3D High Resolution Sub-Bottom Imaging: 3D Chirp

M. Gutowski, J. M. Bull, J. K. Dix, T. J. Henstock, P. Hogarth, T. Hiller, T. G. Leighton

Chirp sub-bottom profilers are marine acoustic devices that use a known and repeatable frequency-modulated source signature to produce vertical seismic reflection cross-sections of the sub-seabed. Here a 3D Chirp system is described that operates in the frequency range of 1.5 to 13kHz, to produce a three-dimensional image of the sub-seabed with typical penetration of 10 – 30m and decimetric horizontal and vertical resolution. The design incorporates a rigid frame that contains the Chirp source array together with 60 receiver elements, with positioning provided by an integrated Real-Time-Kinematic (RTK) Global Positioning System (GPS) together with a GPS based attitude system. The array can be surface towed from a small survey vessel and applied to targets of marine geological, engineering, archaeological and defence interest. The capabilities of the system to image sub-surface structures and buried objects is demonstrated in two data-examples imaging a buried engineering object in the Port of Southampton, UK and a buried wooden ship-wreck in the river Hamble, Bursledon, UK.

Introduction

Seismic reflection methods use controlled acoustic sources to image the sub-surface. The hydrocarbon exploration industry has routinely used marine 3D seismic reflection methods for over 30 years to image geological structures down to kilometres depth, with vertical and horizontal resolutions of some tens of metres. However, near-surface high-resolution sub-bottom profiling typically still relies on single-channel 2D methods, producing 2D sections that have to be interpolated to give a pseudo-3D interpretation of sub-bottom structures. Consequently, the effective horizontal resolution of these data is controlled by the survey line spacing, and reflections originating away from the vertical sections make the data difficult to interpret.

In contrast to the 2D method, the 3D method produces data volumes that can be processed coherently across a site. These processed volumes can then be visualised and interpreted to reveal the true three-dimensional geometry of the subsurface with a horizontal resolution orders of magnitude better than 2D data, thus making it possible to detect small objects and reveal complex geometries. Further, by respecting the three-dimensional wave propagation during data processing, 3D seismic reflection data is of significantly higher quality.

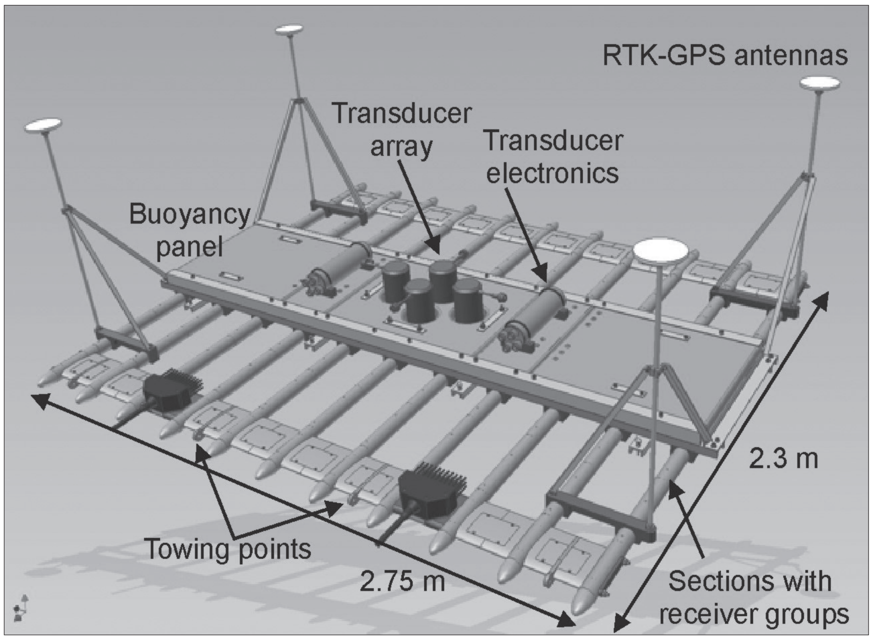

Figure 1: GeoChirp 3D: 3D high-resolution sub-bottom profiling system. The surface towed rigid 2.75m wide by 2.3m long frame holds 60 receiver groups in the longitudinal sections and a four-transducer source array on a central buoyancy panel. The transducers operate at a bandwidth of 1.5 to 13kHz. It is positioned using RTK-GPS and a GPS based attitude system with four GPS antennas attached to the frame.

There have been various projects over recent years aiming at down-scaling the 3D seismic reflection method to produce marine high-resolution 3D seismic data volumes by using high-frequency sub-bottom profiler sources. Henriet et al. [1] and Versteeg et al. [2] used boomer and water-gun sources with a frequency range of 1 kHz to 5 kHz and 100 Hz to 600 Hz respectively; Marsset et al. [3], Missian et al. [4] and Missian [5] used a boomer source with a frequency range of 100 Hz to 600 Hz; and Scheidhauer et al. [6,7] used a mini-airgun source with a frequency range of 50 Hz to 650 Hz.

In the downscaling from conventional to high-resolution seismics it is important that the receiver spacing is adapted to the frequency range to avoid spatial aliasing of the data, and to record adequately the absolute positions of the source and receiver elements during data acquisition. The design concept used in the 3D Chirp profiler described here, is to place all source and receiver elements on a rigid frame that is positioned using Real Time Kinematic (RTK) GPS technology (Bull et al. [8]). This is in contrast to the 3D high-resolution systems referenced above, which use lower frequencies and rely on individually towed and positioned source and receiver elements.

System Design

The 3D Chirp sub-bottom profiler, named the GeoChirp 3D, shown in Figure 1, consists of a surface towed array made up of longitudinal sections holding a total of 60 receiver groups, which are separated by 25 cm in both horizontal directions. The source array, consisting of four Chirp transducers operating on a bandwidth of 1.5 to 13 kHz, is positioned on buoyancy panels in the centre of the array. The source signatures can be chosen depending on the survey target [9]. The system is constructed from glass reinforced plastic and PVC foams making it a rugged, lightweight, overall neutrally buoyant system which is easily deployed and shows stable towing behavior. The array is positioned using Real Time Kinematic GPS positioning technology (Sagitta, Thales Navigation, CA, USA) together with a GPS based attitude system (ADU5, Thales Navigation, CA, USA) making it possible to determine the absolute position of the source and receiver elements with sufficient accuracy for 3D seismic data processing. The four GPS antennas are placed on the system and stay above the water surface during deployment. The construction concept makes it easy to expand the presently 2.75 m wide and 2.3 m long array by adding sections with additional receiver groups, which can be recorded by adding additional channels to the scalable custom-build acquisition system.

Data Acquisition And Processing

The 3D Chirp system is deployed from small survey vessels as shown in Figure 2. The survey area is generally covered by sailing closely spaced lines with a typical survey speed of 4 knots.

The seismic data is recorded with an integrated custom-built data acquisition system, which allows online survey planning, monitoring and data quality control. It combines the positioning and seismic data into the industry standard SEGY format online, which can readily be loaded into standard seismic processing and visualization software. Post-processing includes trace-by-trace seismic processing steps, such as filtering, source sweep correlation and computation of instantaneous amplitude (see for example [10]). The data are then combined into a 3D data volume by assigning the reflection mid-points of the traces, calculated from their associated source and receiver positions, to a regular bin grid with bin sizes as small as 12.5 cm and stacking the traces to produce the data volume. Alternatively a pre-stack 3D Kirchhoff migration algorithm can be applied. This algorithm is based on 3D wave propagation theory and repositions reflection energy to the correct subsurface position and enhances data quality and resolution. The output is a regularly sampled data volume (see for example [11]).

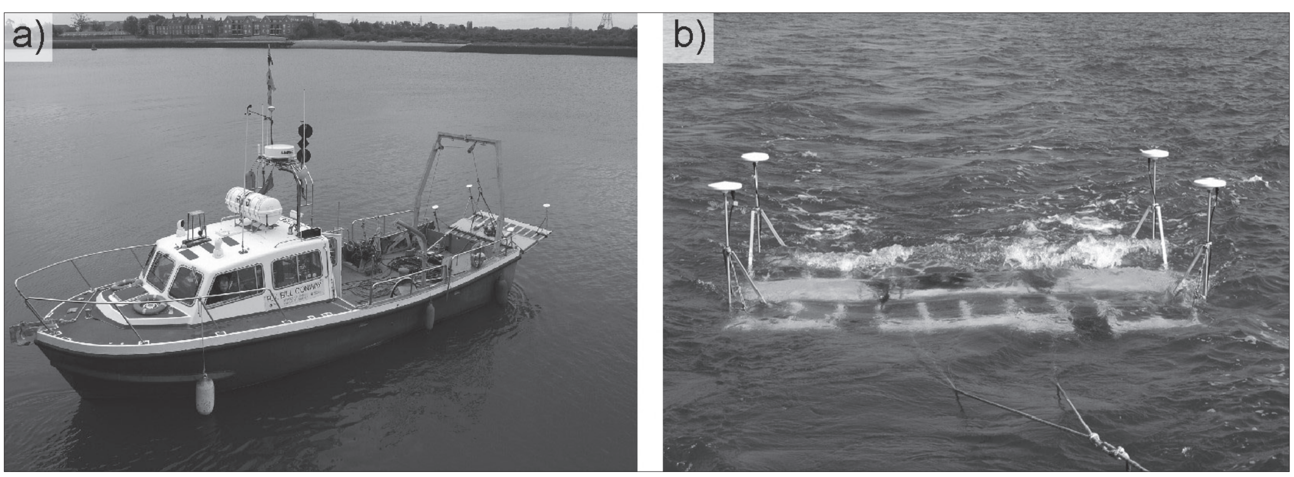

Figure 2: a) The 3D Chirp system is deployed from the A-frame of the 12m long R/V Bill Conway. b) Its lightweight open and rugged construction results in neutral buoyancy and assures a stable towing behaviour. The GPS antennas stay clear of the sea-surface during the survey.

Data Examples

Buried Engineering structure in the Port of Southampton, UK

In the 1970's the Prince Charles Container Terminal was constructed in the Port of Southampton. Prior to the construction of the quay walls a coffer-dam, formed with steel sheet piles, was constructed. This was subsequently toppled into a pre-formed trench and buried. Commissioned by Associated British Ports (ABP) Southampton a survey was completed to locate and image the buried coffer-dam.

The area was surveyed in 6 hours and a seismic data volume was produced for an area of 200 m by 25 m by applying the Prestack 3D Kirchhoff migration algorithm. The data volume is shown in Figure 3.

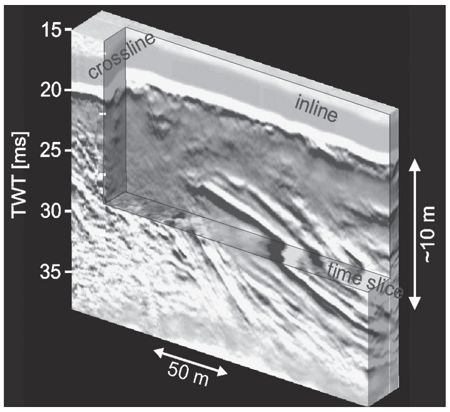

Figure 3: 3D Chirp data volume over the cof-fer-dam area. The data volume covers a 200m long by 25m wide area and images structures down to 15m below the seafloor. Note the vertical inline and crossline sections together with the horizontal timeslice. Dipping bedrock reflectors are apparent which are overlain by sediments and interrupted by a trench containing the buried cofferdam. See Figure 4 for a detailed interpretation.

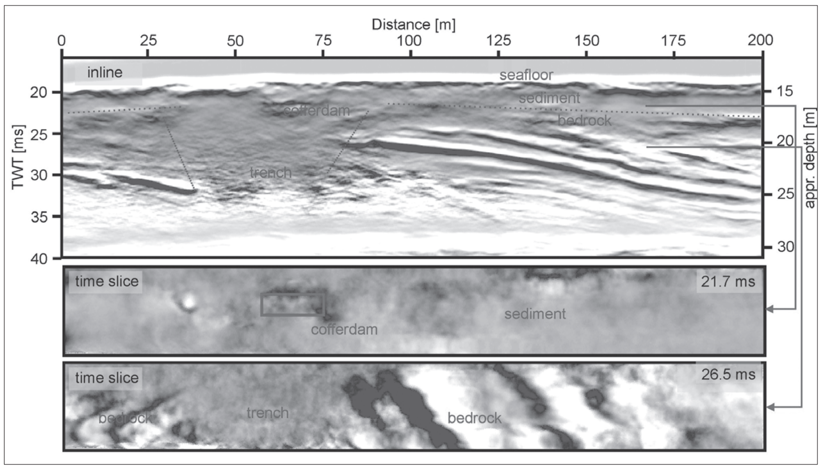

Figure 4: A vertical inline section and two horizontal timeslices from the 3D Chirp data volume of 200m length and 25m width (Figure 3). The seafloor is at c. 15m depth and the maximum penetration is equally 15m. The sections show dipping reflectors in the bedrock which are overlain by sediments. Between 25m and 85m a disturbed area is apparent that is interpreted as the trench which was dredged to hold the toppled cofferdam and then later in-filled. Within the trench the reflection from the top of the cofferdam with a length of 17.5m and a width of 6m is apparent which corresponds to the dimensions recorded in detailed construction drawings of the structure. Note that the true strikes of the bedrock reflectors are apparent from the timeslice at 26.5ms TWT. The timeslice at 21.7ms TWT images the cofferdam within soft surficial sediments (above bedrock).

Sections of the data can be viewed in any orientation, independent of the original survey direction. In Figure 3 vertical inline and crossline sections are highlighted together with a horizontal timeslice, representing the reflection amplitudes at a constant Two-way-travel-time (TWT). The seafloor is at 20ms TWT which equals approximately 15m water-depth and the sub-surface penetration is equally approximately 15m. The bedrock, which underlies a sedimentary cover, shows dipping reflectors whose true dip and strike can be easily deduced from their 3D representation. A disturbed zone that represents the in-filled trench containing the reflection of the cofferdam interrupts the sedimentary cover and the bedrock reflectors. Figure 4 shows an inline section together with two time slices at marked depths, in which the described features are highlighted. The reflection associated with the cofferdam is believed to originate from the top of the structure. Its width of 6m and length of 17.5m matches the dimensions of the cofferdam revealed in technical drawings.

A buried wooden ship-wreck in the river Hamble, UK

A survey was conducted to image a wooden buried shipwreck: the Grace Dieu, who was built in 1418 and has served as the

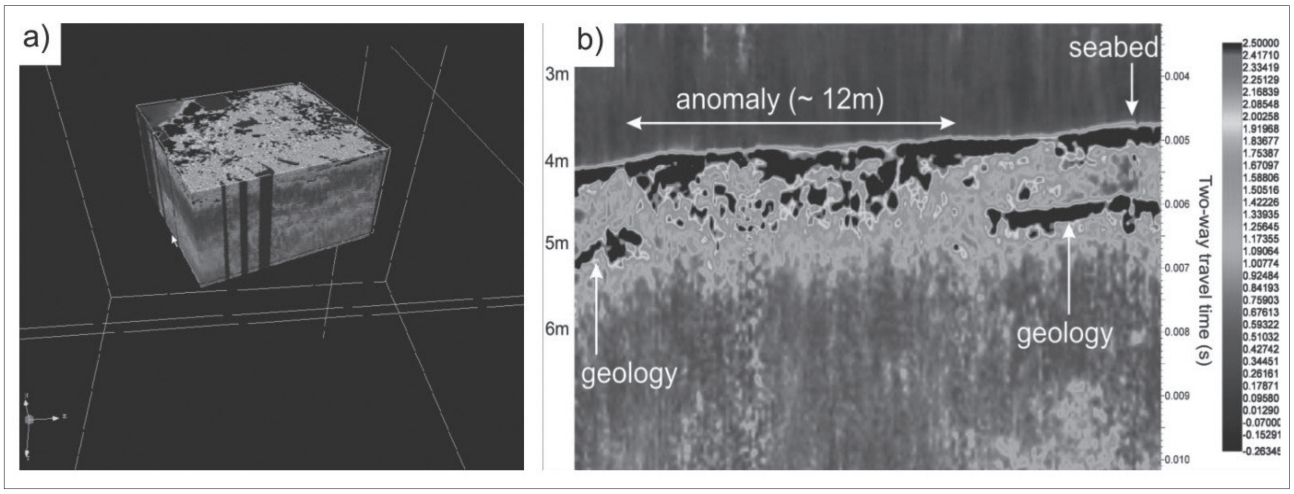

Figure 5: a) Data volume, stacked with a bin size of 12.5cm x 12.5cm, which images the Grace Dieu ship-wreck. b) a vertical cross-section through the data volume showing the seabed reflection at approximately 3m water-depth. The Grace Dieu ship-wreck is marked as anomaly, blanking the reflection of the local geology c. 1m below the seabed. The bottom reflection of the anomaly was interpreted in a 3D seismic interpretation software and is shown in Figure 6.

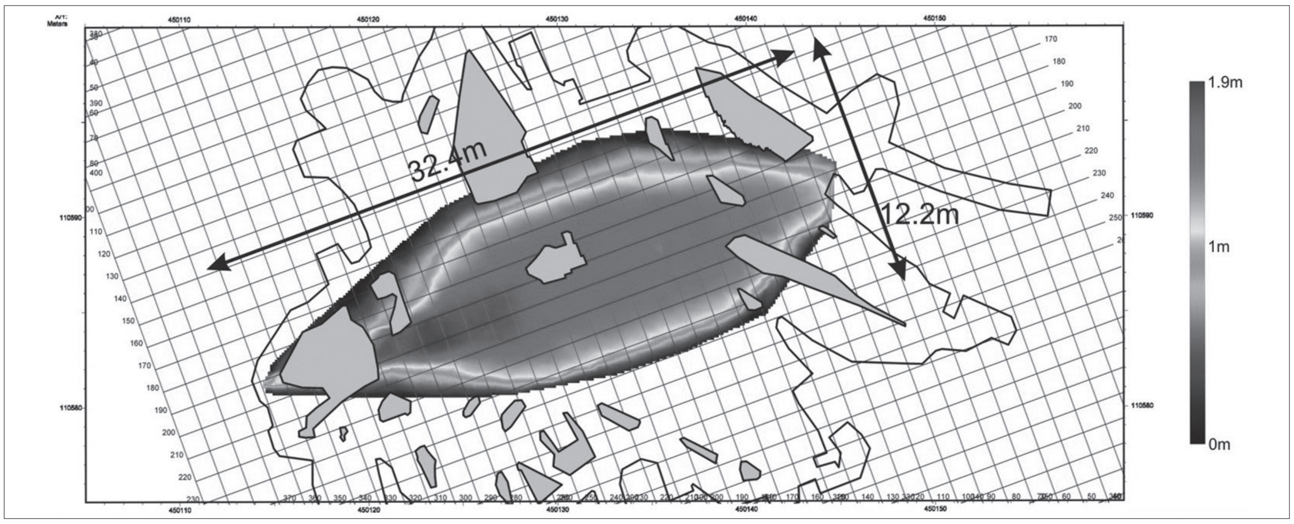

Figure 6: Isopach map showing the thickness of the anomaly representing the ship's hull with an overall length of 32.4m and a width of 12.2m.

'great ship' of Henry V's fleet. See Plets et al. [12] for details of this work. She was the largest ship ever built in England up to that time. Although the site has been studied for over 150 years by archaeologists, there is still very limited information on the basic dimensions and shape of the buried hull since it was never fully excavated [13]. Consequently, the data presented here not only demonstrates the capabilities of the system to image a wooden shipwreck in great detail but also increases the knowledge of this exceptional vessel applying this non-destructive method.

The situation of the survey area in a river bend made it impossible to navigate survey lines as described in the example in 4.1. instead the survey vessels was moored close to the side and the 3D Chirp system, equipped with floats for extra buoyancy, was pushed by divers to cover the 50m x 50m large area during a survey day.

In this case the data traces were binned on a regular grid with a side-length of the square bins of 12.5cm and stacked. Figure 5 shows the resulting data volume together with a vertical cross-section though the volume.

The isopach shows maximum dimensions of 32.4m x 12.2m and a maximum burial depth of 2m. It suggests well defined and pronounced longitudinal and lateral axial (keel) symmetry and indicates that the wreck is slightly tilted towards port side. A full 3D reconstruction of the remains of the hull of the *Grace Dieu* can be created. Additionally small, metre scale, objects are detectable in the data volume of potentially archaeological importance within and around the wreck.

Conclusions

The 3D Chirp system provides three-dimensional imaging of the subsurface for the shallow survey market. It three dimensionally images complex geometries and small objects in the subsurface with high resolution making it a valuable tool for marine engineering, defence, marine archaeology as well as general marine geology and geophysics applications. It is commercially available from GeoAcoustics Ltd.

Acknowledgements

The Chirp sub-bottom profiler was developed by the National Oceanography Centre, Southampton (NOCS) and GeoAcoustics Ltd. The initial project was funded by the EPSRC and GeoAcoustics Ltd. We are grateful to Gary Brown (ABP) for assistance and advice during the Port of Southampton survey. We are grateful to Ruth Plets for making the work presented as data example 4.2 available to us.

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