IWT SBO PROJECT 120003 "SEARCH"

Archaeological heritage in the North Sea

Development of an efficient assessment methodology and approach towards a sustainable management policy and legal framework in Belgium.

Archeologisch erfgoed in de Noordzee

Ontwikkeling van een efficiënte evaluatiemethodologie en voorstellen tot een duurzaam beheer in België.

ACOUSTIC SURVEY TECHNIQUES FOR MARINE ARCHAEOLOGICAL INVESTIGATIONS

WP 1.1.2

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Table of contents

1 Introduction

Marine acoustic methods are the most widely used surveying technique to study the structure and properties of the seafloor and its underlying substrate. The range of available techniques is extensive and their capabilities have no parallel with any other non-invasive investigation technology. They are based on the study of the propagation characteristics of acoustic waves in the propagating media. The basic technique of acoustic methods consists of artificially generating acoustic waves and measuring the time required for the waves to travel from the source to an acoustic receiver. From the knowledge of the travel time and the propagation velocity it is possible to reconstruct the paths of the acoustic waves and hence to deduce information of the structure of the propagating media.

Acoustic methods are widely used for oil and gas exploration [*Telford et al.*, 1990] but also in near-surface or shallow applications like engineering, environmental studies, mineral exploration and archaeological investigations (e.g. Dix 2008). In marine archaeology in particular, penetrative and non-penetrative acoustic techniques have been successfully used to investigate wrecksites and buried landscapes and/or objects.

Unfortunately, and most probably to lack of finance resources, a 'black-box' approach has often been adopted in the archaeological community with regard to penetrative techniques, with users accepting the resultant acoustic image as a definitive 'snapshot' of the sub-bottom substrate without understanding the physical process laying behind the technology. This lack of knowledge has led to an increase in expectations from users who ignore the limits of the techniques. Additionally, archaeologist often have to rely on data acquired for geo-technical purposes which often lack the high-resolution and coverage needed for archaeological analysis.

It is not the intention of this report to provide a comprehensive description of all aspects regarding marine acoustic methods, but to provide an overview of some aspects of high resolution marine seismic profiling. Chapter 2 summarizes the very basics of wave generation, propagation and classification that are required to understand the principle of acoustic methods. In chapter 3, a description of bathymetry systems is given, while in chapter 4, conventional sub bottom profiling methods are covered, paying special attention to their capabilities and limitations. Chapter 5 and 6 cover latest developments in shallow marine investigations like multi-channel seismic reflection and 3D seismic. The last chapters give recommendations to accomplish the project objectives.

2 Principles of wave propagation and classification

This chapter is based on standard exploration seismology textbooks, e.g. [*Sheriff and Geldart*, 1995].

2.1 Sound wave basics and properties

Waves are disturbances or vibrations that travel through the space transferring energy from one point to another, often with no permanent displacement of the particles of the medium. **Sound waves**, in particular, are waves that are not capable of transmitting its energy through a vacuum, therefore, they require a transmission medium to occur.

In general, all waves can be described by the following properties:
Wavelength: The distance between successive repetitions of the waveform.
Wavenumber: number of waves per unit distance.
Amplitude: It can be described as the strength or power of a wave signal. More simply it can be defined as the maximum positive (or negative) displacement of a particle from its undisturbed position.
Period: The time between successive repetitions of the waveform. Measured in seconds.
Frequency: The number of times the wavelength occurs in one second. Measured in cycles per second or Hertz.

2.2 Sound Wave Classification

When sound waves propagate through elastic media (solids) they are called Elastic Waves, whereas when they travel on non-elastic media (fluids) they are called acoustic waves.

Since inelastic media cannot support shearing stress, acoustic waves propagate by longitudinal motion, therefore the motion of the individual particles of the medium is parallel to the direction of propagation.

When elastic waves propagate through the Earth, they are called Seismic waves. For small deformations, rocks can be considered to be perfectly elastic. As a result, they can support both shear and compressional strains. This means that the media can be distorted both parallel and perpendicular to the direction of propagation. As a consequence, seismic waves present different propagation modes that are based on the way the particles oscillate.

There are two major groups of seismic waves:

- **Body waves**, which travel outward in all directions from a vibration source through the volume of a material.
- **Surface waves**, which exist only near a boundary or interface between two media.

Body waves can be classified as:

- Compressional, longitudinal, primary or P-waves. Their particle motion is parallel to the direction of propagation. As the waves pass through the medium, they cause compressions (shortening) and dilations (expansions). Since P-waves travel faster than any other seismic waves, they always arrive first, hence the name "Primary". P-waves can travel through any type of material, including fluids. Their propagation velocity strongly depends on the elastic properties and density of a material. The velocity of P-waves is

$$v_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

where *K* is the bulk modulus (the modulus of incompressibility), μ is the shear modulus (modulus of rigidity, sometimes denoted as *G* and also called the second Lamé parameter), ρ is the density of the material through which the wave propagates, and λ is the first Lamé parameter.

- Shear, transverse, secondary or S-waves. They are characterized by particle motion that is parallel to the wavefront and perpendicular to the direction of motion. S-waves are slower than P–waves. Speeds range from 0 to 70% of the velocity of P waves in any given material [*Sheriff and Geldart*, 1995]. S-waves can only travel through solids, as fluids (liquids and gases) do not support shear stresses. S-wave velocity is mainly a function of the density and shear properties of the medium. The shear wave velocity is

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

where μ is the shear modulus and ρ is the density of the material.

Surface waves

Depending on the media that are in contact we will find different types of surface waves. **Rayleigh** waves propagate along the free surface of a solid; **Scholte** waves propagate near the interface between a fluid and an elastic medium; and **Love** waves only exist when a softer layer is inserted between harder ones. When Rayleigh waves are guided in layers, they are referred to as **Lamb** waves, Rayleigh–Lamb waves, or generalized Rayleigh waves.

All these waves display different particle movement. The all have in common that their amplitude decreases rapidly with depth. Consequently, their geometrical attenuation with distance is lower than for body waves. As a consequence, surface waves are more energetic that body waves. On the other hand, surface waves travel more slowly than body waves.

Another important property common to all surface waves is that their propagation velocity depends on the frequency. This phenomena is called Dispersion. Since velocity in the subsoil normally increases with depth, longer period will be faster than shorter periods who will travel slower because they travel through lower velocity material.

2.3 Sound Wave Propagation Properties

When sound waves travel through a medium, they experience several phenomena that will affect their energy content (and therefore their amplitude), their direction and propagation velocity.

Attenuation
Attenuation is the energy loss of a propagating wave due to absorption, spherical spreading and scattering by particles or bodies present in the propagation path.

Reflection and Refraction
When a wave encounters a change in the elastic properties within the propagating medium, or when it passes through an interface between two different media, part of the energy is reflected and goes back through the same medium. The remaining energy is transmitted into the other media suffering a change in the direction of propagation according to Snell's law. At the critical incident angle, refraction occurs.

Diffraction
When a wavefront encounters a small object or an interface with a sharp edge (i.e. fault) laws of reflection are no longer valid. The energy will be diffracted instead of reflected or refracted. In this case, the irregular feature will act as a point source, radiating waves in all directions.

3 Seabed mapping

3.1 Introduction

The description of the principles of seabed mapping by echosounding techniques is based on standard hydrographic and marine geophysics textbooks, e.g. [*Jones*, 1999].

Echosounding techniques are based on the principle of transmission and reception of acoustic waves in the water. Basically, a transducer emits very high frequency acoustic waves directly to the water's floor, and a receiver records the time it takes for the sound wave to be reflected back after it strikes the bottom. Because sound travels at roughly 1500 m/s in water, it is simple to calculate the water depth at the survey location.

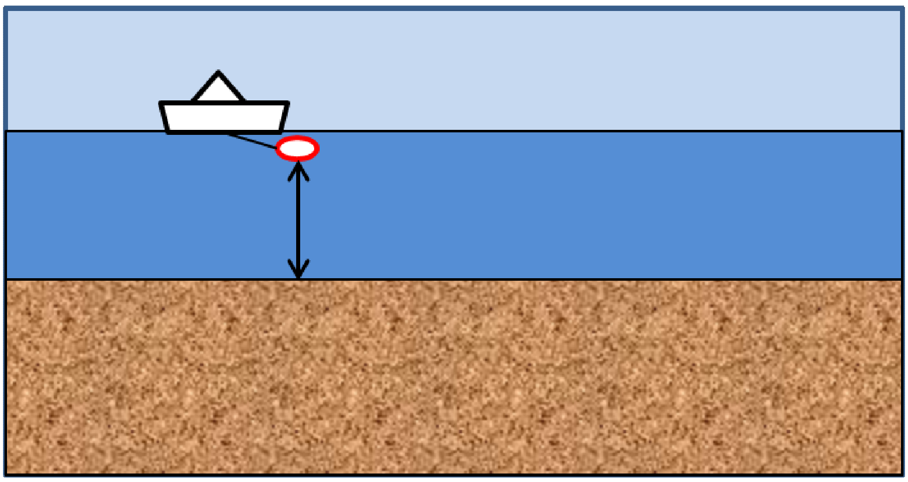

Figure 1. Echo sounding principle

Echosounding techniques use relatively high frequencies. These high frequencies cannot penetrate into the seafloor. Therefore they cannot provide information about the layers or objects beneath the seafloor. They are mainly used to trace the topography of the seafloor. However, they can be used for a variety of other purposes like marine archaeology, where echo sounding methods are commonly used for the detection of shipwrecks.

3.2 Seabed mapping methods

3.2.1 Single Beam Echosounder (SBES)

Single beam echosounders (SBES) are devices for the determination of the water depth. The measurement principle is based on the time interval between the emission of a sonic or ultrasonic pulse and the return of its echo from the seabed. The main characteristic of single beam echosounder is that the generated acoustic energy is projected into the water in the form of a vertically oriented beam with a narrow angle (typically around 7°). Therefore, they only provide information of the water depth directly beneath the research vessel (Figure 2). This process is repeated at a fast rate, on the order of milliseconds, generating a continuous recording of water depth along the survey track.

Theoretically, the water depth can be calculated by using an assumed sound velocity of water of 1500 m/s. Several factors, however, like temperature, salinity, pressure and density affect the sound velocity of water. A sound velocity profiler is therefore used to precisely measure the sound velocity through the water column. These velocities are then used to convert the recorded data in time to depth. Alternatively, the temperature and salinity are measured and the sound velocity in water is calculated using standard formulas like [*Medwin*, 1975]. Single beam transducer produce short pulse lengths with frequencies ranging from 24 kHz for deep water applications to 300 kHz for shallow water applications.

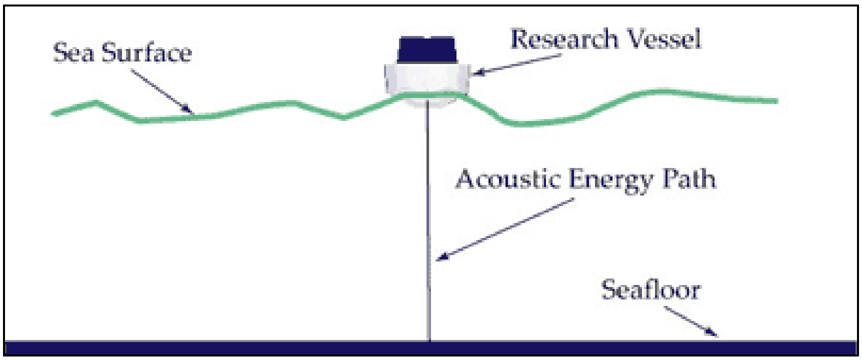

Figure 2. Single Beam Echosounder Principles
From Sea-floor Mapping Group of the U.S. Geological Survey website
(http://woodshole.er.usgs.gov/operations/sfmapping/group.htm)

SBES are an accurate and relatively simple technique for collecting seafloor bathymetry data (Figure 2). They are usually mounted to the hull, or to the side (sidemounted) of the ship. Main applications include, water depth indication, fish location, and seafloor classification.

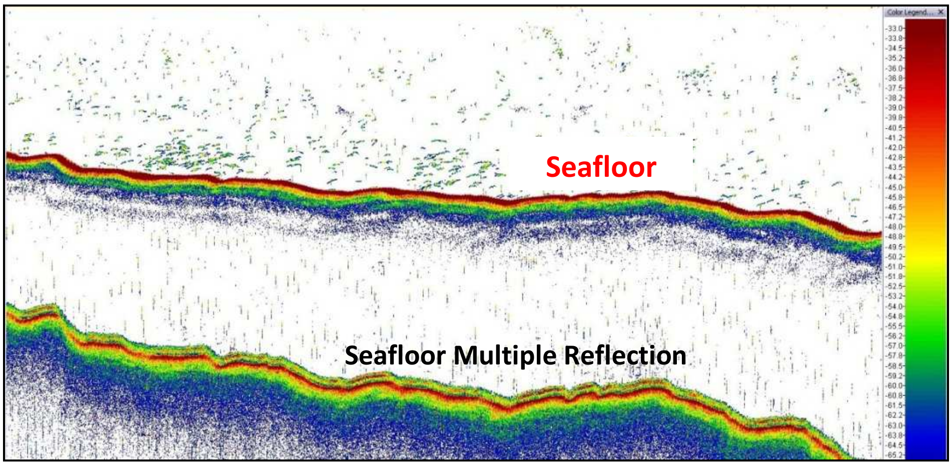

Figure 3. SBES Profile. Courtesy of Mario Veloso (RCMG – UGent)

Single beam data are too sparse for high density seafloor mapping and are more suitable for general seafloor bathymetry over very large areas. Consequently, detecting objects laying on the seafloor with a single beam echosounder is not easy. Using an extremely dense acquisition grid would allow us to cover the whole area of investigation, but this would take time and imply extra costs. Additionally, spatial resolution of a SBES depends on the aperture of the beam which increases with depth. For a given beam width, the illuminated area (or footprint) of the seafloor increases with depth. The footprint generally measures one tenth the water depth, so one could expect an illuminated area of 10m at a depth of 100m. Since the device is not capable of detecting where the reflections come from, any object present in the footprint area will be considered to be located below the vessel.

3.2.2 Multibeam Echosounder (MBES)

Multibeam echosounders are based on the generation of a high frequency fan shaped acoustic transmission pulse directed towards the seafloor that will provide information either side of the vessel's track. Separated transducer arrays for transmission and reception are generally used, where the former is oriented longitudinally and the latter is oriented transversally to the vessel's track. The transmission transducers generate acoustic pulses that are wide across-track and narrow along-track. In contrast, the reception transducers form beams that are narrow across-track and broad along-track, guaranteeing, intersection between the transmission and reception beams (Figure 4). These intersections in the seafloor plan form the areas for which the depths are measured.

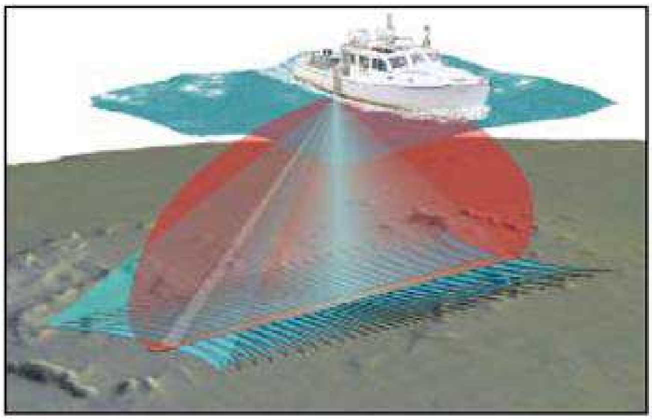

Figure 4. Multibeam Echosounder Principles (transmission beam in red, reception beams in blue)
From Australian Online Coastal Information website
(http://www.ozcoasts.gov.au/index.jsp)

Distance between the centres of the footprint in each beam is related to the spatial resolution of the MBES. The size of the footprint depends mostly on two factors, beam width and water depth. For a narrow beam, the footprint is smaller, producing a finer spatial resolution. Most devices generate beams with width ranging from 0.5 to 2.0 degrees. Water depth will affect resolution in the same way as it affects single beam echosounders. As the sonar pulse travels away from the source, it is subject to spherical spreading, meaning that the area illuminated by the beam gets broader with increasing depth. As a rule of thumbs, resolution is generally about 10 per cent of water depth. In order to avoid loss of data on the edges of the footprint, an overlap of at least 20 per cent is recommended. Surveys must therefore be planned according to the water depth, system technical characteristics, vessel speed and survey application.

As well as providing depth data, the reflected acoustic data also provide amplitude data, providing information about the composition of the seabed (low amplitude = soft sediment; high amplitude = hard substrate). However, not all MBES systems are able to record the amplitude information of the signal.

Various frequencies are utilized by different MBES systems depending on the seafloor depth. For example, low frequency (12 kHz) systems can collect swath soundings at full ocean depths, many up to 10,000 meters. In contrast, high frequency MBES systems (300+ kHz) are utilized for collecting swath bathymetry in depths of 20 meters or less.

Multibeam systems can survey large areas rapidly and accurately. They are essential for the study of the geological morphology of the seafloor (Figure 5).

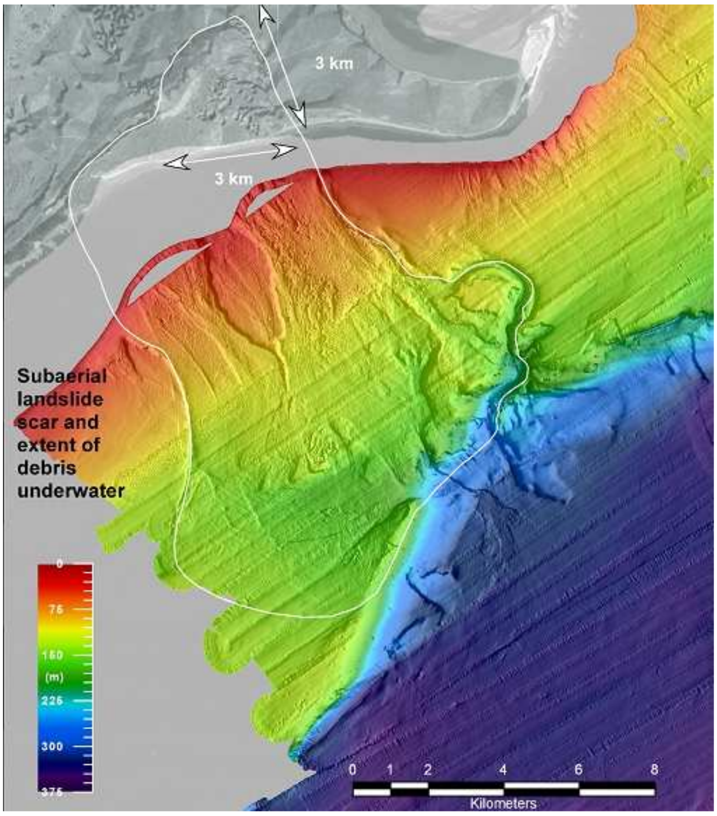

Figure 5. Multibeam Echosounder example showing submarine landslide From Laboratoire de paléomagnétisme sédimentaire et géologie marine (http://paleomag.uqar.ca/spip.php?article75)

With technological advances, multibeam echosounders have become affordable for use on archaeological investigations. Their high resolution and coverage of the seafloor make them ideal for detection of potential shipwrecks and other submerged objects that stick out of the seafloor or cause relief in the seafloor. An example of a MBES record of a shipwreck is shown in figure 6. Additionally, their ability to provide quantitative, repeatable information implies that conditions on submerged archaeological sites can be monitored and compared on a periodic basis.

Figure 6. Multibeam Echosounder example on wrecksite From Adud Deepocean (http://www.adus-uk.com/wreck-images)

3.2.3 Side Scan Sonar (SSS)

Side Scan Sonars (SSS) provide an acoustic, oblique, image of the seafloor. By "ensonifying" a swath of seabed and measuring the amplitude of the back-scattered return signals, an image of objects on the seabed is obtained and information on the morphology can be derived. SSS has a wide beam. SSS are usually installed on a fish towed near the water bottom, which enables the system to work in good stability and noise conditions.

Side scan sonar systems are configured with a linear array of transducers mounted on either side of the tow vehicle. A pressure wave is generated and propagates away from transducers. The emitted acoustic pulse is wide in the transverse direction and narrow the along-track direction. Pulse lengths vary from tens to hundreds of microseconds depending on the acoustic definition and range required. As the pulse of sound emitted by the transducers interacts with the seafloor at angles off normal, most of the energy is reflected away from the transducer. The acoustic backscatter that is reflected back to the transducer from the seabed is recorded for an extended period of time for each ping forming a time series of amplitudes. Using the vessels position, speed of sound in water, and the height of the bottom, the position on the seabed can be predicted for any point on this time series and a line of instantaneous backscatter amplitudes can be created that is referenced to positions along the beam footprint on the seabed. The SSS produces a wide beam to each side of the centre of the SSS fish. The result is a blank strip of no data directly below the vessel (Figure 7). SSS applications are sediment texture, habitats determination, detection of objects, inspection of pipelines and other underwater infrastructure, condition of shore protection, shipwrecks and fishery.

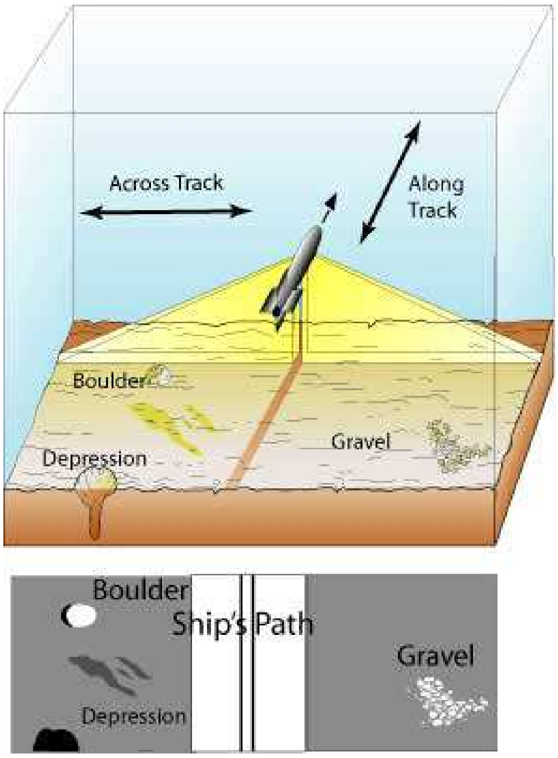

Figure 7. Side scan Sonar Principles
From Seafloor Mapping Group of the U.S. Geological Survey website
(http://woodshole.er.usgs.gov/operations/sfmapping/group.htm)

With specialised mosaicking software, which combines the images of many overlapping lines, the blank strip in the middle of each individual side scan record is removed. Multiple lines are combined to produce a single backscatter image of the seafloor.

The recorded signal can be used to discriminate different types of seabed, by combining areas of similar acoustic signature, and then attributing them with information relating to their biological or physical characteristics. In Figure 8, different bottom textures can be observed. The most pronounced examples consist of coarse sands and reef, the other consist of fine sands.

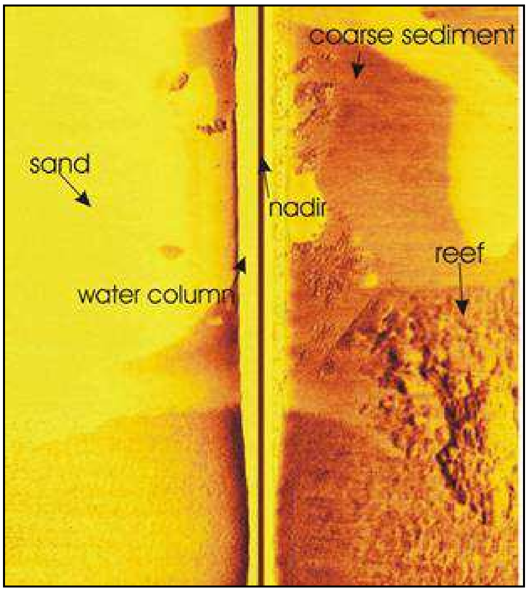

Figure 8. Side scan Sonar Example
From Australian Online Coastal Information website
(http://www.ozcoasts.gov.au/index.jsp)

In the field of maritime archaeology, side scan sonar is considered the instrument of choice for detection of objects laying on the seafloor, both natural (rocks) and anthropogenic (wrecksites). A shipwreck is easily recognised in Figure 9.

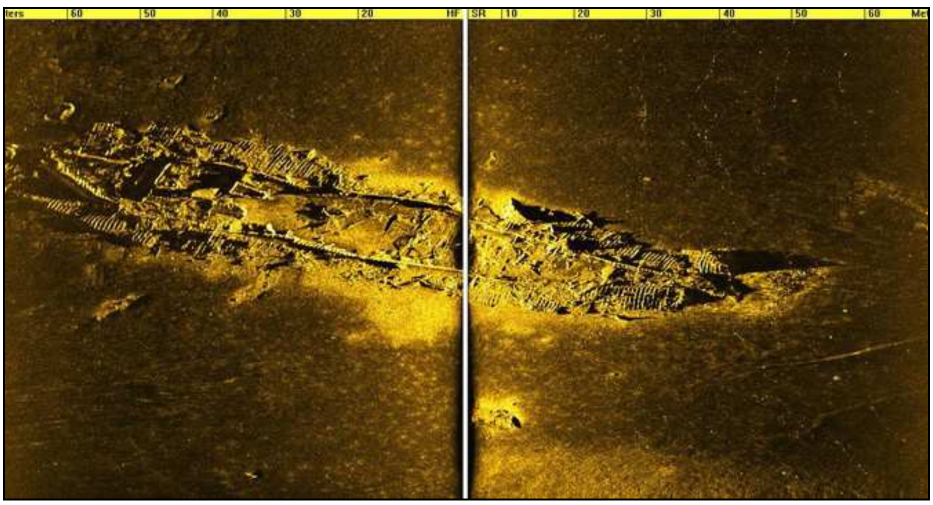

Figure 9. Side scan Sonar Example showing shipwreck
From Edgetech website (http://www.edgetech.com/edgetech/gallery?lid=6)

3.3 Advantages and Limitations of seabed mapping techniques

Data acquisition

Echosounders and sonars provide real time visual display of the seabed. Single beam echosounders (SBES) measure the water depth directly beneath the vessel providing a 2D profile of the water bottom. Multibeam echosounders (MBES) scan a wide swath of the seabed on both sides of the vessel, providing a 3D image of the water depth. Side scan sonar (SSS) systems provide an acoustic, oblique, photo-like image of the seafloor so no direct information of the water depth is obtained. SSS deliver information on both sides of the vessel, ultimately providing full spatial coverage of a targeted area. During acquisition, a rough picture of the seafloor is obtained. For the final image, however, processing is required to obtain a high quality bathymetric image.

The limitations of SSS and MBES are compensated in a new generation of instruments, the "bathymetric Side scan sonars". These instruments have become commercially available recently and combine MBES and SSS in one instrument. These "bathymetric Side Scan Sonars" provide information on both distance (i.e. depth comparable to MBES) and backscatter (comparable to SSS).

Echosounders can be fitted to most vessels either mounted to the hull or on the side of the ship, so acquisition is pretty straightforward. For MBES calibration procedures are complex and can be time consuming compared to those for single beam echosounders. SSS are towed behind the vessel below the water surface. In shallow waters, as a consequence, they can be adversely affected by poor sea conditions.

Data processing

Single beam echosounders do not require any particular post processing, as opposed to multibeam data which require processing before the data can be display as a 3D image. Side scan sonar data also require some post processing but not as much, and with simpler algorithms than multibeam data.

3.4 Recommendations on seabed mapping techniques

The final decision on which technique to use will be dictated the nature of the survey requirements and available resources. For this project in particular, multibeam echosounder techniques or the bathymetric SSS will be used to obtain an accurate image of the seafloor. No particular research will be done in this aspect since none of these techniques provide information on objects or layers lying beneath the seafloor, which comprise the main objective of this project.

4 Single Channel high-resolution sub-bottom profiling

4.1 Introduction

Seismic reflection techniques are also based on the principle of transmission and reception of acoustic waves in the water, however, a combination of powerful sources and relatively low frequencies waves are used to penetrate the seafloor and provide information on the structure and nature of the substrate below the water bottom.

Seismic reflection systems consist of a sound source, either towed behind a vessel or firmly mounted to the hull, that produces an acoustic pulse, and a ship-towed receiver (or array of receivers, called streamer or receiver cable) that records the returning wave field (Figure 10). The generated pulse travels through the water column at a speed determined by water temperature, salinity and suspended material concentration. Part of the acoustic signal is reflected from the seafloor, whereas the remainder penetrates the seafloor and is reflected when it encounters boundaries between layers or objects with different elastic properties. The amplitude and travel times of the returning sound waves are recorded. The result is a continuous record of the seafloor and units below the water bottom (e.g. Figure 11).

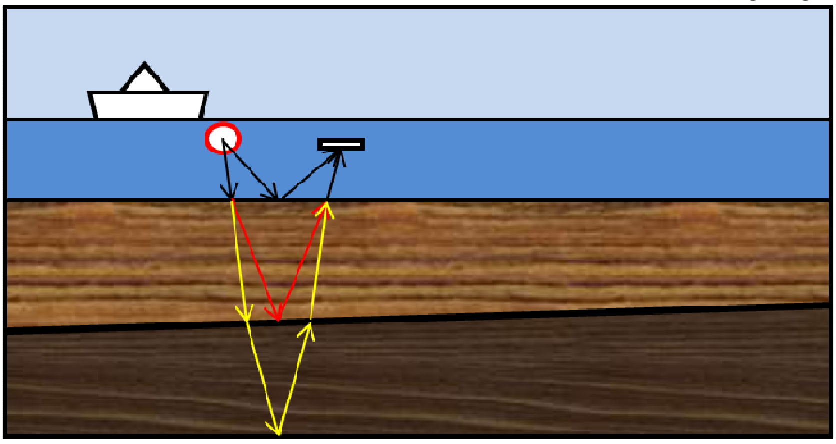

Figure 10. Seismic reflection principle (angles are exaggerated for clarity)

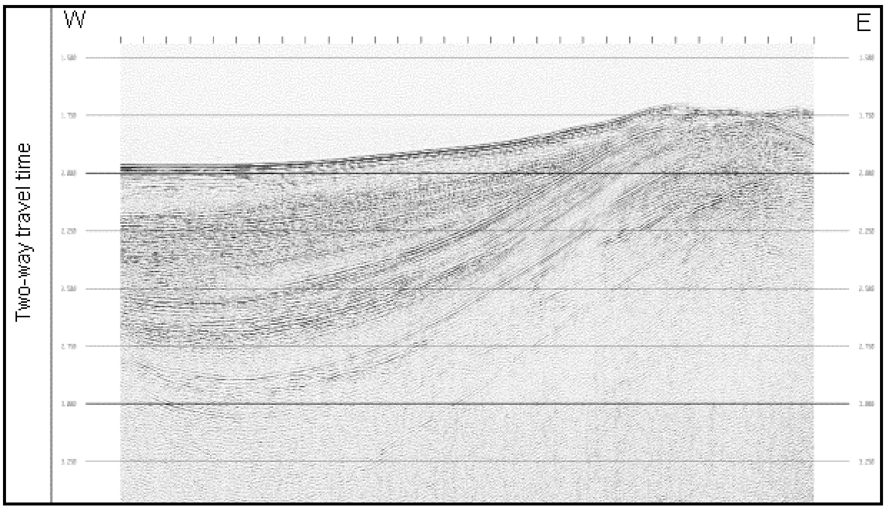

Figure 11. Single Channel seismic profile
From Sea-floor Mapping Group of the U.S. Geological Survey website
http://woodshole.er.usgs.gov/operations/sfmapping/airgun.htm

Conventional shallow, high-resolution, marine seismic reflection surveys are often conducted using a single-channel streamer. This streamer combines the signal of a reduced number of closely spaced hydrophones (usually 8 or 24) to generate one (stacked) signal per shot. This simple profiling system is called Single Channel Reflection Seismic and provides real time, zero-offset sections that are almost ready for interpretation.

Several physical parameters of the emitted acoustic signal, such as signal frequency, output power and pulse length determine the capabilities of the chosen technique. There is a trade-off between resolution and penetration into the seafloor. High frequencies provide higher resolution, but are limited in amount of penetration below the seafloor. On the other hand, lower frequencies provide lower resolutions but better penetration. Increasing output power allows for greater penetration into the substrate. However, in the case of a hard seabed or very shallow water, this will result in multiple reflections (i.e. seafloor echo, e.g. Figure 13) and lower signal to noise ratio. Finally, long pulse lengths yield more energy and result in greater penetration. However, longer pulses decrease the receiver’s ability to discriminate between adjacent reflectors, thus decreasing the resolution. On the contrary, shorter pulses correspond to broader bandwidth frequency response, thus increasing the resolution.

External factors also affect the performance of the sub-bottom profilers. The presence of sub-surface gas deposits within sediments can significantly degrade the acoustic signal. Gas modifies sediment physical properties, thereby reducing sediment strength and sediment sound speed and attenuating and scattering acoustic energy [*Kim et al.*, 2004]. In high-resolution sub-bottom profiles, the gas-bearing sediments appear as acoustic turbidity, acoustic masking or blanking, and enhanced reflections. Acoustic turbidity is a term used for shallow chaotic reflections, caused by the scattering of acoustic energy, that may mask nearly all other reflections possibly present at larger depths. Acoustic blanking produces reflection-free areas in the seismogram [*Missiaen et al.*, 2002]. On the other hand, enhanced reflections are coherent seismic reflections with extremely high amplitudes over part of their extent compared to the surrounding sediments. These high amplitude reflectors indicate that very little acoustic energy is being transmitted through the high reflectivity zone, producing shadow zones below the reflector and in some cases strong multiple reflections.

4.2 Sub-bottom profilers systems

There are many types of sub-bottom profilers. They can be classified on the basis of the frequency and strength of the emitted sound. High frequency profilers like Boomer, Pinger and Chirp provide detailed information about the near surface down to a hundred meters. Medium frequency profilers like Sparkers can penetrate to depths of a few hundred meters with a relative good resolution. Low frequency profilers are less relevant for near surface investigations as they can penetrate several hundred meters and more. They are usually deployed in multi-channel fashion.

4.2.1 Sparker

Sparker sources work by discharging a high-voltage electrical pulse between electrodes in a conducting fluid. The heat generated by the discharge vaporizes the water between positive and negative electrodes leading to the growth and collapse of steam bubbles due to the static pressure becoming smaller than the fluid vapour pressure [*Duchesne et al.*, 2007]. The implosion of these bubbles creates a broadband (200 Hz – 2 kHz) omnidirectional acoustic shock wave that can penetrate several hundred meters beneath the subsurface. The reflected signal is received by an array of hydrophones towed a few meters behind the source.

Figure 12. Acquisition using sparker source (© Geo Marine Survey Systems)

Small sparker sources can be operated from relatively small vessels (Figure 12). It requires a power supply on board of the ship to generate the electrical energy imparted to the point electrodes. It can be deployed off the stern, or may be towed alongside the ship.

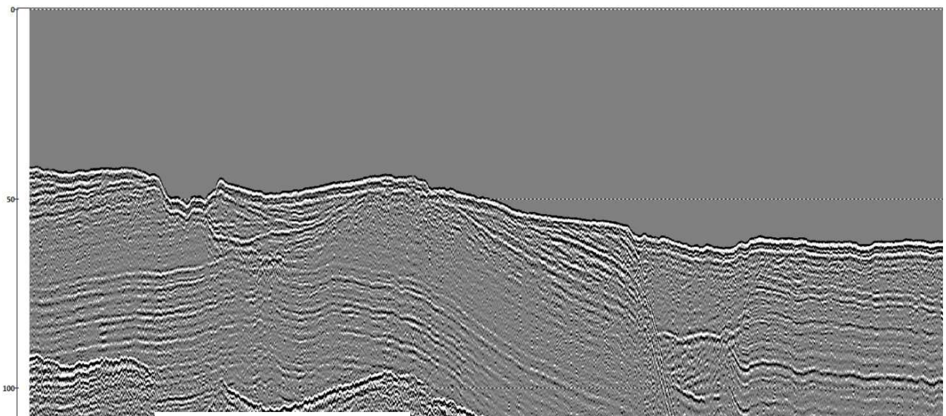

Figure 13. Sparker data example. Courtesy of David Garcia (RCMG – UGent)

Sparkers can provide penetration depths of several hundred meters with vertical resolution going from 50cm to 2m. An example of a sparker record is given in Figure 13. Both resolution and penetration can be varied by changing the capacitance and/or the voltage of the system. Sediments of archaeological interest are generally represented by relatively shallow deposits which are best observed with high resolution sub-bottom systems. Furthermore, sparker data does not show sufficient resolution for shallow sediments of archaeological interest. However, in some geological settings, like coarse and unconsolidated shallow sediments, sparkers are the only systems capable of imaging the sub bottom layers. If the goal of the survey is not to detect archaeological artefacts, but to find large scale buried landscapes sparkers are an option to consider.

Advantages and Limitations of sparker sources

Advantage
Their penetration makes them ideal for mid depth investigations, closing the gap between exploration seismic and shallow profiling. They are also easily deployed compared to other mid- to low frequency sources like the air gun. They are commonly used in regions where compacted sands and other coarse semi consolidated sediments are found.

Limitation
In very shallow waters (< 5 m), the use of sparker sources proves challenging due to the length of the receiver array which can be a long as 25 m. Their low resolution and deep penetration make this system less suitable for most marine archaeological investigations. As mentioned above they cannot be discarded. Depending on the geological setting they will be considered as an investigation tool for the offshore test site.

4.2.2 Boomer

The boomer is an electromagnetically driven sound source. The sound is generated when electrical energy stored in a capacitor is discharged through a flat coil positioned immediately behind an aluminium or cooper plate. Induced electrical currents oppose the coil current, producing repulsive forces to drive the plate and coil rapidly apart [*Mosher and Simpkin*, 1999]. This plate movement produces a broad band, highly repeatable and high amplitude impulsive acoustic signal in the water column. The frequency of the acoustic pulse ranges from 300 Hz to 3 kHz and the pulse length between 100 and 200 µs with the majority of the energy being directed vertically downward.

The source is usually mounted on a towed catamaran and a separate hydrophone array is used to record the reflected data. Such arrays are not practical in very shallow waters, but more recent devices, like the IKB-SEISTEC^{TM} (Figure 14), overcome this problem by placing a *Line in Cone* receiver adjacent to the boomer plate so no separate streamer is needed. The sensitive element of the line in cone receiver is a 20 cm long line hydrophone.

Figure 14. Boomer source (© IKB Seistec)

Depending on sediment types, vertical resolution of the boomer system typically ranges from 0.5 to 2 m, and horizontal resolution in the order of 4 m in water depths of 10m. In optimal conditions, the IKB-SEISTEC can resolve objects separated vertically by 25 cm. Typical penetration depths can reach up to 100 m. An example of a Boomer record, showing two paleovalley systems, is shown in Figure 15.

Advantages and Limitations of Boomer sources

Advantages
Boomer systems are commonly used to investigate submerged coarse grained structures and are capable of identifying submerged river terraces. In certain instances, they are also capable of identifying large scale cut-and-fill [*Dix*, 2008].

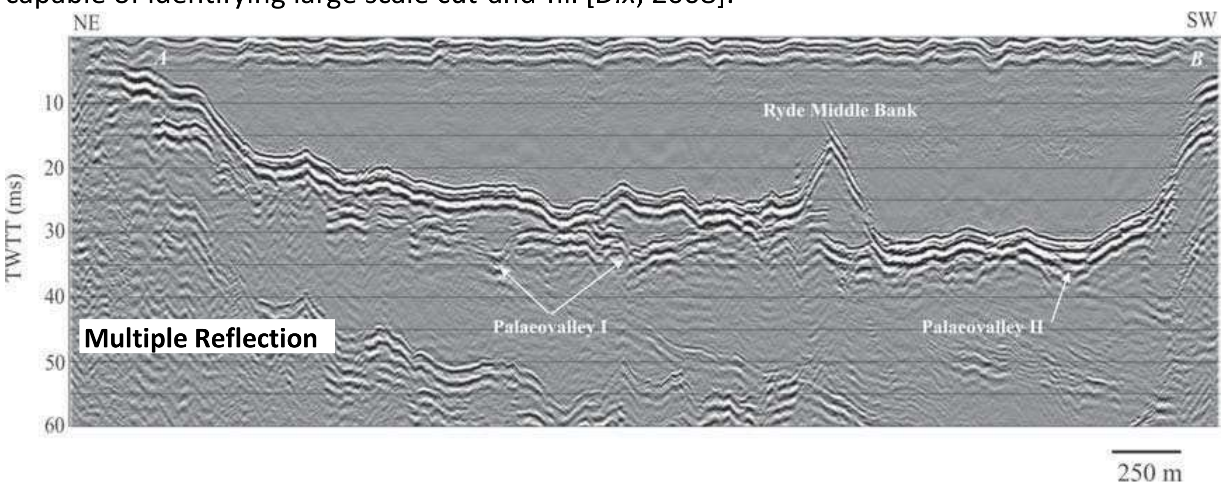

Figure 15. Boomer section showing two paleovalley systems [Dix, 2008]

Limitations
Boomer systems are commonly used by the aggregate/dredging industry to identify deposits and calculate their volume from the identification of its upper and lower reflectors. Due to the inherent trade-off between penetration and resolution of acoustic systems, their vertical and horizontal resolution capabilities makes them incapable of detecting small

buried objects (smaller than 0.5 m) or identifying internal stratification, particularly of fine grained layers, within the aggregate volume.

Boomer sources present very high repeatability with strong directivity. In rough sea conditions, however, the beam direction changes constantly, resulting in low repeatability. Consequently, it becomes difficult to perform post processing and data tends to have a low signal to noise ratio making interpretation of fine layers or objects difficult.

4.2.3 Chirp

Chirp systems are wide-band, frequency modulated sub-bottom profilers. The system generates a signal with a frequency sweep. This means that the transmitted signal is emitted over a period of time (e.g. 30 ms) and over an increasing (or decreasing) range of frequencies usually varying from 1 to 20 kHz. The reflected signal is received by the same transducer array that generates the outgoing acoustic energy. A matched filter, or cross correlation, of the recorded data with the source pulse, collapses the swept frequency modulated (FM) received signal into a pulse of short duration, maximizing the signal-to-noise-ratio. The advantage of using such source is that the emitted pulse shape is well known allowing post processing improvement of the recorded data.

Chirp systems can be operated from small vessels. The 'fish' (transducer unit, Figure 16) is either towed behind the vessel or, when using smaller boats in shallow water, is attached to the side of the ship. Only a combined signal processing and recording unit is needed on board.

Figure 16. Typical Chirp towfish (© Edgetech)

Chirp systems are typically able to achieve very high vertical resolution (down to ~ 5 cm) but in general provide lower penetration than sparkers or boomers, with typical penetration depths of up to 20 m in fine grained unconsolidated sediments. Chirp systems can operate in shallow water depths (> 2.5 m) and have been used successfully to distinguish archaeological features at water depths as shallow as 0.5 m and are especially well suited to distinguish features with a limited horizontal extension. An example of a chirp record is given in Figure 17. Chirp and boomer data are compared in Figure 18.

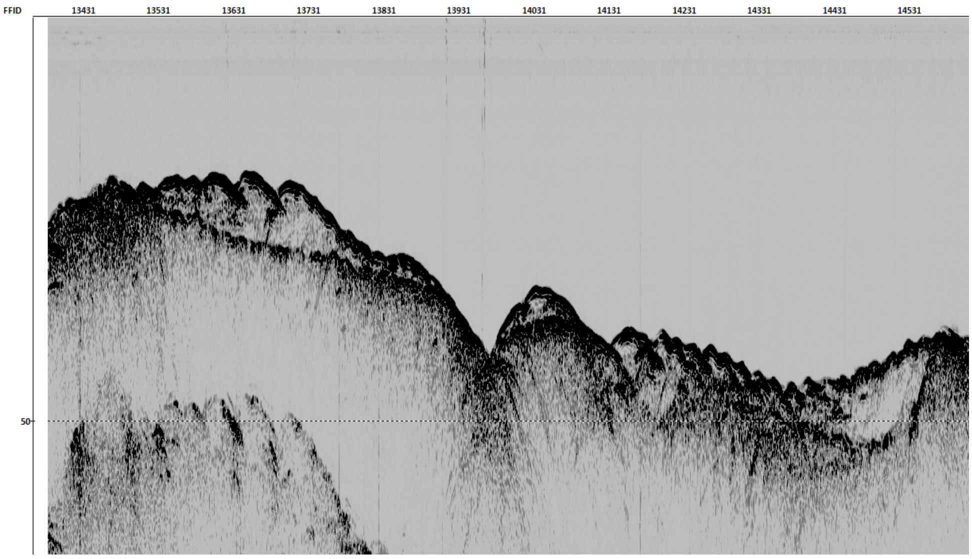

Figure 17. Chirp (0.5 – 4.5 kHz) data example (© Deltares)

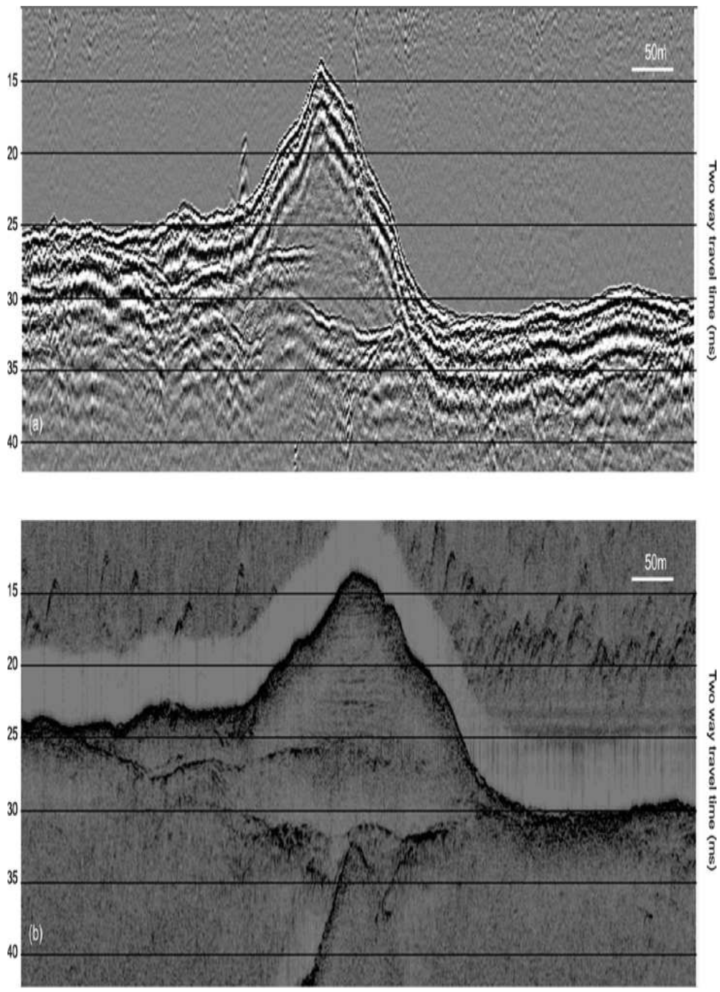

Figure 18. Comparison between boomer (top) and chirp data (bottom) on same location [Dix, 2008].

Advantages and Limitations of Chirp

Advantages

Due to the wide bandwidth of the signal, optimum penetration as well as resolution can be achieved. The signal to noise ratio of Chirp systems is higher than for the previous discussed devises. Additionally, due to the flexibility in frequency range, they can be used in varying bottom sediment types. Newer chirp systems are able to penetrate to comparable levels as the boomer, yet yield extraordinary details of the section. All these aspects make this technique a very suitable tool for maritime archaeological research.

Limitations

There are two fundamental problems with the Chirp systems as the current technology stands: first, their ability to penetrate coarse grained stratigraphies (medium to coarse sands and gravels) is inconsistent. Secondly, they require more post processing than conventional sub-bottom profilers.

4.2.4 Parametric Echosounder

A parametric echosounder is a non-linear transducer source which simultaneously transmits two signals of slightly different high frequencies at high sound pressures [*Grelowska*, 2008]. The parametric echosounder instrument is shown in Figure 20. Due to nonlinear interactions in the water column in front of the transducer, new frequencies are generated. One of them is the difference or secondary frequency which is low and can be used for sub-bottom profiling purposes. Both the primary HF signal (100 kHz) and the secondary LF signal (6 to 12 kHz) are recorded. The generated signal is characterized by a large band width, a short signal length (0.07 ms) and a very restricted beam width (±1.8° at 4-15 kHz). Penetration depth is highly dependent on the bottom sediments. It can reach up to a few tens of meters in soft sediments (see Figure 21).

Figure 19. Parametric Echosounder transducer (left) and acquisition (right) (© Innomar)

The parametric echosounder can be operated from small vessels (Figure 20). The transducer, which acts as emitter and receiver, is normally attached to the side of the ship. Only a signal processing and recording unit are needed on board.

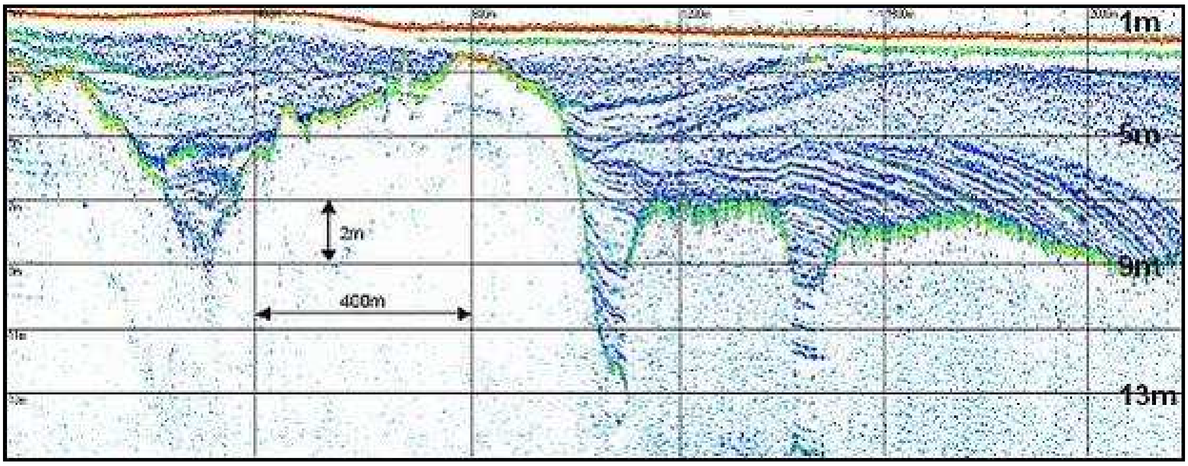

Figure 20. Parametric Echosounder (10kHz) data example (© Innomar)

Due to its high vertical resolution, the parametric echosounder is ideal for marine archaeological investigations. In [*Missiaen*, 2010] a marine seismic survey was conducted (among other objectives) to locate and identify fossil tidal channels buried between 2 and 8 meters below the water bottom (Figure 22). The recent and fossil tidal gullies are interpreted from the seismic record.

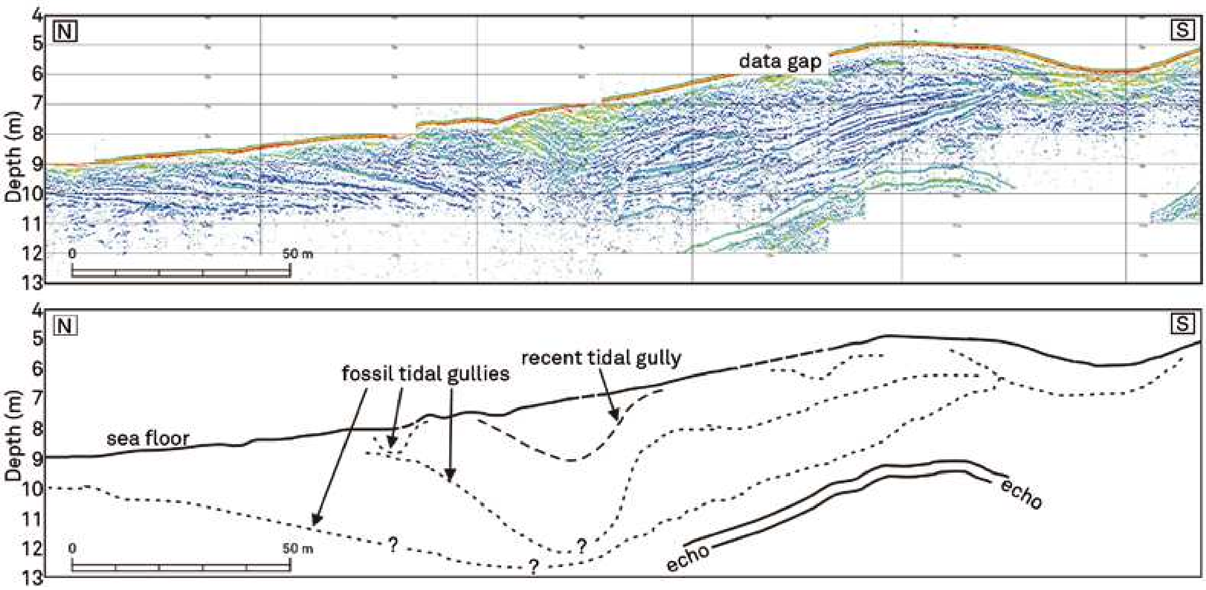

Figure 21. Parametric echosounder record (10 kHz, top) and interpreted linedrawing (below) showing buried tidal channels [Missiaen, 2010]

Advantages and Limitations of Parametric echosounders

Advantages

The fact that transducer and receiver are in the same position allows for a higher precision in the horizontal positioning of features observed than if the reflected signal was picked up by a hydrophone array located some distance away from the source. The same reason makes the acquisition process very simple. As a consequence, the system is suitable for very shallow water environments. The high frequency (100 kHz) allows for accurate water bottom depth measurements without need of additional bathymetry equipment on board. Its very high vertical resolution (around 15 cm) and the small beam width are ideal for detecting small objects in shallow water areas making this equipment perfectly suited for archaeological investigations.

Limitations

Penetration depth of the parametric echosounder is limited. Additionally, the extremely narrow beam requires a very dense grid to search for small objects, resulting in a rather time-consuming survey [*Wunderlich et al.*, 2005]. Bathymetric data is comparable to SBES data, so in 2D only. No 3D coverage is achieved.

4.3 Recommendations on single channel high-resolution sub-bottom profiling

Obtaining a detailed image of the subsurface requires good vertical and horizontal resolution as well as good penetration of investigation. Unfortunately, as seen in the previous pages, there is not a single device capable of producing such product. Many of these systems overlap in their capabilities and/or are complimentary to each other in certain circumstances. The objectives of the investigation and field circumstances will ultimately determine which type of source (or combination or sources) should be used. A combination of several sources and receivers is recommended to be sure to acquire data with sufficient quality on the pilot site.

5 Multichannel high-resolution sub-bottom profiling

5.1 Method of multichannel seismic reflection

Single channel seismic reflection offers a rapid and accurate way to image the structure of the substrate beneath the seafloor at a relative low cost and with low processing requirements. However, single channel data often presents a low signal to noise ratio which sometimes leads to misinterpretation or simply to the impossibility to interpret the data. For example, in single channel data, multiple reflections are quite strong due to the incapacity of these systems to discriminate between events based on their arrival time or direction of arrival. As a consequence, data arriving after the seafloor multiple is often so obscured by the multiples that they are useless. Advanced processing techniques can be applied in order to improve the quality of the data and overcome some of these issues but because of the intrinsic nature of the single channel system most processing techniques are ineffective.

Some of the limitations presented by single channel methods can be surmounted by using multiple channels. These multichannel seismic reflection methods are also available for shallow investigation. Despite providing data with better signal to noise ratio [*Bellefleur*, 2006], they are less favoured in engineering, environmental and archaeological investigations because of their processing requirements and higher costs.

The multichannel seismic reflection technique basically consists of recording the signal with an array of receivers separated by a fixed distance (> 1 m), such as shown in Figure 22. Each receiver will produce a "trace" which represents the response of a single seismic detector caused by the arrival of the seismic energy. In multichannel profiling, one shot is represented by a series of signals (traces) equalling the number of receivers in the array. This is opposed to single channel records, where one shot represents one signal only.

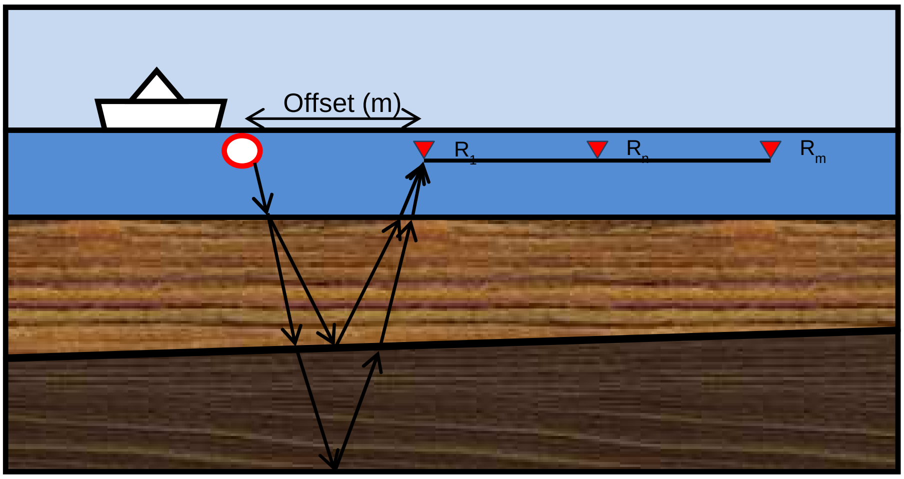

Figure 22. Multichannel sub-bottom profiling principle

Multichannel surveys need a separate source and a streamer of receivers. The source can be an airgun, sparker or boomer.

Shooting several times along a profile will generate a set of shot gathers. After processing, this results in a profile similar to the one obtained with single channel systems. The multichannel profile, however, will have superior signal-to-noise ratio (Figure 23). It can be observed that multi-channel data presents a better signal to noise ratio and provides more information on the deep structures as well as higher resolution through the section.

The difference is caused by the *fold* of the data. Single channel data is *single-fold,* because there is one single trace per sub-surface reflection position only. In multichannel data, each sub-surface position is scanned several times by different combinations of sources and receivers. This results in several traces for each reflecting location. By summing up (stacking) the traces belonging to the same common subsurface of a defined bin-size, a single trace is obtained, with superior signal-to-noise ratio relative to the single-fold results. The increase in signal to noise ratio is due to the fact that when stacking traces for a common reflection location, genuine events will be common to all traces and the addition of their coherent amplitude will enhance the event. On the other hand, random noise will be different between traces, so when adding random noise the amplitude will be averaged out.

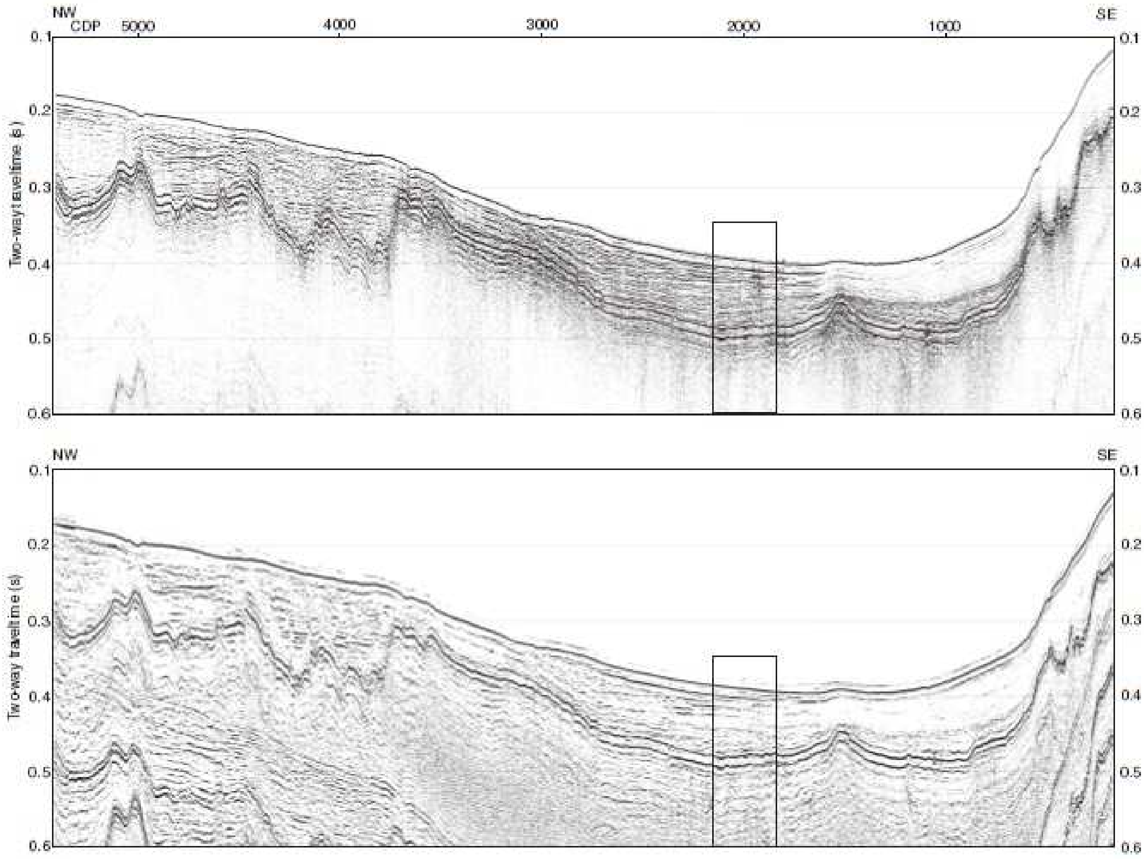

Figure 23. Multichannel sub-bottom profiling (bottom) compared to single channel profile (top) Both datasets acquired using sparker source. From [Bellefleur, 2006]

Multichannel methods have been successfully used in oil and gas exploration for more than 60 years. Due to its cost and processing requirements, it has not been adopted by the engineering industry for near surface studies. In the recent years, more investigations with multichannel data in shallow environments have been carried out improving the quality of the data and increasing the ability to image complex structures. The Geology and Geophysics research group of the University of Southampton has successfully applied high resolution multichannel seismic reflection profiling on shallow waters with a 60 channel hydrophone, with 1 m spacing between receivers and using either boomer or sparker sources.

5.2 Advantages and limitations of multichannel techniques

Advantages

The big advantage of multichannel surveys is to significantly improve the signal to noise ratio of the seismic profile by applying multi-fold imaging that reduces the amount of random noise and multiple reflections. Additionally, the wave propagation velocity of the buried layers can be estimated from multichannel data allowing to migrate the data and produce more realistic images of the substrate. For single channel data it is not possible to obtain the velocities from the seismic data only. Therefore, if migrations are wanted in single channel data, it must be done using information from available boreholes or by making assumptions based on the geological information.

Limitations

The most important limitation of the multichannel seismic reflection technique is that is needs advanced processing to obtain the high quality image of the subsurface. Another limitation is related to the wavelet. If the source wavelet is not well-repeatable, the signals that will be stacked are different and the signal to noise ratio will not improve. Since some shallow marine seismic sources have a non-spherical response, the received signal can be different on the several traces and stacking can decrease the signal to noise ratio.

Additionally, the positions of the source and receivers must be known very accurately for accurate location of the common reflection points. Finally, in shallow water, there are practical limitations on the use of a multichannel streamer because the long streamer can be difficult to tow in congested areas.

5.3 Recommendations for multichannel seismic reflection

Multichannel high resolution seismic reflection profiling has been rarely used in marine archaeological investigations, due to its operational and post processing costs. Additionally, long separations between source and array of receivers possess practical limitations. This kind of array not only makes it complicated to operate in very shallow waters but also requires the use of powerful sources like sparkers and boomers which lack the resolution needed for most archaeological studies. For shallow water, however, the streamer can be adjusted in length, for example to 75 m, which is much more practical in operation. Depending on the geological and expected conditions of the offshore test site we will test a multichannel system and compare it with the results obtained from the single channel array. We propose to use several sources (airgun, sparker, boomer) and a practical compromise between streamer length (and therefore signal to noise ratio) and manoeuvrability.

6 3D High-Resolution Seismic Reflection

6.1 Method of 3D High-resolution seismic

All high-resolution sub-bottom profiling techniques reviewed in the previous chapters collect data along a single line on the water surface and therefore sample data from seismic waves travelling in one thin vertical plane. With this approach, the Earth’s sub-surface is simplified to a two dimensional medium. Its three dimension heterogeneity is ignored, along with the fact that seismic waves travel along expanding spherical wavefronts. In normal 2D surveys, data is acquired by defining parallel and transversal lines that create some sort of grid. Pseudo three dimensional images are deduced by interpolating between the acquisition lines, so features observed on such lines may be located out-of-plane rather than underneath them and small but important features occurring between the lines will be missed producing errors in interpretation. Consequently, the effective horizontal resolution of these data is controlled by the survey line spacing, which can be anything from a few metres to several hundred metres. Therefore, a truly representative image of the sub-surface is only obtained when the entire wave field is sampled in 3D.

3D seismic acquisition has been employed for more than 30 years in the hydrocarbon industry, but has had limited application in near surface and engineering surveys. However, advances in computer technology have stimulated the development and adaptation of 3D seismic acquisition in shallow investigations. Two commercial systems have been developed in the last few years specially designed for shallow high resolution seismic capable of detecting small buried objects.

The first system concerns the 3D Chirp system (©National Oceanographic Centre Southampton, Figure 24). It incorporates a rigid frame (2.75 m wide by 2.3 m long) that contains the Chirp source array (4 transducers) together with 60 receiver elements [*Gutowski et al.*, 2008]. Positioning is provided by integrated real-time-kinematic GPS. Frequency range is 1.5–13 kHz. A 3D image of the sub-seabed is obtained with dm-scale horizontal and vertical resolution. The system can be surface towed from a small survey vessel.

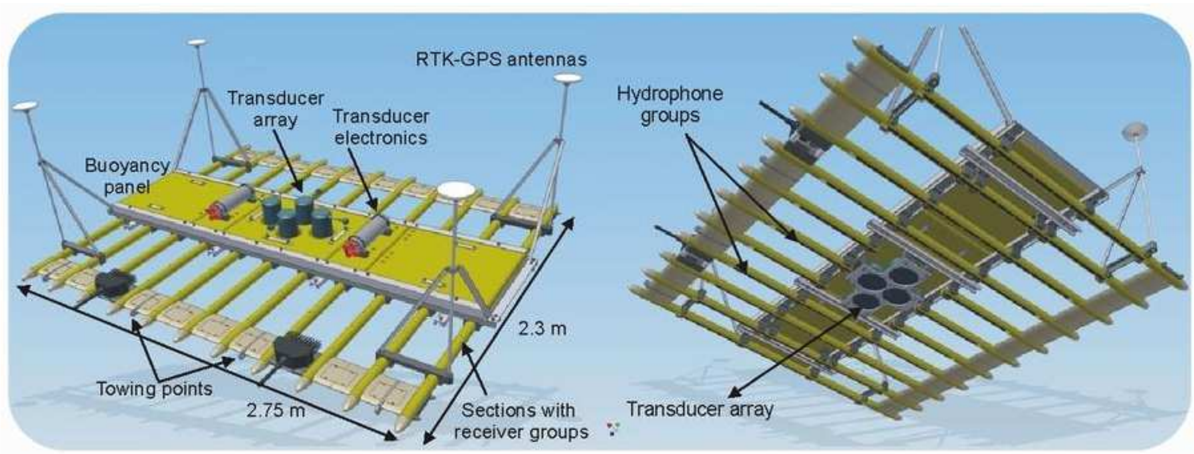

Figure 24. 3D Chirp dispositive (© National Oceanographic Centre Southampton)

Data processing includes a.o. geometry corrections, correlation, binning, and pre-stack migration. The system is typically applied for the detection of buried objects or structures (eg. small trenches or dams) but also to image buried shipwrecks. An example of a subsurface image obtained by the 3D Chirp system is shown in Figure 26.

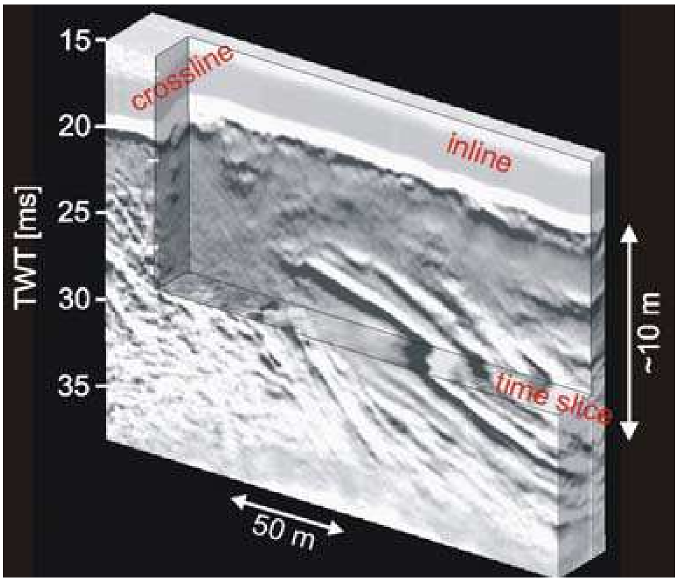

Figure 25. 3D Chirp data example [Gutowski et al., 2008] showing a buried coffer-dam area. Data volume is 200m long by 25m wide

The second system concerns a multi-transducer parametric echosounder system developed by *Innomar* (Rostock, Germany). A line array of up to 5 narrow beam transducers are fix mounted to a survey platform (thus avoiding complicated positioning correction) on a small vessel (Figure 26). The distance between two transducers is variable, depending on the structure size to be investigated. Frequency range is 5-15 kHz.

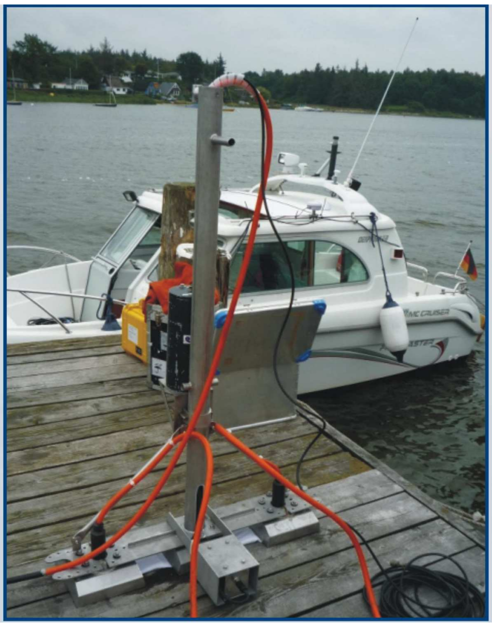

Figure 26. Multi-transducer parametric echosounder system (©Innomar)

A 3D sub-bottom image is obtained with cm resolution vertically and dm resolution laterally. The data set is immediately ready for 3D visualization with volume rendering methods after data acquisition (no migration processing is needed). The multi-transducer parametric array has been tested on archaeological sites containing buried wooden structures (Figure 27). The image represents a time slice through the 3D volume at the depth of the structure (approx. 30 cm below seabed), showing individual crates over the whole area and some possible debris locations.

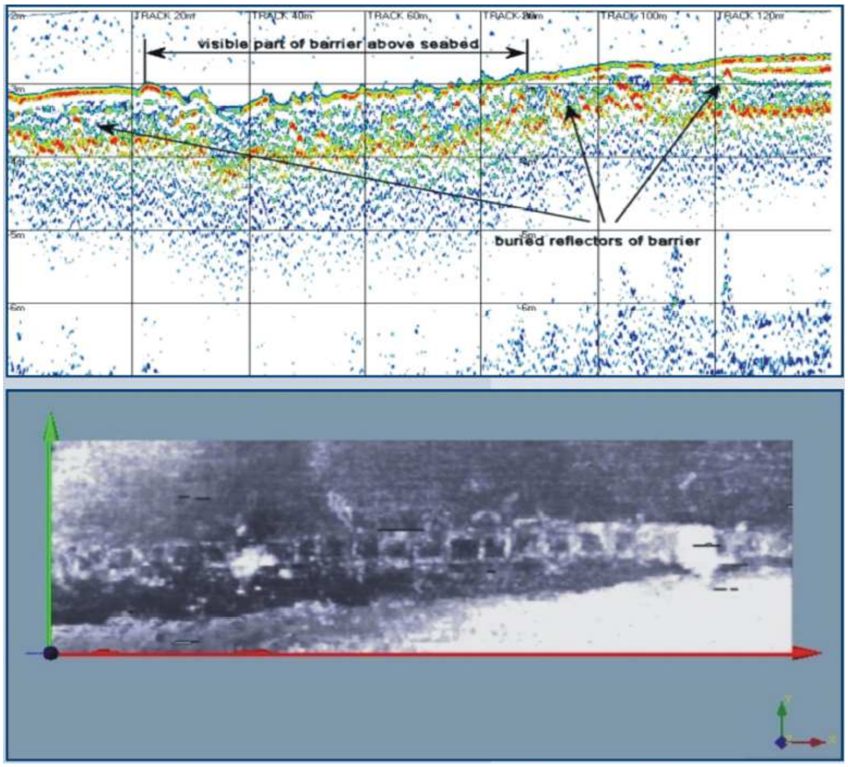

Figure 27. Parametric echosounder data example (©Innomar)
Top: single sub-bottom profile of a buried wooden structure.
Bottom: time slice through the 3D volume at the depth of the structure

6.2 Advantages and limitations of 3D high-resolution seismics

Advantages
3D methods produce data volumes that can be processed coherently across a site, then visualised and interpreted revealing the three dimensional geometry of the subsurface. For a true 3D image, a sufficiently dense grid needs to be surveyed. The 3D volumes can be sliced in any direction at any angle, allowing better visualisation and interpretation of complex structures. Respecting 3D wave propagation during data acquisition and processing, 3D seismic reflection data has higher data quality and resolution than 2D data. This makes it possible to detect small objects and reveal complex geometries.

Limitations
On the other hand, high resolution 3D seismic faces many obstacles like the need for precise navigation information for the vessel, receivers and source, high stability of the source signature. Additionally, high computational power is needed in order to manage large volumes of data. Finally, extra time is required to acquire and process when compared to conventional 2D data.

6.3 Recommendations for 3D High resolution seismics

In this project, the multi-transducer parametric echosounder will be tested on at least one designated test site. Further developments will be made to optimize the source and receiver set-up and to apply smart and innovative data processing. This research will allow to maximize the potential of this novel technique for detailed archaeological site studies. It presents a major step forward in the identification of small buried archaeological artefacts.

7 Summary of available techniques

7.1 Existing acoustic techniques

In Table 1, the characteristics of the various acoustic techniques are summarised.

7.2 Acoustic techniques available at project partners

The equipment listed below is available for use in this project:

Parametric Echosounder
Seistec Boomer
Boomer
Sparker (centipede, SIG, Georesources)
Chirp (X-star SB-512i, X-star 622)
Streamer 24 channel (3.125 m spacing)
Streamer 48 channel (1.5 m spacing)
Single channel streamer (10 channels)
S-wave source (Elvis II)
Dual frequency echosounder
Bathymetric sonar (Klein HC5000 Hydrochart)
Side Scan Sonar (Klein System 3900)

Based on site characteristic and survey objectives (water depth, sediment composition, depth range, resolution required) we will decide on the best system (or combination of systems) to use.

Device	Frequency	Pulse Length	Penetration through seabed	Vertical Resolution	No. Receivers	Advantage	Limitations
Single Beam	10-200 kHz	0.1 - 1 ms	-	-	1	*Simple and cost efficient bathymetry tool	*No information below seabed *Information limited to area below vessel
Multibeam	12-300 kHz	0.025 - 10 ms	-	-	1	*Provides high-resolution 3D bathymetry images	*No information below seabed *Requires post processing
Side Scan Sonar	100-500kHz	1 - 20 ms	-	-	1	*Real time visual display of the seabed	*No information below seabed *Images not precisely geo-referenced
Bathymetry Sonar System	455 kHz	max 16 ms	-	-	1	*Time saving (One system => two data sets)	
Sparker	0.2 - 1 kHz	0.3 - 5ms	< 1000m	2 m	1, 24, 48	*High penetration *Ideal for coarse grained stratigraphy	*Low vertical resolution *Not ideal for very shallow water
Boomer	0.3 - 3 kHz	0.1 - 0.2 ms	> 100m	0.5 - 2 m	1, 24, 48 1 (SEISTEC)	*Good penetration *Decent vertical resolution	*Post processing can be challenging
Chirp	Sweep 1 - 20 kHz	30 ms	< 50m	0.2 m	1	*Frequency flexibility *Adjustable penetration & resolution	*Unable to penetrate coarse grained stratigraphy
Parametric Echosounder	6 - 12 kHz 100 kHz	0.05 ms	< 30 m	0.15 m	1	*Very high vertical resolution	* Reduced penetration
Multi channel seismic	source dependent	source dependent	? 1500 m	2 m	24, 48	*Good signal to noise ratio *High penetration	*Expensive *Post processing mandatory
High-res 3D seismic	system dependent	system dependent	< 25 m	0.1 - 0.2 m	system dependent	* Real 3D volume *Very high horizontal/vertical resolution	*Can be expensive *Post processing can be chalenging

Table 1. Marine acoustic methods (values are average and may vary depending on the device). Based on [McCauley, 2005] and experience from University of Gent, Deltares and Innomar.

8 Conclusions and recommendations

Various geophysical surveying methods are commonly used to study the structure and properties of the seafloor and its underlying substrate, but none of them provide the detailed information that the acoustic methods do.

As described in this report, acoustic techniques comprise a wide range of different tools presenting advantages and limitations. Not one single technique will prove a reliable solution to all the challenges we will encounter, therefore a multi-disciplinary approach will be essential to develop a reliable survey methodology based on geophysical techniques. The investigation's objectives and geological and geographical characteristics of the test sites will finally dictate the systems of choice.

As a departing point we can already state the following conclusions:

- Bathymetric SSS will be favoured over SBES, MBES and SSS, as bathymetric and seafloor imaging tool.
- Single channel reflection seismic with several sources will be used on all sites. The set-up is to be optimized for the depth of interest and the expected vertical resolution needed for the layers/objects to be found.
- Multichannel reflection seismic with several sources will be used on those sites where their use will add some value to the study.
- 3D high-resolution seismic survey will be conducted on the detailed survey area when the interesting and high archaeological potential layers have been identified.

Finally, data will be of little value unless it is collected and interpreted correctly. A close collaboration between the different participants (geologist, archaeologist, geophysicist) of will be fundamental to the success of the investigation.

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