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.

COMPARATIVE REVIEW OF TECHNIQUES
WP 1.1.5

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1. Introduction

In previous reports (WP1.1.2, WP1.1.3, WP1.1.4) the most relevant marine geophysical and remote sensing techniques used in marine archaeological investigations have been reviewed. Their basic principles, applications and limitations have been summarized. In this report, we aim at comparing all these techniques based on their potential for cost-effective marine archaeological assessment studies. It is not our intention to come up with a list of 'good' or 'bad' techniques since the potential of each technique does not only depend on the environmental setting but also on the type of archaeological and/or geo-archaeological indicator. Such review is of vital use for all those involved in marine archaeological investigations, ranging from the industry and governmental agencies to the scientific world.

2. Seabed mapping techniques

Summary and advantages

Seabed mapping techniques provide real time visual display of the seabed. Single beam (SBES) echo sounders measure the water depth directly beneath the device providing a 2D profile of the water bottom. Multibeam (MBES) echo sounders scan a wide band of the seabed on both sides of the vessel, providing a pseudo 3D image of the water depth. Side-scan sonar (SSS) systems deliver an acoustic, oblique, photo-like image of the seafloor on both sides of the vessel, ultimately providing full spatial coverage of a targeted area

Echo sounders are very easy to deploy as they can be fitted to most vessels either mounted to the hull or on the side of the ship. SSS are towed behind the vessel below the water surface. As a consequence, in shallow waters, SSS can be adversely affected by poor sea conditions.

Limitations

The main limitation of these techniques is that they do not provide any information on the heritage that lies buried beneath the seafloor. Therefore their application in this project is limited to the detection of objects laying on the seafloor.

3. Sub-bottom profiling techniques

Sub-bottom profiling techniques rely on a combination of powerful acoustic sources and relatively low frequencies waves to penetrate the seafloor and provide information on the structure and nature of the substrate below the water bottom. Several physical parameters of the emitted acoustic signal, such as signal frequency, output power and pulse length will determine the capabilities of each particular technique. High frequency profilers like Boomer, Pinger and Chirp provide detailed information of the near surface down to a hundred of meters. Medium frequency profilers like the 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 but with low resolution.

3.1. Sparker Sources

Advantages

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 like some sections of the Belgian North Sea.

Limitations

Their relative low frequency produce images with lower resolution and high investigation depths, making this system less suitable for marine archaeological investigations although they cannot be discarded since their efficiency depends on the geological settings of the investigated area.

3.2. Boomer Sources

Advantages

Boomer systems offer a good compromise between resolution and penetration and are capable of penetrating most marine shallow sediment types (although they provide best results on coarser sediments) guaranteeing preliminary imaging of the buried landscapes.

Limitations

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.

3.3. Chirp Sources

Advantages

Chirp systems are a wide-band, frequency modulated sub-bottom profilers. Due to the bandwidth of the signal, optimum penetration as well as high 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 different bottom sediment types. Newer chirp systems are able to penetrate to comparable levels as the boomer, yet yielding extraordinary details of the section. Another advantage of the chirp system is that the emitted pulse shape is well known and highly repeatable, aiding post processing and enabling quantitative sediment/object characterisation.

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 stratigraphy's (medium to coarse sands and gravels) is inconsistent. Secondly, they require more post processing than conventional sub-bottom profilers.

3.4. Parametric Echo sounder

Advantages

A parametric echo sounder is a non-linear transducer which simultaneously transmits two signals of slightly different high frequencies at high sound pressures. When these two signals interact a secondary low frequency wave is generated. The very high frequency (100 kHz) allows for accurate water bottom depth measurements and the low frequency (5 – 12 kHz) can penetrate up to 50m depth and can give decametric vertical resolution making this system ideal for detecting small objects in shallow water areas.

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.

Other advantages of the system are that the secondary beam pattern is virtually sidelobe free, reducing the disadvantageous ringing effects of other sub-bottom profilers in shallow water and the manageable size of the system.

Limitations

Penetration depth of the parametric echo sounder is limited. Additionally, the extremely narrow beam requires a very dense grid to search for small objects, resulting in a rather time-consuming survey. Bathymetric data is comparable to SBES data, so in 2D only. No 3D coverage is achieved. A major disadvantage is the poor conversion efficiency, which is typically <1% of the input energy converted into the secondary wave.

3.5. Multi-channel acquisition

Advantages

The big advantage of multi-channel 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 multi-channel 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 needed in single channel data, it must be done using velocity information from available boreholes or by making assumptions based on the geological information.

Limitations

The most important limitation of the multi-channel seismic reflection technique is that is needs advanced processing to obtain 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 multi-channel streamer because the long streamer can be difficult to tow in congested areas.

3.6. 3D high resolution seismic

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 in order to manage large volumes of data. Finally, extra time is required to acquire and process when compared to conventional 2D data.

3.7. Comparative review of bottom and sub-bottom techniques

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. Comparison of 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.

4. Unconventional geophysical techniques

Sub-bottom profilers are affected by external factors like the presence of sub-surface gas deposits within sediments. Pore materials filled with gas, even in small quantities, represent one of the most important limitations of conventional seismic survey techniques, because it disrupts P-wave transmission and thus obscures underlying strata. Gas modifies sediment physical properties, thereby reducing sediment strength and sediment sound speed and attenuating and scattering acoustic energy.

Other types of seismic waves, like Shear and Surfaces waves are less affected by the presence of gas. Therefore, they represent a valid alternative to conventional acoustic techniques in gas-rich areas, like the Belgian sector of the North Sea. In addition to acoustic techniques, other geophysical techniques based on the difference in e.g. electrical conductivity, magnetic susceptibility or dielectrical properties of the subsurface., might be useful for imaging the subsurface for the purpose of underwater archaeology.

4.1. Shear waves

Advantages

The main advantage of using shear waves to study the sub-seafloor is their capability to image through and below gas accumulations in the sediments. Moreover, their insensitivity to rock's fluids content may allow identification of layers that are undetected by compressional waves in saturated materials.

Considering the V_p/V_s ratios (> 1), for a given frequency, the resolution should theoretically improve on a shear wave stacked section from unconsolidated soils in comparison to an equivalent compressional wave survey.

Finally, since shear velocities are directly related to the stiffness of the rock, important engineering rock properties can be reasonably estimated by collecting both shear and compressional waves along coincident profiles.

Limitations

Shear waves are not as easy to generate and register as compressional waves, in particular in marine environments. A dedicated layout is needed in order to perform an optimal shear wave survey. Additionally, processing shear waves requires extra effort and in some cases different software than processing conventional P-waves. This makes the technique more expensive and as a consequence economically unsuitable for many near surface investigations.

Due to polarization of shear wave components, velocities are rarely the same in the vertical (SV) and in the horizontal (SH) plane. SH velocities may also vary in different azimuths, a situation known as horizontal anisotropy. In this case, the ground spectral response will be different, depending on which way the source and receivers are oriented. This does not influence the processing in itself, but has consequences for interpretation. Therefore, during acquisition, the orientation of the source and the receivers has to be noted. Differences at crossings in a grid might be explained by anisotropy (apart from the influence of noise).

One of the most common limitations of shallow shear wave reflection surveys is that Love wave arrivals can be mistaken as coherent events and might be stacked after NMO corrections, masking true reflections that might be present. Love waves are horizontally polarized shear waves (SH waves) that are guided by an elastic layer. These waves are observed only when there is a low velocity layer overlying a high velocity layer, so appears in a layered earth. The Love wave travel path can produce surface wave arrivals to show apparent hyperbolic curvature on the seismogram. Although surface wave arrivals in theory are linear and should possess no curvature, the apparent hyperbolic curvature often forms at near offset traces due to the near-field effect of surface waves, the wave interference effect, or a combination of both. Consequently, if Love waves are not efficiently removed from the record during processing, misrepresentations of the subsurface will be common.

4.2. Surface waves

Advantages

In comparison to using conventional body-wave methods to achieve similar V_s information the surface-wave method has several advantages:

- Field data acquisition is very simple, because surface waves are very energetic and always represent the strongest energy of the seismic record.
- Data processing procedure is relatively simple.
- No special field equipment is required.
- Because of all above reasons, it represents a cost effective and time efficient methodology to obtain shear wave velocity profiles of the area of investigation.
- Scholte waves are not affected by acoustic masks like shallow gas.
- If combined with information from seismic refraction, sonic profiling or other methods to obtain P-wave velocities, elastic modules can be derived.

Limitations

Surface-wave surveys present important limitations with respect to conventional body wave imaging techniques:

- Since Scholte waves are mainly low frequency, they can only provide information about shear wave velocities of mayor layers but thin layers are undetected. Hence, vertical resolution is very poor compared to shear wave imaging.
- Long record lengths are required, because of the low V_s velocities. This constrains the offset and speed of the boat. Short record lengths do not permit recording the slower part of surface waves. The error in receiver positions due to ship movement during recording becomes increasingly large for lower boat speeds, because of less control on streamer positions. For high boat speed, binning errors occur (general problem in seismic processing), which is increasingly severe for long records.
- The inversion process must be performed keeping in mind the geological setting. Without this, inversion algorithms can produce velocity profiles that are mathematically accurate but geologically unrealistic. With this, there is a trade-off

between resolution in dispersion curves (longer spreads needed) versus lateral resolution (shorter spreads for better resolution).

4.3. Resistivity methods

For archaeological investigations, the discrimination between the unconsolidated and consolidated sediment is often of major importance. The employability of the Electrical Resistivity Tomography (ERT) method in marine archaeological studies is not assessed. There is very little mention of the application in literature. However, the depth range of interest is feasible and might contribute to the image of the subsurface in areas with shallow gas. We therefore suggest trying this method in conjunction with other geophysical methods.

Advantages

Underwater ERT can be used for buried (metal) shipwreck identification or for geological characterisation of the subsurface. In this project, the latter seems to be the most promising. ERT covers the depth range for which acoustics can encounter problems with the presence of shallow gas.

For sufficient penetration the electrodes need to be employed close to the sea floor. So far, the method has been employed mostly in shallow water (mostly for practical reasons i.e. easier deployment of cables and electrodes). The resolution of the method is in general defined by acquisition set-up. As rule of thumb, the maximum resolution is equal to the electrode spacing. In general, this means that maximum resolution is on scale of one or several meters. Resolution decreases with depth, but the lateral resolution is in general good and adequate to identify lateral changes in lithology.

The processing and interpretation of the data is not complicated and comparable to land ERT. For underwater application, the only difference is the presence of the seawater layer, whose influence can be accounted for in the processing phase by standard software.

Limitations

There are numerous questions whether the method is efficient for the specific case of the southern North Sea (only unconsolidated sediments). The main concern is the capability of this method to distinguish between different lithology's that do not give rise to large resistivity contrasts. For areas with shallow gas, however, ERT might give additional information on the structure of the subsurface that will otherwise be undetectable. In any case, it is recommended to use this method only in conjunction with other geophysical methods.

4.4. EM methods

This method is based on the measurement of the electrical resistivity, but in a different way from the previous ERT method. In EM surveys, a magnetic field is generated by a coil, which induces a secondary magnetic field. The amplitude and phase variations of this secondary field allow for the calculation of the conductivity/resistivity of the subsoil.

Advantages

The EM method has been applied successfully several times in shallow water environments to detect shallow structures of varying resistivity/ porosity. The applicability of the method seems to be most appropriate for the identification of large-scale (km-size) buried palaeochannels.

Limitations

The receiver loops should be placed close to the sea floor and it strictly requires a good coupling with the sea-floor, requirements that cannot be always met due to sea-floor condition. The most important drawback of this method is that equipment is not off-the-shelf. Cooperation with relevant research groups is required to have access to it. Due to its low resolution and low cost effectiveness we should discard this method for the moment.

4.5. Magnetic methods

Marine magnetometers measure the total amplitude of the Earth's magnetic field. Variations within the magnetic field are caused by a number of factors: solar activity, geological features, non-geological ferro-magnetic metallic objects on or buried within the seabed. The measured intensity of metallic artefacts on or buried within sediments depends on the material, size, shape, depth of burial and distance to the magnetometer.

Advantages

If ferromagnetic objects such as shipwrecks or remnants of shipwrecks (e.g. anchors) are expected to be present at the site, then the magnetic method is able to accurately detect them. The main benefit from magnetic methods in this project is in gas-rich areas (where we lack sub-bottom profiling data) and/or in areas containing iron artefacts that may be missed out by acoustics. Magnetometer data is easily acquired simultaneously with seismic data.

Limitations

In view of the scope of the project (sub-seafloor archaeology) the magnetic/gradiometric method is only appropriate when expecting buried iron objects. On the other hand, as the strength of the magnetic field is inversely proportional to the cube of the distance from the source, the magnetometer needs to pass the object as closely as possible and needs to be sufficiently sensitive to detect smaller, archaeologically significant, objects.

4.6. Ground Penetrating Radar (GPR)

The application of GPR in salt water environments is even more problematic than in fresh water. Due to the high conductivity of salt water, the damping is so severe that no EM wave can penetrate the subsurface. In the 1990s, the company Groundtracer developed a prototype of a saltwater GPR. Although the results of this instrument were promising, it never reached the GPR market.

Recommendations

In view of the above findings it is recommended not to include GPR in the techniques used in this project.

4.7. Comparative review of unconventional geophysical techniques

Method	Application	Remark
Shear wave reflection	Detect subsurface structures, e.g. geological layers, similar to SBP but with higher resolution	Promising technique, because of resolution and insensitivity to gas. Acquisition by airgun and streamer, close to the seafloor. Sophisticated processing needed.
Scholte waves	Detect subsurface structures, e.g. geological layers	Low spatial resolution. Suitable for areas with gas. Acquisition by airgun and streamer, close to the seafloor. Easy processing of data.
Resistivity method	Detection of subsurface structures and detection of (large metal) objects	Promising technique, but application for unconsolidated sediments is not proven. Electrodes need to be close to seafloor. May provide extra information in areas with gas.
EM method	Detect subsurface structures of varying porosity, e.g. channels	Promising technique but application for unconsolidated sediments is not proven. Coils need to be close to seafloor. May provide extra information in areas with gas.
Magnetic method	Detection of ferromagnetic objects on seafloor and buried	Only for ferromagnetic objects and therefore limited application.
Ground penetrating radar	Detection of subsurface structures, e.g. geological layers and detection of objects	Not available for salt water environments.

Table 2. Summary of non-conventional geophysical techniques for underwater archaeology

5. Remote Sensing Techniques

5.1. Laser scanning

With laser scanning, (laser) light is used to derive the distance between a sensor and an object. A large number of distance and angular measurements will result in a very dense point cloud within a limited time frame. All types of laser scanning systems make use of active, optical, reflection based and contact free scanning methods. A distance is derived by means of measuring the circulation time of a pulse or the wavelength difference of a continuous wave, which is called electromagnetic distance measurement (EDM). The signals are situated in the visible, near- or short-wave infrared range (500-1600 nm). In addition to a backscatter based distance measurement, horizontal and vertical angles are recorded. By transmitting signals from a measuring instrument of which the orientation and the coordinates are known or fixed in three dimensions, the coordinates of a point on the reflecting surface are measured.

5.1.1. Airborne Laser Scanning (ALS)

Airborne Laser Scanning (ALS) systems deflect the laser beam across a flight path from a flying platform in order to acquire a certain field of view. Each separate distance and angle measurement is combined with synchronized observations of a position and orientation measurement system (POS). This enables the direct georeferencing of the measured points in a common coordinate frame. The POS typically consists of a GNSS and an INS. As with all other mobile and integrated spatial measurement systems, the calibration of these different sensors is very important. This calibration consists of the determination of the lever-arm and bore-sight parameters, representing positional and angular offsets of the different local coordinate systems of the sensors.

Advantages

ALS is frequently used to generate 2.5D and 3D models. The main advantages of ALS are the fast and relatively accurate acquisition of topographic point sets, with a wide range of possible point densities. The density is mainly related with the flying height. Besides, recent research on processing ALS data enabled a reliable and straightforward workflow for the generation of DTMs and DSMs. The pulse frequency varies with different topographic airborne units from 20 to 300 kHz (pulse frequency, sampling interval per pulse), where between 5 to more than 400 scan lines per second (scan frequency) can be recorded.

Limitations

Unfortunately, ALS works with single wavelength signals, which will not penetrate water layers. As a result, the sole use of ALS is not advisable for marine applications.

5.1.2. Airborne Laser Bathymetry (ALB)

Airborne Laser Bathymetry (ALB) is a new remote sensing technique that has known a very fast development over the last few years. In most aspects, ALB is very similar with regular ALS systems. However, a common ALB system is equipped with a pulse-based dual wavelength signal emitter and receptor, typically with wavelengths of 1064 nm (near infrared, like in ALS) and 532 nm (green). The first signal is reflected by the dry ground and the water surface; the second signal penetrates into the water and is reflected on the sea bottom.

Advantages

The technique is used for both topographic and bathymetric surveying of shallow coastal waters. However, the technique does not necessarily provide a full coverage of the area, because of interference of the two signals in very shallow waters (approximately 20 cm). Multiple scan campaigns during different tidal situations could solve this data gap issue as well.In the right environmental conditions, it will provide significant efficiency advantages over survey by regular multibeam vessels. The most recent advances have enabled the recovery of reflectivity information from the seabed footprint, leading the way to seabed classification and advanced feature detection. Earlier research has demonstrated the potential of ALB in areas with water turbidity of 2-3 secchi depths. In clear water, this corresponds with approximately 50 m. Due to the active billow and strong tidal current in the near shore North Sea coast, high water turbidity occurs, limiting this secchi requirement to only a few decimetres.

The quality of the ALB data could be comparable with MBES data in near shore areas. Besides, the acquisition time and cost of ALB are lower in comparison with conventional bathymetric acquisition techniques, when very large surfaces are covered.

Limitations

Most ALB systems operate with a frequency of only 1 kHz and result in much lower point densities. In order to penetrate a water column with the green signal and to control the signal to noise ration, a significantly longer and more powerful laser pulse is required. However, this power level is limited by legal void, since high energetic green light may cause irrevocable eye damage. Besides, officially preparatory permission is required to perform the flight, reducing the flexibility of measuring the intertidal zones under acceptable weather and tidal conditions. Besides, ALB campaigns will result in coarser digital surface models with lower accuracies, as an ALS acquisition campaign under the same acquisition circumstances.

5.1.3. Static Terrestrial Laser Scanning (STLS)

Static Terrestrial Laser Scanning (STLS) is a variant of the above mentioned laser scanning techniques, where a huge amount of accurate detail points is acquired from a fixed laser scanner position. STLS is frequently used to model objects of a limited size or at a limited distance from the scanner. The type of application and the range is in this context mainly related to the type of distance measurement (i.e. phase-based with a range up to 100 m or pulse-based with a range up to 1 km).

Advantages

Using a phase-based scanner, scanning speeds of up to 1 GHz can be reached. This data recording leads to an accurate 3D model which offers a point based representation of the object or site.

Limitations
STLS can be used for topographic surface modelling, but it is obvious that the technique suffers from some important drawbacks for intertidal zone mapping: the number of scans is related with the size of the area that has to be scanned. Because of the lack of topographic variability of the terrain, a target based registration is required. Since each target, or materialised reference point, has to be positioned a coordinate system, the campaign can be very time consuming.

An even more important drawback of static measurements is the fact that on flat terrain, the angle of incidence will be very large. A scanner is often placed on a tripod, meaning that the scanning height is around 1.5 to 2.0 m. Even with a range of 8.5 m, there will be an incidence angle of 80^{o}, resulting in large beam spots or radiation angles. Thereupon, lower signal to noise ratios will occur and lower point accuracies will be reached.

Summarizing, it can be concluded that STLS will be very useful for the detailed modelling of small surfaces, but attention on the speed and accuracy has to be paid for the mapping of larger areas.

5.1.4. Mobile Terrestrial Laser Scanning (MTLS)

With Mobile Terrestrial Laser Scanning (MTLS), the system configuration is very similar to an ALS setup. A laser scanner, GNSS and INS are the main components, mounted on a driving platform. As in airborne applications, the combination of GNSS and INS measurements from the POS provide high accurate positioning, whilst the laser scanner produces a very precise point cloud. The accurate determination of the calibration parameters is also essential for the correct use of MTLS.

Advantages
For intertidal beach modelling, the driving platform needs to operate in very shallow water, and in shifting sand. An amphibious vehicle, like the ARGO is then an obvious choice. Although 2D profile scanners can be used for MTLS, it is also possible to deploy regular STLS systems configured as a profiler. Nevertheless, the centimetre accuracy of both systems is comparable. STLS has the advantage of generating point clouds of the surface in a strip-wise manner as with airborne scanning.

Limitations
Using the ARGO, the scanning height will be more or less equal to the height of a scanner on a tripod. The previously mentioned issue concerning the large incidence angles can be reduced by limiting the scanning range and allowing enough overlap between subsequent strips.

5.2. Conventional topographic measurements

GNSS measurements or measurements with a total station are probably the most well-known techniques to generate DTMs. Conventional topographic measurements for a DTM are a mainly manual process. The theoretically possible point density of conventional topography is equal to the other techniques, but this is hardly feasible for practical reasons.

Consequently, these techniques are mainly applied for low resolution surface modelling with high accuracy, e.g. for the calculation of reference surfaces which can be used for quality evaluation of DTMs acquired by more automated techniques. Besides, conventional topography is frequently applied for the measurement of Ground Control Points (GCPs) or reference points as input for the georeferencing of laser scan or image based modelling DSMs.

5.2.1. GNSS

Until a few years, it was very difficult and expensive to measure single points with cm accuracy. Moreover, these measurements were extremely time-consuming. The ability to use data connections over mobile networks have speed up the development of Real Time Kinematic (RTK) GNSS measurements with cm accuracy. The Flemish Positioning Service (FLEPOS) is the implementation of such a system in Flanders, consisting of a network of 40 permanent reference stations. Users can use this FLEPOS service by downloading real time correction messages for their own GNSS measurements.

Advantages
By using FLEPOS, point precisions between 1 and 4 cm (67% or 1 sigma) can be reached for planimetry and altimetry. This easy access to very accurate GNSS measurements has opened a lot of possibilities to use GNSS for the fast and accurate generation of DSMs.

Limitations
The technique is still limited by the achievable resolution of the measurements. For the application of GNSS measurements in the intertidal zone of a beach, an extra error source can be introduced when the pole on which the GNSS antenna is mounted is not perfectly positioned on the beach's surface.

5.2.2. Total station measurements

Advantages
Recent developments towards robotic total stations make it possible to perform reflectorless distance measurements (EDM) by only one operator, significantly increasing the performance of total station measurements. The use of such a total station for surface mapping may result in an accuracy of 1 or 2 cm, although sub-centimetre single point precisions can be reached. Another interesting development is the integration of total stations with imaging sensors.

Limitations
The same remarks have to be made as with the GNSS measurements. Due to the slower measurement speed (in comparison with e.g. laser scanners) and the higher degree of manual intervention by the operator, only a lower point density is achievable.

5.3. Photogrammetry or image based modelling

The use of images for the extraction of 3D and the calculation of digital surface models is known for over a century. In a conventional photogrammetric workflow, stereo couples are processed according to a pair wise and frequently calibrated procedure. Recent developments have also enabled to process large series of both terrestrial and airborne images in a highly automated workflow.

Advantages

New 3D photo modelling software enables to generate 3D models based on a large series of images using SfM-MVS. SfM-MVS is a technique to reconstruct the camera acquisition parameters and a sparse point set of the scene (SfM), as well as a technique to acquire the 3D geometry of an object, or a series of objects (MVS), using a series of 2D images.

Limitations

The initial data for the surface reconstruction using conventional photogrammetry or image based modelling are two or more digital images. As with ALS, airborne photogrammetric campaigns also require predatory permission and are therefore not advisable for intertidal zone modelling. The use of an Unmanned Aerial Vehicle (UAV), like a drone or kite, could be an alternative, notwithstanding the fact that favourable weather and tidal conditions are required. The presence of salt water can be disastrous for the fine electronics on the platform, so a watertight construction is preferred. On terrestrial images, it is very difficult to define corresponding points between different images. Large incidence angles away from the acquisition point of an image result in very large GSD, so terrestrial photogrammetry and image based modelling is only advisable for very small and characteristic areas.

5.4. Comparative review of the different surface generating techniques

Acquisition technique	GSD	Vertical accuracy	Remarks
ALS	10 cm	5 cm	Very fast acquisition Reasonable point density Only suitable for dry topography
ALB	1 m	25 cm	Very fast acquisition Different resolution dry/wet Difficult to apply in the North Sea
STLS	2 cm	2 - 5 cm	Very high point densities Fast acquisition per scanning position, slow for a large beach Variable point quality
MTLS	10 cm	5 cm	Fast acquisition Reasonable point density Flexible system
Conventional topography	-	1 - 4 cm	Slow acquisition High accuracy Low point density
Photogrammetry and image based modelling	2 - 5 cm	2 - 15 cm	Favourable weather and tidal conditions required Difficult defining corresponding points

Table 3: Overview of different surface generating techniques

6. Conclusions

In marine archaeological studies, marine geophysical methods are the best investigation tool as they provide fast, cost-effective and non-destructive high-resolution information of the buried objects and landscapes.

The decision of which technique to use will depend on the type of data that is needed and the reasons for the project in order to justify the use of equipment and shape the survey design. If targets lay on the surface of the seafloor, then bathymetric techniques are the best option. If the goal of the investigation is buried within the sediments or if we are looking for submerged landscapes sub-bottom profilers or acoustic methods in general are the technique of choice. The choice of the seismic source depends on the trade-off between the resolution (requires high frequencies) and penetration (requires lower frequencies) needed for the survey. If, due to external reasons, like presence of gas in the sediments, acoustic methods are not suitable, then alternative methods, that do not depend on the acoustic impedance of the buried materials, are recommended in order to overcome this obstacle and obtain some information of the studied area.

It is highly recommended to use different methods simultaneously in order to make marine surveys more economical and effective.

For intertidal archaeological studies that take place in the transition zone between land and sea a different approach is needed. Often these zones are marked by shallow gas and conventional acoustic methods are less effective. Again the decision of which technique to use will depend on the type of data that is needed (bathymetric or sub-bottom) and the reasons for the project.

If the goal of the investigation is at the surface, surface then a mobile laser scanning platform is the most suitable, next to the use of image based modelling with SfM-MVS. Initially, ALB was selected as a variant of ALS to model the area. However, the Belgian coast suffers from various challenging difficulties (for example weather conditions and water turbidity), resulting in important practical and technical difficulties. Finally, MTLS is the most appropriate alternative way to generate highly accurate and high density DSMs of intertidal zones of beaches.

If the targets are buried and relatively large then unconventional acoustic techniques such as shear wave or surface wave imaging are a good choice. Non-acoustic techniques such as resistivity, EM and radar methods remain difficult due to a lack of marine adapted equipment. Magnetic methods are only effective if the target involves ferromagnetic objects.

Also here it is highly recommended to use different methods in conjunction with each other.