Deltares

Methods to detect shellfish

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Author(s)
Ipo Ritsema
Marco de Kleine
Annika Hesselink
Marios Karaoulis
Peter Frantsen
Albert Oost

Cooperation by
Mark Vardy (Sand Geophysics)
Alexander Bahr (Hydromea)

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Contact	Suzan van Lieshout (Rijkswaterstaat Zee en Delta)

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Doc. version	Author	Reviewer	Approver	Publish
0.1	Ipo Ritsema	Arjan Wijdeveld	Maaike Blauw	
	Marco de Kleine	Peter Herman		
	Annika Hesselink	Chris Mesdag		
	Marios Karaoulis	Mike van der Werf		
	Peter Frantsen			
	Albert Oost			
	Cooperation by			
	Mark Vardy (Sand Geophysics)			
	Alexander Bahr (Hydromea)			

Executive summary

An inventory and assessment of geophysical shellfish bed detection methods has been carried out for Rijkswaterstaat. The inventory included literature, a shellfish bed definition and detection criteria, interviewing geophysical service companies on current and near-market technologies and reviewing shellfish bed detection pilot experiments.
Our analysis has resulted in an overview of promising geophysical techniques for detection of epifauna and infauna shellfish beds at potential sand production locations below 20 meters depth in the North Sea. Recommendations are given for future steps to test and build confidence in the technologies proposed.

About Deltares

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1 Introduction

1.1 Background

The Netherlands is Western Europe's largest marine sand extractor (ICES WGEXT, 2018; Phua et al., 2018). Sand is extracted for two main purposes. First, maintenance of the Dutch coastline is assured with sand nourishments compensating for the effects of relative sea level rise and naturally occurring coastal erosion. Nourishment of beaches and foreshores requires considerable volumes of sand, in the order of 10 million m^3 per year. Second, sand is also mined for construction fill.
The yearly extraction volume for both purposes in 2017 was 20 million cubic meters. This demand for marine sand is still increasing (de Jong et al., 2016).This sand was extracted from the coastal area beyond the -20 m NAP isobath, and within the 12 miles boundary off the coast.

Extraction of sand disturbs the sediment and its benthic organisms, including shellfish. Benthic life provides food for fish, marine mammals and (where diving depth is within physiological limits) marine birds. Sand extraction can therefore affect the complete marine ecosystem. The Marine Strategy Framework Directive (MSFD) outlines a set of requirements needed to maintain a healthy environmental status of the North Sea. Human activities such as sand extraction must preserve the marine ecosystem, its services, biodiversity and resilience. The "integrity of the seabed" (6^{th} GES element of Annex I of the RM) is an important indicator of application in the case of sand extraction. Sand extraction is subject to legal authorization based on the “Ontgrondingenwet” (Ministry of Infrastructure and Water Management) and requires an environmental impact report (EIA) and a monitoring and evaluation programme (MEP) to be executed during implementation.

In 2008, the EIA Committee recommended that the location of shellfish beds be mapped before sand extraction. This advice is included as obligation 5.3 in the Basic Permit for the extraction of sand in the North Sea. Sand extraction is not permitted in a perimeter of 100 metres from living shellfish beds (Ontgrondingenwet, 2018). However, no generally accepted definition of the term 'shellfish bed' is available and surface-covering techniques for mapping shellfish beds are not yet operational. It remains unclear what species form shellfish beds in North Sea sand extraction areas and what is the minimum density or spatial extent required to define it as a bed.

The spatial distribution of shellfish beds changes from year to year, necessitating regular updates of the locations of the shellfish beds. Several monitoring technologies for space-covering inventories have been reviewed as part of the MEP sand extraction for the period 2008-2012 (Rozemeijer 2013). This included Multibeam echosounding (MBES), Side scan sonar (SSS), Medusa, video imaging, digging dredge (‘bodemschaaf’). Although some methods were considered to be promising, none was found to be ready for operational use within reasonable boundaries of cost and labour required.

The MEP 2018-2027 therefore includes the following two questions:
1. Which "type of shellfish bed' should be protected during sand extraction?
2. Is it possible to further develop surveying techniques to map shellfish beds?

1.2 The assignment

To address these questions, Deltares and Wageningen Marine Research have been asked by Rijkswaterstaat to develop a better understanding of the characteristics of shellfish beds in sand extraction areas. Given a shellfish bed definition, an inventory and analysis were requested of geophysical methods capable of detecting shellfish beds.

Further requirements were – in addition to the existing methodology of sea bed sampling on point locations - that the surveying methods should be space-covering, can be executed in a short time frame and are cost efficient.

Wageningen Marine Research and Deltares were commissioned to jointly examine:

1. the definition of shellfish beds, that are present within sand mining areas, their ecological value and spatio-temporal expression;
2. whether existing surveying technologies can be improved and whether there are any new techniques that could be used for detection and mapping of these beds.

1.3 General approach of the project

In order to formally define the concept of 'shellfish bed' the following steps were undertaken:

- determine minimum spatial dimensions and minimum animal densities required to define shellfish beds;
- determine which species need to be considered in the definition of shellfish beds;

Furthermore, the ecosystem functions of the defined shellfish beds were evaluated.

The second objective is the development of an operational technique for detecting these shellfish beds. The surveying methods must be applicable in current sand extraction practice. Any system being developed must meet several requirements including that:

- it can be used in the project area (beyond the extended -20-meter NAP depth line up to the 12-mile limit);
- it is mobile and deployable on different types of vessels;
- it can be developed and executed at acceptable operational costs.

The operational techniques must be able to provide data with a required spatial coverage and resolution; therefore, the following requirements must be met by each technology:

- it needs to cover sea bed and shellfish bed surfaces and volumes;
- the range and limits of resolution and accuracy are appropriate for shellfish bed detection;
- results must be reproducible and as independent of expert judgement as possible.

Much research has already been carried out into the possibilities of detecting shellfish beds on the sea floor and the substrate. Imaging and identifying shellfish beds in these environments requires state-of-the-art technologies and imaging. Imaging of the subsurface/surface is usually obtained using specialized geophysical instruments. The spatial resolution as well as the measured geological/geophysical properties (shape, strength, etc.) varies from instrument to instrument. Furthermore, some of the instruments cannot be used when conditions at sea are too challenging limiting the possibilities to scan the sea bed. Up to now, an adequate solution has not yet been found.

1.4 Structure of the report

In this report, we review and evaluate current, state-of-the-art and new detection technologies for imaging epifauna and infauna shellfish beds with resolution varying form meters to centimetre scale. The report provides for an analysis based on literature, reports, interviews and institutional insight into measurement technologies. We formulate recommendations for a detailed and controlled testing of selected techniques.
In the report the following topics are discussed.

- *Shellfish bed characteristics and detection requirements*

Chapter 2 deals with the characteristics and definition of epi- and infauna shellfish beds within the Dutch sand mining zone of the North Sea. It specifies the technical requirements needed and characteristics relevant for the detection of benthic life. The chapter is based on the “shellfish bed” examination report by Johan Craeymeersch, Wageningen Marine Research (in prep.).

- *Detection method evaluation methodology*

Chapter 3 describes the approach taken to assess detection technologies, including review state of the art, literature study, executed, interviews, analysis and assessment. The state of the art is discussed by using previous comparative studies. New literature now available on potentially useful technologies is identified and evaluated. Additionally, research institutes and companies were interviewed to acquire insight into the current state of sensor technology and data processing/interpretation technologies used today. Based on obtained insights and the requirements following from the shellfish bed definition, the technology readiness level (TRL) of the sensing techniques, and the assessment of the detectability of shellfish beds, the application readiness level (ARL) of a surveying method was evaluated. These scores are used to derive the conclusions and recommendations for next steps.

- *Shellfish bed sensing technologies*

In chapter 4 various detection techniques are grouped into several classes based on the underlying acoustic or electromagnetic principle and sensor that is used in these techniques. Except for the sampling techniques, like the box core and the digging dredge (bodemschaaf), all techniques are indirect techniques, requiring a clear understanding of the physical parameters provided for by these techniques and shellfish beds. The potential improvements per sensing technology is discussed resulting in a Technology readiness level indication.

- *Survey and data analysis technologies*

The survey platform (ships, RoV) and the data processing and analysis are also vital components when mapping shellfish beds using the various sensing technologies for mapping shellfish beds. They are discussed in chapter 5. The status of ship-based versus RoV-based measuring is explored as well as the data processing and analysis technologies to distil the presence, geometry and/or density of shellfish beds. The usefulness of technologies is ranked using an application readiness level score.

- *Synthesis and discussion*

Synthesis and discussion are given in chapter 6. Advantages and disadvantages per technology are listed in the context of detection requirements (bed size, shellfish density, habitat and species, etc.). It is discussed which combination(s) of technologies might provide the desired results.

- *Shellfish bed detection technology development options*

In chapter 7 the results of the project are summarised, and several building blocks or pathways for development and research programme are discussed which can be initiated starting in 2020. The ways these building blocks contribute to validation, controlled testing and combining methods is discussed. Recommendations are given for the design of a smart shellfish bed detection survey approach.

2 Shellfish bed characteristics and detection requirements

This chapter is based upon the research executed by Johan Craeymeersch, Wageningen Marine Research (in prep.).

2.1 Shell(fish) related habitats in the North Sea

In order to specify requirements for detection techniques it is important to have a definition of shellfish beds and to know their characteristics. To date, a generally accepted definition has not been established. The habitats created by molluscs can be classified into three major types:

1) **Reefs** (veneer of living and dead animals);

Reefs are three-dimensional structures of calcareous deposits which have an internal rigidity. Blue mussels (*Mytilus* sp.) and certain types of oysters (*Magallana* sp.) are examples of reef-forming shellfish. Above a certain density they form a distinct, three-dimensional structure. These bivalve beds are usually hotspots for biodiversity, although not invariably (Craeymeersch & Jansen, 2019), and provide a range of ecosystem services such as food provision for fish and invertebrates, water filtration, fish production and, to some extent, shoreline protection (Gillies et al., 2018 and references therein).

2) **Aggregations** (living and dead):

Other shellfish species do not form reefs, but often occur in aggregations. These are concentrations of individuals which are not connected with each other. The sea scallop (*Placopecten magellanicus*), for instance, often occurs in adequate densities to provide habitat for other species (Langton & Robinson 1990). The same holds for the edible oyster (*Ostrea edulis*). The clumps of dead shells and oysters can support large numbers of ascidians, polychaetes and seaweeds (OSPAR Commission, 2009). Other bivalves can be found in high densities just below the surface of the sediment.

Although infaunal species do not provide the same type of three-dimensional structures, the presence of bivalves nevertheless provides increased structural heterogeneity within the sediments, with potential for a larger number of different favourable microhabitats within the sediments and thus increased diversity (Gutiérrez et al., 2003, Norkko & Shumway, 2011). However, a mass recruitment might also result in a decrease in diversity and the community will need some time to recover (Van Hoey et al., 2007). Bivalves provide more services than biodiversity alone. Locally, areas with high densities of *Spisula subtruncata,* for instance, can attract large numbers of shellfish eating ducks in coastal waters (Leopold, 1996, Degraer et al., 2007, Fijn et al., 2017). Bivalves which filterfeed and/or depositfeed are major players in the modification of sediments, and the effects we observe are a combination of both bioturbation and bio-irrigation. The term “bioturbation” refers to the reworking of aquatic sediments by the organisms in the sediments and, in its broadest sense, includes the structuring activities of burrowing animals and rooting plants, as well as microbes. “Bio-irrigation”, refers to the enhanced transport of solutes between the sediment and the overlaying water. This is the flushing of burrows that stems from the suspension feeding of the animals and their ventilation activities to facilitate transport of oxygen and excretory products. Bioturbation and bio-irrigation are integral to a healthy soft-sediment ecosystem and, in general, infaunal bivalves such as clams have a positive, desirable influence on the sand or mud in which they live, just as the earthworms in a vegetable patch or garden compost (Norkko & Shumway, 2011). Thus, traits of shellfish might physically change the sediment conditions. Moreover, if shells are extending from the sediment, this will modify the near bottom currents and, bottom roughness (as e.g. for *Ensis leei*, Witbaard et al., 2017). Of course, such changes depend on the size and the density of the shells themselves and on the local current conditions.

3) **Shell** (dead) **accumulations** (often called ‘shell hash’).

A third type of shellfish habitat is formed by species such as the ocean quahog (*Arctica islandica*), surf clam (*Spisula solidissima*) and sand gapers (*Mya arenaria*) whose shells can persist long after the inhabiting organism has perished. Sometimes abandoned shells accumulate on the seabed and provide significant structure and habitat for a variety of organisms Concentrations of *Spisula* sp. shell accumulations in the sediment, for instance, provide habitat for juvenile lobster, crabs and benthic fishes (Coen & Grizzle, 2007).

Some habitats can be grouped into either category 2 or 3, depending on the relative abundance of dead shell versus live organisms (Coen & Grizzle, 2007).

In this report, we focus on the first two cases, as the permit conditions under the *Mineral Extraction Law* (‘Ontgrondingenwet’) set a distance of 100 meters to living banks of shellfish to be maintained during extraction.

2.2 Presence of shellfish species in the sand mining zone

A bit more than 100 bivalve species occur in Dutch marine waters (de Bruyne et al., 2013). At least 40 of them have been found in the sand extraction area. Most of them, however, are (and will) – to our knowledge - only found in very low densities. Based on records in Dutch reports (Eisma, 1966, Holtmann et al., 1996, de Bruyne et al., 2013), in reports of neighbouring countries (Degraer et al., 2006, Zettler et al., 2018) and data from the fish and shellfish stock assessments (WOT program) (Smaal et al. 2001, Tulp et al. 2008, Tulp et al. 2010, Verver 2015, Troost et al. 2017), we identified 12 species (Table 1.) which locally can occur in large numbers and form beds. All shells are filterfeeders (Su in Table 1.) although *Fabulina fabula* can also use deposit feeding (De in Table 1.).
Most of them are **infaunal** (infauna) species. Most of them are burrow dwellers which will affect the ecological system by a combination of both bioturbation and bio-irrigation.

Some of them are epifaunal. The edible oyster (*Ostrea edulis*), the Pacific oyster (*Magallana gigas)* and the Mussels (*Mytilus edulis*), are epifauna and live on the sea bottom surface. They are attached to the substratum and are reef builders. It is not expected that the Pacific oysters as well as Mussels will form beds deeper than 20 meters (due to intensive fishing), so they are not further included in the analysis.

2.3 Characteristics relevant for detecting shellfish beds

Definitive characteristics per species influencing detectability are:

- Mode of living: Epifauna or infauna;
- Densities of individuals (per square meter);
- Size of individuals;
- Size of beds;
- Individuals or colony/reef;
- Burial depth range;
- Surface expression (i.e. siphon);
- Sediment type.

Values found in literature (a.o. Holtman et al, 1996, Degraer et al., 2006, Degraer et al., 2007, Witbaard et al, 2013) and the WMR-Yerseke database have been combined in Table 1.

Table 1: Species' characteristics

Species	Lifespan (years)	Trophic type	Living habitat	Depth (-m AOD)	Sediment characteristics
Chamelea striatula	3 - 10	Su	Burrow dwelling	1 to 400	Generally, in muddy, fine sand but also in clean sand
Donax vittaus	1 - 3	Su	Burrow dwelling	0 to 30	Clean fine sand (50 to 250 mu)
Ensis leei	3 - 6	Su	Burrow dwelling	+1 to 20	Gently sloping subtidal region to low gradient shifting sands, but also in mud and gravel
Ensis siliqua	3 - 18	Su	Burrow dwelling	0 to 200	Fine, sometimes muddy sand
Ensis magnus	3 - 10	Su	Burrow dwelling	0 to 200	In coarser sand than *E. siliqua*
Lutraria lutraria	3 - 10	Su	Burrow dwelling	1 to 100	Muddy sand
Mactra stultorum	3 - 10	Su	Burrow dwelling	5 to 30	Clean sand
Spisula elliptica	3 - 10	Su	Burrow dwelling	0 to 200	Sand, gravel, mud
Spisula solida	3 - 10	Su	Burrow dwelling	0 to 200	Coarse-grained sediments
Spisula subtruncata	3 - 10	Su	Burrow dwelling	10 to 40	Silt, coarse to muddy fine sand
Fabulina fabula	3 - 5	Su/De	Burrow dwelling	1 to 40	Fine (muddy) sand
Ostrea edulis	> 20	Su	Attached to substratum	0 to 60	Muddy fine sand, sandy mud mixed sediments preferably with some hard substratum (large parts of oyster bed may consist of dead oyster shells)

Species	Body length max (cm)	Densities (ind/m2) **	Reef/ Aggregation (R, A)	Bed size range	Burrowing depth/height (cm ref surface)	Mobility	Degree of attachment
Chamelea striatula	3.5	4-30	A	no data	0 to -5	Sessile	Null
Donax vittaus	4	20-766	A	no data	-5 to -15	Sessile	Null
Ensis leei	16	720-4500	A	no data	> -15	Sessile/ swim	Null
Ensis siliqua	21.5	no data	A	no data	> -15	Sessile	Null
Ensis magnus	18	no data	A	no data	> -15	Sessile	Null
Lutraria lutraria	15	5-103	A	no data	> -15	Sessile	Null
Mactra stultorum	6	1-31	A	no data	-5 to -15	Sessile	Null
Spisula elliptica	3	52-2765	A	no data	0 to -5	Sessile	Null
Spisula solida	5.5	5-88	A	no data	0 to -5	Sessile	Null
Spisula subtruncata	3.5	80 -16800	A	no data	0 to -5	Sessile	Null
Fabulina fabula	2.5	38-1340	A	no data	-5 to -15	Sessile	Null
Ostrea edulis	(3-11) 22	>5 (Ospar)	R	no data	< +5	Sessile	Attached

2.3.1 Densities of individuals and size of beds

Important for a definition of a shellfish bed are:

1) the minimum coverage (%) or density (number of individuals per square meter) of the species. Population structure of bivalves often has – at least – a bimodal size frequency distribution: a clear distinct juvenile cohort and one or more larger adult cohorts. A 'good' recruitment is often followed by a heavy post-settlement mortality (Degraer et al., 1999, Cole et al., 2000). Thus, the minimum density to be set is likely to be different for juveniles and adults. Furthermore, beds might also consist of mixtures of several species which together form the bed.

2) The minimum spatial extent of the area with a specific coverage or density (bed size) of the species.

<u>*Ostrea edulis beds (epifauna)*</u>

Ostrea edulis is the only epifaunal species expected in water depths larger than 20 meters. For the epifauna bivalve *Ostrea edulis* the definition of the shellfish bed should most likely be close to the ones used for other epifauna species. The definition for bed used in San Francisco Bay is – to our opinion – the most useful: **the species occupies more than 50% of an area of more than a few square meters.** The oyster bed – consisting of both Pacific and flat oysters - found in the Voordelta (coastal zone off Zeeland coast, south of Rotterdam) is about 1.3 km^2, with densities of less than 1 to 5 individuals per square meter (Sas et al. 2016). In the Voordelta, the oyster bed established on hard substratum (the 'Blokkendam'). In other places, the bed will consist of many dead shells too.
Thus, a starting definition of an oyster bed could be a bed size of at least 1 km^2 and an average of 5 ind/m^2 s defined in Ospar agreements.

<u>*Spisula subtruncata beds (infauna)*</u>

We will focus on *Spisula subtruncata*, because this species had high stocks in the second half of the nineteens and start of this century (up to 2001). Spisula subtruncata is the main larger infaunal species expected on water depths greater than 20 meters. For *Spisula subtruncata* beds minimum density was estimated in three ways:

1) Minimum density needed to serve as possible food source for the common scoter;
2) Minimum density where the total biomass reaches 80% of the total standing stock in Dutch coastal waters;
3) Minimum density based on a certain age (juvenile, adult) with a certain density.

For a full discussion the reader is referred to Craeymeersch, J. (in prep.), where it is concluded that the densities of 1-year old and older *Spisula* in a bed are apparently higher than 100 ind/m^2, and so we are indeed safe to set 100 ind/m^2 as the lower limit. This corresponds to the minimum density above which the bed can serve as food for birds, where depth is appropriate. We assume that other predators will have a similar minimum density threshold. For juveniles, we propose to set the minimum density tot 1,000 ind/m^2.
Thus, the starting definition of the shellfish bed for this variety of shellfish we assume 100 ind/m^2 as the lower limit and for juveniles, we assume a minimum density of 1,000 ind/m^2.
The minimum bed size we propose is 3 km^2 (personal comment J. Craeymeersch).

Other shellfish

The other species are infauna. For detection purposes the same definitions as used above are also assigned for these species: a bed size of 3 km^2 with an average density of 100 ind/m^2, for adults and 1000 ind/m^2 for juveniles. This could be refined when additional information becomes available. Please see Table 2. for an overview of the detection criteria.

Table 2: Overview of detection criteria

Species	Age	Individuals per square meter	Area in square kilometres
Infauna	Juvenile	1000	3
	Adult	100	3
Epifauna	Juvenile	5	1
	Adult	5	1

The minimum coverage and the minimal spatial extent differ between different species and the parameters define the requirements for the detection methods. The larger the physical contrast for which the sensor is sensitive and the closer the match between sensor resolution and size of the shell-bed targeted for, the higher the accuracy and resolution of the data acquired with that sensor will be. The impact of species on sediment may be detectable.

From Table 2. two main types of shellfish beds are identified:

1) Epifauna which form a structure above the surrounding seafloor with a high roughness and an irregular surface.
2) Infauna which may slightly influence the surface with deposit feeding (*Fabulina fabula)* of filterfeeding (all other shells).

Infauna will be difficult to assess based on structure of the sediment surface although geophysical methods penetrating the sea bed should be able to distinguish variations in density and/or sediment composition.

2.3.2 Traces of shellfish in sediment and water

Besides the minimum coverage and the minimal spatial extent, also the impact of shellfish on their surroundings has been reviewed in order to determine if this could form an indirect parameter to detect shellfish beds. The following impacts have can be considered: bioturbation effect on sediment structure and traces of living organisms in the water column.
Habitat for other species related to shellfish beds, temperature effects and hydrodynamic effects could be additional indicators of shellfish beds but have not been considered. These characteristics have been categorised as ‘not distinctive’ and the detection requirements may differ per target species.

2.3.3 Overview of characteristics per shellfish species relevant for detection

Table 3. lists the characteristics potentially relevant for detection per species and values are divided into classes corresponding to a relative score indicating whether it contributes to the likelihood of detectability.

Table 3: Overview of detection characteristics per species with relative score of influence on detectability

Species	Size	Buried	Surface expression/roughness	Holes/ Siphon	Bio-turbation	Burial depth	Traces
Chamelea striatula	Medium (3)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Shallow (3)	Maybe (0)
Donax vittaus	Small (1)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Intermediate (2)	Maybe (0)
Ensis leei	Large (5)	Yes (1)	Intermediate (3)	Yes (1)	Yes (1)	Deep (1)	Maybe (0)
Ensis siliqua	Large (5)	Yes (1)	Intermediate (3)	Yes (1)	Yes (1)	Deep (1)	Maybe (0)
Ensis magnus	Large (5)	Yes (1)	Intermediate (3)	Yes (1)	Yes (1)	Deep (1)	Maybe (0)
Lutraria lutraria	Medium (3)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Deep (1)	Maybe (0)
Mactra stultorum	Medium (3)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Intermediate (2)	Maybe (0)
Spisula elliptica	Medium (3)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Shallow (3)	Maybe (0)
Spisula solida	Medium (3)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Shallow (3)	Maybe (0)
Spisula subtruncata	Medium (3)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Shallow (3)	Maybe (0)
Fabulina fabula	Small (1)	Yes (1)	Small (1)	Yes (1)	Yes (1)	Intermediate (2)	Maybe (0)
Ostrea edulis	Medium (3)	No (2)	Large (5)	No (2)	No (2)	Surface (4)	Maybe (0)

Using these characteristics and the relative scores for detection, a first qualitative estimate is made of the likeliness of detection per species. Two distinct classifications have been made: the first one includes all parameters and the second excludes burial depth (see Table 4.).

Table 4. suggests that the 3 types of *Ensis* infauna species and *Ostrea edulis* and potentially other epifauna species have the highest potential of detectability, whereas the *Chamelea striulata, Mactra stultorum* and 3 types of *Spisula* infauna species have a moderate likeliness to be detected and the species *Donax vittatus* and *Fabulina fabula* a very low likeliness to be detectable. Other factors that could be included to improve these estimates may include data on distance between individuals or calculated surface and volumetric density.

Table 4: Overview of detection likeliness (relative scale green colours indicate high chance for detection red colours low chance)

Species	Score incl. burial depth criteria	Score excl. burial depth
Chamelea striatula	10	7
Donax vittatus	7	5
Ensis directus	12	11
Ensis leei	12	11
Ensis magna	12	11
Lutraria lutraria	8	7
Mactra stultorum	9	7
Spisula elliptica	10	7
Spisula solida	10	7
Spisula subtruncata	10	7
Fabulina fabula	7	5
Ostrea edulis	17	13

3 Detection method evaluation methodology

3.1 Overview

Using the shell bed definition and characteristics defined by WMR (Chapter 2), Deltares followed a systematic approach and activities including the:

- physics-based framework to compare and assess potential surveying technologies;
- review of previous assessments and literature on surveying technologies;
- collection of new information from interviews and recent experiences of stakeholders;
- assessment of technologies for detecting shellfish beds;
- conclusion and recommendations as discussed with RWS.

3.2 Physics-based framework of potential surveying technologies

Detection methods surveyed can be classified into 2 main groups:

1) Invasive (sampling) detection techniques in which the sea bed is sampled. Techniques include digging dredge (bodemschaaf), Van Veen grab and box-cores. Geophysical techniques are typically used to infill data between sample locations. Sampling techniques are 2D imaging methods; in this report they are only discussed in relation to their possible role as ‘ground truth’ providing methods, and as a benchmark for comparison and calibration of the geophysical methods.
2) Non-invasive detection techniques, subdivided into
    - Geophysical techniques based on acoustic energy, such as low frequency subbottom profiler and high frequency side scan sonar and MBES technology (https://discloseweb.webhosting.rug.nl/nl/tud-project);
    - Geophysical methods based on electromagnetic energy, such as electromagnetic methods or optical cameras.

Geophysical techniques are considered indirect methods as they are based on the contrast between physical - acoustic or electromagnetic - properties of shellfish beds and bare sediments. To verify and calibrate geophysical surveys results, direct sampling is always required.

Classification of acoustic (AC) sensing technologies from high to low frequency

The potential acoustic based surveying techniques include, from high to low frequency: Sonar and MBES with a small wavelength compared to shellfish size; Sub-bottom profiler, Seismic, deformation and gravity sensors with increasing with a long wavelength compared to shellfish size. As sea water has a limited influence on the transmission of acoustic energy (minimal diffraction and dissipation effects) high frequency technologies can capture measurements from a relatively large distance from the target. The lower the frequency and larger the wavelength, the larger sea bed penetration will be, but the lower resolution achieved. For clarity, a short overview of frequency and wavelength in water of the different acoustic surveying methods is provided in Figure 1.

The following acoustic techniques are discussed:

- Side Scan Sonar technique,
- Multibeam Echo Sounder backscatter technique,
- Synthetic Aperture Sonar,
- Sub-bottom profiler/3D sub-bottom profiler technique.

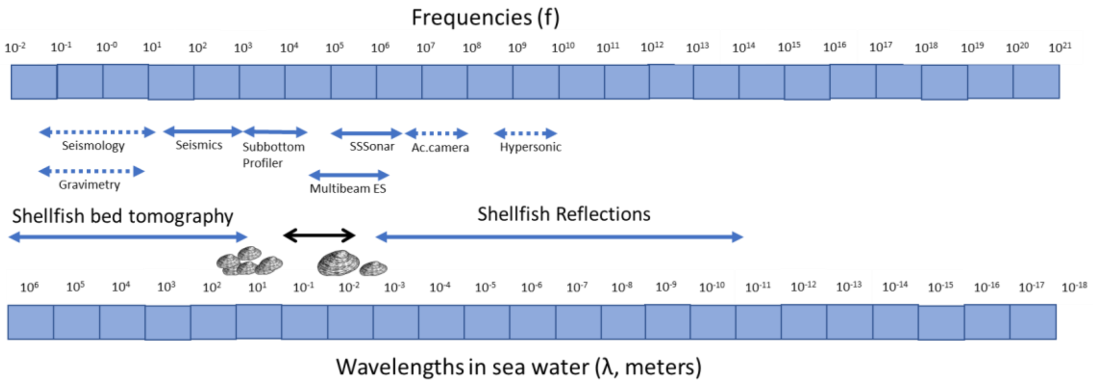


Figure 1: Marine acoustic surveying methods versus frequency and wavelength in water (Deltares)

Classification of electromagnetic (EM) technologies from high to low frequency
Potential electromagnetic based survey techniques include, (from high frequency and small wavelength to low frequency and long wavelength) gamma ray, visible light, infrared, microwave, radio waves and low frequency electromagnetic and electrical or magnetic techniques (Figure 2).

The electromagnetic technologies can - taking shellfish size as reference - with respect to wavelength be divided in high frequency (reflective, scattering) and low frequency (transmissive, induction) methods each requiring specific data processing procedures (resp.: image processing, amplitude versus angle, texture analysis/classification versus seismic processing and interpretation methods).

As seawater is an influencing factor on the transmission of electromagnetic energy (mainly by inductive dissipation) high frequency technologies need to sense or measure in close proximity to the target investigated. The advantage of using the high frequency techniques is the detail provided in the results. Lower frequency techniques allow for greater measuring distances but have lower spatial resolution.

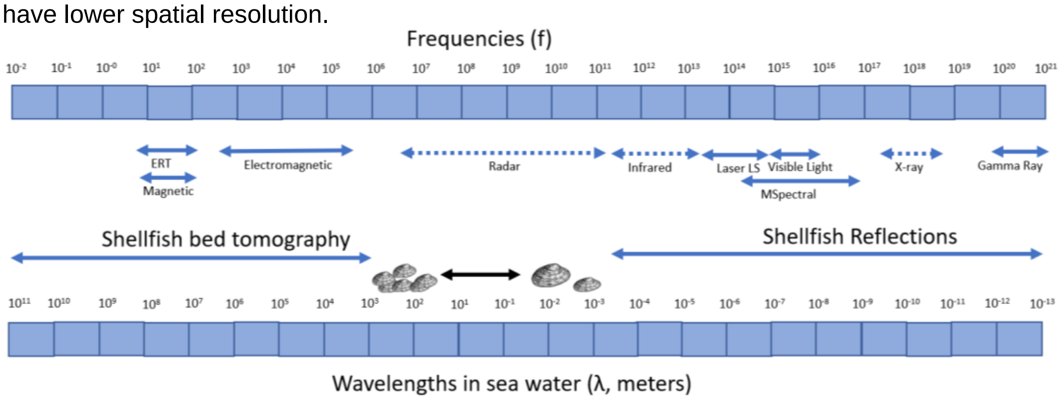


Figure 2: Marine electromagnetic surveying methods versus frequency and wavelength in water (Deltares)

The following high frequency electromagnetic detection methods are discussed:
- Natural Gamma Ray Radiation;
- Hyperspectral cameras;
- Optical (visible light) cameras;
- Laser line scanning.

The following low frequency electromagnetic detection methods are discussed:
- Electromagnetic techniques;
- Electrical Resistivity Tomography;
- Magnetometer/Gradiometer.

3.3 Review previous assessments and literature on geophysical surveying technologies

Over the last decade several inventories of marine survey methods have been made in The Netherlands. Sampling techniques have been tested and are used for their capability to detect shellfish beds including box-core sampling and digging dredge.

In Table 5. a reference overview is given of previous studies in The Netherlands on the feasibility of geophysical methods for shellfish bed detection.

Table 5: The state-of-the-art references on geophysical detection. The results as listed were adapted from the referenced document and as such not a conclusion from the current study

Electromagnetic and acoustic quick-scan detection methods in the Dutch Monitoring and evaluation programme for sand extraction RWS LaMER (2007 & 2008-2012)				
Research	Purpose	Method	Results	References
Monitoring mud content at the surface; September 2009 – March 2010.	Testing method for suitability to show presence of shellfish beds	Medusa AC: acoustic	Not specific enough	de Vries et al., 2011
Benthos mapping using side scan sonar at Noordwijk.	Idem	Geophysics AC: side scan sonar	Resolution too small	Paap, 2011.
Submerged video Voordelta & Zeeuwse banken.	Idem	Geophysics EM: video camera	Has potential; vulnerable to weather conditions and turbidity	Lengkeek et al., 2010
Submerged video N off Ameland.	Testing method for suitability to show presence of benthos	Geophysics EM: video camera	Has potential; vulnerable to weather conditions and turbidity	Didderen et al., 2011
Additional MEP 2012 quick scan methods				
Acoustic habitat and shellfish mapping and monitoring in shallow coastal water – Side scan sonar experiences in The Netherlands	Testing method for suitability to show presence of shellfish beds	Geophysics AC: side scan sonar; using backscatter data	Applicable, used frequency 325 kHz, Modern techniques use frequencies up to 1600 kHz which will deliver better resolution	Overmeeren et al., 2009
The use of an acoustic technique in mapping beds of jackknife clams (Ensis sp.)	Testing method for suitability to show presence of Ensis sp.	Geophysics AC: Multibeam; using backscatter data	Has potential. Modern techniques will deliver better results	Troost et al., 2012.
A Bayesian approach to seafloor classification using multi-beam echo-sounder backscatter data	Test method for sediment classification	Geophysics AC: using backscatter data	Has potential for showing presence of shellfish beds	Simons & Snellen, 2009, Snellen at al., 2018

Disclose (https://discloseweb.webhosting.rug.nl/nl/tud-project/)	Ecological mapping of North Sea seabed	Multi-beam echo-sounder with backscatter observation	High resolution observation of sea bed	NIOZ, TUD en RUG: ongoing
Disclose (https://discloseweb.webhosting.rug.nl/nl/tud-project/)	Ecological mapping of North Sea seabed	Combining multi-beam echo-sounder with side scan sonar and sub-bottom profiler	High resolution observation of and in sea bed	NIOZ, TUD en RUG: ongoing

Acoustic methods such as the side scan sonar and multibeam techniques using backscatter data have large potential, given the fast development and advancement in techniques. Such methods focus on physical contrasts causing scattering of acoustic signals. Also based on the above-mentioned studies, it was recommended to carry out tests of side scan sonars with higher frequencies and up-to-date multifrequency multibeam using backscatter data. Optical techniques are based upon either visual analysis or, potentially, automated image processing techniques whereas acoustic techniques are relying on contrasts in density, reflectance and possibly image processing. Optical cameras were considered to have potential but are vulnerable to weather conditions and turbidity. The question is whether this can be improved using another part of the electromagnetic spectrum. In contrast to optical systems, other instruments from the electromagnetic domain have not been tested for this field of application.

3.4 Gathering new information from interviews and recent experiences

Interviews

During this study several institutes and companies were interviewed, and a summary of the results can be found in Table 6. This was done for several reasons. First, to acquire insight in the current state of the art of sensor technology and data processing/interpretation technologies. Second, was to explore the possibility of future cooperation and/or determine if it is possible to join in on current programs or research lines to help facilitate fast and efficient development of new methodologies for shellfish bed detection. Third and somewhat less explored, to determine if the development of these technologies could be beneficial for similar or other applications related to shellfish beds.
In order to achieve the necessary innovation within this field, cooperation with several key players is required. The interviews were essential to generate or expand the possible cooperation as the aim was to lay the foundations of a future partnership as well as to improve the cooperation in the subsequent project phases.

The following institutes, research groups and companies were visited and interviewed, or only interviewed (Table 6). Their activities, interests and possible contributions are listed in Tables 7 and 8. In addition, information of company products or services were assembled via internet.

Table 6: Overview of the visited and interviewed institutes, research groups and companies

Institute	Country	Visited and Interviewed	Reviewer of this report
Bedford institute of Oceanography, Fisheries and Oceans Canada	CA	X	
Centre for Coastal and Ocean Mapping, University of New Hampshire	USA	X	
Centre for Environment, Fisheries and Aquaculture Science	UK	X	
Deltares	NL	X	X
Edgetech	USA	X	
French National Institute for computer science and applied mathematics (INRIA)	F		X
Ixblue	F		X
Koninklijk Nederlands Instituut voor onderzoek der Zee (NIOZ)	NL		X
Kraken	CA		X
Metinco	NL		X
National Oceanographic centre	UK	X	
Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (TNO)	NL	X	
Norwegian Defence Research Establishment	N		X
Nova Scotia Community College. NSERC Industrial Research, Integrated Ocean Mapping Technologies	CA	X	
Plymouth Marine Laboratory	UK	X	
Sand Geophysics	UK	X	
Scottish association for marine science	UK	X	
TUDelft	NL	X	X
University of Århus	DK		X
University of Southampton	UK	X	
USnavy	USA	X	
Vlaams Instituut voor de Zee (VLIZ)	B	X	
Wageningen Marine Research (WMR)	NL	X	X
Woods Hole Oceanographic Institute	USA	X	

Deltares and the TU Delft are collaborating in the field of multibeam backscatter analysis. Deltares' researchers were asked to provide input on working together with the specialists from the TU Delft. In the tables we combined the TU Delft and Deltares group as one where the TU Delft is mainly active in the field of multibeam backscatter analysis and Deltares covers a wider range of methods.

Table 7: Overview of capabilities and interests per interviewed institute/company. X= present, (X)= partially present/in development, focus on processing, analysis and interpretation

Research Institutes and companies versus Sensing Technologies	Side Scan Sonar (SSS)	Multibeam Echosounder backscatter sonar (MBES)	Synthetic aperture sonar (SA Sonar)	Subbottom profiler	3D subbottom profiler	Natural Gamma Ray	Hyperspectral camera	Visible light camera	Laser Line Scanning	Electromagnetic techniques (EM)	Electrical resistivity tomography (ERT)	Magnetometer/ Gradiometer
Bedford institute of Oceano-graphy, Fisheries and Oceans Canada												
Centre for Coastal and Ocean Mapping, University of New Hampshire	X	X					X	X				
Centre for Environment, Fisheries and Aquaculture Science	X	X						X				
Deltares	X	X		X		X	X		(X)	X	X	X
Edgetech	X	X	(X)	X								
French National Institute for computer science and Applied mathematics (INRIA)												
Ixblue	X		(X)		X							
Koninklijk Nederlands Instituut voor onderzoek der Zee (NIOZ)	X	X						X				
Kraken			X						X			
Medusa		X		X		X						(X)
Metinco	X	X		X								
National Oceanographic centre	X	X			(X)			X				
Nederlandse Organisatie voor toegepast natuurwetenschappelijk onderzoek (TNO)	(X)	(X)	X		X							
Norwegian Defence Research Establishment	X	X	X									
Nova Scotia Community College. NSERC Industrial Research, Integrated Ocean Mapping Technologies	X	X	X				X	X				
Plymouth Marine Laboratory								X				
Sand Geophysics	(X)	(X)		X	X							X
Scottish association for marine science	X	X										
TUDelft	X	X		X		X	(X)		(X)	X	X	X
University of Århus										X	X	X
University of Southampton	X	X		X	(X)			X				
USnavy			X									
Vlaams Instituut voor de Zee (VLIZ)					X			X				
Wageningen Marine Research (WMR)	X					X	X	X	X			
Woods Hole Oceanographic Institute	X	X		X				X	X	X		

Table 8: Overview of platform and processing technologies per interviewed institute/company. X= present, (X)= partially present/in development

Research institutes and companies versus Platform and processing technologies	Autonomy	Methodology	Test facility	Stock assessment	Habitat mapping	Effect and recovery studies	Lower cost solutions	Joint inversion
Bedford institute of Oceanography, Fisheries and Oceans Canada			X	X	X		X	
Centre for Coastal and Ocean Mapping, University of New Hampshire		X	X		X			
Centre for Environment, Fisheries and Aquaculture Science		X		X	X	X		X
Deltares	X	X	(X)	X	(X)	(X)	X	X
Edgetech								
French National Institute for computer science and applied mathematics (INRIA)		X						X
Ixblue								
Koninklijk Nederlands Instituut voor onderzoek der Zee (NIOZ)	(X)	X	(X)	X	X	X		
Kraken								
Medusa	X							X
Metinco								
National Oceanographic centre	X	X	X					(X)
Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (TNO)			(X)					(X)
Norwegian Defence Research Establishment		X						
Nova Scotia Community College. NSERC Industrial Research, Integrated Ocean Mapping Technologies		X	X		X			X
Plymouth Marine Laboratory		X		X	X			
Sand Geophysics								X
Scottish association for marine science	(X)	X		X	X	X	(X)	
TUDelft	X	X		X	(X)	(X)	X	X
University of Århus								X
University of Southampton	(X)	X						(X)
USnavy								
Vlaams Instituut voor de Zee (VLIZ)	X		X				X	
Wageningen Marine Research (WMR)		X	X	X	X	X		
Woods Hole Oceanographic Institute	X	X			X			X

3.5 Assessing technologies for detecting shellfish beds

For each technology the following aspects have been described:

- Method;
- Relevant examples;
- References;
- Improvements made since previous comparative studies.

In the context of this study we distinguish not only the Technology Readiness Level, TRL, level as defined and used by the EU (Table 9) for the sensing technology but also a similar scale to distinguish the application readiness level (ARL), which we define as the readiness level of this technique to be applied specifically for shellfish bed detection. The ARL (Table 10) is a combined factor based upon 1) the TRL of the sensing technology, 2) the platform technology applied, 3) the processing technology required to move from data to information and 4) the available validating experience with this sensor for shellfish detection.

Table 9: Description of Technology Readiness levels (After: www.cloudwatchhub.eu)

Level	Stage		Description
0	Idea	Idea	Unproven concept, no testing has been performed
1	Idea	Basic research	You can now describe the need(s) but have no evidence
2	Idea	Technology formulation	Concept and application have been formulated
3	Idea	Needs validation	You have an initial “offering”: stakeholders like your slideware
4	Prototype	Small scale prototype	Built in a laboratory environment (“ugly” prototype)
5	Prototype	Large scale prototype	Tested in intended environment
6	Validation	Prototype system	Tested in intended environment close to expected performance
7	Validation	Demonstration system	Operating in operational environment at pre-commercial scale
8	Production	First of a kind commercial system	All technical processes and systems to support commercial activity in ready state
9	Production	Full commercial application	Technology on “general availability for all consumers

For each technology we have estimated the TRL level (according to Table 9.) and the ARL levels. The TRL levels are aimed at the sensors itself and the application in the marine environment and not the readiness for the specific application.

Table 10: Description of Application Readiness levels (After: www.cloudwatchhub.eu)

Level	Stage	Description
1	Hypothetical Idea	First idea of shellfish bed detection surveying method
2	Prototyped in Lab	Method of application defined and verified in laboratory application; example of being developed in other fields, publication
3	Validated in pilot	Method applied in pilots and references of method maturity in other application areas
4	Demonstration in the field	Method applied in operational environment for shellfish bed detection on North Sea
5	Production by multiple surveyors	Method on “general availability for all consumers

For ARL level we use a scale from 1-5. The ARL level indicates the maturity of the surveying method to detect shellfish bed using the sensing technology. The required distance between the sensor and the seabed varies from technique to technique and is determined by the local conditions (for example turbidity) and the sensitivity of the sensor. This aspect is an important operational factor. Recent developments in autonomous underwater vehicles could be a solution to minimize these negative effects. Therefore, in this study, a division has been made between ship-based and RoV-based application readiness level.

Within this study we present the potential of these techniques for mapping shellfish beds in the less transparent North Sea, but knowledge developed here could be used at different more transparent locations (i.e. the Caribbean) where conclusions about a technique could differ.

3.6 Conclusions, recommendations in discussion with stakeholders

During the initial, intermediate and final project stages, conclusions and recommendations were discussed with stakeholders (Rijkswaterstaat), research groups and the market.

Based on the findings, different complementary pathways for developing a shellfish bed detection methodology and monitoring strategy have been identified.

4 Shellfish bed sensing technologies

4.1 Introduction

In each subsequent section a short description of the geophysical sensing technologies is presented with examples and references. The same applies for recent developments of the selected technologies since the previous review of shellfish bed detection methods. These improvements can focus on the transmitter-sensor design or configuration (chapter 4) or the processing and/or the method of usage (chapter 5). A summary of pros and cons, and the technology readiness (TRL) assessment of the different techniques are summarized in section 4.6.

4.2 Geophysical sensing techniques using acoustic energy

4.2.1 Side Scan Sonar technique

Method

Side scan sonar (SSS) systems normally use the wide-angle sound signal of 100-1600 kHz wave bandwidth, yielding a high resolution and producing detailed wide-angle images of the seabed on both sides of the ship (with a blind zone in the middle) in which different features can be recognized. The resolution of the side scan sonar can be in the range of mm to cm, depending on frequencies and the distance from the instrument to sea bottom. The side scan sonar system is towed behind the ship to keep the instrument sufficiently close (typically 5 meter) to the sea bottom. Theoretically it is possible to detect objects as small as mussels or oysters. The side scan sonar method, certainly at high frequency range, is unsuitable for detecting sub-seafloor features and buried shells as most energy is reflected at the sea floor.

Relevant examples

In 2009 it was shown that with the side scan sonar, it is possible to explore large areas with high resolution, in a relatively short time (van Overmeeren et al, 2009). The system used in 2009 was CM 2 of C-Max Ltd, with a fixed frequency of 325 kHz. Side scan sonar images of some epifaunal shell beds on the tidal flats of the Wadden Sea, recorded at high tide, showed a marked resemblance with the optical Google Earth images of the same epifaunal beds (Figure 3). Note that this concerns epifauna beds, for which this technique is suited as limited penetration of acoustic wave is needed.

Improvements since previous comparative studies

The frequency and resolution of side scan sonar systems have steadily increased (up to 1.600 kHz) and these options have also been incorporated in multi frequency side scan sonar systems. In addition to the standard side scan sonars (using one or a few single frequencies), interferometric and chirp type side scan sonars (based on a sweep of frequencies) could provide added value over the sonars tested in the past.
Another development is in the 3D side scan sonar techniques, a different configuration of scanner and multibeam sonars using volumetric pulses and receiver arrays, which do have potentials to have higher resolution than the standard single and multibeam systems and multispectral side scan sonar systems. For now, these are not seen as having much added value to the techniques already listed as they are operating in the same frequency range.

Integrating new side scan sonar technologies within current surveying practices where vessels are being used is a possible development path. Mounting the side scan sonars on a remotely operated platforms (ROV and USV) or autonomous platforms (AUV and ASV) on sea and subsea

platforms (RV, AUV, USV) could help to increase the resolution and efficiency of this technology. In future swarms of these vehicles might be operated from a surveying ship.
The increasing dynamic range of new digital side scan sonar recorded data allows for enhancing the signal to noise ratio, providing better images for object detection processing. Also, the processing principles of optical and radar techniques (i.e. image processing) could potentially be applied to side scan sonar data, to improve image quality.
After statistical correlation analysis, automated processing and interpretation of data sets, such texture mapping and object detection could be one of the most likely steps forward. The higher along-track and cross-track resolution of side scan sonars (with respect to comparable multibeam systems) is an important added value of this technique.

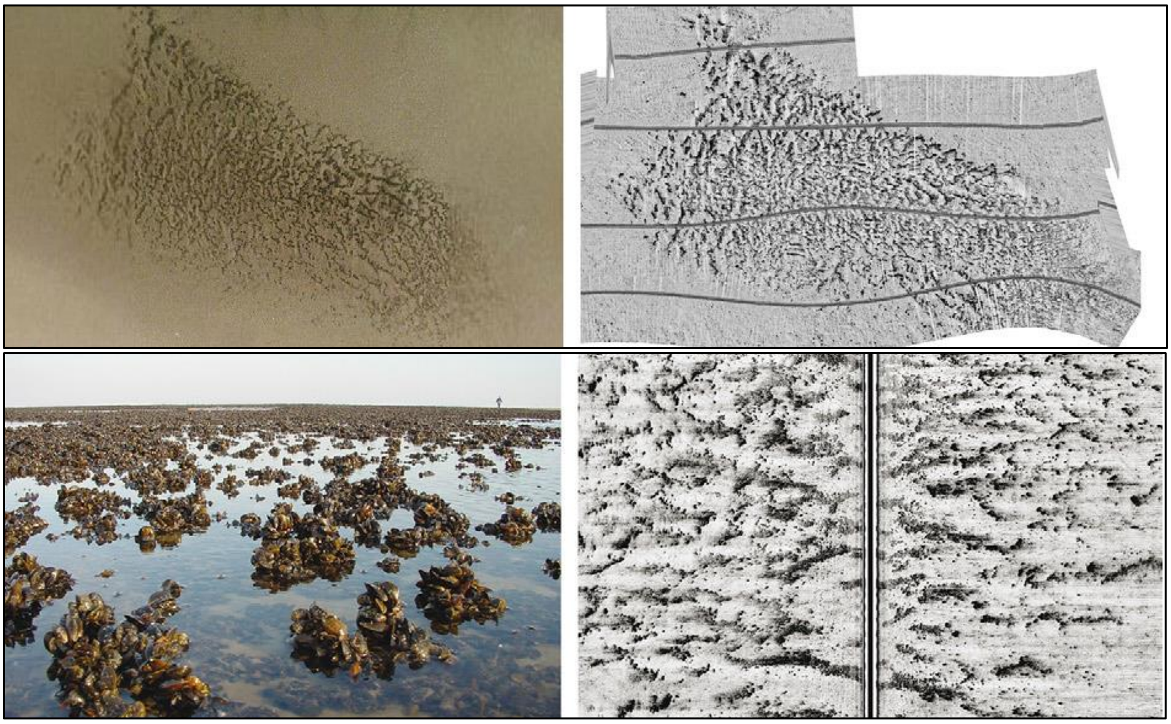


Figure 3: Examples of dense epifauna mussel beds in the Wadden Sea (top-left, Google Earth) and acoustic images (right) (van Overmeeren et al, 2009)

4.2.2 Single beam and multibeam Echo Sounder backscatter technology

Method
Single and multibeam echo sounders are a type of beamed sonar that is used to map the morphology (bathymetry) of the seabed. The normal frequency range for shallow water systems is similar to the lower frequency range of side scan sonar, 100-800 kHz. Deep water echo sounders use frequencies in the range of 10-100 kHz. Single beam echo sounders are not discussed further as they are much less relevant than multibeam echo sounders. In a multibeam echo sounder (MBES) series of sound waves beams are emitted in a wide fan shape beneath a ship's hull to extract directional information from the returning soundwaves, producing a wide spread, or swath, of depth readings, therefore covering a much larger area.

Instead of only deriving the bathymetry from the directional distance of returned signals, the MBES also measures the characteristics (intensity, signal deformation, etc.) of the returned signal (the backscatter), which is a reflection of the characteristics of the seabed sediment that can be used for an automatic sediment classification of the sea bed (e.g. Geoswath, Edgetech6205, pingdsp technologies, Wilson et al., 2006). Simons and Snellen (2009) presented a Bayesian approach for the unsupervised classification of the seabed. By curve fitting the measured backscattered signal (histogram) can be approximated by a small number of Gaussian (probability density functions), which each represent an individual sediment type. The method calculates what number of classes best represents the measured histogram. Sediment type is then assigned to the classes of the bed classification by ground truthing, i.e. seabed sediment sampling. The method has since been refined into a more robust method (e.g. Carey et al., 2015, Snellen et al., 2018 and references therein). Several commercial packages are also available on the market, not always offering equally satisfying results. If automated seabed classification based on multibeam backscatter data is applied, it is important to correct the backscatter for the local bathymetry. Correction should not only be applied for the depth but also for the slope (steepness and direction) of the specific grid cell.

Relevant examples
The algorithm of Simons and Snellen (2009) is displayed in Figure 4, the left side showing the bathymetry. The right side of Figure 4 shows the results after applying the classification algorithm. Multibeam data has also been used to detect *Ensis*, (Troost et al., 2012). The *Ensis sp*. beds appeared to give a detectible acoustic signal and the use of backscatter data appeared to be most suitable to detect *Ensis* beds. Similar backscatter processing technologies (amplitude versus angle or diffraction analysis) can probably be used to detect other surficial shellfish beds. For shellfish beds within the seabed, a multispectral multibeam echo sounder would be more promising.

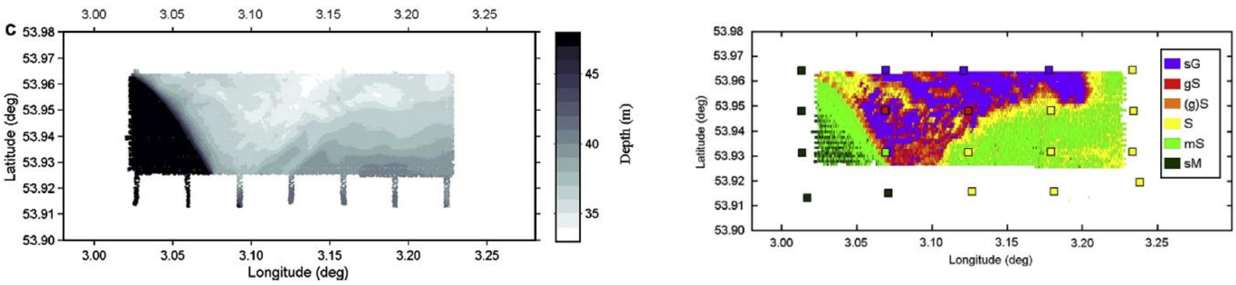


Figure 4: The Cleaver bank pilot area. Left: bathymetry as determined from the MBES measurements; Right: sediment classification map from the backscatter data. Also indicated are the data grab samples (see Simons and Snellen, 2009)

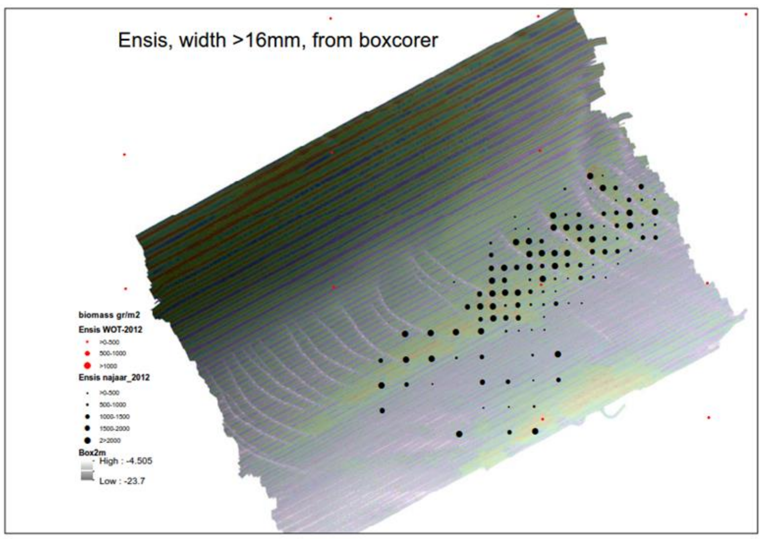


Figure 5: The relation between backscatter MBES data and Ensis biomass (Troost et al. 2012)

Improvements since previous comparative studies

A new development in MBES's is the multi-frequency multibeam echo sounder, which operates on 3 or more different frequencies in the range from 40 or 90 kHz to 450 kHz, depending on the system. The high-frequency signals provide information of the seabed (surface), whereas the lower frequency signals penetrate further into the seabed (max. of around 1 to 1,5 m, depending on the sediment and frequency). These systems have great potential for in-fauna detection by further improvement of the processing and classification of multibeam data (Arunima et al., 2016, Gaida et al., 2018a, Gaida et al., 2018b, Brown et al., 2019). In 2018/2019, initial tests with multispectral multibeam were executed by TUDelft in the Netherlands. The horizontal resolution (along track and cross track) of the high-end systems can be better than 1 degree.

Mounting the sonars on a swarm of remotely operated and autonomous platforms (ROV, AUV, USV, ASV) could help to increase the resolution or efficiency of this technology but require more development than for applying the (multispectral) multibeam echo sounder.
Processing and analysis of backscatter multibeam echo sounder data has been steadily improving in recent years which is also valuable for shellfish bed mapping (Amiri-Simkooi, 2019). However, a combination with side scan sonar processing techniques could help to further improve the (automated) interpretation of data sets. Using multiple frequencies, a classification card can be made per frequency. Due to the properties of the frequencies used, different backscatter classification maps are created simultaneously. These can complement or reinforce each other (Gaida et al., 2018a, Gaida et al., 2018b). More information can be found in annex A.

Combining and automating improved backscatter data analysis with texture analysis and image object recognition techniques could form a powerful tool (Feldens, 2018).

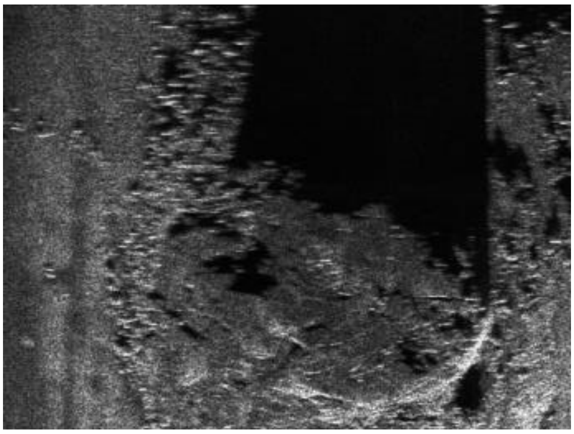
4.2.3 Synthetic Aperture Sonar

Method

The principle of synthetic aperture sonar (SAS) is to combine multiple pings along the same track to increase the along track coverage and resolution (Hansen, 2011). SAS uses the normal sonar frequency range, 100-800 kHz. This technique was developed 1) to increase the range (swath width) of the sonar and 2) to detect and delineate objects. The advantage of SAS relative to SSS mainly is found in the higher resolution data of the SAS. In principle, these systems can also detect buried objects, because these sonars also use the lower end of the frequency bandwidth compared to SSS or MBES systems.

Relevant examples

SAS technology has not been widely used for the detection of shellfish. In the inventory only two systems were found to be available at the market. They are much higher priced than the MBES system. Examples from buried object detection are scarce, because this is a military development and therefore classified. However, commercial systems have become available to the civil market. Hagen et al. (2007) shows a comparison of resolution of industry standard SSS system and SAS system, the images of the SAS system show an increase in resolution when compared to the SSS (Figure 6).



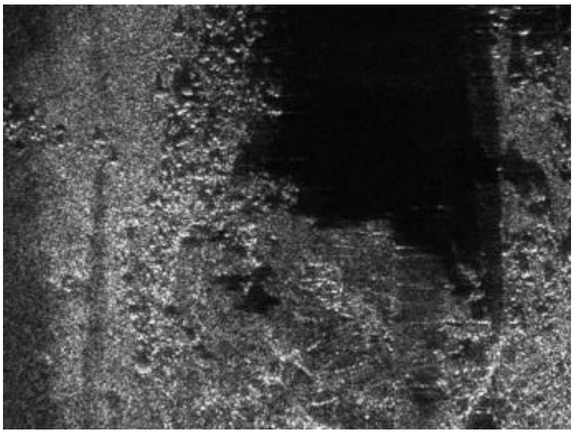


Figure 6: Comparison of resolution of industry standard SSS system (left) and SAS system (right), the images of the SAS system show an increase in resolution when compared to the SSS. From Hagen et al., 2007

Improvements since previous comparative studies
The SAS technology is developing slowly but steadily. The sensors are available, but the data acquisition and processing are still challenging. The integration with AUV systems is already operational. The application of this technology for the detection of buried and surface shellfish beds is new. The current status of the technology is not fully known because most developments take place for military applications which are not always open to the public and/or published. In theory, this is a very promising technique however further investigation and testing is required to determine the truly added value for this field of application. The commercially available sensors are expensive, and not all tools and capabilities are available for the public domain.

4.2.4 Sub-bottom profiler/3D sub-bottom profiler technique

Method
Relevant sub-bottom profiler/3D sub-bottom profiler uses low frequencies, 2.4kHz – 100kHz. Lower frequency subbottom profilers, which go back as low as 2kHz, result in too low resolution. This range of frequency enables the acoustic waves to penetrate the seabed. Maximum resolution depends on the frequencies used but are in the order of a decimetre or larger.

Relevant examples
Sub-bottom profilers are used for many applications related to mapping the structure and/or properties of the subsurface (see Figure 7). This technology is suited to map continuous layers of shells or rock when these are present below the sea floor. Interpretation of subbottom profiling data is relatively difficult and needs high experience and knowledge of the environment. This method has not yet been used much for shellfish mapping, but mostly for mapping shallow sedimentary layers. The resolution is – as the wavelengths are larger than those used in Sonar or MBES, limited when compared to MBES or SSS based systems.

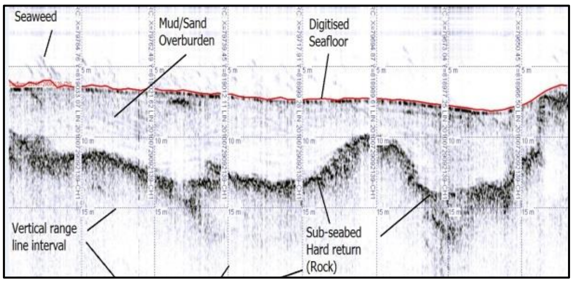


Figure 7: Sub-bottom profile example, average depth to reflector is 5-10 meter (Deltares)

Improvements made since previous comparative studies
Sub-bottom profilers have to some degree been tested for the detection of shellfish beds, in recent years at least two commercially available 3D systems (e.g. SyQuest, Kongsberg) have been developed. These systems could open opportunities for mapping buried shellfish beds. Processing and classification software have also improved in recent years. These new capabilities have not yet been tested for shellfish detection. More information on recent developments can be found in annex B.

4.2.5 Acoustic cameras

Method
Acoustic cameras consist of arrays of sending and receiving acoustic transducers. They operate with high frequencies signals ranging from 1 – 100 Mhz. The sensing distance varies from a few meters to 40 meters.

Relevant examples
They are normally applied to detect objects in sea water (fish, divers, submarines, etc.). They have the advantage that they are less influenced by visibility as electromagnetic cameras are. No literature was found so far on applying them for detection of epifauna shellfish (because of the high frequencies there is no penetration in sediment).

Improvements made since previous comparative study
Acoustic cameras operating in sea water have become available on the market in the last ten years. They can be mounted on subsea platforms. Note: This method was added later to the report and no further discussed.

4.3 Electromagnetic sensing technologies

4.3.1 Natural Gamma Ray Radiation

Method
Gamma rays are the highest-energy form of electromagnetic radiation. This technology is used for many applications, among which borehole logging. Sediment emits gamma rays, which can be classified based upon the level of radiation and the radiation type (K, Th, Ur). Attempts have been made to determine variations in median grainsize of the sea bed sediments by using gamma ray collectors/spectrometers. In theory, organisms could influence the levels and type of natural gamma ray radiation either directly (by absorption) or indirectly by their effects on sediment distribution.

Relevant examples
Examples of underwater applications for gamma ray detection are not common. Medusa has executed several projects in which this methodology was applied to map the median grainsize distribution of the seabed sediment. Attempts have been made to also map the presence of (dead) shellfish or shells at the seabed by combining the sensor with an acoustic sensor. In general, the mapping of the sediment type works relatively well (Figure 8.), especially after calibration. Hence, it may be possible to distinguish between sand/mud and shells. Unfortunately to date, no calibration project has been carried out.

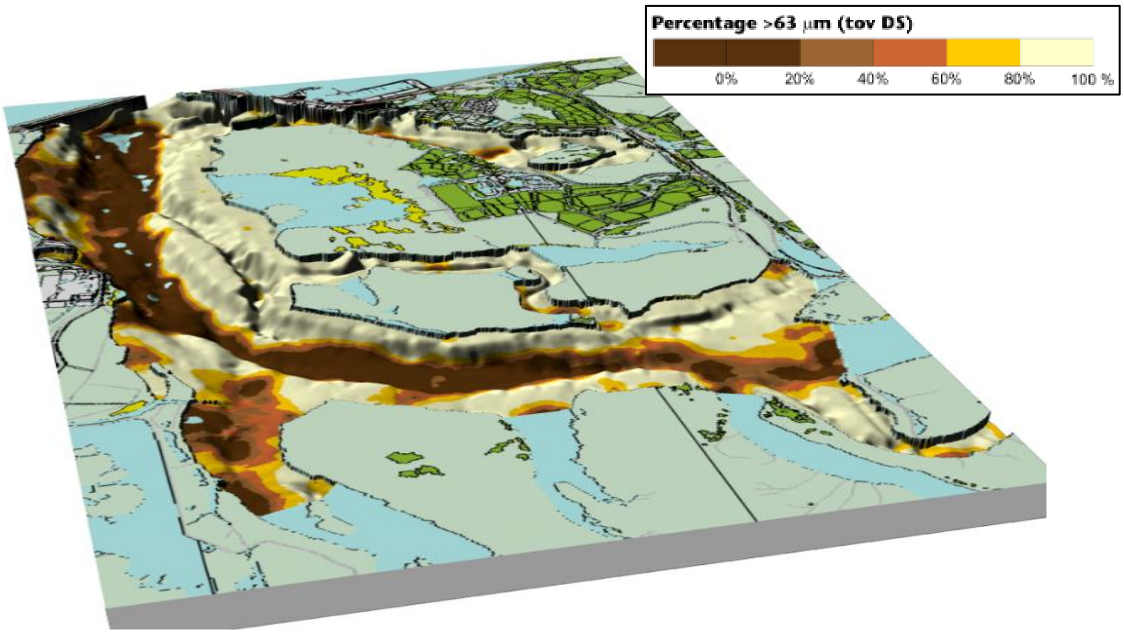


Figure 8: Median grainsize mapping of lakebed (Lauwersmeer) sediments. Source: http://the.medusa.institute/display/GW/Sediment+mapping+with+an+underwater+gamma-ray+spectrometer

Improvements since previous comparative studies
This technology has not yet been applied for the detection of shell fish. For now, it is not possible to predict which developments (if any) are required. Sensors fit for marine application are available and it is possible to detect rather subtle variations in radiometry (K, U, Th). In recent years, the technology was applied in many remote sensing types of operations (drone based).

4.3.2 Hyperspectral Camera technique

Method
Hyperspectral imaging is defined as the acquisition of images in hundreds of contiguous spectral bands so that a broad spectrum is recorded for each image pixel. Each pixel spectrum contains different spectral electromagnetic radiation components. The spectrum is determined by the illumination source (typically the sun or a multispectral light source), reflection by the surface material or vegetation, from influences by the transmission medium such as water or atmosphere and from the hyperspectral sensor itself.

Relevant examples
Dumke et al., (2018) used the hyperspectral camera to detect manganese nodules on the ocean floor. They were able to detect particles sometimes smaller than a centimetre and classified even the smallest sediments. Dierssen et al. (2015) used the method to identify different types of algae populations (Figure 9). The various bands of the spectrum were absorbed to a different extent by the various algae.

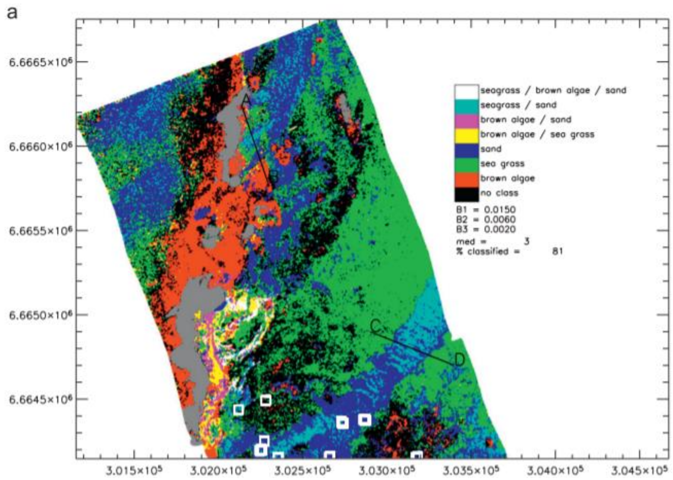


Figure 9: Classification of different algae populations (Dierssen et al., 2015)

Improvements made since previous comparative studies
This technology has not been reviewed in the previous comparative studies. Usage of this technology for this specific application is new, and, therefore, not a proven technology. The hyperspectral technology is quite mature in satellite and in situ measurements (Dicky, 2006, Fearns, 2011, Petit, 2017). The existing 'ecology based' classification software needs to be retrained and/or reprogrammed to be able to detect shellfish or indirect effects of shellfish on sediments. This technique has disadvantages as penetration is close to zero and when application in the turbid North Sea waters is questionable.
The combination of this sensor with an AUV or a deep tow carrier could help to minimise the distance between the sensor and the seabed, which improves the applicability of this sensor. However, this limits the swath width of the technique. In recent years the resolution of the non-marine systems has improved, and the costs have been lowered. This is not yet the case for the marine under water systems needing artificial illumination.

4.3.3 Optical (visible light) Cameras

Method
A wide range of optical cameras using natural or artificial light are being used in marine studies. Kwasnitschka et al. (2016) used an AUV-based optical system for autonomous visual mapping of large areas of the seafloor (square kilometres) in up to 6,000 m water depth. Because of the limited swath and AUV speed, it is rather time consuming. The unmanned vehicle Geomar AUV ABYSS is equipped with a high-resolution camera Canon 6D. The resolution is 1.9 mm – 5 mm.

Relevant examples
Kwasnitschka et al. (2016) examined an area of approximately 200 m × 450 m in the DISCOL experimental area of the south-east Pacific Ocean offshore Peru. The photo-mosaic consists of 13,000 photos taken from an altitude of 4.7 m on average, captured during 3.5 h in 4100 m water depth (Figure 10.).

At the Woods Hole Institute for Oceanography the Habcam system has been developed. This system is mounted on an AUV which does not only record the data but has also a built in Artificial Intelligence capability to process and analyse the data. This system has a self-learning capability with respect to survey design, based upon the real-time observations by the Habcam. The unit optimizes the survey layout itself by making a true autonomous mapping system (ref. (https://habcam.whoi.edu/data-and-visualization/).

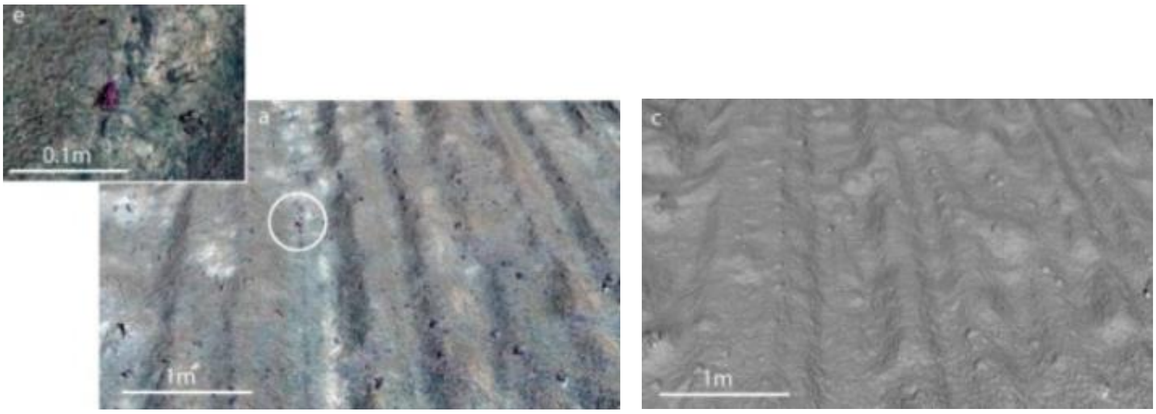


Figure 10: Photogrammetric dense point cloud reconstruction delivers geometry with approx. 1 mm resolution from an altitude of 4.7 m. Renderings shows (a) artificially perturbated sediment with manganese nodules and holothurian. (c) Shows the shaded relief of (a,) while (e) shows details of an epifauna organism (white circles) depicted with their rough geometrical shape. Point density equals about one per 2 mm (Kwasnitschka et al., 2016)

Improvements made since previous comparative studies

Due to the muddy North Sea Waters the same disadvantages apply as for the Hyperspectral Camera. The quality of underwater cameras is steadily increasing, and the costs of lighting is decreasing. These developments will help to increase the resolution of the acquired data. Many image recognition techniques are available, but these have not yet been applied for the detection or recognition of shellfish (military and counter terrorism applications do exist).However, retraining of existing software should be possible which would be a step towards a robust and efficient methodology, primarily to detect epifauna shellfish or traces of infauna shellfish at the seabed, such as syphons.

4.3.4 Laser Line Scan technique

Method

The Laser Line Scan technique (LLS) provides the efficiency and spatial coverage of a remote survey system, at an image resolution approaching that of visual observations (West Coast & Polar Regions Undersea Research Centre (NURP), 2001). LLS produces high contrast underwater light field images, at millimetre to centimetre scale resolution and at two to five times the range of conventional video and photographic systems. Resolution and area covered by the images vary with water clarity and tow height above the bottom. The maximum resolution is up to 1 mm (Figure 11.).

Relevant examples

To evaluate the capabilities and effectiveness of LLS technology for fisheries habitat research, the results of a field test of a commercial LLS system for imaging a range of sea floor habitats is presented in Figure 8. The LLS system was deployed for a total of 45 hours, towed at 2-3 knots at 3 to 9 meters above the sea floor. Under these conditions, the system imaged a swath of sea floor 4 to 13 meters wide.

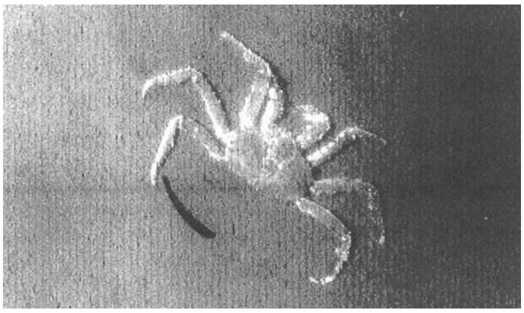


Figure 11: Laser line scan image of an Alaskan Red King Crab (https://oceanexplorer.noaa.gov/explorations/06laserline/)

Improvements since previous comparative studies
Due to the muddy North Sea waters the same disadvantages apply as for the Hyperspectral Camera. Currently different wavelengths of laser line scanning systems are under investigation for the application of 'Lidar based bathymetry'. This development could be beneficial for under water applications as well. Automated processing protocols for this type of technology are only available for bathymetry/altitude. However, for onshore applications (LIDAR) some protocols exist for filtering which potentially could be useful for mapping items extruding from the sea bed (i.e. shellfish). Classification type automated processing is not yet available. In theory this should be possible.

4.3.5 Frequency or time domain electromagnetic techniques

Method
The electromagnetic (EM) survey uses an electromagnetic technique - using transmitting coils generating 500 Hz to 25 kHz magnetic fields, which induce electrical currents into the subsurface - to measure and map electrical conductivity and magnetic susceptibility. It provides the capability of mapping subsurface features or contaminants that are associated with or produce changes in conductivity. The method has been extended for mapping the seafloor conductivities (related to sediment type, water quality).

Relevant examples
EM is usually used to detect fresh-saline water interfaces or buried lithological structures producing a conductivity anomaly. Deltares recently used large scale EM survey to map the salt water interface on Walcheren. Some survey lines were flown above the coastal area. The results obtained show the electrical resistivity values of the subsurface in the area. Based on these data information about soil type, water quality etc. can be analysed.
Resistive anomalies may also be produced by organisms on the seafloor since shells and the shellfish organisms are typically non-conductive. The depth of investigation depends on the system used and its frequency, and varies between 1 – 100 m. Therefore, it would be possible to map shells that are buried in the subsurface.

Müller et al. (2012), showed a benthic profiling and data processing approach based on controlled-source electromagnetic (CSEM) imaging to quantify the magnetic susceptibility and the electric conductivity of shallow marine deposits.
Some examples are available for seabed porosity variation mapping of near surface seabed sediment, executed in salt water by using a towed sensor at depth. This is a relevant development for the potential of this technique for shellfish bed mapping (Pers. comm. R.L. Evens, Wood Hole Oceanographic Institution). Shellfish beds causing extensive bioturbation may increase seabed porosity and decrease electrical resistivity. These studies were executed in salt water by using a towed sensor at depth.

Improvements made since previous comparative studies
This technology has not yet been applied for detection of shellfish. It has two main challenges. First, to determine if there is a correlation between the acquired signal and the presence of shellfish beds. Second, to acquire data with the required resolution. Nevertheless, some successful studies have been done on mapping seabed porosity using towed marine EM systems. If shellfish beds influence the seabed porosity (which is probably the case) this would be a good indicator of the potential use of this technology for (infauna) shellfish mapping.

Currently many developments on marine electromagnetic systems are in progress, all related to the detection of unexploded ordnance and cables/pipelines. For shellfish detection developments are required on improvement of sensor efficiency and processing. If characteristics of the seabed, the shellfish and the sensor are known it would be possible to model the expected electromagnetic response of certain shellfish densities. This technology exists for other electromagnetic applications. This could be the starting point of an automated classification method.

4.3.6 Electrical Resistivity Tomography

Method
Electrical Resistivity Tomography (ERT) is a geophysical technique for imaging sub-surface structures from electrical resistivity measurements made at the surface, on the sea bottom or by electrodes inducing electrical current in one or more boreholes. ERT is essentially a direct current (0-10 Hz) tomographic method. Data acquisition off shore is done using cables with multiple current injection and voltage measuring electrodes, which are towed by a ship on or near the sea bottom. The actual depth of investigation depends on the local conditions (contact resistance, soil type, saline and fresh water).

Relevant examples
The project of nature development “Marker Wadden” (lake Markermeer, The Netherlands), includes extraction of sand from large scale pits. During this extraction, archaeological values that may occur in the subsoil plan area may be affected. In October 2017, Deltares performed a marine ERT survey in the lake Markermeer for archaeological research. The investigation is focussed on determination of the top of the buried Pleistocene surface as archaeological promising spots (Figure 12). Lake Markermeer is a freshwater lake. Surveys on salt water will be more challenging when trying to achieve a high depth of investigation (DOI). However, for shellfish detection a high DOI is not required. The research was carried out using a combination of geophysical and geotechnical methods.

Improvements made since previous comparative studies
This technology has not yet been applied for detection of shellfish. Existing survey equipment needs updating (cables with smaller distances between electrodes) to be able to potentially achieve the required resolution. For the design it is needed to determine what is a contrast in electrical resistivity in the first meter of seabed between sediments including live shellfish shells in the bed and sediment without them. The acquisition units are available. A special cable (sensor) would have to be designed, built and tested. It is possible to design a grid of electrodes to increase swath coverage, for instance reusing and reconfiguring pulse fishing platforms and equipment. The amount of available sea worthy sensors and commercial systems is limited. For more background information see appendix C.

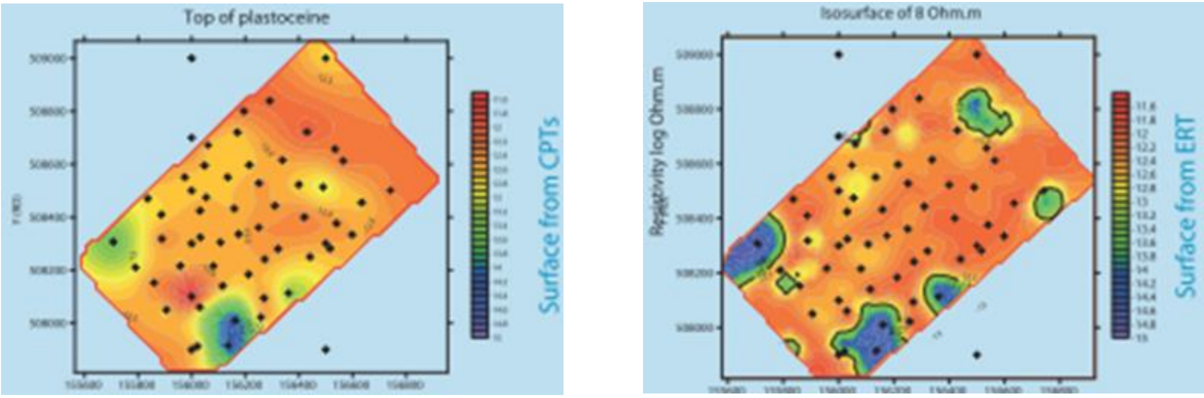


Figure 12: Example of ERT data acquired on the Markermeer (Karaoulis et al., 2018)

4.3.7 Magnetometer/Gradiometer

Method

A magnetometer is a device that measures magnetic fields, the direction, strength, or relative change of a magnetic field (gradient) at a particular location. They are used to detect magnetic anomalies of various types. Most observed magnetic anomalies are due to the small number of ferro- or ferrimagnetic substances. Magnetometers are also used in the military to detect bombs or submarines. The magnetometer is generally a towed sensor.

Relevant examples

The magnetic method has been used in a variety of mining and archaeological studies (Dalan and Banerjee, 1998; Evans and Heller, 2003; Long et al., 1998). Sediment magnetic characterisation studies show that through processes such as burning, weathering or microorganisms' excretions, magnetic minerals are subsequently ingested and cause the sediment susceptibility to increase (Fassbinder et al., 1990; Le Borgne, 1955; Maher, 1986; Tite and Mullins,1971).

At this moment, there are very few studies on the magnetic susceptibility of shellfish beds (see Connah et al., 1976) or magnetic measurements documented. A reason might be their complex stratigraphy. However, the potential of this technique to provide information on depositional events is worth noting. A recent study (Rosendahl et al., 2014a, Rosendahl et al., 2014b), showed that integrating geoarchaeological approaches, including magnetic susceptibility, helps to establish subtle changes in shell mounds.

Another recent example (https://www.periplus.nl/en/projects/news//magnetic-anomalies-reveal-prehistoric-channels/) shows the result of an alternative processing approach for magnetometer data. With this processing it is possible to map small channel infills below the Markermeer (Figure 13.). The magnetometer is either able to pick up the differences in lithology, sediment origin or sediment organisation in these channels. It was not known that such structures could be mapped using a standard magnetometer. It is yet unclear whether this approach has also potential for shellfish bed or sediment bioturbation mapping.

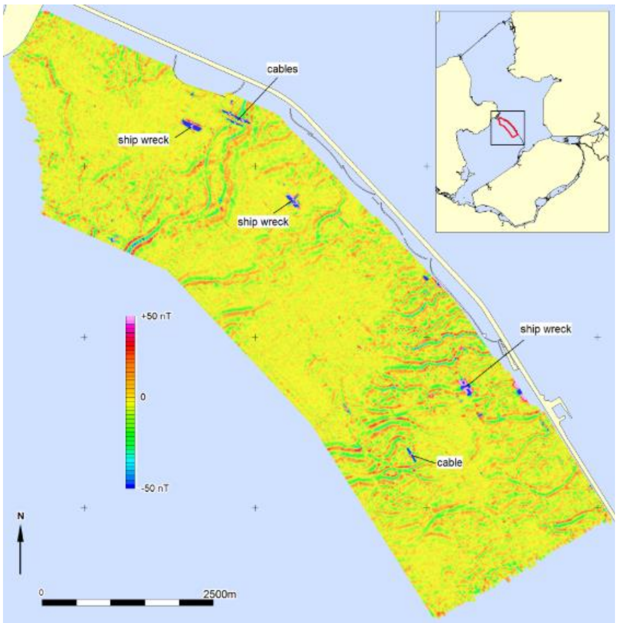


Figure 13: Representation of magnetometer data from Markermeer, this processing has revealed linear structures that are related to channel infills. (www.periplus.nl/nl/projecten/news// magnetic-anomalies-reveal-prehistoric-channels-1/).

Improvements made since previous comparative studies
This technology has not yet been applied for detection of shellfish. It has two main challenges. First to determine if there is a correlation between the acquired signal and presence of shellfish beds. Second to acquire data with the required resolution. Currently, many developments on marine magnetic/gradiometer systems are in progress. These are all related to the detection of unexploded ordnance and cables/pipelines. For shellfish detection developments are required on improvement of sensor, efficiency and processing. The sensitivity of the sensor and the processing should match the magnetic contrasts caused by the shellfish.

If characteristics of the seabed, the shellfish and the sensor are known it would be possible to model the expected electromagnetic response of certain shellfish densities. This technology exists for other electromagnetic applications. This could be the starting point of an automated classification method.

4.4 Other sampling techniques

For each geophysical method ground truthing data, i.e. sample data, are necessary. These datasets can be used to calibrate responses measured and eventually help in training automated processing and shellfish parameters detection. The review of other sampling methods is not part of this study but in order to have a complete document we have chosen to list the most common techniques. It is also relevant to consider the integration of sampling technologies with camera-based techniques.

4.4.1 Physical Sampling techniques

Method
The most common physical sampling techniques are:
- Box-core round;
- Box-core square;
- Van Veen grabs;
- Digging planedredge (“bodemschaaf” or “kokkeldregger”)

To our knowledge only limited developments have been done in recent years. Some attempts have been made to combine cameras with for example the dredge which could form a valuable addition to physical sampling techniques. Royal NIOZ operates a box core that can be equipped with a camera.

Improvements made since previous comparative studies
The sampling techniques are well developed and proven methods. However, some improvements could be worthwhile looking into.

The area and volume of seabed sampled by these techniques is quite limited. The typical area of sediment sampled is in the order of 0.1 m^2 at most. This reduces the probability of finding animals in a grab or core sample. However, at the density values discussed here (order 100 m^{-2} at least, chapter 2) the probability of not finding any animal in a single sample becomes very small. Assuming random distribution of animals in space, this probability is given by the zero-term of the Poisson distribution, and equals 4.5 10^{-5}. Therefore, the size of grab samples is sufficient to detect and delineate shellfish beds, using the operational definition given. By adding sensors (optical or geophysical) to these systems the area covered by a sample would increase because one knows how the actual sample area relates, in its optical properties, to a larger surrounding area. The training and calibration of indirect measurements could benefit from such an approach, if it is able to directly relate a sample to one of a multitude of different adjacent or interspersed sediment classes. This requires, however, that the optical image can refer one-to-one to one of the indirectly determined classes.
In theory, it should also be possible to create a sampler like a dredge which does the complete analysis, like sieving and counting, in situ. Such a system is technically possible but would require a lot of development and engineering. No information on the retrieved species would be obtained, such a system would primarily focus on determining the present biomass.

4.4.2 Sediment Profile Imaging

Method
Sediment Profile Imaging (SPI) is an underwater seabed penetrating device that images the top layers of the seafloor in a vertical cross-section using a visible light camera. This technique provides high resolution images of the seabed. The SPI can image down to a depth of 15 to 20 cm from the sediment surface, but this depth is only obtained in soft muddy sediments. Practical tests in the Disclose project (https://discloseweb.webhosting.rug.nl/nl/tud-project/) showed that penetration depth in sandy sediments off the Dutch coast was very limited, a few cm only (P. Herman pers. comm.). This jeopardizes the usefulness of the technique for mapping shellfish beds. The image gives both quantitative and qualitative information about the biological (bioturbation, epifauna), and physical (stratification, human/natural disturbance) nature of the sediment (Figure 14, Germano et al., 2011).
The SPI camera can only resolve shellfish that are quite close to the vertical plane sampled. The maximum penetration distance depends on the size of the animals but can be estimated as a few cm only. Consequently, the SPI camera, with a typical width of 10 cm and a penetration depth of 2 cm, only samples 0.002 m^2 of the horizontal plane. Even at a density of 100 individuals.m^{-2}, the chance of missing out on any individual is 0.82: only in 18% of the images one expects at least one animal to be seen. This is not enough for mapping shellfish beds at the defined minimum density.

Relevant examples
SPI has been used in many (monitoring) projects in which the environmental impact of human activity on the sea bed (i.e. fishing) has been studied. But also, for habitat mapping this methodology is frequently applied (Figure 14).

Improvements made since previous comparative studies
The current SPI systems are adequate, for soft sediments, but lack penetration depth in hard sandy sediments. A possible development is combining the SPI with some of the sensors used for indirect mapping (see also paragraph 4.5.1 Improvements made since previous comparative studies).

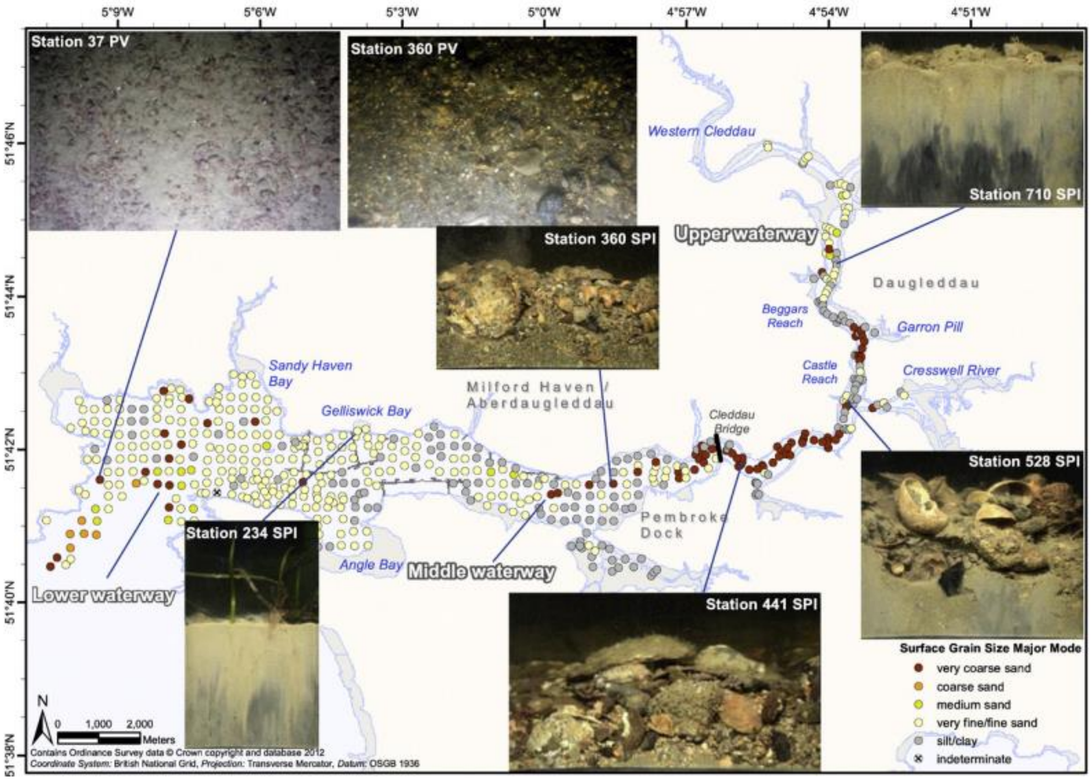


Figure 14: Example of habitat mapping in UK in which the SPI system has been used intensively

4.4.3 Traces

Method
This sampling technique has not been investigated in detail but was brought forward during one of the sessions with the external institutes. It is a collection of techniques, which is not aimed at detecting the shellfish themselves directly but determines their traces vented by shellfish to the water column or perhaps the sediment. These could be either chemical tracers like nitrates, or environmental tracers like eDNA. Systems exist that instantaneously measure tracers' concentrations in the water column.

Improvements made since previous comparative studies
The amount and quality of water quality sensors is gradually increasing. If some key chemical tracers can be identified it could be possible to map these parameters in-situ probably even with an autonomous system. Currently, there is much development on eDNA (environmental DNA), but techniques still rely on water sampling and are semi-quantitative at best. eDNA is very useful to prove the occurrence of a species in an area, but not to delineate areas of high density that can be qualified as shellfish beds. Because of the longevity of DNA in the water and the turbulent mixing over relatively large scales, it cannot be expected that eDNA will soon become available as a suitable technique for the purpose of precisely mapping shellfish beds.

4.4.4 Sampling: Biomass orientated sampling

The presence of shellfish beds can also be determined by taking a set of dredge samples at a wide spaced grid and run the material trough a coarse sieve. Then select the dead shells from the living ones and weight or count them. Such an approach would focus on the biomass present and not the distribution at species level. It would also not require an expert to be on board. Alternatively, some samples from shellfish concentrations could be collected, which then could be analysed later, in more detail using the existing methodology.

4.5 Summary of pros and cons and technology readiness assessment

The advantages (pros) and disadvantages (cons) of all geophysical technologies are assembled in the overview in Table 11. Based on maturity of the sensing technology (instruments and years of use in any applications) a Technology Readiness Level could been determined for the sensing technologies.

Table 11: Technology readiness levels of sensing technologies (green is suited, yellow is less suited, red is not suited, grey is unknown)

		Acoustic energy method					Electromagnetic method (1)		
		Acoustic camera	Side scan sonar technology	Synthetic Aperture Sonar technology	Multibeam Echo Sounder backscatter technology	Sub-bottom profiler/3D sub-bottom profiler technology	Natural Gamma Ray Radiation technology	Hyper-spectral Camera technology	Optical (visible light) Camera's technology
Data	Seabed depth "sampled"	Millimetre range	Decimetre range	Decimetre range	Decimetre-meter range	Meters range	Millimetre range	Millimetre range	Millimetre range
	Swath width	Intermediate	High	High	High	Intermediate	Low	Intermediate	Intermediate
	Scale/swath (m)**	ca. 1-10	ca. 10-200	ca. 10-200	ca. 10-200	ca 10-20	< 2	< 5	< 5
	Area mapped (km^2/hr)**	ca. 0.01	ca. 1-3	ca. 1-3	ca. 1 - 5	ca. 0.1 - 0.8	< 0.001	< 0.01	ca. 0.01 – 0.2
	Resolution horizontal (m)	< 0.02 (not reported) **	0.2**	0.02 (not reported) **	1.0 **	1-2 **	0.01-0.001**	0.01-0.001**	0.01-0.001**
	Proximity to seabed	Close	Intermediate-Far	Intermediate-Far	Far	Far	Close	Close	Close
Functioning of technology	Limited by turbid North Sea water	No	No	No	No	No	No	Yes, unless with lighting	Yes, unless with lighting
	Accuracy versus depth	No data at greater depth	Declines with water depth	Declines with water depth	Declines with water depth	Little accuracy loss	No data at greater depth	No data at greater depth	No data at greater depth
Maturity	Proven technology	Technique is in development, equipment not widely available	Mature, Experience for this specific application	Technique is in development, equipment not widely available	Mature, Experience for this specific application	Mature, not used for shellfish bed detection	Previous experiences are not convincing	Technique is in development	Experience for this specific application
	Recent improvements	New system maturing (UXO on sea floor)	Multi-frequency, classification software	New systems maturing (UXO on sea floor)	Multi-frequency, classification software	3D subbottom profilers, larger swath	Unknown	Multispectral band classification	Cheaper systems
Costs (k€)**		no data	> 30	>150	> 50	> 30	No data	> 10	> 10
TRL sensor (1-9)		6	9	6	9	7-9	7	7	9
Frequencies		1100-3500 kHz	100-800 (1600) kHz	100-300 kHz, Optimal operation at 50-100 kHz*	30-800 (1600) kHz	2-100 kHz	Around 10^{21} Hz	Around $10^{13\text{-}16}$ Hz	Around 10^{15} Hz
Remarks		Size of surface coverage (swath) depends on the frequency used* Hardly any penetration in seabed	Allows the use of backscatter data to characterize substrata* Limited penetration in seabed	Limited penetration in seabed	Allows the use of backscatter data to characterize substrata* Limited penetration in seabed	Narrow beam sub-surface coverage* Full penetration in seabed	No penetration in seabed	Natural or manmade sources of light are needed No penetration in seabed	Allows mega-epibenthos identification and provides ground truth for acoustic survey mapping technology* No penetration in seabed

		Electromagnetic method (2)				Other sampling techniques		
		Laser Line Scan technique technology	Electromagnetic technology	Electrical Resistivity Tomography technology	Magnetometer/ Gradiometer technology	Physical Sampling techniques technology	Sediment Profile Imaging technology	Traces technology
Data	Seabed depth “sampled”	Millimetre range	Meters range	Meters range	Meters range	Decimetre range	Decimetre range	None
	Swath width	Intermediate	Low	Low	Intermediate	Point measurement	Point measurement	Point measurement
	Scale / swath (m)**	< 10	ca. 10-20	ca. 10-20	ca. 10-20	< 2	< 1	No data
	Area coverage (km^2)**	ca. 0.05	ca. 0.1-0.8	ca. 0.1-0.8	ca. 0.1-0.8	< 0.05	<0.05	No data
	Resolution (m)	0.01**	1-2	1-2	1-2	0.002**	0.002**	Unknown
	Proximity to seabed	Intermediate	Intermediate	Intermediate	Intermediate	Close	Close	Close
Functioning of technology	Limited by turbid North Sea water	Intermediate	No	No	No	No	No	No
	Accuracy versus depth	Declines with water depth	Declines with water depth	Declines with water depth	Declines with water depth	Not relevant	Not relevant	Not relevant
Maturity	Proven technology	Recent development	Experience for shellfish bed detection is negligible, Sensors not operational	Experience for shellfish bed detection is negligible	Experience for shellfish bed detection is negligible	Mature	Recent development	Uncertain if laboratory analyses of automated sensors are available or required
	Recent improvements	Cheaper systems	Processing (related to UXO below sea bottom mapping)	Towing systems	Processing (related to UXO below sea bottom mapping)	Not checked	Not checked	Not checked, DNA traces
Costs (k€)**		> 75	No data	> 25	No data	No data	> 25	No data
TRL sensor (1-9)		7	5	6	8	Not checked	Not checked	Not checked
Frequencies		Around 10^{12} Hz	100 Hz – 20 kHz	0- 5 Hz	0-5 Hz	High quantitative data on the macro and meiofauna requires specialists and additional analysis in a laboratory*	Sediment/water interface inspections*	No data
Remarks		No penetration in seabed	Full penetration, limited by signal strength and absorption	Full penetration, limited by signal strength and absorption	Full penetration, limited by signal strength and absorption	Full penetration	Limited penetration	No penetration

* From ICES ASC September 2000: Theme session on classification and mapping of marine habitats. An overview of seabed mapping technologies in the context of marine habitat classification A. J. Kenny, E. Andrulewicz, H. Bokuniewicz, S. E. Boyd, J. Breslin, C. Brown, I. Cato, J. Costelloe, M. Desprez, C. Dijkshoorn, G. Fader, R. Courtney, S. Freeman, B. de. Groot, L. Galtier, S. Helmig, H. Hillewaert, J. C. Krause, B. Lauwaert, H. Leuchs, G. Markwell, M. Mastowske, A. J. Murray, P. E. Nielsen, D. Ottesen, R
** After Methods for the Study of Marine Benthos: Edition 4 Anastasios Eleftheriou (editor). April 5, 2013, chapter 3 Chris J. Smith and Heye Rumohr and Guidelines for the study of epibenthos of subtidal environments H.L. Rees, 2009, annex 3.

5 Survey platform and data analysis technologies

5.1 Introduction

For detecting shellfish beds not only the sensor technology is important but also the distance to the sea bottom. This is different for different survey platforms (vessels, sampling devices, unmanned autonomous vehicles). In addition, for each sensing technology, the chosen data acquisition geometry allows for different data processing and detection methods.
Sensing technology (discussed in the previous chapter), should be considered together with the measurement platform and data analysis methods when developing and accepting a new surveying and detection methodology for mapping shellfish beds.

The available and upcoming technologies in measurement platforms and data analysis are discussed in this chapter.

The use of autonomous systems can be a potential game changer for the application of some of the sensor technologies listed. The autonomy in these systems have the potential to lower the survey cost (Figure 15), allowing for increased survey time to collect larger data sets. This would require a new processing/analysis approach as manual interpretation of big data sets is time inefficient. In this case the development of automated processes for data classification/interpretation could be the solution. Machine learning based analysis has been applied for remote sensing applications successfully. Part of the methods proposed in this document, mainly the optical techniques, are similar to remote sensing technology and might profit from these image analysis methods.

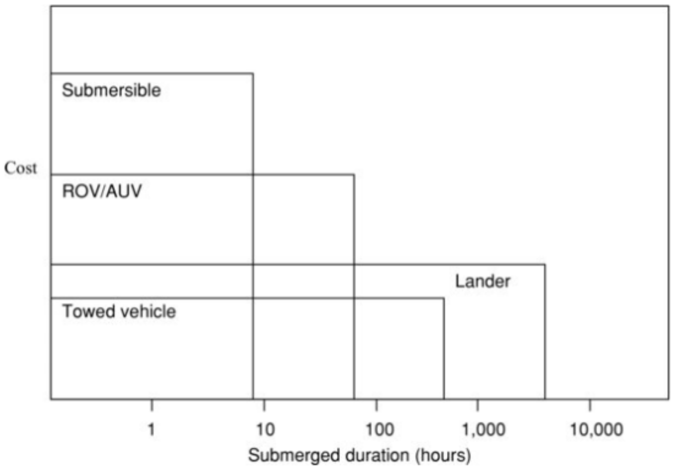


Figure 15: Relative cost against duration of recording of different imaging platforms. Reprinted from: Methods for the Study of Marine Benthos: Edition 4 Anastasios Eleftheriou (editor). April 5, 2013, chapter 3 Chris J. Smith and Heye Rumohr

5.2 Survey platform technologies

5.2.1 Existing monitoring vessels

In the area of interest, several surveys are being executed on a regular basis:

- WOT shellfish monitoring program of WMR;
- MWTL marine water quality monitoring program of RWS;
- Sediment sampling of sand extraction areas of stakeholders;
- Furthermore, the RWS survey vessels frequently visit the area of interest.

By equipping these vessels with additional acoustic or electromagnetic geophysical sensors more temporal and spatial data can be acquired. In addition, available sampling devices can be extended with camera-based sensing technologies.

5.2.2 Vessels of opportunity

Sensor development is evolving in two directions:

- Increasing resolution of sensors and development of new high spec sensors (at high costs) resulting in very sensitive and specialized sensors.
- Minimizing costs of sensors (and data processing) by developing simpler (often less sensitive) sensors which will be used in bulk.

Mainly because of costs the first option will result in the availability of very high-resolution data for small areas measured by dedicated vessels. The second option is targeted at achieving the opposite, low resolution data but in great quantity by multiple platforms using cheaper sensors. Smart planning could make the mapping of a large area with enough resolution feasible. The lower costs would make integration in so-called vessels of opportunity. This a ship (or ships) that pass through the area of interest frequently (i.e. a ferry). The vessel is used as carrier of these low-cost sensors, and to some degree as ‘free’ survey vessels. For many applications the large temporal and spatial coverage of such a data, is more valuable than very high-resolution data at a limited number of locations, at a single moment in time.

5.2.3 Remotely operated and autonomous submerged systems

In the last decade the use of subsea survey platforms has grown from an idea to almost full-scale operations. Two types of autonomous systems are relevant for this study. Unmanned small boats (USV and ASV) and autonomous underwater vehicles (ROV and AUV), like submarines. The advantage is that survey costs can be significantly lowered by this technology. The efficiency of expensive ships can be greatly increased and furthermore the weather dependence of autonomous submerged surveys is reduced as sensors can move much closer to the seabed. Of course, numerous technological and legislation challenges remain, but the potential for autonomous (submerged) systems is rapidly increasing. For this project these two advantages of this technology are of interest:

- Lowering costs;
- Lowering distance of sensor to seabed.

Lowering costs can be achieved by either (partially) replacing manned ships or by increasing the area to be surveyed during a survey by combining a manned vessel with unmanned vessels increasing the area covered during a single survey day.

Reducing the distance of sensor to seabed is also a valuable development. The resolution of an important part of the sensors is limited by the distance between the sensor and the seabed. Especially the optical techniques suffer from this. Bringing a camera closer to the seabed could to some degree limit the negative effect of turbid water on data quality (which is frequently the case in North Sea operations). When combining techniques, decreasing swath width by lowering the distance between sonar and seabed is one of the downsides.

In addition to these main advantages, autonomous platforms bring more innovations. Some examples are listed below:

Swarm technology: Swarms of low-cost subsea survey platforms can carry many sensors simultaneously and cover significant areas within limited times. The sensors could be of high quality (at higher costs) or of low(er) quality. In the latter case, the sheer volume of observations would help to achieve the required resolution. A major development is needed both instrumentally and with respect to processing.

Remotely operated and autonomous monitoring: By revisiting an area numerous times, more temporal is obtained which will yield new insights into the dynamics of shellfish beds. Moreover, it could also increase the quality of the measurements. By repeating and combining measurements a better so-called signal-noise ratio can be obtained (in geophysics this process is called stacking) increasing the accuracy of observations significantly.

Scouting: By sending out a remotely operated and autonomous systems prior to the sampling vessel the efficiency and spatial resolution of a survey could be increased. The autonomous system maps the area of interest during the sampling campaign and based upon the observations of the system the sampling mission can be optimized real-time. This would help to optimize the sampling efforts and help to determine which areas of the survey area are represented by the samples.

This development may soon become as important for the improvement of shellfish bed mapping as is the improvement of existing sensor technology or implementation of new sensor technology.

5.3 Data processing technologies

5.3.1 Multi-sensor approach

So-far, most studies focus on the interpretation of data of one sensor and a set of core samples. As mentioned before, all sensors have strong and weak points, which also depend on the target species (epifauna and infauna) and spatio-temporally variable field conditions. By combining data from different types of sensors in a single survey a more robust and accurate mapping can be achieved (Sen at al, 2016). Combining data from different sensors could give information that cannot be revealed by using single types of sensors alone. This approach comes with additional costs compared to simpler surveys, but these would be significantly lower than the costs made when executing an unsuccessful survey. Furthermore, deploying multiple sensors also gives freedom of choice in terms of sensors, data acquisition and data analyses. Only those which are required given the local conditions, need to be processed. In such a setup only when the preferred sensor did not yield the required information, the data from the additional sensors will be analysed. Hence, controlling the costs and mitigating the risk, reduces the chance of an unsuccessful survey.

5.3.2 Joint inversion

When using different types of data, basically, two main types of analysis methods are available. In the first type of methods data from all sources are processed and analysed separately and independently. Next, independent results are compared and synthesised. For example, multibeam data and sonar data are first processed separately, followed by comparing or combining into interpreted maps.

The second type of methods is called ‘joint inversion’. In recent years, this method is applied more and more for geophysical mapping. In this method, the data processing is not only done for data from each sensor individually, but also for the complete set of observations. In the latter the total data set is processed as an interdependent and coherent data set. This method increases the quality of the processing and will also give more insight into the uncertainty of the final product.
In the process of joint inversion, the interaction between different physical parameters is (mathematically) analysed.
Both remote sensing and geophysical models are used to explain and translate the acquired measurements into the required information. In most cases multiple model solutions exist, where the built models all fit the acquired data. The most likely model is then selected based upon secondary information or knowledge. However, this selection method is not always optimal and

often provides only qualitative information. In joint inversion, the process of building and selection of the most likely model is constrained by all combined sensors/observations.
For example, when both optical data and multibeam recording anomalies (i.e. shell fish) occur at the same location, the chance of this being a realistic ‘anomaly’ is higher compared to detection of anomalies by constraining with data of only a single method. Also, on a physical level this method can be applied. An object that gives an acoustic contrast can also yield an electromagnetic contrast, or vice versa which could help (in theory) to differentiate between live and dead shellfish. The use of joint inversion data analysis will help to refine the model output and give insight in the reliability of the results.
Furthermore, this methodology of joint inversion, is successfully being applied in a range of applications, varying from in oil and gas related geophysics to EM based groundwater mapping projects.

5.3.3 Integrating ‘uncommon’ processing techniques

This type of data processing is based upon using the (pre)processing routines and methodologies from other technologies and applications. For the purpose of shellfish bed detection two possible improvements of processing current data sets could be possible when the processing routines from other technologies are ‘borrowed’.

Data processing and analysis from optical techniques is typically done by either visual (manual) analysis or image processing and object recognition (optical cameras) or by processing spectral data (hyper spectral cameras).
Processing and analysis of acoustic data (MBES/SSS) is generally based upon travel times or angle dependent amplitudes of the return signal received after reflecting from the seabed. But the resulting data from these systems is also used to make seabed imagery. This imagery is often analysed by manual (visual) inspection only. However, image recognition techniques can also be used to analyse the data and help to map textures and roughness typical for shellfish beds. Furthermore, a joint inversion approach between the imagery analysis results and the backscatter type signal processing can then help to decrease uncertainties and increase the accuracy of the data interpretation. This approach is in principle not new, all elements and algorithms are available, but applying it in a systematic manner is not often done yet.

The same applies for the field of sonar and radar technologies. Interferometric Synthetic Aperture Radar (Insar) is used to monitor minute vertical movements of the earth surface from space. This type of data processing is a well-established method in remote sensing and used for a broad range of projects. In principle InSar is not relevant for mapping the submarine environment. However, this methodology is also (partially) applied on sonar data via synthetic aperture sonar (SAS). The main strength of the Insar application is however the temporal approach, which is repeating measurements over time and then looking for differences. This part of the methodology can also be applied to the SAS again helping to increase the resolution which is required for mapping of buried shellfish beds changes and associated reworked sediments.

5.3.4 Machine learning and Artificial Intelligence

Terms and methodologies like machine learning, big data and artificial intelligence are not new. In recent years the number of examples where this technology is being successfully deployed is steadily growing, especially to detect changes in monitoring datasets and images.
Especially in the field of remote sensing numerous examples of semi-automated data processing and interpretation/classification are known. Their added value is clearest in analysing dynamics from repetitive surveys. Remote sensing-based techniques are also potentially applicable to most of the data sets obtained by sensors described in this document.
Depending on the survey strategy selected, large datasets can be obtained. When such data sets are processed and classified in the ‘classical’ way, the costs of data processing and analysis becomes so high that it the use of other valuable techniques. Therefore, not only testing and

evolution of the sensor and the sensor platform are required but also on the data processing and classification techniques. The continuous development of machine learning based techniques is valuable and should be an integral part of the next phases of the project. It is no use developing better sensors or acquiring more data if this data cannot be analysed in an efficient way.

5.4 Summary of pros and cons of platforms and processing technologies

The pros and cons of all different platform and processing technologies have been brought together in an overview in Table 12. Based on maturity and costs of the platform and processing technologies, some could become part of a recommended method.

Table 12: *Maturity and costs of different platform and processing technologies (green is suited, yellow is less suited, red is not suited, grey is unknown)*

		Acoustic energy method					Electromagnetic method (1)		
		Acoustic camera	Side scan sonar technology	Synthetic Aperture Sonar technology	Multibeam Echo Sounder backscatter technology	Sub-bottom profiler/3D sub-bottom profiler technology	Natural Gamma Ray Radiation technology	Hyper-spectral Camera technology	Optical (visible light) Camera's technology
Ship or AUV/ROV	Dimension, mobile	Small	Small, yes	Intermediate, yes	Small, not always	Intermediate, yes	Small, yes	Small, yes	Small, yes
	Sensor on autonomous system	Yes	Yes	Yes	Yes	Yes, on its own	Yes	Yes	Yes
	Remarks	On regular monitoring ships, But equipment needs to mount to AUV/ROV frame (slow, expensive/km2)	On regular monitoring ships and AUV/ROV (but slower, expensive). Equipment easy to mount	On regular monitoring ships and AUV/ROV (but slower, expensive)	On regular monitoring ships, Costs advanced multifrequency sensors could be high, not many suppliers	On regular monitoring ships and AUV/ROV (but slower, expensive). Equipment easy to mount	On regular monitoring ships, But equipment needs to mount to ROV frame (slow, expensive/km2)	On regular monitoring ships, But equipment needs to mount to AUV/ROV frame (slow, expensive/km2)	On regular monitoring ships, But equipment needs to mount to AUV/ROV frame (slow, expensive/km2)
Processing effort	Processing required	Intermediate	Yes	Yes	Yes	Yes	Intermediate	Yes	No
	Amount of processing	None	High	High	High	High	None	Intermediate	None
	Automation of processing	Yes	Some	Some	Some	Some	Yes	Yes	Yes
	Amount of interpretation	Low	Intermediate	Intermediate	Intermediate	Intermediate	Low	Low	High
	Automated interpretation	No	Yes	No	Yes	No	No	In theory	Yes
	Autonomous option	Yes	Yes	Yes	Maybe	Maybe	Maybe	Yes	Yes
	Processing time (h) and labour intensity	No data	8***	Large	8**	2**	No data	Large	2**
Complexity	Data quantities	Small	Large	Large	Large	Large	Small	Large	Large
	Multifrequency algorithms ready	No	In development	Unknown	In development	Ready	Ready	In development	Ready
Costs (k€)		€€	€€€	€€€	€€€	€€	€€	€€	€€
Remarks			Bottom samples still required; Costs of advanced sensors could be high, not many suppliers	Can be integrated on monitoring ships	Can be integrated on monitoring ships	Automated vegetation mapping exists	No data	No data	No data

		Electromagnetic method (2)				Other sampling techniques		
		Laser Line Scan technique technology	Electromagnetic technology	Electrical Resistivity Tomography technology	Magnetometer/ Gradiometer technology	Physical Sampling techniques technology	Sediment Profile Imaging technology	Traces technology
Ship or AUV/ROV	Dimension, mobile	Small, yes	Small, yes	Small, yes	Small, yes	Large, no checked	Large, not checked	Not checked, not checked
	Sensor on autonomous system	Yes	Not yet	Not yet	Yes	Not checked	Not checked	Not checked
	Remarks	On regular monitoring ships, Equipment needs to mount to ROV frame (slow, expensive/ km2)	On regular monitoring ships, Equipment easy to mount Towed from ships	On regular monitoring ships, Equipment easy to mount Towed from ships	On regular monitoring ships, Equipment easy to mount Towed from ships	Not checked	Not checked	Not checked
Processing effort	Processing required	Yes	Yes	Yes	Yes	Not checked	Not checked	Not checked
	Amount of processing	High	Intermediate	Intermediate	High	Not checked	Not checked	Not checked
	Automation of processing	Some	Yes	Yes	Some	Not checked	Not checked	Not checked
	Amount of interpretation	Intermediate	Intermediate	Intermediate	Intermediate	Not checked	Not checked	Not checked
	Automated interpretation	In theory	No	No	No	Not checked	In theory	In theory
	Autonomous option	Yes	Maybe	No	Maybe	Not checked	Not checked	Not checked
	Processing time (h) and labour intensity	8**	No data	No data	No data	No data	2**	No data
Complexity	Data quantities	Large	Small	Small	Small	Not checked	Not checked	Not checked
	Multifrequency algorithms ready	Ready	In development	Ready	Ready	Not checked	Not checked	Not checked
Costs (k€)		€€	€€	€€	€€€	Not checked	Not checked	Not checked
Remarks			No data	No data	No data	No data	No data	No data

** From Methods for the Study of Marine Benthos: Edition 4 Anastasios Eleftheriou (editor). April 5, 2013, chapter 3 Chris J. Smith and Heye Rumohr and Guidelines for the study of epibenthos of subtidal environments H.L. Rees, 2009, annex 3.

6 Synthesis and discussion

6.1 Synthesis

Many of the listed sensing techniques and survey methods have the potential to improve the current methodology for shell fish bed mapping, definitively for epifauna species and a challenge for infauna species. The methods and their potential have been summarised in Table 13. and expressed in Technology Readiness Level. The TRL is determined by evaluating the number of commercial systems internationally available, the robustness of those instruments and number of experienced service providers in any application field (not only sediment classification or benthos detection).

For the sensing technologies, it can be seen from the table that:

- Visible light cameras, Side scan sonar, Multibeam echo sounder and Subbottom profiling are commercial systems (TRL=9);
- Natural gamma ray, Magneto(gradio)meter are demonstrated and to limited extent used for other applications (TRL=8)
- Hyperspectral camera, Laser line scanning and 3D Subbottom profiler have the status of demonstration systems (TRL=7);
- Synthetic aperture sonar is classified as prototype systems and not easily available (TRL=6);
- EM tomography and ERT tomography are at the level of large-scale prototypes, not widely available (TRL=5).

The Application Readiness Level (ARL) is determined by assessing the maturity of a sensing technology for benthos detection. The ARL for ship-mounted or ROV-mounted technologies is separately scored and is summarized as follows.
On ships:

- Visible light camera[1], Side scan sonar, Multibeam echo sounder is ready for other applications, not yet for shellfish detection (ARL=3);
- Magneto(gradio)meter, Natural gamma ray, Laser line scanning, Synthetic aperture radar are new promising technologies (ARL=2);
- Hyper spectral cameras, EM tomography, ERT tomography, 3D subbottom profiler are at the level of idea (ARL=1).

On unmanned subsea vehicles (remotely operated, ROV or autonomous, AOV):

- Visible light camera, Side scan sonar and Multibeam echo sounder are used in other application areas, not for shellfish bed detection (ARL=3);
- Hyper spectral cameras, Laser line scanning, Synthetic aperture radar are in application studies mainly defence industry (ARL=2);
- Natural gamma ray, EM tomography, ERT tomography, Magneto(gradio)meter and 3D subbottom profiler are at the level of idea (ARL=1).

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[1] *All locations have their specific characteristics which have an impact on the success and applicability of survey techniques. In the North Sea, especially the turbidity has an impact on the optical techniques. Getting good data from optical cameras depends on weather conditions and sometimes the tides. Lowering the camera close to the seabed is an option but this is often not possible, or it results in very low survey speeds (hence high costs). This limits the application of camera systems, known to be very efficient elsewhere.*

Table 13: Sensing techniques and survey methods and their potential. The ARL are framed red. (green is suited, yellow is less suited, red is not suited, grey is unknown)

		Acoustic energy method					Electromagnetic method (1)		
		Acoustic camera	Side scan sonar technology	Synthetic Aperture Sonar technology	Multibeam Echo Sounder backscatter technology	Sub-bottom profiler/3D sub-bottom profiler technology	Natural Gamma Ray Radiation technology	Hyper-spectral Camera technology	Optical (visible light) Camera's technology
Evidence by examples	Relation between measurements and shellfish	Not known	to some degree known	to some degree known	to some degree known	Not known	Not known	Not known	to some degree known
	Distance of sensor (and light source) to sea bed	One to twenty meters	Tens of meters	Tens of meters	Tens of meters	Tens of meters	Small	Small	Small
	Detect holes	Maybe	Maybe	Maybe	Maybe	No	No	Maybe	Yes
	Detect bioturbation	No	No	Yes	Maybe	Yes	Maybe	Maybe	No
	Sediment Roughness	Yes	Yes	Yes	Yes	No	Maybe	Maybe	Yes
Epifauna & Infauna	Detection of benthos on top of the sea floor	Yes	Yes	Yes	Yes	Intermediate	Yes	Yes	Yes
	Detection of partially submerged benthos	Yes	Yes	No data	Yes	No data	Yes	Yes	Yes
	Detection of buried shellfish	No	No	Yes	No	Yes	In theory	No	No
	Dead vs. alive	No	No	No	No	No	No	May be	May be
ARL ship (1-3)		1	3	2	3	3	2	1	3
ARL autonomous (1-3)		2	3	2	3	2	1	2	3
Remarks								Potentially able to discriminate dead from living shells	

		Electromagnetic method (2)				Other sampling techniques		
		Laser Line Scan technique technology	Electromagnetic technology	Electrical Resistivity Tomography technology	Magnetometer/ Gradiometer technology	Physical Sampling techniques technology	Sediment Profile Imaging technology	Traces technology
Evidence by examples	Relation between measurements and shellfish	Not known	Not known	Not known	Not known	Known	Known	Not known
	Distance of sensor (and light source) to sea bed	Small	Tens of meters	Tens of meters	Tens of meters	Small	Small	Small
	Detect holes	Maybe	No	No	No	Yes	Yes	No
	Detect bioturbation	No	Maybe	Maybe	Maybe	Yes	Yes	No
	Sediment Roughness	Yes	No	No	No	Yes	Yes	No
Epifauna & Infauna	Detection of benthos on top of the sea floor	Yes	Yes	Yes	Yes	Yes	Yes	No
	Detection of partially submerged benthos	Yes	Yes	Yes	Yes	Yes	Yes	No
	Detection of buried shellfish	No	In theory	In theory	In theory	Yes	Yes	In theory
	Dead vs. alive	No	May be	May by	No	Yes	Yes	May be
ARL ship (1-3)		2	1	2	2	Not checked	Not checked	Not checked
ARL autonomous (1-3)		2	1	1	1	Not checked	Not checked	Not checked
Remarks						Direct observation	Direct observation	

The specific advantages and disadvantages are listed in Table 13 for each technology evaluated. Only a limited number of techniques has the (potential) capability to detect buried shellfish. The main improvement is observed in (1) combining multi-frequency sensing systems on ships, (2) the rapid development of autonomous vehicles and (3) improving on data processing and joint inversion.

The most complicating factors in shellfish bed detection are the turbidity issues experienced during previous data acquisition studies and the need for detection of infauna species.
The latter hinders the use of optical techniques to varying degrees. The infauna species might be captured by analysing of their effects at the seabed surface from by both optical and acoustics techniques (side scan sonar and multibeam echo sounders), but this would require the highest possible resolution from these techniques and then the resolution differences and sensitivity to turbidity become very relevant parameters. The higher resolution of side scan sonar systems and possibly laser line scanners might then be the more obvious choices to observe seabed surface. Recent advances in multibeam systems and processing are also very relevant for infauna mapping. In general, the TRL and ARL level of these techniques are quite high. The techniques that penetrate the seabed (Multibeam echosounder and Sub-bottom profiler) have so far not specifically been tested for buried shellfish bed or shellfish detection or only to a limited extend. These techniques require more evaluation before their potential can be confirmed, resulting in now in medium ARL scores. Despite their lower ARL, we are convinced that the EM and the 3D acoustic techniques (3D sub bottom profilers and possibly synthetic aperture sonar) are promising.

As discussed, the use of appropriate platforms and processing methods are key components of a fit-for-purpose solution.

6.2 Shellfish bed practical experiences

In general, the interviewed institutes are working on related topics and are interested in this study. The consensus is that, although improvements have been made on sensor, sampling and processing technologies, there is a need for further improvements. Increasing resolution and accuracy, improving grip on uncertainties, lowering costs, developing monitoring capabilities and developing methodologies for assessing buried shellfish beds are of interest to most parties. Combining survey techniques, joint inversion, autonomous systems and machine learning techniques are generally seen as the way forward.

The Dutch setting differs to some degree from the sites studied by the other institutes, mainly because of variations in the relevance of habitat mapping. Where for many areas, mapping habitats can be a good indicator for shellfish occurrences, the habitats in the area of interest for the Dutch case are expected to be non-discriminating. The known variability in habitat in the area of interest (sand production) is low as it consists mainly of sand with limited grainsize variations and relevance of these minor variations in habitat on shellfish populations is not well established and open for discussion.

Experiences in other fields of application
Experiences on many other applications were shared and discussed in the interviews as they could be relevant for a new shellfish mapping technology, amongst which experiences in:

1. Seabed monitoring.
2. Gravel mapping;
3. Environmental impact assessment of windfarms;
4. Screening/mapping of sediment dump sites;
5. Mapping other infauna or surface organisms and reefs;
6. Stock assessments;
7. Mapping see cucumbers;
8. Uxo mapping;

9. Mapping of cables and pipelines;
10. Marine archeology;

Conversely, the added value of new technology in the field of shellfish bed mapping is bigger than in the field of application discussed in this document. The chances of finding parallel project and potential cooperation projects are therefore very high. The added value of monitoring of and cooperation with these institutes is therefore very evident.

6.3 Discussion on shellfish bed detectability

6.3.1 Reference data on physical properties of shellfish beds

The detectability is determined by the contrast in physical properties of shellfish beds with or without living organisms to the physical properties of sediment and sea water. Relatively little is known about these properties.

Literature searches and sample experiments to get more accurate values on the following properties are required to assess a sound theoretical basis to judge applicability of the methods:

- Acoustic parameters of shellfish beds (mixture of sediment, shells, imprints in sediment) needed are; acoustic velocity and impedance, acoustic frequency bandwidths for reflection and tomographic methods for shellfish bed detection, acoustic radiation spectrum (in any case sound frequencies);
- Electromagnetic parameters of shellfish beds (mixture of sediment, shells, imprints in sediment) needed are: electromagnetic resistivity and impedance, electromagnetic bandwidths for reflection and tomographic methods for shellfish bed detection, electromagnetic radiation spectrum (in any case for gamma ray frequency).

So far, only sparse empirical information has been found.

6.3.2 Some considerations on sedimentary condition

The success of the methodologies listed in this study depend on many factors among which sediment type and local conditions. For this study we focus mainly on sandy sediments.
Before an area is selected for sand extraction, desk and field studies have been executed to determine the most suitable areas for extraction. Therefore, information on the sediment type is often available.
Clay layers and peat layers are not of interest for dredging because the material cannot be used for nourishments or industrial purposes. Gravel layers are rare in the area of interest and are often related to glacial deposits. These are generally avoided, because they can be close to clay layers and/or layers with boulders.

6.3.3 Epifauna versus infauna shellfish species and beds

Only a few shellfish species live (currently) on the sea floor surface. Methods to detect those are relatively easy to further develop.

Detection of buried species is one of the main challenges for mapping shellfish. Mapping traces of individual shellfish is only possible under optimal field conditions. Most examples available use optical camera data. Further testing it required to determine how robust such a method would be for the North Sea. The dependence, only performing under optimal conditions, makes this method vulnerable for this specific area.
The 3D sub bottom method, low frequency MBES and the SAS method are considered as the most promising solutions for direct detection, whereas ERT and to a lesser extent EM and Magnetometers are considered te be interesting but more experimental. Detection of individual (smaller) shellfish under field conditions would be very challenging and most likely not possible with the current technology. Detection of concentrations of individuals or their effects (i.e. bioturbation) is considered to be possible. In a sandy matrix shellfish will show up as concentrations of larger objects in an otherwise relatively homogeneous medium. The size and property difference between

shellfish and sand will be an order of magnitude bigger than the variations within the sandy sediment itself. Hence this contrast can only be related to the presence of shellfish. However, three situations should be considered in which this hypothesis is not valid; in clay layers, in areas with coarse gravel in the seabed and in areas with high numbers of dead shells. Clay areas will not be dredged because this material is to be avoided anyway. Sand with coarse gravel is rare in the area of interest, if present the gravel is fine which should not be a problem. Dead shell concentrations remain an issue which probably only can be addressed by ground truthing at selected sites.

Bulk acoustic properties of the upper meter of the seabed could be an indicator for the presence of shellfish beds. The acoustic techniques (high frequency subbottom profiling or low frequency multibeam echosounding as their wavelengths correspond best with the shellfish bed dimensions) should in that case either be able to map changes in seabed loosening or compaction (as caused by shell density and bioturbation) or changes in acoustic scattering (as caused by the presence of shells), both of which are in theory possible with these techniques. Changes in compaction could be deduced form variation in seismic velocities, impedances or damping. Typically, 3D type subbottom chirp data or 3D synthetic aperture sonar (SAS) is required.

For the EM, ERT and Magnetic techniques either the reorganization of the sediment or the difference in water content (porosity) would be the parameter to map. From which porosity mapping is the most tested, but experimental, technique using marine EM systems.

6.3.4 Dead versus live shellfish

Distinguishing between living shellfish and dead shells is one on the challenges that must be dealt with. This is especially challenging for the infauna species. Examples are available where siphons have been mapped with visual techniques and some observations have been done with sonar data. However, both only work under optimal conditions and have not been evaluated for all shellfish species. Further improvements to these techniques could help to resolve this.
Potentially the EM, ERT and (hyper) spectral techniques can also help to distinguish between dead and live benthic communities. Living organisms in the shells do have distinctly different, higher electrical resistivity values and impedances.
There are some indications that acoustics techniques might help to distinguish between live and dead shellfish concentrations but only when the dead shellfish are no longer in their ‘living’ position. There is a study where differentiation between closed upright (live) and open shells (dead) has been made by looking at the intensity of the scattering of acoustic data.

6.4 Monitoring strategy for shellfish bed detection

Given the results of the potential shellfish bed detection system assessment and the shellfish bed monitoring challenge ahead the following monitoring strategy is proposed:

1. Monitor the morphological, sedimentary environment by using ships with common sensing technologies (regular SSS, MBES with subbottom profilers). This enables to eliminate sedimentary areas in which shellfish beds are not to be expected.
2. Monitor the shellfish bed at large by using ships with existing sensing technologies (Multifrequency SSS, MBES and High-Frequency Sub-bottom profiler) and dedicated configurations and processing. This enables the detection of the shellfish beds at large. In the surveys new technologies could be added and validated. Note that the yearly WOT shellfish surveys, based on digging dredge samples, provides excellent ground truthing for such an approach.
3. Monitor individual beds with sampling tools or autonomous vehicles (including cameras and High Frequency SSS and SAS) to verify and detail the shellfish bed characteristics (species).

7 Shellfish bed detection technology development strategy

7.1 Conclusions of this study

The main insights and conclusions obtained are described here.

Shellfish bed definition

- A first definition consisting of most relevant characteristics for detection has been proposed for shellfish beds which could be used for this assessment.
- The epifauna shellfish beds (Ostrea species) in the project area are relatively easy to detect with a combination of various acoustic sensing technologies on ships or ROVs/AUVs or other platforms but are currently hardly occurring in the project area.
- Apart from possible future developments of *Ostrea edulis* beds, all shellfish beds in the project area are composed of infauna species. The detection of infauna species is challenging and requires different technologies than currently used (except for in situ sampling).

North Sea conditions

- North Sea habitat mapping using sampling technology only is not regarded as an optimal indicator for the presence of shellfish beds, on the other hand surface covering techniques have hardly been applied.
- Integrating new mapping and monitoring techniques with existing survey efforts on the North Sea could yield valuable information (i.e. WOT and MWTL sampling).
- Autonomous survey systems are fast-developing game changers with good potential for shellfish bed mapping at a closer distance to the seabed floor.
- The visibility conditions in the North Sea lower the success rate of various optical cameras and related techniques; laser line scan or techniques using even lower frequencies are favoured.
- Validation and calibration of geophysical measurements by in situ sampling needs to be part of any strategy.

Sensing technology developments

- All recent developments in sensor and processing technology combined have great potential for generating a robust shellfish bed detection methodology.
- The number of projects and literature integrating several technologies and/or using wider frequency bandwidths of instruments are increasing.
- Combining different types of sensor acoustic technologies is generally seen as the way forward for shellfish detection.
- As the main complicating factors in shellfish bed detection are the requirement to detect infauna species and the turbidity conditions in the North Sea experienced in previous studies, the proper selection of instrument and frequency settings is crucial.
- Current technologies have individually been improved but further steps need to be made if higher reliability and accuracy in shellfish bed detection is required.
- Sub bottom technologies and EM based techniques could be used for mapping infauna species, the achievable resolutions must be determined.
- Because of its high-resolution data being continuous over the entire swath range, synthetic aperture sonar is a possible way forward for detecting infauna species. However, this technology has been (and still is) very much in development and not widely available.

Autonomous platform developments

- Testing the added value of fast developing sensing instruments mounted on remotely operated or autonomous subsea systems (decreasing the sensor to seabed distance) in such a setup would be valuable.
- Main challenges for remotely operated and autonomous subsea platforms are: (1) integration of electromagnetic and acoustic sensing techniques enabling higher resolution images and, (2) reduction costs of surveying with these subsea vehicles in swarms.

Processing technology developments

- An acoustic-electromagnetic joint multimethod 2D and 3D data physics-based processing and inversion approach yields great potential to reduce uncertainties in classifications and interpretation.
- New artificial intelligence/deep learning and remote sensing-based processing techniques are not used yet but very promising.
- On board processing and interpretation (exiting technology, although not always commercially available at the moment) reduces project time and could optimise data acquisition strategies.

Potential spin offs

- There are many other potential applications (defence, fisheries, shipping, off shore industry, nature development, etc.) for the technology needed for the detection of shellfish beds. In case detection techniques are developed and/or improved during the next phases of the study other fields of application will benefit too. It is recommended to set up a joint development for multiple targets/applications.
- The need for monitoring techniques for shellfish bed and shellfish population dynamics is apparent in different fields, for example aquaculture, restoration and recolonization. Monitoring studies can, in addition, document the effects on shellfish beds of fisheries, sand extraction and other disturbances.
- Time series information is generally considered to be very useful but scarce, this development could help to make this information more available.

7.2 Options for next steps

All sensing, platform and processing technologies have pros and cons and have variable degrees of ‘readiness’ for the application of mapping shellfish beds. Not a single technology will be a 100% solution for all conditions and all potential targets to be detected. Improving and combining methods and designing smart survey approaches may support resolving these issues.

Future developments could be focussed on:

- Improving resolution of individual sensors, improving of operational aspects of sensors, testing new sensors and processing routines.
- Combination of extra sensing technologies on various platforms: on existing shipping infrastructure and on new subsea (ROV and AUV) platforms or by replacing or upgrading existing sensing systems.
- Survey with a combination of sensing technologies, and the integration of processing and classification methods.

In order to stimulate these developments, one approach could be to develop, design, test and configure one-off shellfish bed solutions to the local conditions and the target species on a project by project basis. However, this will have a fragmented character, from which it will be more difficult to validate solutions properly and to compile the different studies in order to gain system knowledge.

Alternatively, a robust and coherent programme could be set up, in which a combination of existing and new methods will be developed and tested in a few pilot locations - supported by tests under controlled laboratory or field-like conditions - and in which relevant data are collected in order to enable researchers to systematically compile the required physical parameter information.

Taking these considerations into account the following building blocks - each having advantages and disadvantages - for such a development programme have been defined:

0) to test new analyses and processing methods on existing datasets measured with existing tools on ships, align developments of potential partners;
1) to verify the shellfish bed acoustic and electromagnetic transmissive and reflective/scattering properties on a small set of representative samples in a lab;
2) Select the two to three most promising techniques and start a test program, under field conditions, in which recent developments on sensor and processing methodologies will be evaluated;
3) A) to test the combinations of new and existing ship-based technologies in the field under controlled conditions;
   B) to test the presented combination of new and existing remotely operated and autonomous subsea technologies in the field under controlled conditions.

A comprehensive programme including several of these tracks is also a possibility.

7.2.1 Building block 1: Test new analyses and processing methods to identify shellfish beds on existing datasets

Existing data sets obtained with existing technologies (Side scan sonar and Multibeam echo sounder for bathymetry and sediment classification and Sub-bottom profiler for mapping sand resources and geotechnical sites) could - when proper metadata is available - be reprocessed and re-analysed to determine if recent developments in processing and object detection methodology are enough to get shellfish bed detection operational.
The main advantage of this approach is that this is a relative low effort and low budget exercise, compared to the other building blocks. However, the chances of it being successful are considered to be low.
A major disadvantage is that little ‘ground truth’ information on shellfish banks at the time of the surveys might be available to come to evidence-based conclusions. This option also means that new techniques cannot be tested on all existing data sets, for example, multibeam backscatter analysis is only possible if during data acquisition the correct parameters and data were stored. Furthermore, the amount of data sets in which multi-sensor data are available is expected to be low. Hence ‘joint inversion’ type analysis on existing datasets will be difficult to execute. Also, the potential lack of enough adequate and collocated calibration data (samples) to link the indirect measurements to sample observations limits the added value of this approach.
It might only be relevant when robust data processing and shellfish bed detection procedures have been developed.

7.2.2 Building block 2: Verify shellfish bed acoustic and electromagnetic properties in the lab

Regardless of the technology that will be selected, we propose to investigate what the acoustic or electromagnetic properties of the shellfish beds are. To this end, the properties relevant for the various evaluated sensing technologies needs to be determined, which can be done on relatively small samples in a well-equipped laboratory. This would result in a proper database of:

- Acoustic geometries, textures and properties (such as acoustic wave velocities and impedances) depending on shellfish bed type, shellfish densities and sediment properties

- Electromagnetic geometries, textures and properties (such as electromagnetic properties as electrical resistivities and impedances) depending on shellfish bed type, shellfish densities and sediment properties.

In addition, it would also be possible – using the acoustic and electromagnetic responses – to execute a synthetic modelling analysis of the resolution and capabilities of the new and/or improved sensors. Such an analysis would comprise of building a computer modelling environment in which instrument response simulations can be run for various sensors. However, we do expect that because of the many variables and unknowns, the effort required for this building block might be high and the chances for success somewhat limited. On the other hand, this step could help to focus and limit the amount of testing to be done.

7.2.3 Building block 3: Test a combination of new and existing technologies in field-like conditions

In this method a selection of the most relevant remotely operated and autonomous ROV/AUV/USV/ASV based sensors and sensor-processing solutions will be evaluated in a large controlled test facility representing realistic conditions. Under these controlled conditions it will be possible to have the optimal calibration means. It allows for a range of techniques to be tested relatively efficient on a range of shellfish bed densities. Furthermore, in sufficiently deep flumes, autonomous systems could be evaluated by simply increasing or decreasing the distances between sensor and seabed. This feature is expected to be an important advantage of autonomous survey systems.

A challenge of this approach is that an experimental test facility needs to be found, built and configured. The size of the facility must be adequate (at least in one dimension) because some techniques have wide swath or need enough distance between instrument and target and cannot always be downsized.
Another challenge is building representative sea beds with -preferable living shellfish- in such a facility. Concerns exist that creating shellfish beds with living shells will be difficult. However, NIOZ-Texel and NIOZ-Yerseke experience is available in this respect. However, the second best - using dead shells, will also give insights but less convincing.
In any case, the facility should allow working with sea-water, as electromagnetic properties depend strongly on salinity and cannot be tested in freshwater. When the aim is to keep animals alive, high-discharge running seawater facilities must be available.
A pitfall of this approach could be the risk of testing too many variables and getting responses from the facilities itself. The institutes interviewed for this study all conformed the need and added value for controlled testing of new and existing sensors and the processing techniques.

7.2.4 Building block 4a: Select the 2-3 most promising ship-based mounted technologies and do field tests

Recently developed sensor and processing technologies will be evaluated by selecting the two to three most promising techniques in a test program in the field, so that ultimately the optimal technologies can be found. Ground truthing by means of camera observations and/or sea bed sampling needs to be part of this exercise.
This option has the advantage that two to three datasets over a large frequency range will be collected from the same area under comparable conditions. Since new data will be collected, all required parameters can be collected with the required level of data quality.
This approach can start with a combination of the most promising technologies identified in this report (Side scan sonar, Multi frequency Multibeam Echo Sounder and high frequency range (chirp) sub-bottom profiler) covering the largest range of interest.

Thereafter, other techniques – available, but not used so far - could be tested in the same area. Using both the most promising technologies and new technologies will provide a well underpinned conclusion on shellfish bed detection strategy using ships.
An important risk is that within this building block testing would be done under field conditions, which can complicate matters from an operational and form a validation point of view.

7.2.5 Building block 4b: Select the 2-3 most promising ROV/UAV-mounted technologies and perform field tests

Select the two to three most promising techniques and a start test program in field conditions, in which recent developments on sensor and processing methodology will be evaluated.
This option has the advantage that two to three datasets of different nature (acoustic and electromagnetic) will be collected from the same area under comparable (when done during the same deployment even under the same) conditions. Since, new data will have to be collected, careful study design is required to ensure the right amount and quality of calibration data is collected.
This approach is a more innovative track. As a start, single technologies can be mounted on ROV's or the most promising technologies identified in this report can be combined (Side scan sonar, Multi frequency echosounder and cameras) covering the range of interest.
Subsequently, other techniques – available, but not used so far in other application fields - could be tested in the same area. Doing both will provide for a well underpinned conclusion on shellfish bed detection strategy using ROVs or other (autonomous) platforms.
An important risk is that within this building block, testing would be done under field conditions which complicates matters from an operational and form a validation point of view.

7.3 Collaboration

In the effort to bring shellfish bed detection applications to ARL 5 (market ready), financial and technical collaboration between research, market and authorities is required and recommended by several stakeholders interviewed, because:

- Setting up such cooperation and joining efforts would also help to achieve optimal results in an efficient way; integration of the available expertise combined with experiments is the way forward;
- Many stakeholders (Sand extraction, Fisheries, Off shore industry, Rijkswaterstaat, Defence, etc.) in the North Sea can contribute and take advantage of improved seabed characterisation technologies;
- Many institutes are working on related topics varying from sensing techniques, to new ROV/AUV/ASV/USV platforms and new processing methodologies;
- Many options on potential collaboration are present and welcomed, which could align or be sponsored by research (NOW) or innovation (TKI) program funding;
- The availability of a controlled testing environment for seabed and shellfish bed mapping technologies would be beneficial for further improvement of a variety of existing methodologies and acceptance of these newly applied technologies.

7.4 Recommended options and development programme

Our advice is to first discuss the document with peers, further improve the shellfish bed definition, explore the costs and direction of each building block, to perform a proper risk analysis and to form consortia. Also, the international collaboration option needs to be identified and explored. This will help to define a cost-effective programme.

Preliminary recommendations of the project team are that:

- Building block 1 (duration less than 1 year) is attractive but not recommended because of a high risk of becoming inconclusive;

- Building block 2 (duration 1 year) and 3 (duration > 2 years) are more scientific tracks, which can start soon and should include universities and research institutes in the consortium;
- Building block 4a (duration 1 year) is a pragmatic track, which can start soon and should include surveying companies in the consortium;
- Building block 4b (duration > 2 years) is an innovative track, which can start when existing scientific or operational platform are made or when available (e.g. NIOZ or RWS) remotely operated or autonomous platform suppliers are interested and collaborate in the consortium.

Initiating a comprehensive (international) programme consisting of these building blocks also needs a strong and focused programme management.

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A MBES back scatter

A.1 Introduction

Hydrographic backscatter is the acoustic signal that is received back at the echo sounder after scattering of the full acoustic signal at the seabed. In marine sciences, backscatter mosaics, which record the strength of the sonar return from the ocean floor, help us understand characteristics of the sea floor (Lurton and Lamarche, 2015). Multibeam echo sounders use beams of sound to map the ocean floor. These sonar systems collect two types of 3D surface data: sea floor depth and backscatter. The sea floor depth, or bathymetry, is computed by measuring the time it takes for the sound to leave the sonar, hit the sea floor, and return to the sonar. Backscatter is computed by measuring the strength of the sound that is received by the sonar from the sea floor. Different bottom types scatter sound energy differently, telling scientists about their relative hardness and roughness. Harder bottom types (like rock) result in a higher backscatter strength (BS) than softer bottom types (like mud), and smoother bottom types (like pavement) result in higher backscatter strength (BS) than bumpier bottom types (like coral reef). Combining bathymetry and backscatter data collected by multibeam echo sounders allows scientists to create very detailed maps of the sea floor and the habitats present there. The information is used for multiple purposes, including marine ecosystem protection, coastal hazard preparedness, and navigation safety.

Backscatter of shellfish

Several studies show the feasibility of side scan sonar and backscatter to map shellfish. To name a few: Van Overmeeren et al. (2009) presented results from shallow coastal waters in the Netherlands, in which they showed that filtering techniques and FK filtering is a simple and effective method to remove selected linear trends, such as emanating from wave ripple structures or beam trawl marks, from mosaics. Then they used pattern recognition and quantification of macrofauna to separate the backscattering produced by biological targets from backscattering coming from other sources.

Results of acoustic habitat mapping in other European countries bordering the North Sea have been published by (a.o.) Brown et al. (2002, 2004, 2005) and Degraer et al. (2003, 2008). Recently, Brown and Collier (2008) presented the results of acoustic habitat mapping on the west coast of Scotland. In this continental shelf environment with water depths between 10 and 60 m, biological ground-truthing was provided by underwater video footage and several grab sampling locations.

Sen et al. (2016) used multibeam echo sounder bathymetry and acoustic backscatter data, reclassified on topographical features from two different depths above the seafloor in a cold deep Congo channel, to predict tubeworms.

Van Dijk et al. (2012) showed possibilities of habitat mapping and bed classification and benthic fauna variation over tidal ridges.

Recent developments

Multibeam backscatter (MBES) is the reflectivity measurement (a calculated process), whereas the sidescan sonar (SSS) imagery is the actual (uncorrected) intensity of the return signal. The 'backscatter' and 'seabed image' provided by Kongsberg multibeam systems, for example, are created after beamforming, the sample amplitudes are corrected for by processing gain and beam pointing angle depending on variations in source level and receiver sensitivity.

The backscatter values given in the depth datagrams of the raw data files are an average value of the sample amplitude values inside the detection window (footprint); basically, one averaged amplitude intensity value per beam. The seabed imagery value is high-density data, based on geo-referenced beamformed raw amplitude samples; basically, multiple intensity values per beam. The data is corrected for by applying Lambert's law.

The multibeam system is always installed on a survey platform (whether a ship, AUV or ROV). The Side scan sonar towing configuration provides greater manoeuvrability compared to MBES configuration, as the depth of the tow-fish above the seafloor can be adjusted, in view of the swath width, but also complicates the horizontal positioning.

The difference between multibeam positioning (hull-mounted and thus known) and the side scan sonar positioning is that the side scan towed fish is found behind the ship, and hence this needs to be corrected for, in relation to the onboard DGPS navigation system. However, hull mounted side scan sonars systems exist. With the introduction of autonomous underwater vehicles positioning needs to be solved as well.

Multibeam bathymetry is based on the fact that they have multiple directional beams. They map the seafloor by generating several hundred beams over a crosstrack profile for each ping, and each beam generates at least one depth sounding. While the platform sails forward the seafloor is covered with a dense pattern of soundings producing high-resolution bathymetry data and geo-referenced high-resolution seabed imagery throughout the survey area, providing 100% coverage of the seafloor. As the MBES systems have been developed to offer narrower beam widths, there has also been a complementary increase in the number of beams provided. This development has become necessary in order to retain the ability for full ensonification of the seabed. Other enhancements have been made to improve the density of data provided by MBES. Dual-head configured MBES-systems can provide for a wider (combined) swath by emitting simultaneous ‘pings’ from both heads, rather than alternate transmissions. Further, systems are now available that provide the option of dual-swath, which simultaneously provides two transmissions at each ping for both single and dual-head MBES systems. The purpose of this facility is to provide double the along-track density of soundings; thus, the second swathe is positioned slightly ahead of the first swathe. This feature complements the increase in (across-track) number of beams, but also has the advantage of allowing greater survey speeds for a given ping spacing, thus potentially increasing the efficiency of acquisition. For some studies, the processing of dual head data, with or without dual swath (dual frequency), may need extra processing (i.e. correcting for four different frequencies around a centre frequency.

The quest for higher quality systems is primarily realised by increases in system resolution. These advances are largely achieved by producing systems of smaller beam widths and reduced pulse lengths. Thus, it is now quite common to find systems with half-degree beam widths, and beams of 0.3 and 0.4 degrees are available. These specifications are to be found in systems catering for the shallow-water markets, which operate in the higher frequency range. Naturally, there is a trade-off between frequency and range. In order to achieve the highest resolution, a high frequency is necessary but useable range will then be compromised. Manufacturers are overcoming range limitations by introducing a frequency modulated (FM) sweep, in addition to the traditional continuous wave (CW) pulse. This feature allows greater energy in the pulse, providing enhanced range. In order to allow some flexibility in operations, systems are now available that allow a selection of frequencies, typically in the 200 – 400kHz range for shallow-water operations, although at least one manufacturer has a system available with the additional option of 700kHz. In the SSS industry the resolutions are surpassing 1000 kHz. At this frequency, the systems are approaching the same band occupied by scanners and imaging sonar systems, and it is evident that the technologies are converging around certain applications in the survey and inspection markets. In the medium and deep-water sectors various manufacturers also offer dual frequency capability.

A new development is the multi-spectral multibeam echo sounder, which emits three frequencies in the range of 40 or 90 kHz to 450 kHz, depending on the system, on a ping-to-ping basis. The lower frequencies penetrate into the subsurface (up to ~1 m, depending on the sediment type (Gaida et al., 2018)). The multi-frequency multibeam echo sounders therefore produce more 3D data, with not only the seabed (surface) information from the higher frequency, but also the subsurface information.

	Pros	Cons
MBES	Collect Backscatter Collect depth High Quality	Depth High grazing angle Far from the seabed Somewhat lower resolution (compared to SSS)
SSS	Low Grazing angle Close to seabed High quality Could collect depth High resolution	Layback System Cabling No backscatter analyses possible, No position each pixel

Table: Pros and cons of MBES and SSS systems, please note that these differences are changing due to the availability of UAV based MBES and SSS systems and the increasing resolution of both sonar systems

A key parameter to interpret the backscatter mosaics is bed classification by investigating the sediment backscatter strength that can be derived from the intensities of the received echo. In general, classification methods employing measured backscatter data can be divided into model-based and image-based methods (supervised and unsupervised methods). Model-based methods are attributed to techniques that perform inversion based on physical backscatter models either to exploit the measured backscatter strength directly or the angular backscatter response to invert for sediment properties (e.g. mean grain size, roughness spectrum, volume scattering coefficient). Image-based methods are based on statistical relationships and patterns within the backscatter data. Whereas model-based methods require accurate models for predicting the backscatter strength and well-calibrated systems for measuring backscatter strength, image-based techniques are also applicable to relative backscatter values from poorly or uncalibrated systems. In the sediment classification, seabed samples are used to assign sediment characteristics to the acoustic classes. Brown et al. (2011) gives a review of various strategies and methods employing acoustic remote sensing techniques including SBES, SSS and MBES to produce sediment or habitat maps. Simons and Snellen (2009) and Snellen et al. (2019) describe methods of sediment classification from MBES backscatter, as applied to the Cleaver Bank in the North Sea.

Future work
Deltares collaborates with the team of M. Snellen and D. Simons of Delft University of Technology, on applying the bed classification algorithms that they developed. Snellen et al. (2018) presented a paper where they apply two different sediment classification methods to MBES backscatter data acquired on different vessels during different surveys carried out in various time periods and to investigate the repeatability and agreement of the resulting sediment maps. To accomplish this goal, the Bayesian approach and PCA in conjunction with k-means clustering approach are applied to backscatter data acquired. This way, the repeatability of the data using different hardware is addressed and the classification method works in different data sets. Solutions for alternative calibration techniques, such as cross calibration or using calibration survey areas, are described by Montereale Gavazzi (2019), who also compares the unsupervised and supervised (machine learning) methods of sediment classification. Testing the acoustic response from different sediment types, as called for by Montereale Gavazzi (2019), is being set up in a collaboration of Deltares, Delft University of Technology and Belgian and French experts in the subject of MBES backscatter. A study in which the multi-spectral multibeam echo sounder will be used for infauna shellfish detection is being set up by Delft University of Technology in collaboration with, among others, Rijkswaterstaat and Deltares.

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B 3D sub-bottom profiling and seismic data processing

SAND Geophysics	Deltares – Acoustic Mapping of Benthic Colonies	Doc. No: T259-2018	
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Acoustic Methods for Mapping Buried or Part-Buried Marine Benthic Colonies

Dr Mark E. Vardy - SAND Geophysics Ltd

SAND Geophysics Ltd (SAND) were contracted by Deltares to scope the potential application of marine geophysical methods for the mapping and classification of buried or part-buried benthic colonies. In particular, the scope was to focus on the application of ultra-high-resolution acoustic techniques.

The successful mapping of totally or partly buried marine benthic colonies using acoustic techniques relies on solving two principle problems: detectability; and characterisation. SAND has developed or is currently developing new equipment and novel processing/interpretation techniques that could be used to address both of these challenges.

True 3D Acoustic Imaging – 3D Chirp

The successful detection of buried benthic colonies using acoustic techniques relies on coherently mapping variations in sub-surface acoustic properties at a very high-fidelity across the target area. While traditional 2D sub-bottom profiling techniques provide the required vertical resolution (typically < 20 cm), they do not coherently map the spatial variability. Incorporating the spatial component requires the acquisition of true-3D data that records the full 3D nature of the reflected acoustic wavefields and therefore the complete subsurface structure.

The 3D Chirp is a down-scaling of hydrocarbon industry 3D seismic surveying techniques that produces a very clean and coherent 3D seismic volume where sediments and structures can be tracked through cross-sections and time-slices. Originally developed jointly by the University of Southampton and Kongsberg GeoAcoustics, the system is now jointly being applied, developed and marketed by SAND Geophysics and the University of Southampton.

Figure 1 shows a time-slice 1m below the seabed for a UXO survey in a port. Depressions in the underlying bedrock have caused finer sediment infill to accumulate, appearing as more "transparent" areas, while discrete objects within this near-surface time-slice appear as dark shapes of high-amplitude. This kind of section, produced at successive depth intervals, makes for extremely effecting delineation of both geological structure and UXO identification.

Figure 2 demonstrates how complex diffractions from point reflectors, such as potential UXO or other small-scale features, can be collapsed using pre-stack 3D migration processing. The resulting image preserves the true size, shape, and orientation of the reflection. In the case presented in Figure 2, **the** buried object was resolved to be L-shaped just under 2m long and 0.4m wide at its widest point. The imaged dimensions and shape correspond excellently with the coincident recovered object, which was found to be an old boom for fishing, in doing so demonstrating accurate decimetric resolution imaging in all 3-dimensions.

http://www.sandgeophysics.com

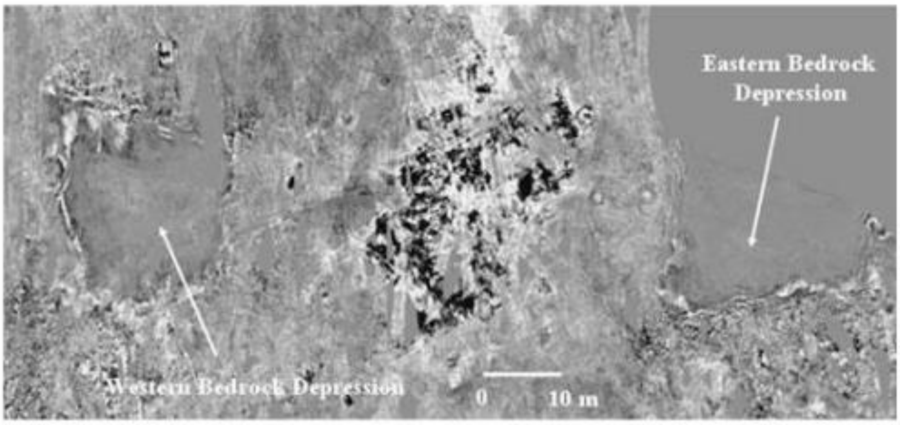

Figure 1: Complete time-slice approximately 1m beneath the seabed showing continuous decametre-scale structure as well as decimetre-scale resolution of isolated UXO point targets.

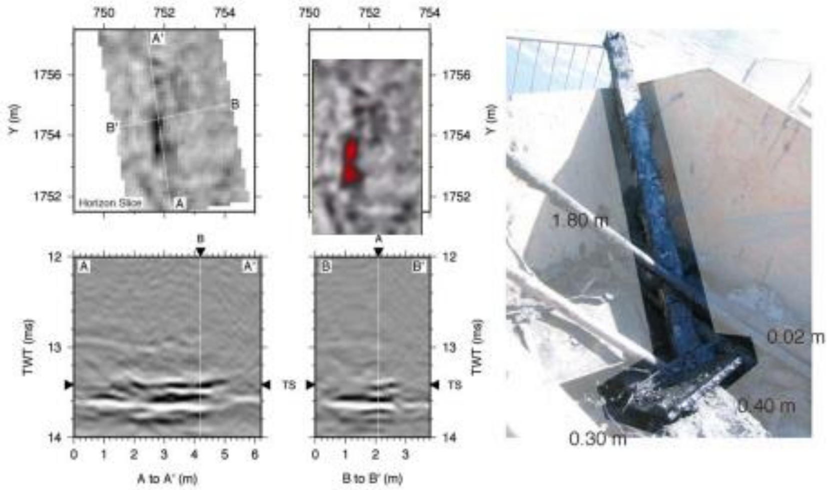

Figure 2: Excellent example of migrated target geometry with the recovered buried object.

Inversion for Physical Properties

While the acquisition of true-3D, decimetre-resolution seismic reflection volumes using the 3D Chirp permits the subsurface structure to be imaged at high-fidelity, the reflection data alone would not allow benthic colonies to be reliably differentiated from other, geological features. However, the application of seismic inversion methods, which derive a quantitative characterisation of the physical properties of the subsurface from the seismic reflection data, provide intuitive information that has the potential to differentiate between geological, anthropogenic and biogenic structure.

SAND Geophysics has developed a range of bespoke seismic inversion methods as part of their Quantitative Seismic Imaging (QSI) software package. These techniques are developed specifically for application to high- and ultra-high-resolution seismic reflection data, including sub-bottom profilers, and are cast within a stochastic framework. The resulting algorithms are therefore more computationally expensive than classical deterministic approaches, but have the advantages of requiring significantly less a priori information, provide more robust results, and enable confidence intervals on inverted parameters to be derived along with the statistically 'best' solution. Specifically, for application to 3D Chirp data, it is possible to derive coherent quantitative information in 3D regarding the spatial variability in acoustic impedance and intrinsic attenuation. Together, these parameters quantify the subsurface in terms of its mechanical compressibility and hydraulic permeability, averaged over the seismic wavelength (10 - 20 cm at Chirp wavelengths).

These parameters offer extra layers of information that may be critical for differentiating between geological features and benthic colonies, as well as providing a quantitative characterisation of the internal variation within individual clusters. Additionally, intrinsic attenuation is highly sensitive to the presence of free gas, and therefore could be used to identify and map any free gas accumulations associated with the colonies.

Micro-Scale Roughness

Further to quantifying the subsurface in terms of bulk parameters using classical seismic inversion methods, SAND Geophysics are also in the process of developing algorithms to better utilise information stored in the decaying tail from a reflected wavelet. These data have the potential to quantify the interface roughness of the seabed and subsurface boundaries at, what would traditionally be called, sub-seismic scales.

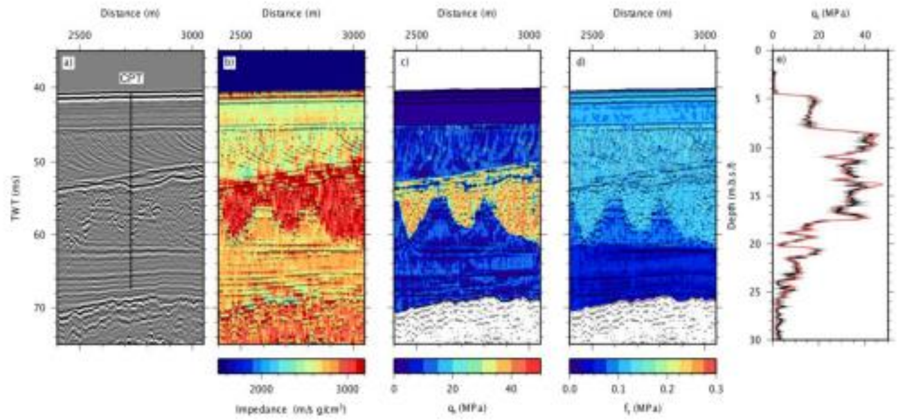

Figure 3: Inverted physical properties from single-channel boomer data, including the application of machine learning methods to predict geotechnical properties.

This is analogous to the surface scattering methods that have been used for some time to differentiate between different geological substrates using side scan sonar and (more recently) MBES backscatter data. The individuals within a benthic colony should present a very different backscatter profile to any geological substrate, while it may also be possible to different between some benthic species based on their backscatter profiles.

Multi-Parameter Data Integration

Fundamentally, however, seismic reflection techniques are unlikely to ever be used in isolation when mapping benthic colonies. As well as other geophysical methods, it is likely that non-geophysical data (such as intrusive samples, camera trawls, diver/ROV surveys, etc) will also be acquired. Effective integration of all the different data types is critical in providing optimal results.

SAND Geophysics have developed a machine learning based data integration framework that allows multiple different data types to be effectively integrated into a more comprehensive interpretation. This has proved hugely beneficial for engineering ground investigation surveys, where geophysical, geological, and geotechnical data have been integrated into a single engineering ground model (e.g., Figure 4). Additionally, it is showing significant early promise for reducing the number of false positives seen in UXO site investigation.

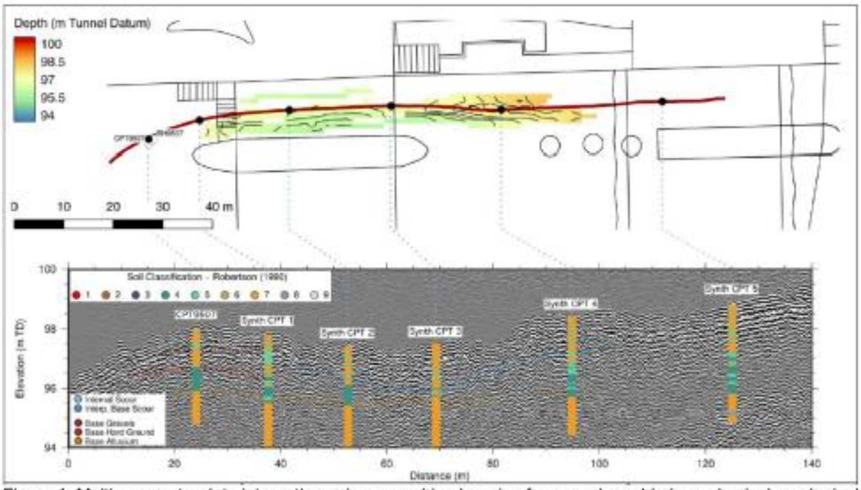

Figure 4: Multi-parameter data integration using a machine learning framework enabled geophysical, geological and geotechnical data to be effectively and efficiently integrated for this shallow infrastructure site investigation survey.

C Electrical resistivity & electromagnetic technologies

C.1 Introduction

Electrical properties of soils are related to the chemistry and mineralogy of the soil material, temperature and the porosity and any fluids on the grains or in the pores of the soil. The electrical properties can provide indirect indications on the nature and spatial variation of soils. There are two types of sources to measure the electric field, galvanic and inductive. The first is known as the geo-electrical method (VES when data are collected in 1D and ERT when data are collected in 2D and 3D) and the latter as electromagnetic induction (TDEM), which we explain in the following sections. Both methods provide models of resistivity values on the subsurface, from various depths (from few cm to 100 of meter). Thus, those measurements are useful to map the local conditions in temperature, salinity and soil type, up to few meters. Additionally, resistivity measurements could be used also as direct observation of shellfish, but we were not able to find relevant literature. The concept is the following:
The resistivity ρ (or conductivity σ=1/ρ) of a porous rock is measured as

$$\sigma' = \frac{1}{F}\left[s_w{}^n \sigma_w\right] \sigma' = \frac{1}{F}\left[s_w{}^n \sigma_w\right] \sigma' = \frac{1}{F}\left[s_w{}^n \sigma_w\right]$$

where s_w is the water saturation, σ_w is the fluid conductivity (S/m), $F=\varphi^{-m}$ the formation factor, φ denotes the connected porosity and m is constant (typically m=2), known as Archie's law

In other words, in the subsurface, due the presence of soil that "replaces" water, we observe higher resistivity values. In areas where shellfish is present, we expect changes in resistivity, because part of the grains have been replaced by shellfish. We expect shellfish to have similar behaviour like sea water when filled with water or small pebbles when filled with living organism.

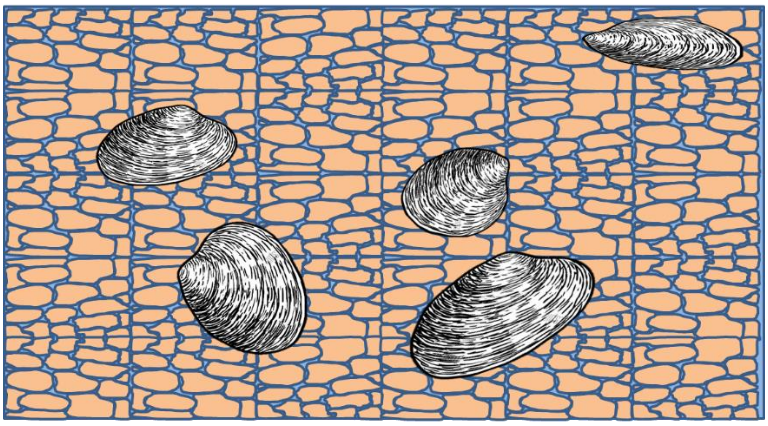

Figure 1: A porous sea water filled sandy sediment system with some shells larger than grains

C.2 Electrical resistivity tomography (ERT)

Marine ERT is a natural extension of the counterpart land based ERT and has been widely used in the past for a variety of application. The idea to extend the use of electrical methods in water was introduced by Taylor (Taylor R.W. 1992), but recently some experiments demonstrated its applicability (Belaval et al., 2003), (Snyder D. D., 1997).
Data acquisition can be carried out according two operating methods: 1) electrodes floating on the water surface 2) electrodes settled on the bottom. The former allows to acquire data both in static

and in dynamic way and with continuous profiling (Snyder, 1997) while the latter allows only static way also using roll along measurements (Nyquist, 2008). Recent tests also by Deltares, showed that towing cables in the seabed are also possible, to increase the resolution near the seabed and avoid the very low resistivity values of the sea water.
In data processing, the upper elements of the mesh are used to model the water layer, while the lower elements are used to describe the resistivity distribution of the subsoil (Loke and Lane, 2004). Furthermore, modelling of the conductive layer in terms of thickness and electrical resistivity of water improves quality of inversion process (Day Lewis et al., 2006). Recently, Deltares developed a special type of cable, with flexible spacings to adjust the required resolution and applied it to map the top of Pleistocene (Karaoulis et al, 2018). The principles of the method are identical in fresh salt water environments, but the requested injection current is much higher in the saline water (typically about 10 Ampere).

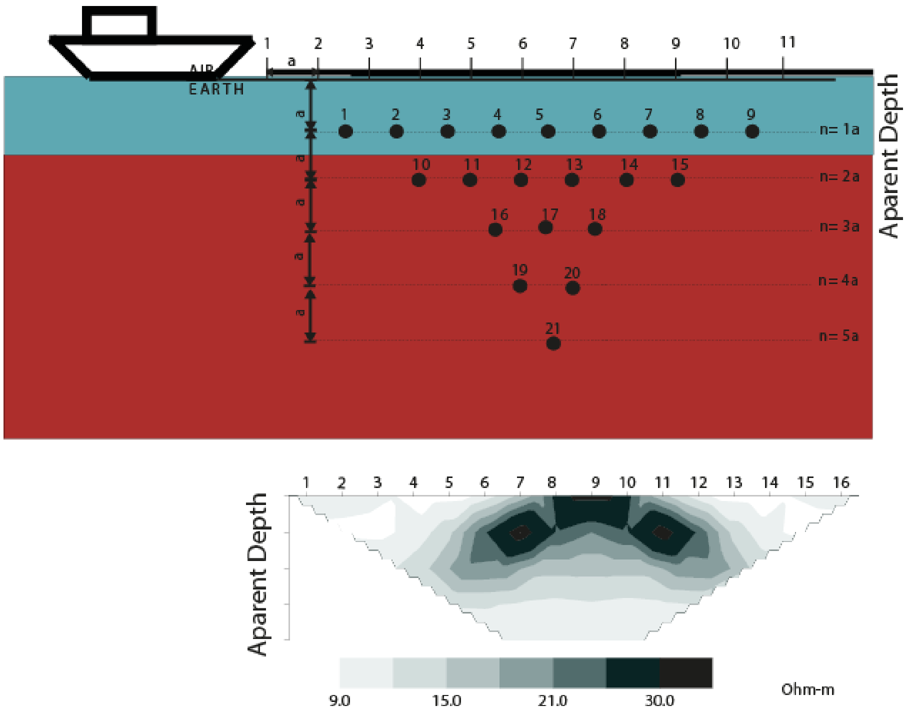

Figure 2: A typical towed ERT system, with a cable dragged behind a ship. Data are collected and processed to generate resistivity images of the subsurface

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C.3 EM, Controlled Source EM

Controlled source electromagnetic methods (CSEM), one of the available types of EM systems, have been used in exploration of the offshore environment for over 50 years to map the resistivity structure of the earth. In general, this technology has been used for submarine oil and gas exploration related surveys (in which very low frequencies are used), however in recent years developments have been made to expand the field of application to the near surface (or in this near seabed) domain. Studies have been done which the porosity of the near surface seabed had been mapped.

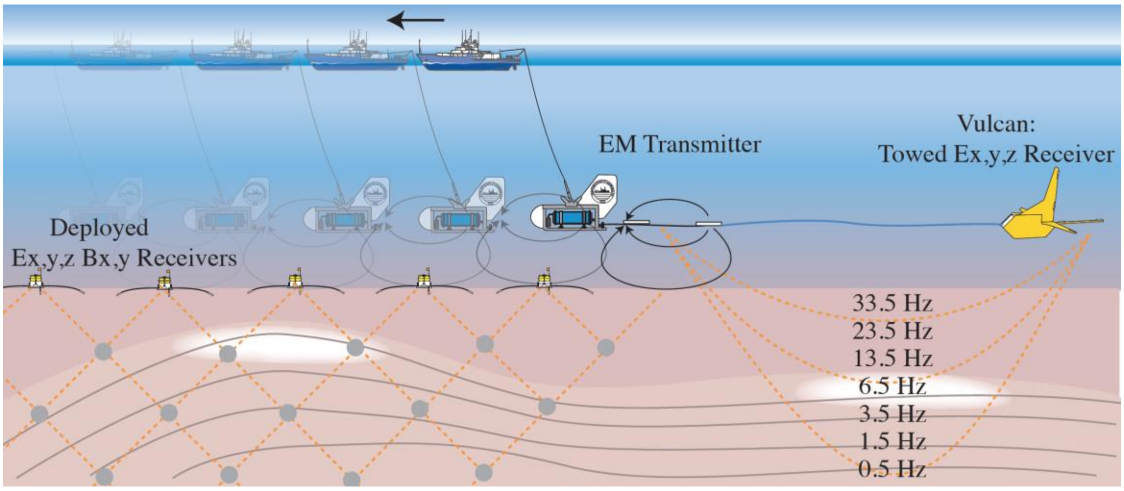

Figure 3: Modified figure from Weitemeyer and Constable, 2010. Diagram of the Vulcan Triaxial electric field receiver, a constant offset deep tow system

Developments in both instrumentation and computational power have led to much advancement that have led to discoveries and insights about the subsurface. One of these advancements has been the development of towed EM acquisition systems, in contrast to the stationary receivers used in the past.
The first theoretical paper describing controlled source electromagnetic exploration in shallow water was by Peter Bannister in the sixties (Bannister 1968).
More recently there has been interest in improving shallow water exploration technologies for geotechnical, energy and research purposes (Evans et al., 2009, Andreis and MacGregor, 2007).
Shallow water compared to deep water it has its own set of logistical and survey challenges from surf, near shore currents, increased fishing activity, as well as piloting ships into areas with shallow draft. Besides logistical challenges, correctly modelling the airwave in shallow waters cannot be overlooked.
Mapping the porosity of near shore sediments is important for understanding continental shelf processes and hydrogeology. Some previous experiments have floated commercially available terrestrial equipment (Greenwood et al. 2006) in shallow lagoonal environments. The Geologic Survey of Canada has a towed system that is dragged on the sea floor as described in Evans et al.,1999 where up to 40m offsets were recorded, having sensitivity to the upper 20m.
A short offset bottom towed system has been used to study groundwater interactions and geology offshore of Wrightsville Beach, NC (Evans and Lizarralde, 2011). Many of these studies have used

a Geonics EM31 or EM3 (http://www.geonics.com/) transmitter with offsets up to 40m limiting these studies to shallow depths of investigation.
A bottom dragged magnetic source system developed at Woods Hole Oceanographic Institution, based on the Canadian system, has some logistical and data collection advantages compared to previous studies with Geonics equipment, but still can only image the top 20---30m (Evans, 2007).
The Scripps Porpoise system is a towed electromagnetic source and receiver that can be used with or without seafloor instruments.
The towed system consists of one horizontal electric dipole (HED) transmitter and 4 receivers spaced every 250m for offsets up to 1km.

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Alexander Bahr, Hydromea

Seabed monitoring using swarms of unmanned vehicles

Seabed mapping operations, be they for the creation of bathymetry maps, sub-bottom profiling or the detection of unexploded ordnance (UXO) require a sensor to be passed in closed proximity to the area which is to be mapped. As the vessel moves forward its sensors typically cover a band of the seabed. The width of this band, the swathe width, highly depends on the type of the sensor. Bathymetry sonars flying at high altitude reach swath widths of several kilometers while high-sensitivity magnetometers for UXO mapping only reach a few meters. The area that can be covered by a single mapping vehicle in a given time is thus highly dependent on the sensor's swath width as well as the speed with which the sensor can be moved while still being able to provide sufficient resolution. In most applications the maximum forward speed of the sensor and not the maximum speed of the survey vessel is the limiting factor for the latter. Swath width and maximum sensor speed are then the two key factors determining the time it takes to survey a given area and, combined with the daily operational cost of the survey vessel, the total cost of the seabed survey.

While swath width and maximum forward speed have been improved in recent years, these improvements remained incremental. In order to significantly improve survey speeds and lower the cost per km^2 mapped it is necessary to drive the mapping sensors with unmanned platforms (Autonomous Underwater Vehicles AUVs or Autonomous Surface Vehicles ASVs) with significant gains being possible by deploying swarms of AUVs and ASVs. Having multiple unmanned platforms mapping an area would not only increase the survey speed as these platforms would be mapping in parallel, but it would also significantly drive down the survey cost as the number of expensive assets (ships, etc.) and personnel deployed would be small compared to the number of operating mapping platforms.

Equipping AUVs with mapping sensors, specifically high-resolution bathymetry sonars, has been industry practice for the past 20 years. The goal behind using an autonomous platform though was to get a bathymetry sonar closer to the sea bottom compared to a vessel-based sonar and thereby increase the mapping resolution. This type of operation however required a large vessel to shadow the surveying AUV. While the move to an autonomous platform thus provided a significant increase of resolution (at the expense of the swath width) it did not lower the survey cost. Surveys where unmanned vessels were operating without a support ship or at least several vessels were operating using a single support ship, have to date been confined to trial cases. This was originally due to the low availability and reliability of autonomous platforms.

With availability and reliability having significantly improved in the past years, the main limiting factor to swarm operations today are the difficulties of communication and navigation underwater. While ASVs, which can rely on GPS for navigation and high-speed radio for communication, the absence of both underwater provides a significant challenge to AUV swarms. The short range (typically only a few kilometers) of acoustic modems, used for underwater communications, and ultra-short baseline transceivers, used for underwater navigation limit the operating radius of a potential AUV swarm to a few kilometers around a mother-ship.

Another limiting factor is the typically large size and weight of AUVs. This limits the number of vehicles which can be deployed at any given time due to the time and space needed to operate large launch and recovery systems (LARS) and the footprint of each vehicle on the deck.

Hydromea has been developing several pieces of technology and software which circumvent or overcome these limitations and make the deployments of large swarms with a small group of operators possible. By relying only on other members of the swarm for navigation information and short-range underwater communication, the AUVs can operate without or far away from a mother-ship. Additionally, by aggressively reducing the size and price of the individual vehicles an AUV swarm becomes affordable and can be rapidly deployed without a LARS.

The largest benefit of operating AUV swarms will be in applications where the mapping sensor used is small and affordable enough to fit on a large number of small, low-cost AUVs and has a small swath width which drives up the survey cost in a conventional scenario where a single sensor is tied to a single survey vessel. Typical examples of these applications are photogrammetric seabed mapping (Figure 1) where a single camera shot can only cover a few m^2 and UXO mapping with magnetometers which only have a detection range of a few meters. Other applications which are very suitable for swarm-based mapping are passive-acoustic monitoring or seep detection.

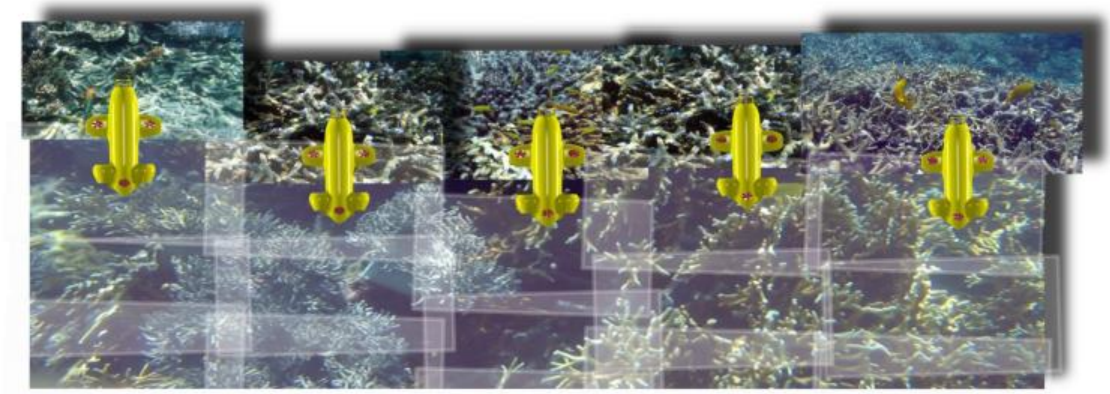

Figure 1: Swarm of Hydromea's VERTEX AUVs creating a photo mosaic of the sea floor