Journal of Archaeological Science 36 (2009) 408–418

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

The use of a high-resolution 3D Chirp sub-bottom profiler for the reconstruction of the shallow water archaeological site of the *Grace Dieu* (1439), River Hamble, UK

Ruth M.K. Plets [a,*,1], Justin K. Dix [b], Jon R. Adams [c], Jonathan M. Bull [b], Timothy J. Henstock [b], Martin Gutowski [d], Angus I. Best [b]

[a] *Memorial University, Department of Geography, St. John's, Newfoundland, A1B 3X9, Canada*
[b] *School of Ocean and Earth Sciences, National Oceanography Centre, Southampton, European Way, Southampton, SO14 3ZH, UK*
[c] *School of Humanities, Avenue Campus, University of Southampton, Southampton, SO17 1BF, UK*
[d] *GeoAcoustics Ltd., Shuttleworth Close, Gapton Hall Industrial Estate, Great Yarmouth, NR31 0NQ, UK*

ARTICLE INFO

Article history:
Received 29 July 2008
Received in revised form 15 September 2008
Accepted 16 September 2008

Keywords:
Shipwreck
Chirp sub-bottom profiler
Grace Dieu
Geophysics
Buried wood
Degradation
Reconstruction

ABSTRACT

The remains of Henry V's flagship, the *Grace Dieu*, currently lie buried within the inter-tidal sediments of the River Hamble (S. England). Previous archaeological investigations have been hindered by difficult excavation conditions resulting in a poor understanding of the dimensions, shape and degradation state of the hull's deeper structure. This study therefore aimed to image, characterize and reconstruct the buried remains of this vessel using a high-resolution 3D acoustic sub-bottom Chirp system with RTK-GPS positioning capability. The accurate navigation and high-resolution data that were acquired enabled the construction of a full 3D image of the site that not only identified the remains of the wooden hull, but also features buried within it. In addition, the degradation state of these buried wooden remains were investigated by calculating reflection coefficients while a hypothetical larger reconstruction of the *Grace Dieu*'s hull was achieved, through the use of the ShipShape ship design software package.

The results of this project demonstrate that (i) acoustic data can be used to successfully image buried wooden shipwrecks, (ii) artefacts are buried within the hull of the *Grace Dieu*, (iii) there is variation in the degradation state of the buried timbers, as calculated from the acoustic data, with the shell of the vessel being moderately well preserved, and (iv) the *Grace Dieu* was a very large ship for its time (possibly over 60 m long and 16 m wide).

The outcomes of this research not only have considerable implications for the management and monitoring of submerged and buried archaeological sites but also for planning intrusive surveys, should they be required.

1. The site

In July 1416, work began in Southampton to build the fourth and last of the great ships for Henry V, the *Grace Dieu* (Friel, 1993). The new ship was to be of 1400 tons (Carpenter Turner, 1954), the biggest ship ever constructed, and was clinker-built, made up of triple thickness planking (Anderson, 1934). Historic records suggest that some 70% of trees used consisted of oak, with the remainder made up of beech (Carpenter Turner, 1954; Friel, 1993). After her blessing in 1418 (Carpenter Turner, 1954), it was not until 1420 that she made her maiden (and only) voyage. It proved to be a fiasco with a number of men mutinying, marking the end of the *Grace Dieu*'s active service (Friel, 1993). By the end of 1420, the vessel was moored in the River Hamble, functioning as a technological marvel to impress foreign dignitaries. Albizzi, a captain of a Florentine galley fleet, dined on board the *Grace Dieu* in 1430 and wrote in his diary that he had never seen 'so large and splendid a construction'. In 1434, the *Grace Dieu* was towed up the River Hamble to Bursledon, where she was laid up in a dock on the mud (Friel, 1993). A major part of the hull burnt out after being struck by lightning on 7 January 1439, and only some of the bottom planking and keel remained embedded in the mud (Fig. 1a).

The first recorded identification of the wreck was by the local residents of Bursledon in the 1820s, who thought it was a Danish galley dating to about 900AD (Friel, 1993). A partial salvage attempt in 1875 resulted in the destruction of some of the timbers and it was not until the 1930s that the ship was carefully examined and

* Corresponding author. Tel.: +1 709 737 6127.
E-mail address: rplets@mun.ca (R.M.K. Plets).
[1] Formerly at School of Ocean and Earth Sciences, National Oceanography Centre, Southampton, European Way, SO14 3ZH, UK.

0305-4403/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2008.09.026

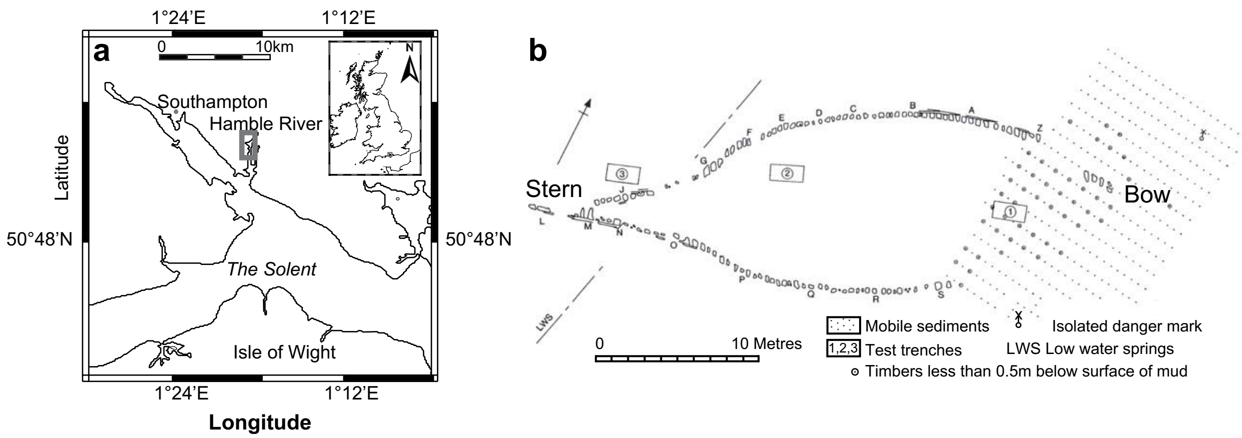

Fig. 1. (a) Location of the shipwreck site and (b) published site plan (Clarke et al., 1993).

identified as the *Grace Dieu* (Anderson, 1934). In 1970, the University of Southampton bought the wreck for £5 from the Ministry of Defence (Clarke et al., 1993). The results of several field seasons of terrestrial and underwater surveys were published in 1993 (Clarke et al., 1993; Friel, 1993; McGrail, 1993), including a site plan. This plan (Fig. 1b) shows marginal timbers protruding from the mud, the location of test trenches and evidence, derived from probe surveys, of timbers buried within the hull less than 0.5 m below the riverbed. Today, this protected wreck is still buried within intertidal muddy sediments, covered by 2–5 m of water and only during exceptionally low tides can some timbers be seen protruding from the mud. Particle size analysis of sediment samples in the vicinity of the wreck site showed a mean grain size of 4.7 ϕ (silt).

Burial of the wreck and difficult excavation circumstances within this shallow, tide-dominated river mean that information regarding the dimensions and shape of the deeper structure are still poorly understood. A previous study by Plets et al. (2008) demonstrated that a well-constrained 2D Chirp survey managed to image the remains of the *Grace Dieu*. The site was revisited with a high-resolution 3D Chirp sub-bottom profiling system in order to:

(1) demonstrate the effectiveness of this sub-bottom system for detecting shallowly buried objects in very shallow water;
(2) study the material properties of the remaining buried wooden structures through acoustic analyses;
(3) create a 3D reconstruction of the buried remains;
(4) use this 3D reconstruction to produce a hypothetical reconstruction of a larger part of the vessel.

2. Method

2.1. Survey and data collection

The 3D Chirp system is made of a 2.2 × 2.5 m rigid frame, containing an array of four Chirp transducers, in a Maltese Cross configuration, 60 receiver groups with a 25 cm horizontal spacing, a real time kinematic global positioning system (RTK-GPS) antenna and a three antenna GPS based attitude system (Fig. 2) (Bull et al., 2005). In the past, this system has been used successfully in shallow water for engineering purposes to detect small objects buried within the seabed (Vardy et al., 2008). For the purpose of this archaeological survey, conducted on 4 and 5 November 2005, the Chirp transducers transmitted a 16 ms long, 1.5–13 kHz linearly swept pulse, shaped with a sine-squared 8th Envelope, with a −3 dB bandwidth of 9.89 kHz, at a rate of eight pulses/second (Fig. 3). Modelling experiments have demonstrated that this particular Chirp sweep and transducer configuration should produce a theoretical vertical resolution of 0.076–0.11 m, and a horizontal resolution of 0.4–0.7 m in water depths of 2–5 m respectively using the Fresnel zone criterion. The RTK-GPS positioning and attitude system provided centimetric accuracy in the *x*- (easting), *y*- (northing) and *z*- (height) direction. This system received positional information from a temporary reference station on the adjacent shore, surveyed in by a terrestrial RTK system to an accuracy of <0.02 m.

A major problem encountered when using traditional acoustic/seismic survey methods (i.e. a seismic/acoustic source towed behind a survey vessel), in exceptionally shallow water is excessive acoustic blanking in the water column, created by the wake bubble cloud of the survey vessel's propellers. In order to increase the signal-to-noise ratio (SNR), bubble turbulence in the water column was avoided through a non-motorized deployment by moving the 3D frame over the site by divers. Within a total of 6 h of marine surveying, spread over two high tides, a surface area of approximately 50 × 50 m was surveyed (Fig. 4).

During the exceptionally low tides of the spring equinox in 2005, the surviving timbers protruding from the mud were surveyed with a terrestrial RTK-GPS system (Fig 4), a procedure which has been described in detail by Plets et al. (2008).

2.2. Acoustic data processing

The acoustic data, recorded in an uncorrelated format with a sample frequency of 50 kHz, was processed using PROMAX 3D

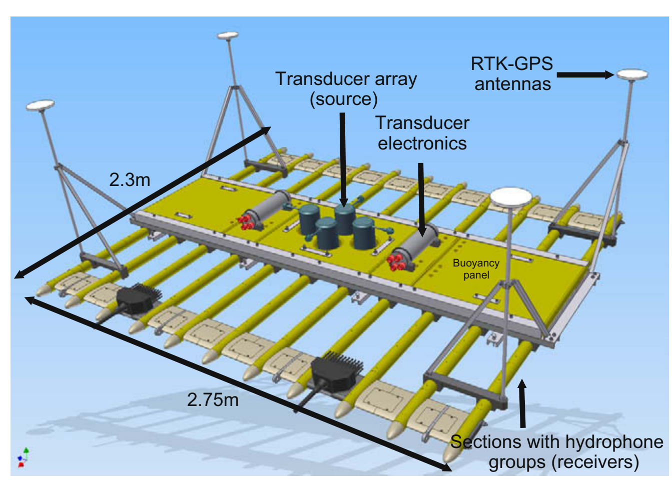

Fig. 2. Survey equipment configuration; high-resolution 3D Chirp system.

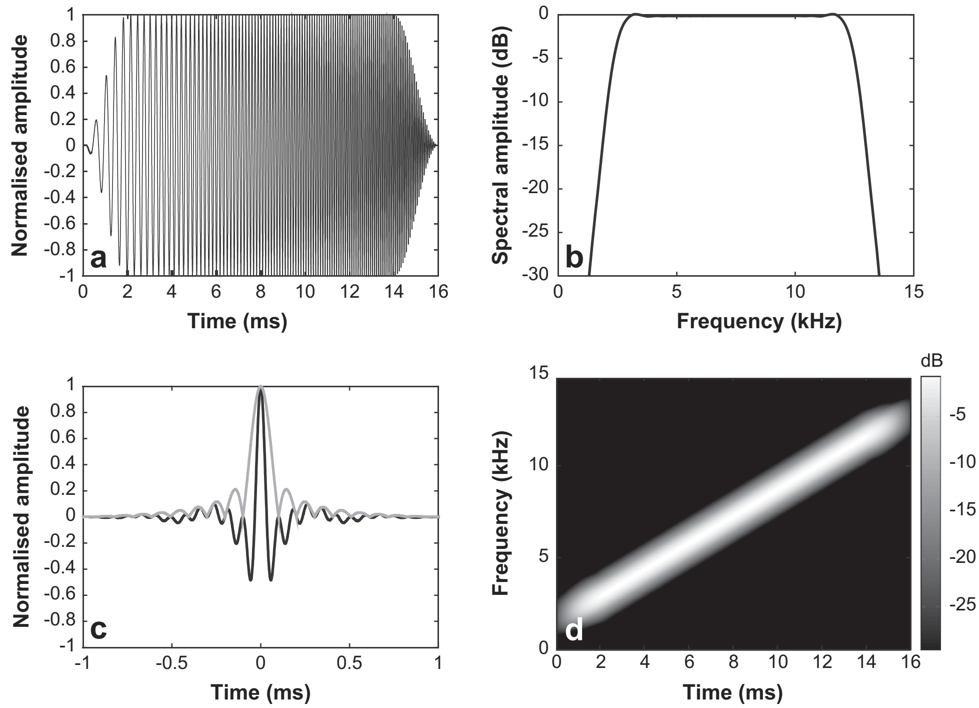

Fig. 3. Source sweep. (a) Time domain representation showing sine-squared 8th sweep. (b) Power spectrum of 1.5–13 kHz pulse. (c) Klauder wavelet, the normalized auto-correlation function of the sweep, with its envelope. (d) Spectogram showing linear frequency function (dB scale).

seismic processing software and consisted of: (1) 'bandpass filtering', eliminating low frequency noise; (2) 'cross-correlation', correlating the raw data with a replica of the initial Chirp sweep, improving the SNR; (3) 'geometry processing', computing the position of the source and individual receiver groups and combining this navigational data with the acoustic data; this step also includes tidal corrections; (4) 'binning', dividing data into 0.125×0.125 m square bins; for this particular data set, the number of traces within each bin varied from 1 to over 1800, with the majority of bins having at least 20 traces; (5) 'normal move-out correction', correcting for the variation of the reflection arrival owing to the variation in distance between the source and 60 receivers; (6) 'instantaneous amplitude calculation', applying an envelope to the acoustic signal; (7) 'stacking', combining all traces positioned within the same bin, increasing the SNR; and (8) 'automatic gain control', varying the gain down the acoustic section.

2.3. Data interpretation

All visualization and interpretation of the 3D volume was undertaken using Kingdom Suite Software, enabling the interpreter to slice the data in any vertical or horizontal (time slice) orientation, independent of the original survey direction. In order to create a full 3D reconstruction of the wreck, features believed to indicate remains of the *Grace Dieu* were picked manually on the horizontal and vertical slices.

To characterize features acoustically, reflection coefficients were calculated from the correlated data, without instantaneous amplitude or automatic gain control applied. This reflection coefficient, a value between −1 and +1, can be related to the physical properties of a material, namely its density and acoustic velocity (Kearey and Brooks, 1991). The technique used was derived from a method described by Warner (1990) and assumes normal incidence of the acoustic wave. The full derivation can be found in Plets et al. (2008).

In summary, the reflection coefficient of a deeper reflector (RC_{DR}) can be expressed as:

$$RC_{DR} = \frac{A_{DR}\left[v_w\left(TWT_p/2\right) + \overline{v_{DR}}\left(TWT_{DR} - TWT_p\right)/2\right]}{x} \qquad (1)$$

with A_{DR} the amplitude of the deeper reflector, v_w the velocity of sound through water, $\overline{v_{DR}}$ the velocity of sound through the sediments, TWT_p and TWT_{DR} the two-way-travel time to the riverbed

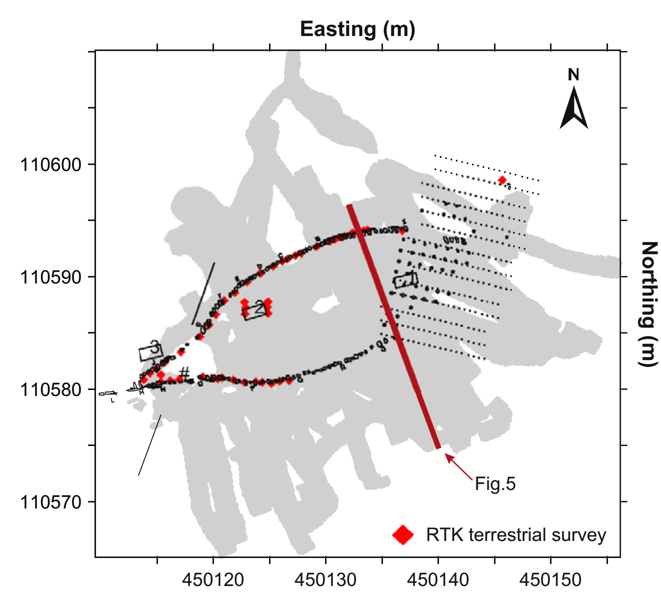

Fig. 4. Result of terrestrial RTK survey (◆), used to georectify the site plan (Clarke et al., 1993) and calibrate the marine acoustic data. Grey area indicates the 3D Chirp data volume. The coordinate system used for all maps is Ordnance Survey Great Britain 1936 (OSGB36).

and the deeper reflector respectively, and x the calibration coefficient, which can be written as:

$$x = \left| \frac{A_p \cdot v_w \cdot (TWT_p/2)}{RC_p} \right| \quad (2)$$

with A_p the amplitude and RC_p the reflection coefficient of the riverbed:

$$RC_p = \frac{A_m}{A_p} \cdot \frac{TWT_m}{TWT_p} \quad (3)$$

with A_m and TWT_m the amplitude and two-way-travel time to the multiple respectively. For the acoustic velocities, a water velocity of 1484 m/s (velocity of salty water at 10 °C and 30 ppt (Lovett, 1978)) and a sediment velocity of 1517 m/s were used (calculated from quadratic regression equations for a mean grain size of 4.7 φ (Robb et al., 2005)). In order to extract amplitude information from the acoustic data, the positive and negative peaks, directly adjacent to the chosen time slice, were exported with their corresponding TWT and the largest absolute peak was used to compute the reflection coefficient.

The reflection coefficient calculated from the acoustic data was consequently compared to predicted coefficients of archaeological wood based on the work of Arnott et al. (2005).

Finally, the picks from the acoustic data were used to create a true 3D image of the buried remains of the *Grace Dieu*. Not only was this used to create a body plan of the remains, but also to reconstruct a hypothetical larger part of the vessel. To achieve this, a software program, ShipShape, was used which assists naval architects in defining, fairing and drawing a set of ship's lines. The fairing software uses cubic splines through specified points, describing an elastic beam held at the nodes (Cross-Whiter, 1998), an interpolating method which is particularly good for the reconstruction of wooden shipwrecks.

3. Results and discussion

3.1. Acoustic data

The vertical sections show a high amplitude anomaly up to 2.5 ms TWT (c. 1.9 m) below a north-westward dipping riverbed (Fig. 5a). This anomaly truncates a high amplitude reflector, sub-parallel to the riverbed, believed to be a geological horizon (possibly Tertiary bedrock) (Fig. 5c). On the raw, correlated data (Fig. 5b), the anomaly is recognizable as a chaotic acoustic facies underlain by a reflector free acoustic blanking zone and separated from the sub-parallel geological reflectors by a truncation surface.

The horizontal sections, or time slices (Fig. 6), provide an image with greater clarity enabling the extraction of the dimensions, shape and location of the anomaly. On the time slice corresponding to the riverbed (Fig. 6a), lower amplitudes can be seen along the northern border of the shipwreck, 0.3–0.6 m to the south of the known position of the exposed timbers. In contrast, deeper time slices (Fig. 6b–f), taken parallel to the riverbed, illustrate the occurrence of a high amplitude zone with a distinct ovate plan form, coincident with the wreck location and anomaly seen on the acoustic profiles. Additionally, within the north-eastern part of this ovate feature (0.5 ms; c. 0.38 m) (Fig. 6b), a further high amplitude zone can be distinguished. This area shifts towards the south-west part of the wreck area on deeper slices (0.75 and 0.9 ms; c. 0.57 and 0.68 m) (Fig. 6c,d), indicating that this event dips to the south-west. On the time slice 0.9 ms (c. 0.68 m) (Fig. 6d) beneath the riverbed a distinct rectangular object, located at 450127E – 110580N at 1.4 ms (1.06 m) above the deepest point of the anomaly and with

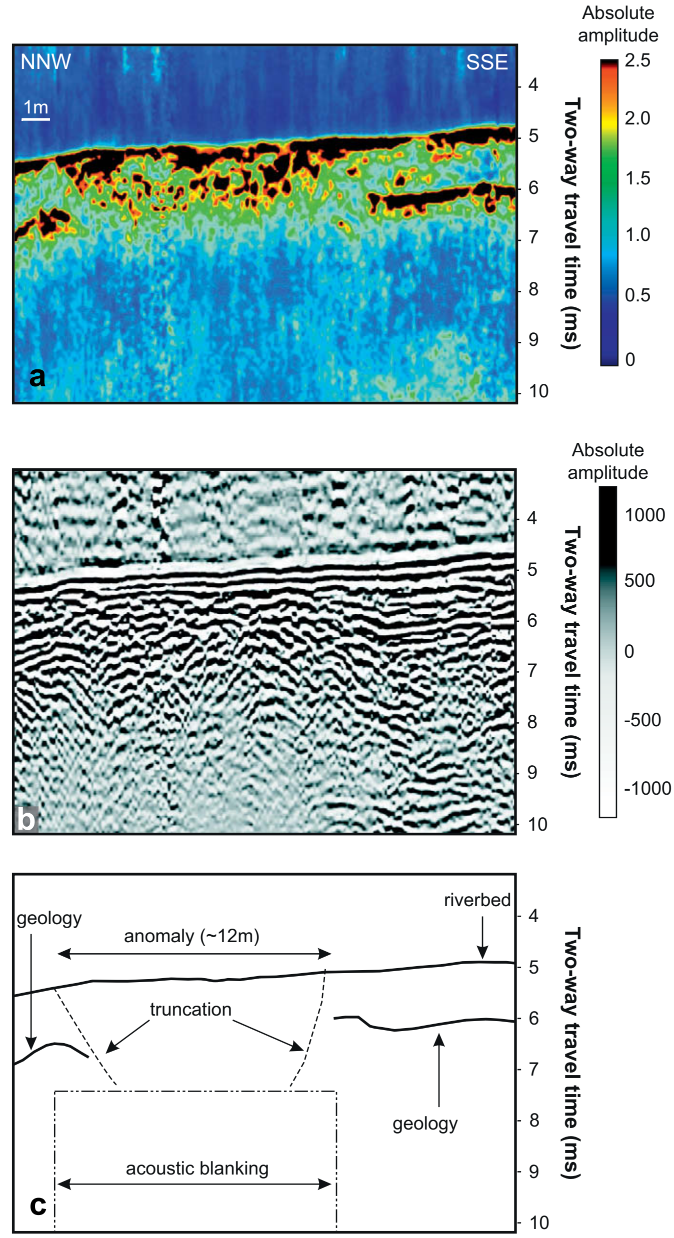

Fig. 5. Typical vertical section acquired over the wreck site (Line 183 indicated in Fig. 4). (a) Enveloped correlated data, (b) raw correlated data and (c) acoustic interpretation.

dimensions of 1.7 × 2.2 m, dominates the image. While the ovate feature has dimensions of 28 × 10 m at 0.5 ms (c. 0.8 m), it becomes shorter and narrower on deeper time slices (i.e. 22 × 1.3 m at 1.3 ms (c. 0.99 m) (Fig. 6e). On the time slice beneath the high amplitude anomaly (2.7 ms; c. 2.05 m) (Fig. 6f), i.e. in the acoustic blanking zone, no more high amplitudes occur within the shipwreck zone.

Based on the acoustic interpretation and correlation with the terrestrial survey data, the low amplitude zone seen on the riverbed is interpreted as the exposed timbers of the *Grace Dieu*. The ovate plan form is believed to be indicative of the buried hull structure and the high amplitude zone within it, dipping to the south-west, is interpreted to be planking buried within the hull. Finally, an initial interpretation of the rectangular feature is that it could relate to the mast step. Anderson (1934) excavated the mast step and described it as 'a flat piece of wood almost 3 ft (1 m) wide and 6.5 ft (2 m) long. It is 4 inch (10 cm) thick and has a hole in it measuring very

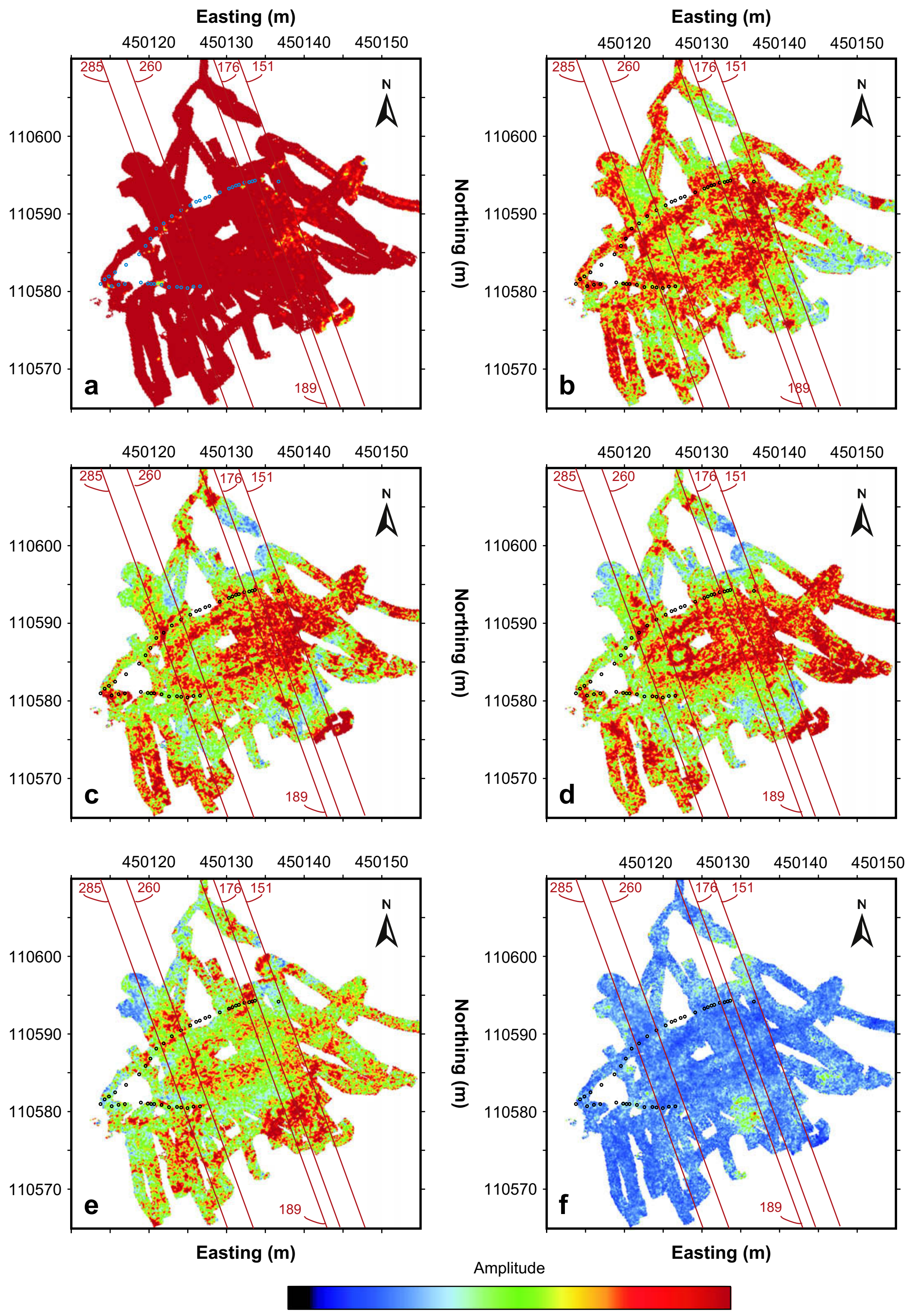

Fig. 6. Amplitude maps in relation to the RTK survey (a) at the riverbed, (b) 0.5 ms TWT, (c) 0.75 ms TWT, (d) 0.9 ms TWT, (e) 1.3 ms TWT and (f) 2.7 ms TWT beneath the riverbed. The colour bar represents absolute amplitudes. Indicated vertical acoustic sections have been discussed in the text (target characterization).

nearly 1 ft (30 cm) fore and aft by 2 ft (60 cm) aftwartships.' Further, on his construction plans, he drew it 4.2 feet (1.3 m) above the lowest part of the keel. Assuming that the deepest point of the imaged anomaly is the upper part of the keel, the position of the potential mast step within the shipwreck corresponds to archaeological facts. Further, the rectangular shape and horizontal position of the feature seems to match that of a mast step and its dimensions are close to what Anderson (1934) described, considering the horizontal resolution of the sub-bottom profiler.

3.2. Target characterization

In order to determine the material characteristics of these acoustic anomalies, reflection coefficients were compared with theoretical values for archaeological wood, based on the work of Arnott et al. (2005). In particular, reflection coefficients were calculated for the following possible features, identified from the original site plan and/or the acoustic data:

(1) exposed timbers related to the frame;
(2) buried timbers related to the frame and/or shell;
(3) buried planking dipping to the south-west;
(4) a rectangular feature, possibly the mast step.

To examine the exposed timbers, the reflection coefficient for the riverbed was calculated for a single acoustic section (line 285) (Fig. 7). The processed data (Fig. 7a) illustrates how the exposed timbers correspond to a gap in the riverbed. In other words, the acoustic wave did not reflect at this location because of the lack of acoustic impedance contrast between the brackish river water and the timbers. The actual reflection coefficients for this line (Fig. 7c) are seen to decrease to a value of zero in the location where the timbers are exposed. This pattern was observed in a number of acoustic sections, indicating that the timbers are acoustically invisible in the water column.

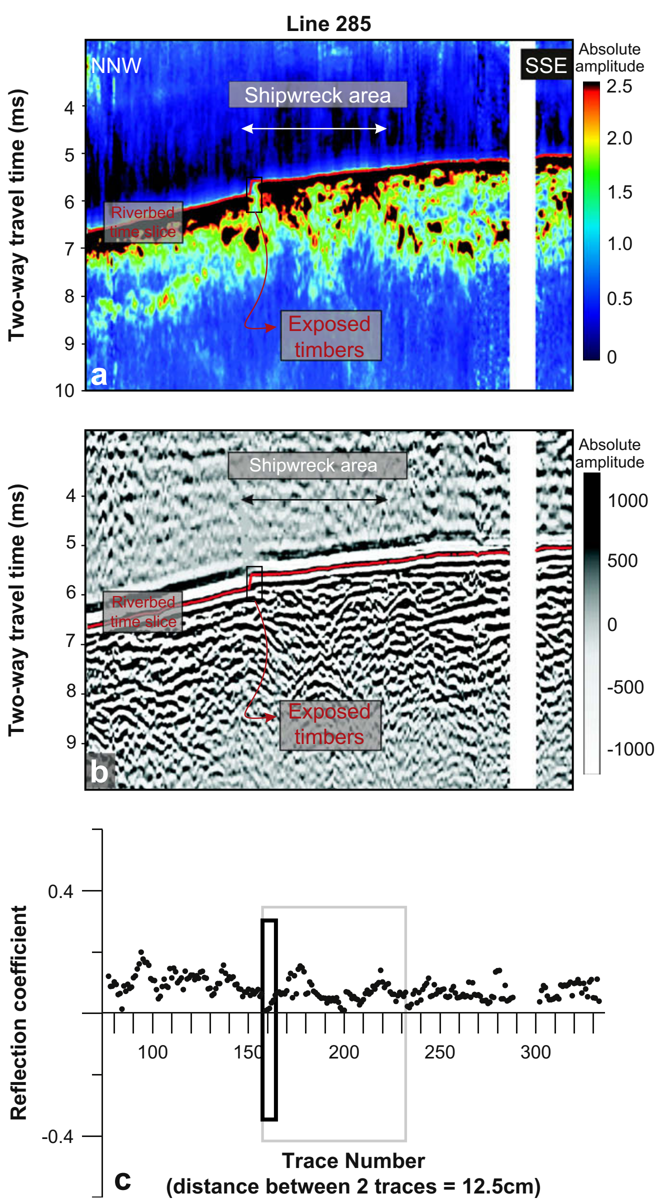

Fig. 7. Reflection coefficient calculation for line 285 (see Fig. 6); (a) Correlated, enveloped data; (b) correlated, raw data and (c) reflection coefficients along the line for the riverbed. Back box indicates position of the exposed timbers; grey box indicates position of shipwreck; colour bar represents absolute amplitudes.

There is no clear indication for the buried timbers related to the hull structure on the acoustic sections. Although a truncation surface was noted on the correlated data (Fig. 5b), it is unusual to find a discrete reflector associated with it. However, when a (discontinuous) reflector is associated with the position of the hull, the reflection coefficient rarely exceeds |0.1|, a value typical for the marine inter-tidal sediments surrounding the wreck (Kearey and Brooks, 1991). Nevertheless, in order to get an estimate of the reflection coefficient for the buried hull timbers, the reflection coefficient was calculated for an area 0.5 ms (c. 0.38 m) beneath the riverbed at an interval of 62.5 cm along the longitudinal axis of the vessel, for those vertical acoustic lines on which the position of the exposed timbers is well known. This calculation resulted in a reflection coefficient of |0.086| (77% negative), which is low and similar to or slightly larger than the reflection coefficient of the surrounding sediments (|0.03|–|0.09|).

The high amplitude zone within the remains of the hull was investigated by calculating reflection coefficients along three individual lines (line 151, 176 and 189) at a depth of 0.75 ms (c. 0.57 m) (Fig. 8a–i). In general, the reflection coefficients are larger in the shipwreck area (grey box, Fig. 8g–i) than for the adjacent region. For line 151, the reflection coefficient increases from |0.09| (45% negative) for the areas adjacent to the wreck to |0.19| (56% negative) for the shipwreck zone itself. Similarly, for line 176, the reflection coefficient increases from |0.07| (61% negative) for the bordering geology to |0.12| (60% negative) for the wreck area. Finally, for line 189, the reflection coefficient varies from |0.09| (63% negative) for the surrounding sediments to |0.12| (52% negative) for the shipwreck site. The individual high amplitude reflectors (black box on Fig. 8a–f) are believed to be the remains of a horizon of collapsed or abandoned timbers. This interpretation is strengthened by probe findings conducted by Clarke et al. (1993) (Fig. 1b), indicating the possible occurrence of buried timbers at a depth of c. 0.5 m. In order to characterize this horizon of planking, the reflection coefficient for a bright reflector has been calculated for the three separate lines (black box on Fig. 8g–i). Values of |0.30| (88% negative), |0.25| (94% negative) and |0.21| (77% negative) were found for the reflection coefficients for lines 151, 176 and 189 respectively.

Finally, the rectangular feature, clearly imaged at a depth of 0.9 ms (0.68 m), was analysed by calculating the reflection coefficient for a single line (line 260) (Fig. 9). This rectangular target, initially interpreted as the mast step, shows up as a bright reflector (Fig. 9a) with a reflection coefficient of |0.23| (11% negative) (Fig. 9c).

What do these numbers, summarized in Table 1, tell us about the physical properties of the objects? Wood is a structurally extremely anisotropic material, i.e. the distribution of cells differs between directions within the tree (Bucur, 1988). In order to describe these directions, three orthogonal axes can be defined: (1) parallel to the trunk of the tree (longitudinal – L); (2) perpendicular to the growth rings (radial – R); and (3) parallel to the growth rings (tangential – T) (Arnott et al., 2005; Dix et al., 2001; Quinn et al., 1997). As a consequence, wood also acoustically behaves as an anisotropic medium, with degradation affecting this behaviour. Arnott et al. (2005) described a method to estimate this degradation state of buried wood, caused by macrofaunal activity in aerobic conditions and, to a lesser extent, by microfaunal activity in anaerobic conditions. This work showed that reflection coefficients for oak samples show a linear relation with conventional density (ρ_c); conventional density being an established proxy for the degradation state of archaeological

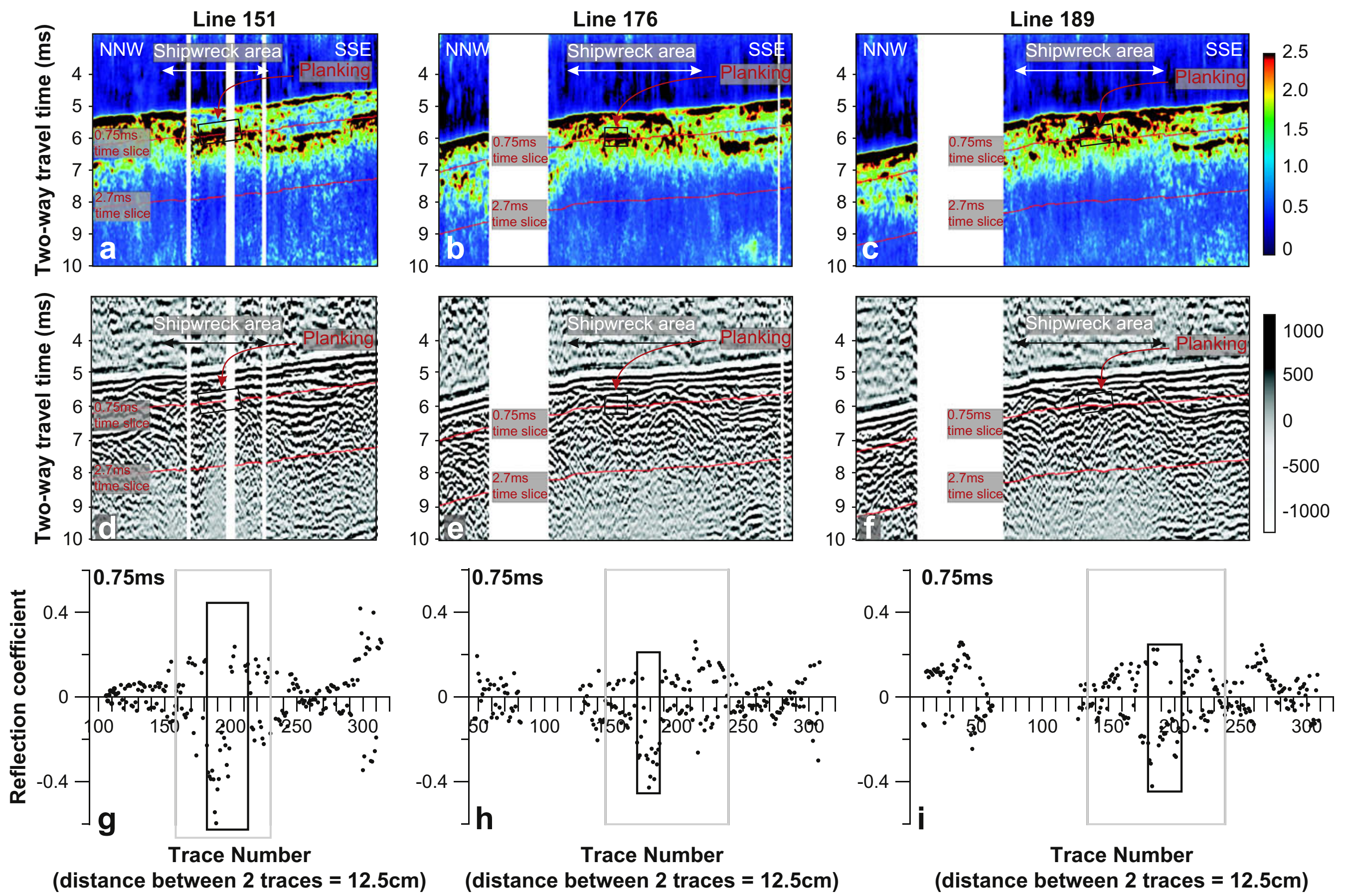

Fig. 8. Reflection coefficient calculation for lines 151, 176 and 189 (see Fig. 6). (a–c) Correlated, enveloped data; (d–f) correlated, raw data; (g–i) reflection coefficients along the lines at a depth of 0.75. Black box indicates position of possible buried planking, grey box indicates position of shipwreck; colour bar represents absolute amplitudes.

wood, which typically ranges from 580 kg/m^3 for undegraded to 280 kg/m^3 for heavily degraded oak (Arnott et al., 2005). From Richardson and Briggs (1993), the sediment density (ρ) of the inter-tidal sediments with a mean grain size of 4.7 ϕ can be calculated:

$$\varphi \ (\mathrm{g/cm^3}) = 22.85 - 10.275\rho \ (\mathrm{g/cm^3}) \tag{4}$$

resulting in a sediment density of 1766 kg/m^3. These values can be used to calculate theoretical reflection coefficients of degraded oak buried within the sediments of the *Grace Dieu* site. The results of these reflection coefficient (RC) calculations for the longitudinal, radial and tangential directions can be plotted against conventional density (Fig. 10), with linear regression relationships and correlation coefficients (r^2) of:

$\mathrm{RC} = 0.0007\rho_c - 0.0844$ for the longitudinal direction ($r^2 = 0.77$),
$\mathrm{RC} = 0.0012\rho_c - 0.6181$ for the tangential direction ($r^2 = 0.90$),
$\mathrm{RC} = 0.0013\rho_c - 0.6754$ for the radial direction ($r^2 = 0.92$).

Further, because some of the timbers protrude from the mud, the same procedure was performed for degraded wood in brackish water (with a density of 1023 kg/m^3). The resulting linear regression relationships are (Fig. 10):

$\mathrm{RC} = 0.0006\rho_c + 0.2191$ for the longitudinal direction ($r^2 = 0.77$),
$\mathrm{RC} = 0.0011\rho_c - 0.3335$ for the tangential direction ($r^2 = 0.89$),
$\mathrm{RC} = 0.0013\rho_c - 0.3898$ for the radial direction ($r^2 = 0.92$).

Based on the knowledge of the literature and excavations (Carpenter Turner, 1954; Clarke et al., 1993; Friel, 1993), it can be assumed that the majority of the wood buried on the *Grace Dieu* site consists of oak. Hence, these regression equations can be used to test our initial interpretation of the imaged objects and determine their degradation.

The exposed frame timbers protrude from the mud at an angle. More specifically, towards the stern, where a reflection coefficient of zero was found, this angle varies between 25 and 45°. Consequently, the emitted acoustic waves travelled through the wood at an angle with the three orthogonal axes. Unfortunately, no experiments have been conducted to test the acoustic behaviour of wood in any other direction than the three main axes. One can only assume that the linear regression relationship for such cases would plot between the three end members. From recent excavations and results published by Clarke et al. (1993), it is known that the material of the exposed timbers is very sound wood throughout. This reported low degradation state, together with a reflection coefficient of zero for the exposed timbers and the plotted results for reflection coefficients of oak in brackish water (Fig. 10), suggest that the acoustic behaviour of wood at an angle of 25–45° with the radial axis is closer to the radial and tangential directions than the longitudinal directions. If this is correct, a conventional density in the region of 300 kg/m^3 would be typical for the exposed timbers, indicating moderate to heavy degradation. The heavy degradation is probably only limited to the outer couple of centimetres of the timbers, with sound wood towards the core of the wooden planks.

Once below the riverbed, these sub-vertical frame timbers start to curve, becoming more concave. Furthermore, it is known that shell planking, attached to the frame, has been preserved below the riverbed. Therefore, the structural wood directions, through which the acoustic wave travels, change to radial and tangential directions at greater depths. Assuming that the low negative reflection coefficients found for the buried timbers are

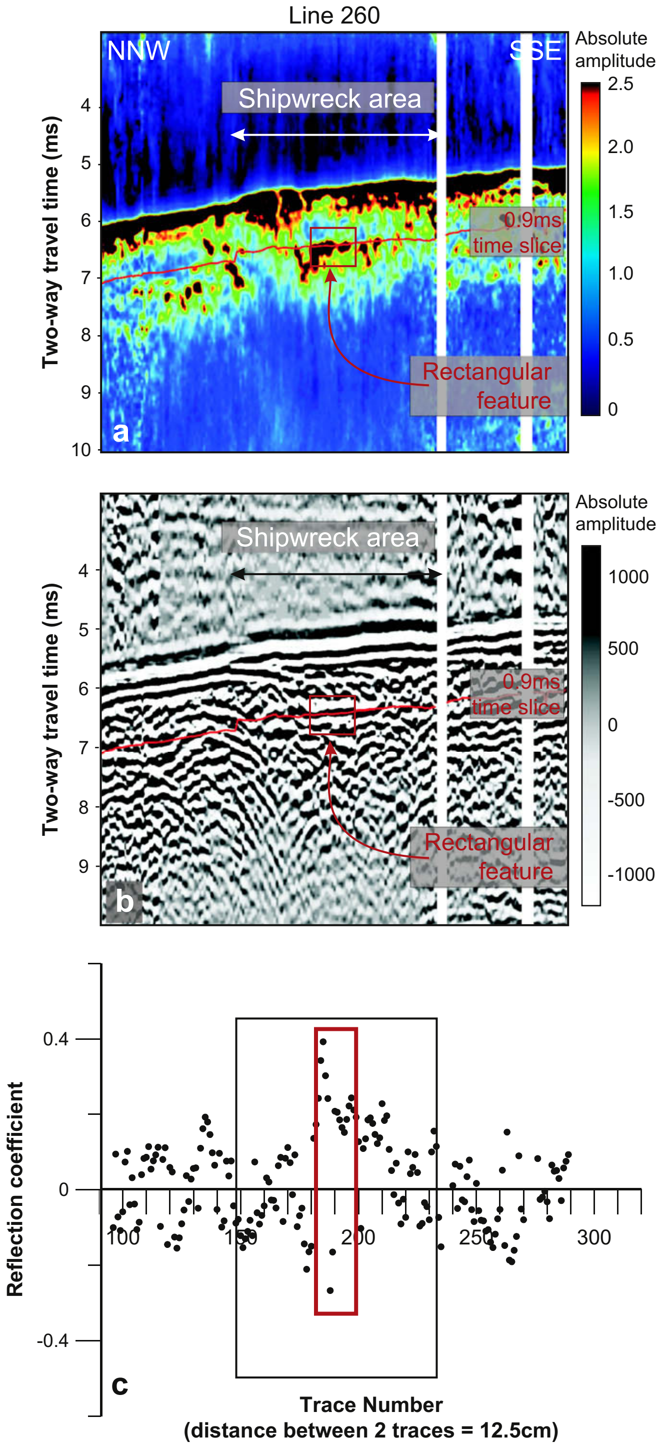

Fig. 9. Reflection coefficient calculation for line 260 (see Fig. 6). (a) Correlated, enveloped data; (b) correlated, raw data; and (c) reflection coefficients along the line at a depth of 0.9 ms. Black box indicates position of the shipwreck, red box indicates position of the rectangular feature; colour bar represents absolute amplitudes.

Table 1
Reflection coefficients calculated for features within the shipwreck area, as discussed in the text

Feature within wreck area	Reflection coefficient
Exposed timbers	0
Buried timbers	−0.086
Buried planking	−0.21 to −0.30
Rectangular feature	+0.23

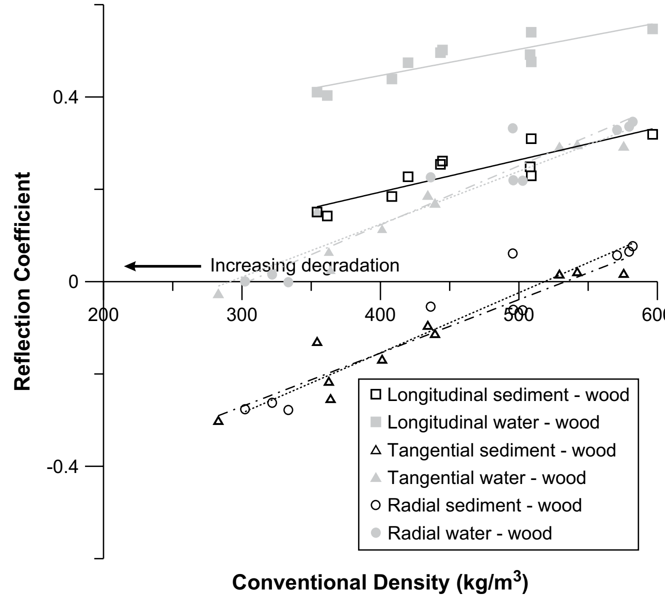

Fig. 10. Reflection coefficients for longitudinal, tangential and radial samples plotted against conventional density for oak samples buried in inter-tidal sediments (black) and oak samples in brackish water (grey).

associated with planking orientated with the longitudinal direction perpendicular to the incoming acoustic wave, the conventional density for the buried planking (Table 1) can be determined using the radial and tangential regression equations. A conventional density of 443 and 453 kg/m^3 respectively suggests that the buried part of the hull, and more particularly the shell, is moderately well preserved. This finding is close to the excavation findings and implies that the buried remains of the hull probably have not been exposed since their burial nearly six centuries ago and that macro- and microfaunal attack has been minimal.

The horizon of planking buried within the hull, with its strong negative reflector (Table 1), shows the typical acoustic characteristics of degraded oak buried in fine grained sediment (see Bull et al., 1998; Quinn et al., 1997). These planks are most probably buried with their tangential and/or radial axes perpendicular to the riverbed. Hence, the regression relationships suggest a conventional density between 265 and 340 kg/m^3, and between 288 and 358 kg/m^3 respectively. If these planks are oak timbers, these results indicate moderate to severe degradation, implying that they must have been exposed on the riverbed for a period of time during the past six centuries or have been subject to microfaunal degradation. Alternatively, these planks could be made of beech, a wood that is more vulnerable to wood boring organisms and susceptible to bacterial deterioration in anoxic environments than oak. Beech is known to have been used in the building of the *Grace Dieu* (Carpenter Turner, 1954), and six centuries of macro- and/or microfaunal attack would have caused extensive decay. Unfortunately, no acoustic laboratory results are available for degraded beech, making it impossible to estimate their conventional density. Except for the indication of planks from probe tests (Clarke et al., 1993), there is no further information in the literature which could test the two hypotheses.

The last feature, the rectangular features with its high positive reflection coefficient (Table 1), challenges the mast step hypothesis. If the mast step is a nearly 2 m long single piece of wood, as suggested by Anderson (1934), it would have its longitudinal axis parallel to the riverbed. Fig. 10 (R & T) suggests that the

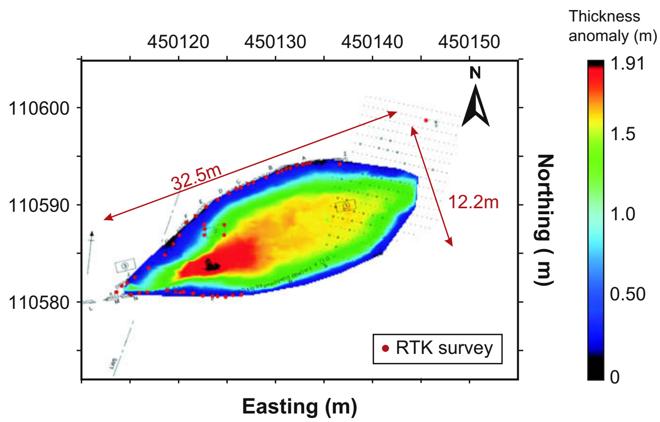

Fig. 11. Isopach map showing the thickness of the anomaly (in metres) and comparison with the terrestrial RTK data and excavation plan (Clarke et al., 1993).

conventional density, corresponding to a positive reflection coefficient of 0.23 would be higher than that of fresh oak. The only way this high positive reflection coefficient could represent part of a mast step would be if the single oak timber is not degraded and buried within much finer sediments (i.e. clay) than the surrounding inter-tidal silty sediments (Arnott et al., 2005). Until further excavations have been conducted, the rectangular feature cannot be positively identified as the mast step of the *Grace Dieu* based on acoustic material characterization. There is a possibility that it is an artefact created during previous archaeological surveys. Alternatively, if it is a feature related to the *Grace Dieu*, constructed from oak timber and buried within the inter-tidal sediments, then it would have to be a composite of several timbers with their longitudinal axis perpendicular to the riverbed. The conventional density would then be 449 kg/m^3, indicating that the timbers are only a little to moderately degraded, agreeing with reflection coefficients calculated for the buried shell planking.

These results show that the remote acoustic characterization of wood is not yet an exact science, and that archaeological excavation will always remain an integral part of shipwreck investigations. However, acoustic imaging and characterization can aid archaeologists to target specific features, thereby optimizing excavation and minimizing its impact. Further, this method could prove to be ideal for the monitoring and management of known, excavated sites for which in-situ preservation is preferred over recovery and storage on land.

3.3. 3D reconstruction

At present, reconstructing sunken shipwrecks requires that sites are exposed and, therefore, such reconstructions are often the end result of many months or years of extensive excavation and detailed logging, combined with historical information (Adams, 2003). Because the remains of the *Grace Dieu* are buried within inter-tidal sediments and excavation in these conditions has proven difficult, resources have not been directed to any extensive excavation. The original size and form of this unique structure have, therefore, remained defined by partial excavations and inexact dimensions noted at the time. As no ship plans were used in the construction of vessels in the 15th century, it is unlikely that any further historical information exists. However, using the obtained acoustic data, an attempt could now be made to create a full 3D image of the buried remains of this extraordinary vessel.

Firstly, an isopach map was created, showing the depth of burial of the wreck beneath the riverbed. To do this, the base of the high amplitude anomaly was picked manually on each vertical acoustic section, with the help of the horizontal time slices. The generated surface was then subtracted from the picked riverbed surface (Fig. 11). Fig. 11 shows how the vessel is dipping to the WSW under the riverbed with the keel (defined here as the deepest part of the vessel imaged on the acoustic data) at the stern end (WSW) being buried deeper than at the bow section (ENE), and indicates that the wreck is slightly tilted towards port side. The imaged remains have a minimum length of 32.5 m, a maximum width of 12.2 m and a maximum burial depth of 2 m.

Secondly, the acoustic picks were used to create a true 3D picture of the remains (Fig. 12). The vertically exaggerated (2×) representation shows how the preserved hull has very steep sides just beneath the riverbed, with flat timbers at its deepest point (Fig. 12a–c). Moreover, from this image, and the more realistic 1:1 reconstruction (Fig. 12d–f), the hull appears to be hogged, i.e. the keel arches upward in the middle and has sagged at the bow and stern, a common phenomenon in larger wooden ships.

Finally, comparison of the outline of the anomaly from the interpreted Chirp data with the terrestrial RTK survey and Clarke et al.'s (1993) site plan (Fig. 11), shows a strong visual correlation in the northern and south-western border. In the southern border,

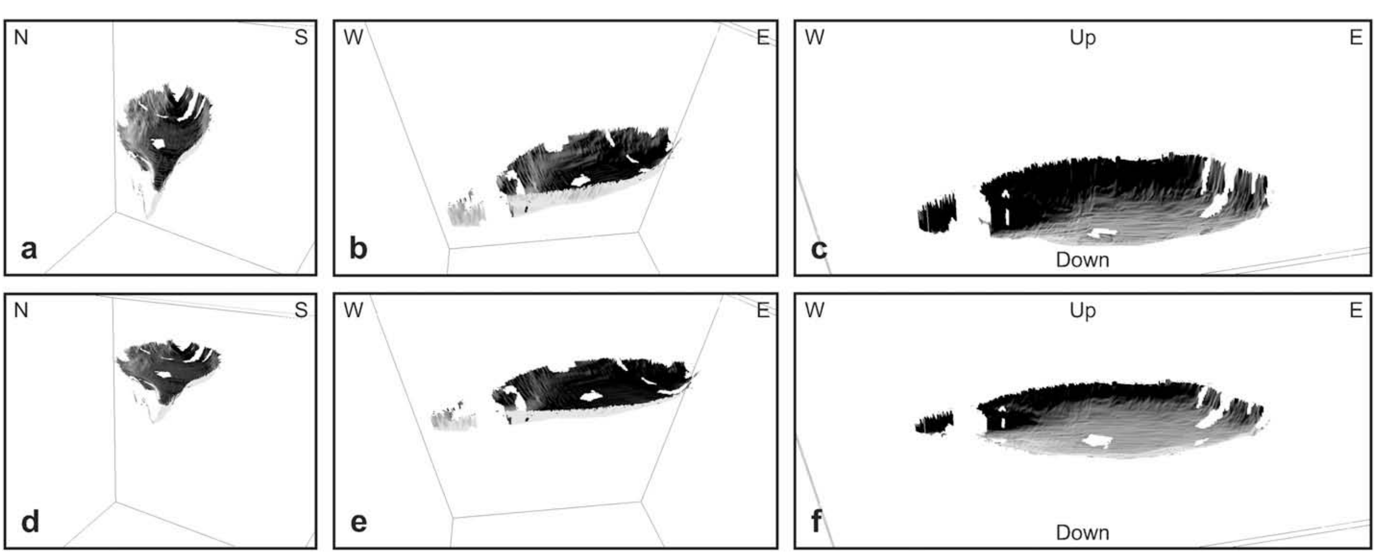

Fig. 12. 3D reconstruction of the buried remains of the *Grace Dieu* (a–c) with a 2× vertical exaggeration, and (d–f) with a 1:1 scale.

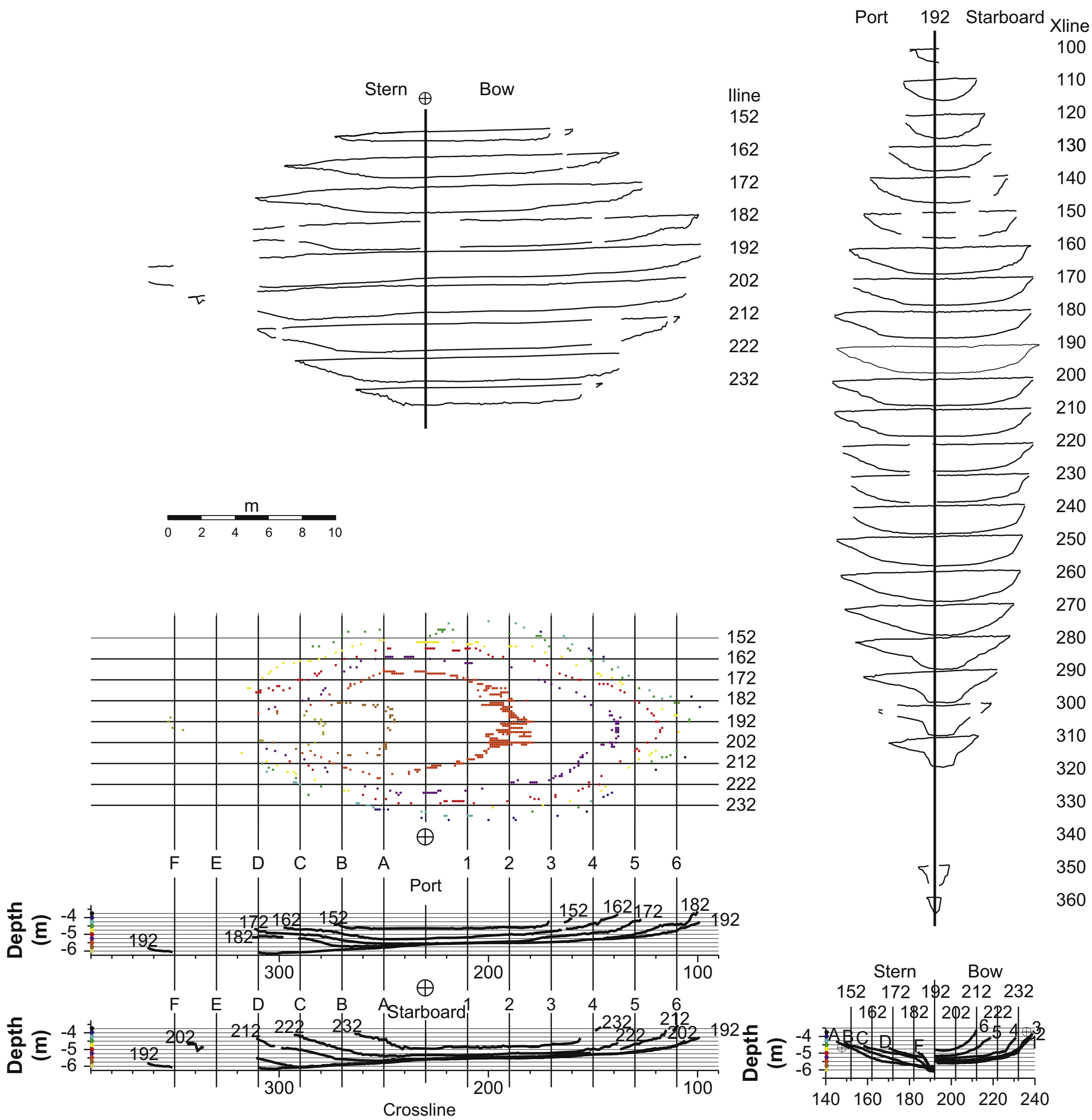

Fig. 13. Body plan of the buried remains of the *Grace Dieu*, derived from the 3D reconstruction.

where no terrestrial RTK data is available, the acoustic data implies that the hull is wider than suggested by Clarke et al. (1993).

Although this 3D reconstruction (with decimetric vertical and horizontal resolution) will never obtain the same level of accuracy as can be recorded manually from exposed wrecks by divers, the acoustic data can still be used to portray a faired version of the original hull of this vessel. It has been possible to create a body plan of the remaining hull of the *Grace Dieu* (Fig. 13), which was then used to generate a reconstruction of a larger part of the vessel, up to 5.5 m above the keel, using ShipShape software (Fig. 14). In the medieval and early modern shipbuilding process, the use of battens or the curvature of the planks themselves provided much of the

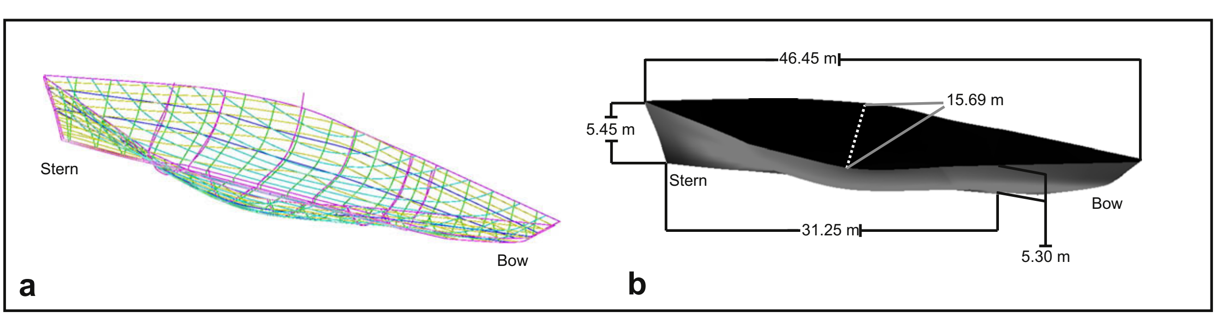

Fig. 14. Hypothetical faired 3D reconstruction of the bottom ~5.5 m of the *Grace Dieu* using ShipShape software: (a) hypothetical lines, cyan = buttock lines; green = frame; blue = longitudinals; yellow = waterlines; magenta = initial frames as derived from the acoustic data, the added stern- and stempost and border (for a reference to the colour scheme used, the reader is referred to the web version of this paper). (b) Shaded view of the hypothetical reconstruction with the indication of derived dimensions.

control of the hull form. Hence, with enough hull coordinates, derived from the constructed body plan (Fig. 13), a hypothetical set of lines was derived (Fig. 14). Several historic vessels have been reconstructed in this way (Adams, 2003) and the resulting fidelity of the reconstruction depends on the quality and quantity of spatial data recorded. However, this is the first time it has been attempted from acoustic data. The high degree of correlation of the reconstruction with the visible timbers suggests that this is a viable approach. For the *Grace Dieu* in particular, this hypothetical reconstruction suggests that the full length of the vessel must have been over 50 m and possibly over 60 m long and about 16 m wide, confirming Albizzi's historic account of a length of 67 m at the main deck (with the height of the forecastle about 15 m above the waterline) and a width of 15.4 m. More generally, this technique could become a useful aid for broad identification of buried wrecks based on dimensional and shape information. Further, it can confirm or refute historical and archaeological evidence of known wrecks and help determine their wrecking history.

4. Conclusion

This paper has demonstrated successful use of a 3D Chirp system for the detection of buried, inundated archaeological objects. All four initial aims were fulfilled:

(1) The buried hull of the *Grace Dieu* was successfully imaged as an assemblage of high amplitude reflectors on the vertical sections, with an eye-shaped planform on the horizontal time slices.
(2) Four features, buried within the wreck site, were characterized acoustically. The exposed hull timbers, buried hull timbers and possible planking were positively identified as wooden objects buried within inter-tidal sediments. A varying degradation state was determined for these objects. Conversely, from the results obtained from the acoustic characterization method, it was concluded that the rectangular feature buried within the hull might not be related to the mast step. Overall, the outcome of the target characterization showed that this method, established under laboratory conditions, needs further testing and calibration in the field. However, these findings demonstrate the potential of this method for future archaeological surveys and management projects.
(3) The vertical sections and horizontal time slices made it possible to create a full 3D reconstruction of the *Grace Dieu* for the first time. This reconstruction identified the dimensions and shape of the remaining hull.
(4) A hypothetical larger reconstruction using ship science software, has confirmed that the *Grace Dieu* was indeed a large ship for its time (possibly over 60 m), as suggested by historical information. This technique could be used in the future to identify minimum and maximum possible dimensions of buried wrecks, which could help the identification or confirmation of the identity of such vessels.

Geophysical methods will never be able to replace the detailed and accurate work the archaeologist performs, but it is hoped that the results from this study will optimize future excavation both in terms of the information retrieved, and also the resources expended and irreversible impact on the site.

Acknowledgements

This project was part of a PhD study, funded by the School of Ocean and Earth Sciences (University of Southampton) and the former Challenger Division for Seafloor Processes (now: NERC Strategic Research Division, National Oceanography Centre). The 3D Chirp project was developed with funding from the Engineering and Physical Sciences Research Council, GeoAcoustics Ltd and English Heritage. ShipShape software has been designed by the Wolfson Unit for Marine Technology and Industrial Aerodynamics (University of Southampton). Thanks to Dr D. Wheatley for the RTK survey and data-processing and to Dr D. Hudson for the reconstruction of the vessel in ShipShape. The authors would like to thank M. Vardy for the help with field work and the divers (Kieran, Jim and Adam) for braving the cold water. Finally, we are grateful to the three anonymous reviewers who helped to improve this paper.

References

Adams, J.R., 2003. Ships, Innovation and Social Change. Aspects of Carvel Shipbuilding in Northern Europe 1450-1850. Stockholm Studies in Archaeology 24, Stockholm Marine Archaeology Reports 3. Stockholm.
Anderson, R.C., 1934. The Bursledon Ship. Mariner's Mirror 20, 158–170.
Arnott, S.H.L., Dix, J.K., Best, A.I., Gregory, D.J., 2005. Imaging of buried archaeological materials: the reflection properties of archaeological wood. Marine Geophysical Researches 26, 135–144.
Bucur, V., 1988. Wood structural anisotropy estimated by acoustic invariants. International Association of Wood Anatomists Bulletin n.s 9 (1), 67–74.
Bull, J.M., Gutowski, M., Dix, J.K., Henstock, T.J., Hogarth, P., Leighton, T.G., White, P.R., 2005. Design of a 3D Chirp sub-bottom imaging system. Marine Geophysical Researches 26, 157–169.
Bull, J.M., Quinn, R., Dix, J.K., 1998. Reflection coefficient calculation from marine high resolution seismic reflection (Chirp) data and application to an archaeological case study. Marine Geophysical Researches 20, 1–11.
Carpenter Turner, W.J., 1954. The Building of the *Grace Dieu, Valentine* and *Falconer* at Southampton, 1416–1420. Mariner's Mirror 40, 55–72.
Clarke, R., Dean, M., Hutchinson, G., McGrail, S., Squirrell, J., 1993. Recent work on the R. Hamble wreck near Bursledon, Hampshire. International Journal of Nautical Archaeology 22 (1), 21–44.
Cross-Whiter, J., 1998. Hull design and geometry definition. In: Claughtin, A., Shenoi, A., Wellicome, J. (Eds.), Sailing Yacht Design. Essex: Addison Wesley Longman Limited, pp. 215–234.
Dix, J.K., Arnott, S.H.L., Best, A.I., Gregory, D.J., 2001. The acoustic characteristics of marine archaeological wood. In: Leighton, T.G., Heald, G.J., Griffiths, H.D., Griffiths, G. (Eds.), Acoustical Oceanography. Institute of Acoustics, Bath, Institute of Acoustics, pp. 299–305.
Friel, I., 1993. Henry V's *Grace Dieu* and the wreck in the River Hamble near Bursledon, Hampshire. International Journal of Nautical Archaeology 22 (1), 3–19.
Kearey, P., Brooks, M., 1991. An Introduction to Geophysical Exploration, second ed. Blackwell Science, Oxford.
Lovett, J.R., 1978. Merged seawater sound-speed equations. Journal of the Acoustical Society of America 63 (6), 1713–1718.
McGrail, S., 1993. The future of the Designated Wreck site in the R. Hamble. The International Journal of Nautical Archaeology 22 (1), 45–51.
Plets, R.M.K., Dix, J.K., Adams, J.R., Best, A.I., 2008. 3D reconstruction of a shallow archaeological site from high-resolution acoustic imagery: the *Grace Dieu*. Applied Acoustics 69, 399–411.
Quinn, R., Bull, J.M., Dix, J.K., 1997. Imaging wooden artefacts using Chirp sources. Archaeological Prospection 4, 25–35.
Richardson, M.D., Briggs, K.B., 1993. On the use of acoustic impedance values to determine sediment properties. Proceedings of the Institute of Acoustics 15 (2), 15–24.
Robb, G.B.N., Dix, J.K., Best, A.I., Bull, J.M., Leighton, T.G., White, P.R., Seal, A., 2005. The compressional wave and physical properies of inter-tidal marine sediments. In: Papadakis, J., Bjorno, L. (Eds.), Underwater Acoustic Measurements: Technologies and Results. Heraklion, Crete, Greece, pp. 1087–1092.
Vardy, M.E., Dix, J.K., Henstock, T.J., Bull, J.M., Gutowski, M., 2008. Decimeter-resolution 3D seismic volume in shallow water: a case study in small-object detection. Geophysics 73 (2), B33–B40.
Warner, M., 1990. Absolute reflection coefficients from deep seismic reflections. Tectonophysics 173, 15–23.