ$), (ii) strong negative correlation ($R^2 = 0.6202$) between the height of the SSS vehicle above the seafloor and the wreck separation level ($S$) (Fig. 8b), and (iii) a rather weak positive correlation ($R^2 = 0.4472$) between the ground distance of the target and “$S$” (Fig. 8c) and (iv) the pulse frequency exhibits a very weak correlation ($R^2 = 0.1163$) to “$S$” (Fig. 8d). To visually understand the above findings, Fig. 9 presents examples regarding four SSS records acquired over the wreck site, under different SSS data acquisition parameters along with their maximum kurtosis Independent Component (IC), the respective Incidence angle ($\theta_a$) and the “$S$” values obtained. It is evident that higher $\theta_a$ produce IC representations with higher wreck separation level “$S$” between the wreck and the other seafloor features (i.e. “$S$” values, 63% and 97% with $\theta_a 57.5^\circ$ and 84°, respectively (see Table 1, EdgeTech 2L and Klein 3). It is clear from the above mentioned, that higher incidence angles produce very different image textures between the pile of amphorae and the surrounding scattered rocks and outcrops.

The regression line of Fig. 8a corresponds to the function $S = 1.1 \times \theta_a$. This function can be used by a surveyor to define the $\theta_a$ that will
produce the desired “S” value and set the right survey parameters accordingly (vehicle height above the seafloor and optimal ground range) to initialize the survey. Following the above procedure, Fig. 10 presents a nomogram aiding the decision making of the optimal survey parameters in relation to the desired S and the survey requirements, for instance towing the vehicle at a certain height above the sea floor and/or using sonars with certain swath range limits. In section 4 a more-in-depth discussion of the nomogram is provided, followed by specific examples.

3.2. Archaeological characteristic of the shipwreck

The above presented SSS and “chirp” SBP data showed that the ship’s dimensions would have been about 34 m long and 13 m wide, as the cargo’s measured length and width is 30 and 12 m, respectively, whilst the hull height is about 3.5 m. The shipwreck, based on the type of the amphorae (Fig. 5b), is dated at between 1st century BC and 1st century AD (Geraga et al., 2015) and therefore, it is considered as a Roman period wreck. The dimension of the shipwreck makes it one of the four largest merchant shipwrecks from the above-mentioned period, that have been found in the Mediterranean to date. The other three wrecks with an estimated length of about 40 m were the ‘Madrague de Giens’ (1st century BC), the ‘Albenga’ (1st century BC) and the ‘Machdia’ (1st century BC), which lie in the western Mediterranean Sea, off the Madrague de Giens cape near Toulon in France, Genoa Bay in Italy and in Tunisia, respectively (Parker, 1992; Carlson, 2011; Strauss, 2006, 2013). Ships of this size were capable of carrying a cargo of about 400 tons with an estimated carrying capacity of between 6,000 and 8,000 amphorae or probably more (Carlson, 2011). The height of the “Fiscardo” cargo (3.3 m), as deduced by the chirp plane sections (Fig. 7a and b), suggests the amphorae were probably stowed in five layers in the ship’s hull. The dimensions of the ship along with the assumption that the amphorae were fairly homogeneous and 0.8 m in height and 0.4 m width indicate that the ship was carrying about 6,000 amphorae.

3.3. Wreck perturbation – vulnerability assessment

The elongated oval shaped mound of amphorae on the seafloor displayed on the sidescan sonar record and the photomosaic (Fig. 5a and b) resembles the outline of ships of that period, as defined by the ship’s side rail. This indicates that the cargo has kept the outline of the ship and along with the almost flat and gently sloping seafloor that prevails around the shipwreck (Fig. 4a) suggest that the ship sank very slowly in an up-right position and came to rest on its keel and then gradually tipped to one side with the hull keeping its overall structure, intact (Geraga et al., 2015).

The above allow us to speculate that the ship sank in good weather conditions rather than in stormy weather. Furthermore, the shipwreck’s sonar image and photo-mosaic show that the amphorae assemblage is crossed by a linear trench-zone about 1 m wide cleared of amphorae (Fig. 5a b). This zone, as suggested by Geraga et al. (2015), probably resulted from a vessel dragging an anchor over the seafloor during anchoring maneuvering. The presence on the seafloor of anchor dragging traces in the vicinity of the shipwreck is probably related to anchoring at the entrance to the Fiscardo embayment.

As anchoring of yachts and cruise ships off Fiscardo harbour increases every year, the risk of the shipwreck being damaged by this kind of human activity continuously increases. On the contrary, the damage to the shipwreck by the dragging of trawling nets is negligible, as no trawl-mark traces were detected on the seafloor in the vicinity of the shipwreck, due probably to the presence of rocky outcrops around the wreck.

4. Discussion – conclusions

4.1. The optimal SSS survey settings for ancient shipwreck exploration

In the last 30 years a significant number of ancient shipwrecks and their cargo have been found in the Mediterranean Sea, but most of them were found by Scuba diving. These shipwrecks on the seafloor usually appear as low elevation - high texture seabed features, such as many other small seabed features, with the wooden frame most often dis-integrated and the cargo, mainly amphorae, dispersed around the wreck. The above characteristics do not permit their “footprint” to be clearly visible in the sonar images thus making their detection on the seafloor difficult.

In this study, it was shown that high resolution sidescan sonar surveys can successfully image and separate ancient shipwrecks and their amphorae cargo on the seafloor, especially when the collected sonar images are processed using dedicated image texture analysis techniques.
In this work, Independent Component Analysis application on SSS image texture features, highlighted targets potentially corresponding to low relief ancient wrecks and their amphorae cargo, thus increasing their detection rates and reducing the survey time needed in the reconnaissance survey stage.

This work represents the first controlled experiment that examines the optimal surveying set-ups for separating ancient wrecks on SSS records, that their initial framework has been disintegrated and only their amphorae cargo lies on the seafloor as a pile of low relief objects, amongst other seafloor features.

In this context the optimal sidescan sonar seafloor data acquisition parameter for obtaining appropriate perspective seafloor sonar images to maximize the separation of the shipwreck target from the other proximal seafloor features, such as scattered rocky outcrops and coralligenous communities, are: (i) the incident angle, which has a very significant positive correlation ($R^2 = 94\%$) to the “wreck separation level” (S), (ii) the SSS vehicle altitude above the seafloor which has a strong negative correlation ($R^2 = 62\%$) and (iii) the ground range to the wreck, which has a rather weak ($R^2 = 42\%$). Based on the aforementioned and Fig. 10, as a rule of thumb, a project manager of a wreck exploration survey should have in mind that the seafloor of an area under investigation should be scanned at ground ranges greater than 2, 3.5 or 8.5 times the average altitude of the SSS vehicle above the seafloor, in order to achieve wreck separation levels greater than 70%, 80% and 90% respectively. For example using an SSS at an operational frequency of: (i) 100 kHz, towed at 20 m above the seafloor and with 200 m swath range (100 m at each side), the appropriate ground range to the wreck for achieving a separation level between 70 and 80% would lie between 40 and 70 m from the ship’s surveying line, (ii) using a 500 kHz SSS, towed at 10 m above the seafloor and with a 100 m swath (50 m at each side), the appropriate ground range would lie between 20 and 35 m from the ship’s surveying line and (iii) using a 900 kHz SSS, towed at 2.5 m above seafloor, the appropriate ground range to the wreck should be over 25 m to achieve wreck separation levels higher than 90%.

Quinn et al. (2005) carried out a similar controlled experiment to determine the optimal SSS survey settings for achieving the best resolution (that is the minimum distance between two objects to be displayed on the SSS record as separate) to identify isolated objects on the seafloor based on their geometry. The resolution in the SSS imagery along and perpendicular to the line of travel “transverse” and “range” resolution respectively, is controlled by the pulse length and the beam angle. Quinn et al. (2005) suggested that to obtain the optimal resolution the

Fig. 7. Two ‘chirp’ sub-bottom seismic profiles along the longitudinal axis of the amphorae cargo showing two plane sections of the shipwreck and the overall seabed stratigraphy. The arrows indicate the side limits of the cargo and the dashed white line probably the hull bottom. The hard substrate and the surficial sedimentary cover (SC) are also shown.

This work represents the first controlled experiment that examines the optimal surveying set-ups for separating ancient wrecks on SSS records, that their initial framework has been disintegrated and only their amphorae cargo lies on the seafloor as a pile of low relief objects, amongst other seafloor features.

In this context the optimal sidescan sonar seafloor data acquisition parameter for obtaining appropriate perspective seafloor sonar images to maximize the separation of the shipwreck target from the other proximal seafloor features, such as scattered rocky outcrops and coralligenous communities, are: (i) the incident angle, which has a very significant positive correlation ($R^2 = 94\%$) to the “wreck separation level” (S), (ii) the SSS vehicle altitude above the seafloor which has a strong negative correlation ($R^2 = 62\%$) and (iii) the ground range to the wreck, which has a rather weak ($R^2 = 42\%$). Based on the aforementioned and Fig. 10, as a rule of thumb, a project manager of a wreck exploration survey should have in mind that the seafloor of an area under investigation should be scanned at ground ranges greater than 2, 3.5 or 8.5 times the average altitude of the SSS vehicle above the seafloor, in order to achieve wreck separation levels greater than 70%, 80% and 90% respectively. For example using an SSS at an operational frequency of: (i) 100 kHz, towed at 20 m above the seafloor and with 200 m swath range (100 m at each side), the appropriate ground range to the wreck for achieving a separation level between 70 and 80% would lie between 40 and 70 m from the ship’s surveying line, (ii) using a 500 kHz SSS, towed at 10 m above the seafloor and with a 100 m swath (50 m at each side), the appropriate ground range would lie between 20 and 35 m from the ship’s surveying line and (iii) using a 900 kHz SSS, towed at 2.5 m above seafloor, the appropriate ground range to the wreck should be over 25 m to achieve wreck separation levels higher than 90%.

Quinn et al. (2005) carried out a similar controlled experiment to determine the optimal SSS survey settings for achieving the best resolution (that is the minimum distance between two objects to be displayed on the SSS record as separate) to identify isolated objects on the seafloor based on their geometry. The resolution in the SSS imagery along and perpendicular to the line of travel “transverse” and “range” resolution respectively, is controlled by the pulse length and the beam angle. Quinn et al. (2005) suggested that to obtain the optimal resolution the
Fig. 8. Wreck separation level ($S$) versus SSS data acquisition parameters: (a) the incidence angle, (b) the height of the vehicle above the ground, (c) the ground range and (d) the pulse frequency.

Fig. 9. Four selected SSS seafloor images taken over the wreck-site during the site-specific survey, using different SSS data acquisition parameters (see Table 1). The highest kurtosis Independent Component (IC) is shown next to each respective record together with the incidence angle ($I_a$) and the wreck separation level (“$S$”) showing that the higher the incidence angle ($I_a$) the higher the wreck separation level “$S$”. Arrows indicate the target with the overall highest IC values.
most important factors are: (i) small grazing angle, that is low vehicle flight over the seafloor and (ii) close proximity (20–30 m) to the vehicle. They also found that the operating frequency of the SSS does not have any control on the SSS resolution, which agrees with the findings of the present study regarding ‘wreck separation level’

4.2. Archaeological potential of the Fiscardo shipwreck

The mapping of the shipwreck and the surrounding area with underwater sonar remote sensing techniques revealed that the shipwreck is of significant archaeological potential. Cross-referencing the findings of this survey with existing data-bases (Parker, 1992; Strauss, 2006, 2013) and papers (Carlson, 2011), it can be concluded that the ‘Fiscardo’ shipwreck can be listed as one of the largest four found in the Mediterranean Sea and more specifically, the largest found to date in the eastern Mediterranean Sea. Its cargo is estimated at about 6,000 amphorae, which are still in very good condition. The presence of the ‘Fiscardo’ shipwreck off the present-day Fiscardo fishing port, where relics (houses, bath complexes, a theatre, a cemetery and a tomb), dating to Roman times between 146 BC and 330 AD, were recently found, indicate that Fiscardo was an important port at that time (Milstein, 2007). Furthermore, based on the abovementioned databases, the ‘Fiscardo’ shipwreck is one of four that was found along the eastern part of the Ionian Sea representing the Late Republic to early Imperial period (Fig. 1b). The two, “Dascalio” and “Antisami”, which lie in the Ithaka-Kefallinia Strait (Dellaporta, 2006; Theodoulos, 2011) (Fig. 1) are in bad condition and have been looted, the third approximately the same size as the “Fiscardo” shipwreck lies off Vlora port in Albania and is in very good condition (Semin, 2011). Finally, the fourth shipwreck, which lies off the Antikythera island (not shown in Fig 1b), is the most known world-wide because in its cargo the world’s oldest known analog computer, the Antikythera mechanism, was found (Kaltsas et al., 2012). It should be mentioned here that a shipwreck described by Dellaporta et al. (2006) without providing the coordinates of the shipwreck but stating only that it is located in the northern end of the Kefallinia – Ithaka straits, may be the same as the one presented in this paper. However, the shipwreck reported by Dellaporta et al. (2006) was 25 m long, which is about 5 m shorter than the ‘Fiscardo’. All the above mentioned provides further evidence that the eastern Ionian Sea was part of an important trading route ferrying goods from the Aegean and the Levant to the peri-Adriatic Roman provinces and that Fiscardo port was a significant calling place. Taking into consideration the date, length and the strong possibility of the amphorae and the ship’s wooden frame preservation, further study of the ‘Fiscardo’ wreck would shed light on sea-routes, trading, amphorae hull stowage and ship building in the period between 1st century BC and 1st century AD. All the above demonstrate that the shipwreck on one hand covers a wide range of values such as scientific, cultural, socio-economic and educational, but on the other hand lies in an area of continuously fast growing tourism which affects all the above intrinsic values if protective measures are not taken very soon. Concluding, the paper shows that the analysis and interpretation of the data collected using high resolution underwater sonar remote sensing techniques were adequate in assessing the potential significance of the shipwreck and its vulnerability to anthropogenic activity.

Declaration of competing interest

The authors, mentioned below, declare that there are not any conflicts of interest associated with this publication.

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Appendix A. Supplementary data

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References