In: Geomatic Solutions For Coastal Environments
Editors: Mohamed Maanan and Marc Robin, pp.
ISBN 978-1-61668-140-1

Chapter 5

ACOUSTIC IMAGERY FOR BENTHIC HABITATS MAPPING AND MONITORING

Jérôme Fournier(1), Agnès Baltzer(2), Laurent Godet(1), and Andrea Panizza (3)
1.CNRS, UMR 7208 BOREA, CRESCO 38 rue du Port Blanc, 35800 Dinard, France
2. Université de Caen, UMR 6143 M2C, 2-4 rue des tilleuls, 14000 Caen cedex, France
3. MNHN, CRESCO 38 rue du Port Blanc, 35800 Dinard, France

ABSTRACT

Some shallow subtidal marine benthic habitats cannot be well mapped using classical remote sensing techniques such as satellite imagery or aerial photographs. Conversely, sidescan sonar is a very useful tool for mapping subtidal benthic features and monitoring some threatened habitats over small or large areas. Despite the increasing use of multibeam technology in benthic habitat mapping, sidescan sonar is efficient in detecting small-scale features in coastal environments, such as *Zostera marina* beds, *Lanice conchilega* and *Serpula vermicularis* reefs or large-scale features such as maerl red marine algae *Lithothamnium calcareum* beds. Sidescan sonar is a method of underwater imaging using beams of acoustic energy transmitted out to each side of the towfish and across the seafloor. The imagery is a reflection of the acoustic energy that is backscattered from the seafloor and is displayed in different levels of grey. The differences in backscattering are determined by the geometry of the sensor-target system, the angle of incidence of the beam, the physical characteristics of the surface and the intrinsic nature of the surface (composition, density, relative importance of volume *vs* surface diffusion/scattering for the selected frequency (100-500 kHz). Highly fragmented habitats could clearly be detected using sidescan sonar by interpretating of their acoustic facies. The aim of this chapter is to describe the different techniques used in the geoprocessing of acoustic imagery for benthic habitats mapping and monitoring from a conservation perspective.

INTRODUCTION

Mapping subtidal coastal benthic habitats is essential for monitoring and preserving coastal areas. In this context, adapted methods allowing long-term monitoring are required. From a scientific perspective, seafloor maps are the basis of both pattern and process assessments. From a management and/or conservation perspective, the increasing marine space and resource consumption raises an urgent need for identifying the highest-conservation stake places and the most perturbed areas. The current context of global changes is leading to new goals in seafloor mapping. Few long-term monitoring methods exist in the marine environment. They concern usually structured habitats for which the long-term spatio-temporal dynamics can be monitored by remote sensing methods including acoustic imagery in the deepest areas of the coasts. The study of the dynamics of such habitats is very useful as potential ecological indicators (e.g. *Zostera* beds). The new goal is therefore a shift from the sole seafloors maps of a few set of habitats to a long-term monitoring of a large number of habitats (Kenny et al., 2003 ; Malthus and Mumby, 2003 ; Pratson and Edwards, 1996), especially human-impacted habitats. Various methods have been used to map benthic macrofauna and/or sediment along regular grids with core sampler or grab from oceanographic ships. The habitats are statistically determined *a posteriori* according to different methods that clustered the similar stations based on their physical and biological characteristics. Other methods can be used to map shallow subtidal marine benthic habitats such as remote sensing techniques (satellite imagery, aerial photographs and scuba diving methods according to the scale of analysis) (Degraer et al., 2008; Pasqualini et al., 2000). However, Sidescan sonar alone is the only very useful and adapted tool for mapping subtidal benthic habitats and monitoring certain threatened habitats over large areas with accurate results (Freitas et al., 2003 ; Kendall et al., 2005 ; McRea et al., 1999 ; Pasqualini et al., 1998 ; Sauriau et al., 1998 ; Siljeström et al., 1995a). Despite the increasing use of multibeam technology in benthic habitat mapping (the use of this technology remains expensive) (Clarke et al., 1996 : Kostylev et al., 2001), sidescan sonar is efficient in detecting small-scale features in coastal environments, such as *Zostera marina* beds (Komatsu et al., 2003; Pasqualini et al., 2000; Piazzi et al., 2000; Siljelström et al., 1995b), *Lanice conchilega* (Degraer et al., 2008) or *Serpula vermicularis* reefs (Moore et al., 1998, 2009; Poloczanska et al., 2004) or large-scale features such as maerl red marine algae *Lithothamnium corallioides*/*Phymatholithon calcareum* beds (Brown et al., 2002, 2004, 2005; Forster-Smith et al., 2004). The aim of this chapter is to show some different techniques used in the geoprocessing of acoustic imagery. The first part will show the technical aspects of the acoustic imagery, the second part will show an application in the use of sidescan sonar for serpulid reefs mapping and the third part will show how this tool is useful for the monitoring of seagrass meadows.

1. SIDESCAN SONAR IMAGERY AND BOOMER PROFILES

Sidescan sonar is a method of underwater imaging using beams of acoustic energy transmitted out to each side of the towfish and across the seafloor (Blondel and Murton, 1997). The imagery is a reflection of the acoustic energy that is backscattered from the seafloor and is displayed in different levels of grey. The differences in backscattering are determined by the geometry of the sensor-target system, the angle of incidence of the beam, the physical characteristics of the surface and the intrinsic nature of the surface (composition, density, relative importance of volume *vs* surface diffusion/scattering for the selected frequency (100-500 kHz). Certain frequencies work better than others, high frequencies such as 500 kHz give good resolution (<10 cm) but the acoustic energy only travels a short distance limiting scan range to about 100 m per channel. Lower frequencies such as 100 kHz give lower resolution but the distance that the energy travels is greatly improved being typically up to 300m range per channel. Highly fragmented habitats could clearly be detected using sidescan sonar by interpretating their acoustic facies (Cochrane and Lafferty, 2002: Kennish et al., 2004 ; Miller et al., 1991).

1.1. Acoustic Data Acquisition

Geophysical surveys in marine areas rely on the propagation analysis of an acoustic signal. The acoustic signal assimilated to an acoustic “ray” is emitted by an artificial “source”. The reflection of this ray on different interfaces will be represented by seismic reflectors. There is a reflection of the ray only when there is a difference in the impedance “Z” of successive layers; with $Z = D*v$ where v is the sound velocity characteristic of the layer and D is the density of this layer. For example, if Z1 is the impedance of the upper layer (the water column) and Z2 is the impedance of the above layer (seafloor sediments), a reflector will be generated at the interface between the water and the sediment, thus at the seafloor bottom.

The frequency of the emitted signal will condition the depth of the signal propagation (the signal penetration) and the resolution power. Low frequency waves (from 10 to 100 Hz) will allow the acoustic signal to cross the sediment cover to a depth of a few kilometres, giving an idea of the internal geometry of the morphological structures, but does not allow the obtention of a good resolution (i.e. the possibility of discriminating between 2 successive layers). For example, the oil industry uses “conventional seismic”, which provide a seismic profile section on a thickness of 3 to 5 km but with low resolution (around ten metres).

1.2. The Boomer IKB Seistec

In contrast, the seismic tools used to prospect the coastal areas are characterised by a “Very High Resolution” based on a high frequency (1 to 10 kHz) which is necessary to obtain a high resolution (<1m). The IKB Boomer Seistec is one of these recent VHR Boomer (Figure 1).

The Seistec Boomer System (IKB Ltd) is used to record sub-bottom profile data in both deep (130 m of water depth) and shallow (5 m of water depth) water. The system has a frequency range from 1 to 10 kHz and a pulse duration ranging from 75 to 250 m at a power of 150 J. The system is towed at a speed of 3.5 knots and fires at a rate of 2 shots per second.

The system is able to reach a spatial resolution of 25 cm, with a penetration up to 100m in soft sediment and 200 m in deep water soft sediments.

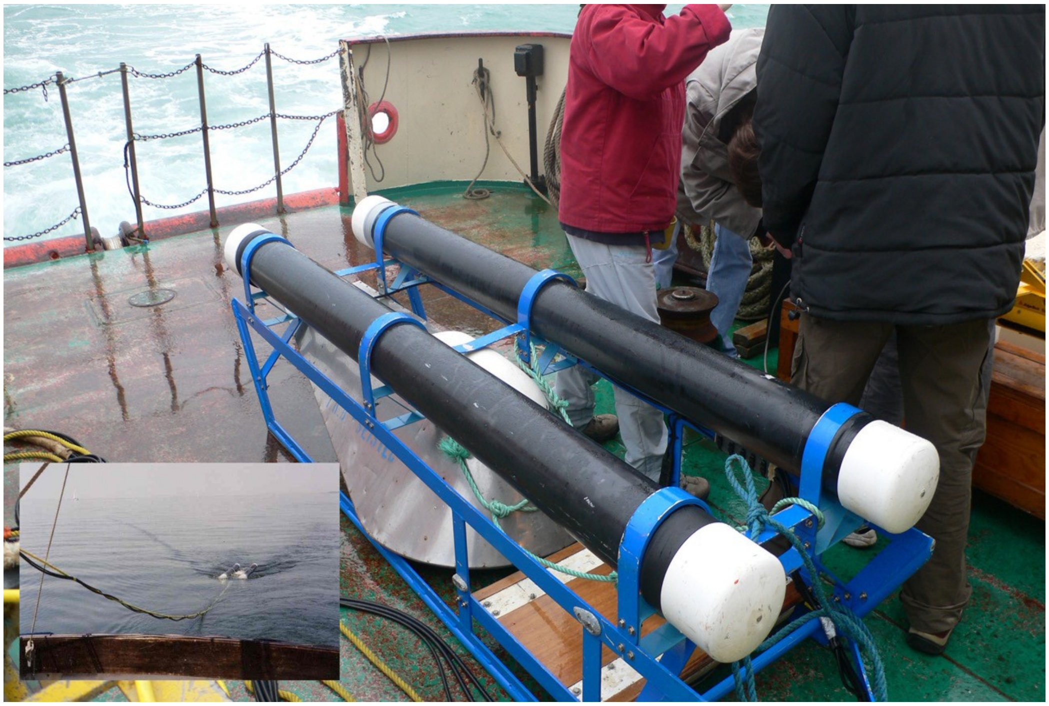

Figure 1. Photograph of the Boomer IKB Seistec aboard the oceanographic vessel « *Côte d'Aquitaine* » CNRS, normand-breton Gulf, France, 2007.

In the following example about the monitoring of the distribution of a reef-building tubeworm in a Scottish loch, 34 profiles, covering 60 km, were acquired in the loch with an average penetration of 50 m except in some areas where gas occurrence prevented any signal penetration. Two examples of profiles are shown in figure 6. The data is recorded using an Elics-Delph acquisition system with positioning obtained by d-GPS. The Elics-Delph system is used for subsequent processing and interpretation of the data.

1.3. The Sidescan Sonar Edgetech 272 TD

The sidescan sonar is characterised by two very high frequencies: it could be used either at 100 kHz or at 475 kHz (Figure 2). It provides an "acoustic image" of the sea floor similar to a black and white photograph. It is a very powerful tool to delimit and map areas of different acoustic facies and to identify different sedimentary morphologies such as dunes, sand-waves, ripples or biological features likes seagrass meadows, reefs and to understand their evolution throughout the time scale (Chavez, 1986).

Due to its high frequency, the signal penetration is under five centimetres: it is possible to detect anchor chains buried under a thin sand cover at 100 kHz but not when using a higher frequency. This is the reason why the sidescan sonar is usually towed with a 100 kHz frequency at around 10 m height above the sea floor. This configuration gives the possibility to acquire an image of 100 m width on each side (lateral) with a horizontal resolution of 30 cm.

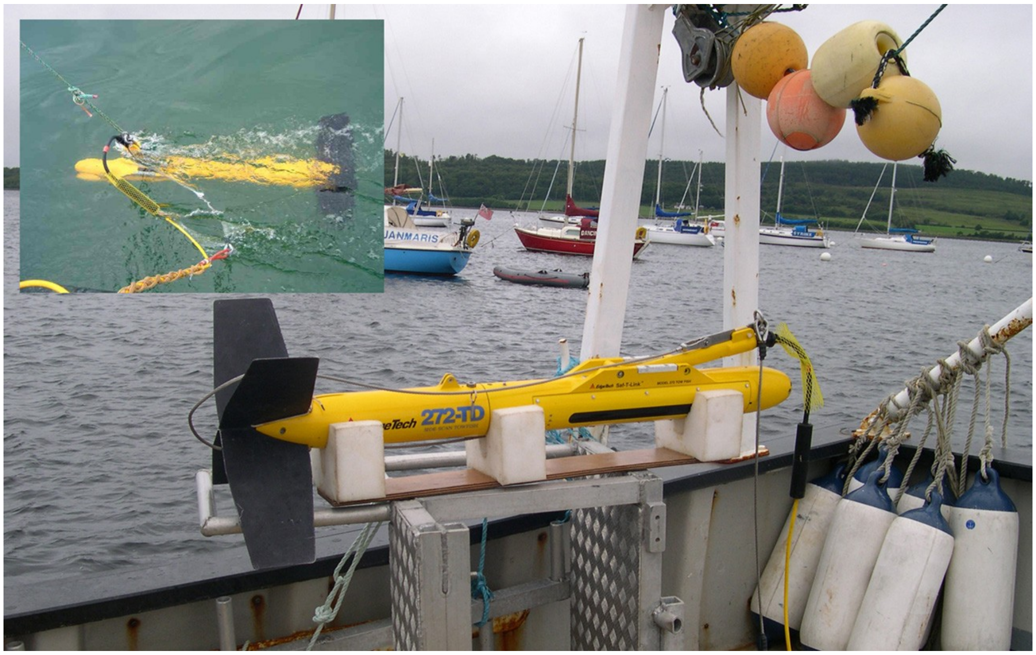

Figure 2. Photograph of the sidescan sonar EdgeTech 272 TD abord the oceanographic trawler « *Serpula* » Heriot-Watt University, Loc'h Creran, Scotland, 2004.

The software ISIS Sonar is used for data acquisition, together with the d-GPS position (Trimble Pathfinder Pro XRS). To build mosaics, which are composed of several joined images, we use the ISIS Sonar and the Delph Map systems.

The resulting backscattered image depends on 3 factors:

1) the seafloor nature (the roughness of the bottom): combination between sediment and fauna and flora. A mud cover will appear in light grey or white and coarse sand will appear in dark grey;
2) the topography of the seafloor, especially the slopes morphology will appear as a dark limit;
3) the compaction state of the sediment linked with the interstitial water pressure, which could give a light backscattered image for unconsolidated coarse sand.

As it is an undirect prospection tool, it is necessary to obtain the “ground truth” by sampling the seafloor sediment (and fauna or flora) via Shipek or surface coring systems, or by scuba-diving observations (Figure 3). Figure 4 gives an example of the complexity of a sidescan sonar image. The seagrass meadow is characterised by a high acoustic facies backscatter, giving a dark (almost dark grey) features to the figure. We observe white or light grey band and gaps which correspond to fine sand, making the transition to a grey acoustic facies assimilated to coarse sand with ripples in the low part of the image. In this last facies, it is possible to see numerous ripples when zooming into the image.

Figure 3. View of the Shipek corer and close-up of the contents (maerl).

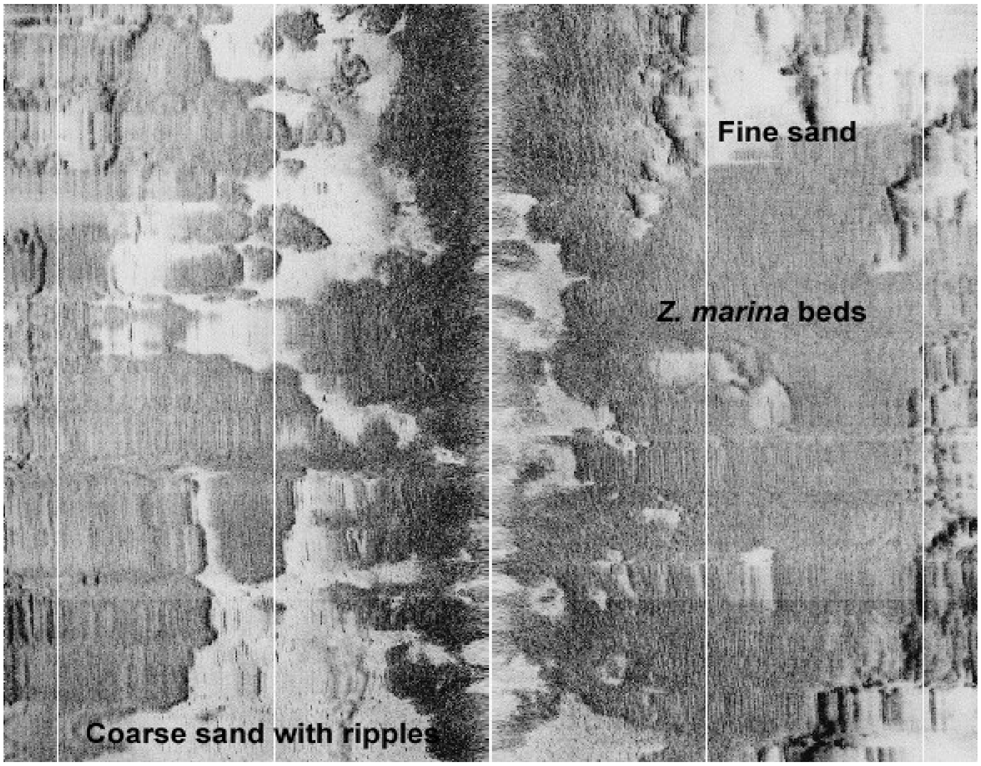

Figure 4. Acoustic patterns of *Zostera marina* beds, and two sandy bottoms in a channel of the Chausey archipelago.

2. MAPPING THE DISTRIBUTION OF THE REEF-BUILDING TUBEWORM *SERPULA VERMICULARIS*

Loch Creran is a sea loch of 13.3 km² with a mean depth of 13.4 m. This loch is divided into a large lower basin and a small upper basin separated by a sill with a mean depth of 1 m (Figure 5). There is a further 4 m sill at the narrow loch entrance creating a 4 knot spring tide currents at the mouth. Loch Creran is used for aquaculture (e.g. salmon), fishing, yachting and effluent disposal. Salmon cages and oyster beds are present at several sites in the western half of the main basin. Salmon farming causes organic enrichment of the sediment in the immediate vicinity of the cages and is the actual major source of pollution.

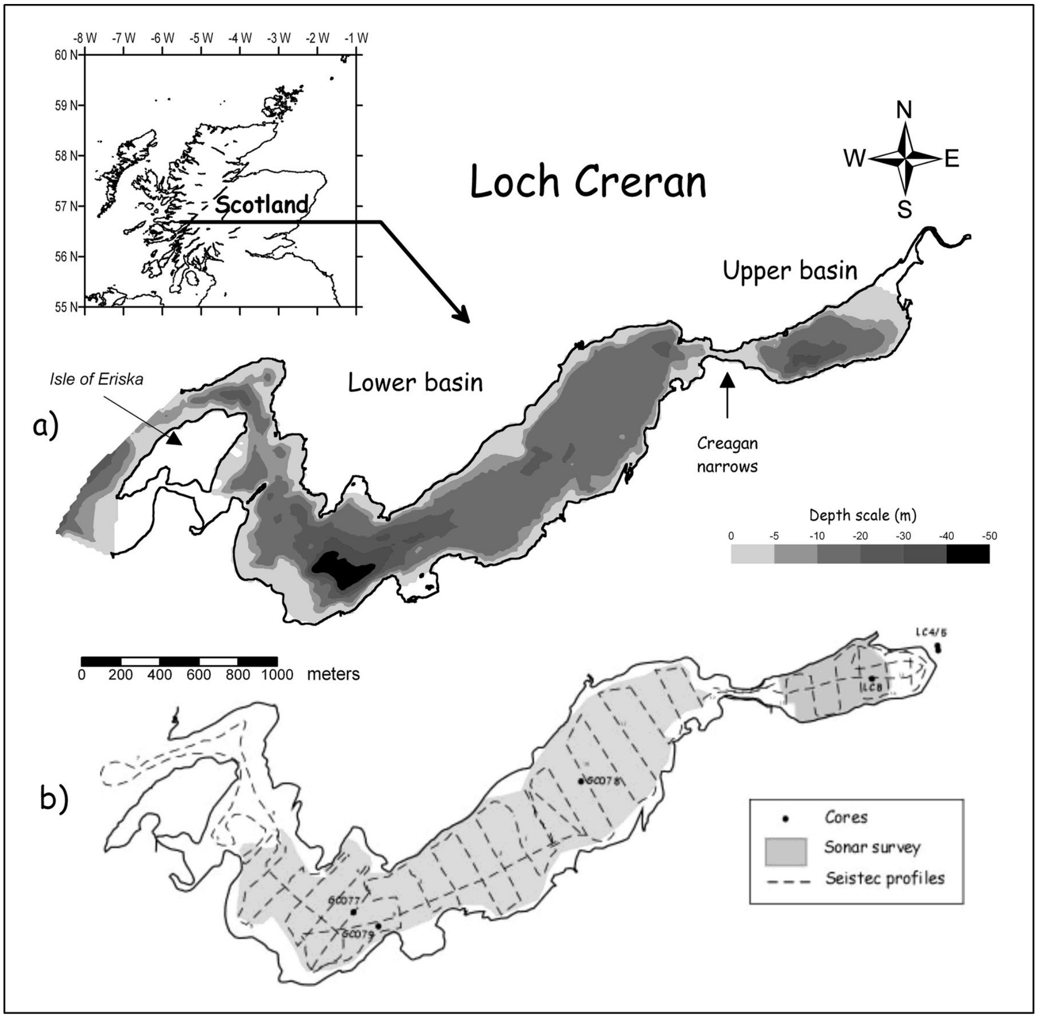

Figure 5. Location map of the study area. a) Bathymetry of the Loch Creran, b) Indication of the area covered by sidescan sonar mosaic and location of the cores.

2.1. Presentation of the Reefs of *Serpula vermicularis* of the Loch Creran (Scotland)

Serpula vermicularis is mainly distributed around the North-West coasts of the United Kingdom and Ireland with scattered records in the Channel (including the French coasts). One of the best known locations of *S. vermicularis* reefs is located in the Loch Creran, Scotland. This species is known to mainly occur in some locations in Ireland (Bosence, 1973) and Scotland (Moore et al., 1998; Poloczanska et al., 2004). The tubes can be found attached to hard substrata such as rocky platforms or outcrops, stones and bivalve shells from the sublittoral zone to depths of up to 200 m. In very sheltered areas, this tubeworm constructs extensive aggregations of calcareous tubes (e.g. several hundred square metres), attaining 30 cm in height and 3 m in width. Serpulid reefs provide a habitat for an abundant and rich associated fauna but no detailed community studies have been published yet. The hard substrate provided by the aggregated tubes reef-like structure is colonised by a sessile macrofaunal assemblage dominated by sponges, ascidians, bryozoans, spirorbids etc. This fauna is attractive for several consumers like amphipods, crabs, echinoderms, and fish which use these reefs for feeding, refuge and egg-laying. The presence of *S. vermicularis* reefs in the Loch Creran explain why this Loch is a Marine Consultation Area of the Scottish Natural Heritage, the first step before the creation of a marine reserve. This example explored the utility of sidescan sonar in mapping reef distribution, which is necessary in view of the threat from aquaculture, bottom fishing and mooring. This information will be used to identify the main threats to the reefs, after which appropriate strategies for conservation management can be determined.

2.2. Methodology and Data Set

The Loch Creran was prospected during two surveys carried out in August 2002 and June 2004 with a sidescan sonar. It was possible to systematically cover the whole subtidal area (9.2 km²) in 3 days, identifying details with a 10 cm resolution. These surveys operated with an Edgetech 272 TD sidescan sonar towed at a 3.5 knots speed from the 'Serpula', the boat of Heriot Watt University, Edinburgh. Thus 80 km of sonar profiles were collected to ensure a complete mosaic for acoustic facies interpretation. The sidescan sonar was used with a 100 kHz frequency, tracked around 10 m above the seafloor, which allows a coverage band of 200 m width. All the data were recorded with an Elics-Delph® and Isis Sonar® acquisition systems, and d-GPS (with a positional accuracy of 5 metres) positions were directly fed into the systems. Five cores were acquired to calibrate the acoustic facies, 3 sampled by a Kullenberg system (GC077, GC078, GC079) and two by a Russian core (LC8 and LC4/5), completed by scuba-diving observations.

Using the softwares Isis Sonar® and DelphMap®, a mosaic was constructed from all sonar tracks (Figure 6). Moore et al. (1998) provided the bathymetric range of 1-13 m for Loch Creran reefs, which allowed us to select the potential region of presence. To perform a supervised classification using the maximum likelihood criterion, training areas were defined around known areas of reefs. Spatial analysis and Grid extensions of the ArcGIS® software were used to map serpulid reef areas. A photo-interpretation was required to generalise the targeted areas (Figure 7).

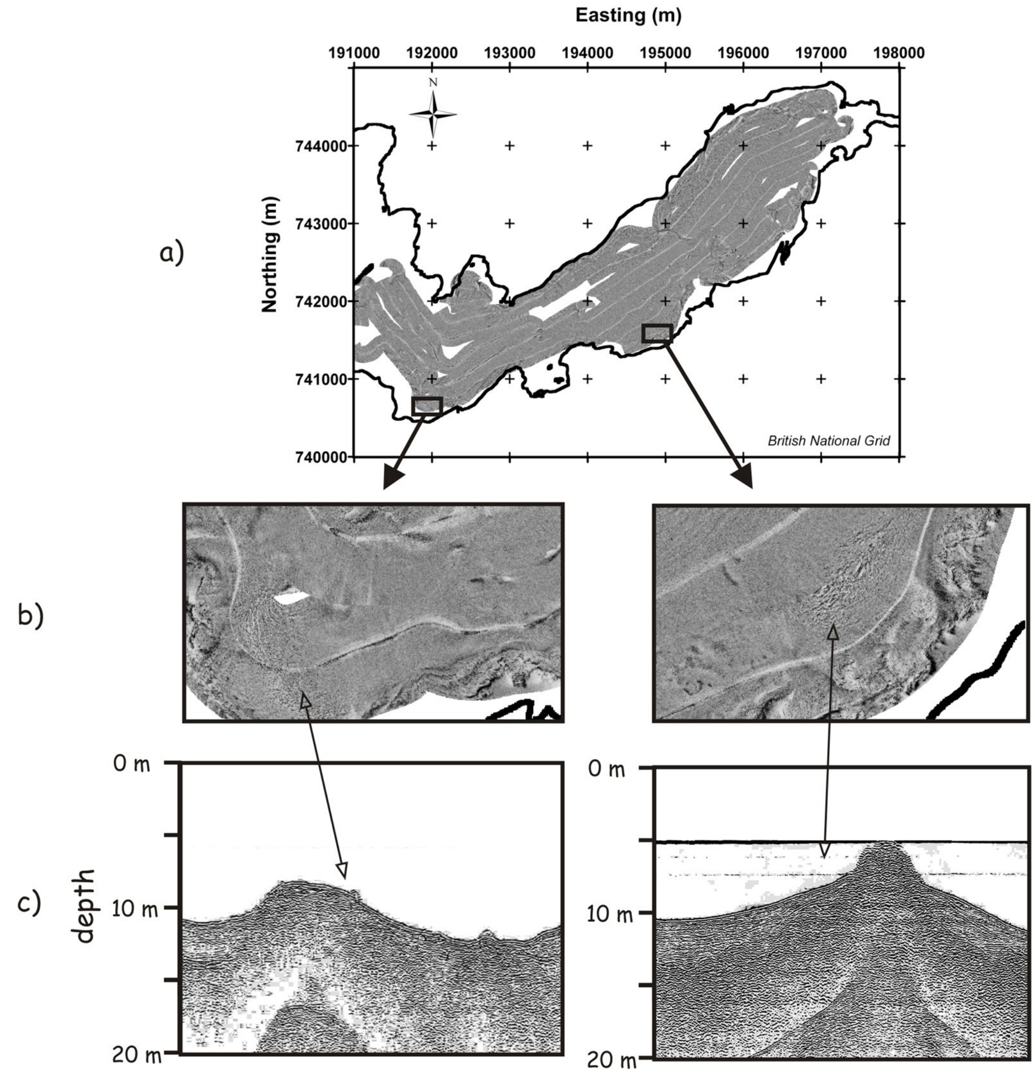

Figure 6. Acoustic patterns of *Serpula vermicularis* reefs in the lower basin of Loch Creran. a) Sidescan sonar mosaic of the lower basin, b) Close-up of the sidescan sonar image, c) Seismic profiles of the reefs.

2.3. Results and Discussion

Figure 8 is showing a typical example of sonar data acquired in the upper basin. The area corresponds to a specific sonar acoustic facies: black spots (holes) and sediment ripples and irregularities. The diving carried out by the scientific divers confirmed the presence of a black mud with burrows of Norway lobsters, also known as scampi (*Nephrops norvegicus*).

Regions of the loch occupied by non-aggregated serpulid worm tubes, small aggregations and sparse reefs can be identified despite the resolution limits of the sonar equipment (Figure 9).

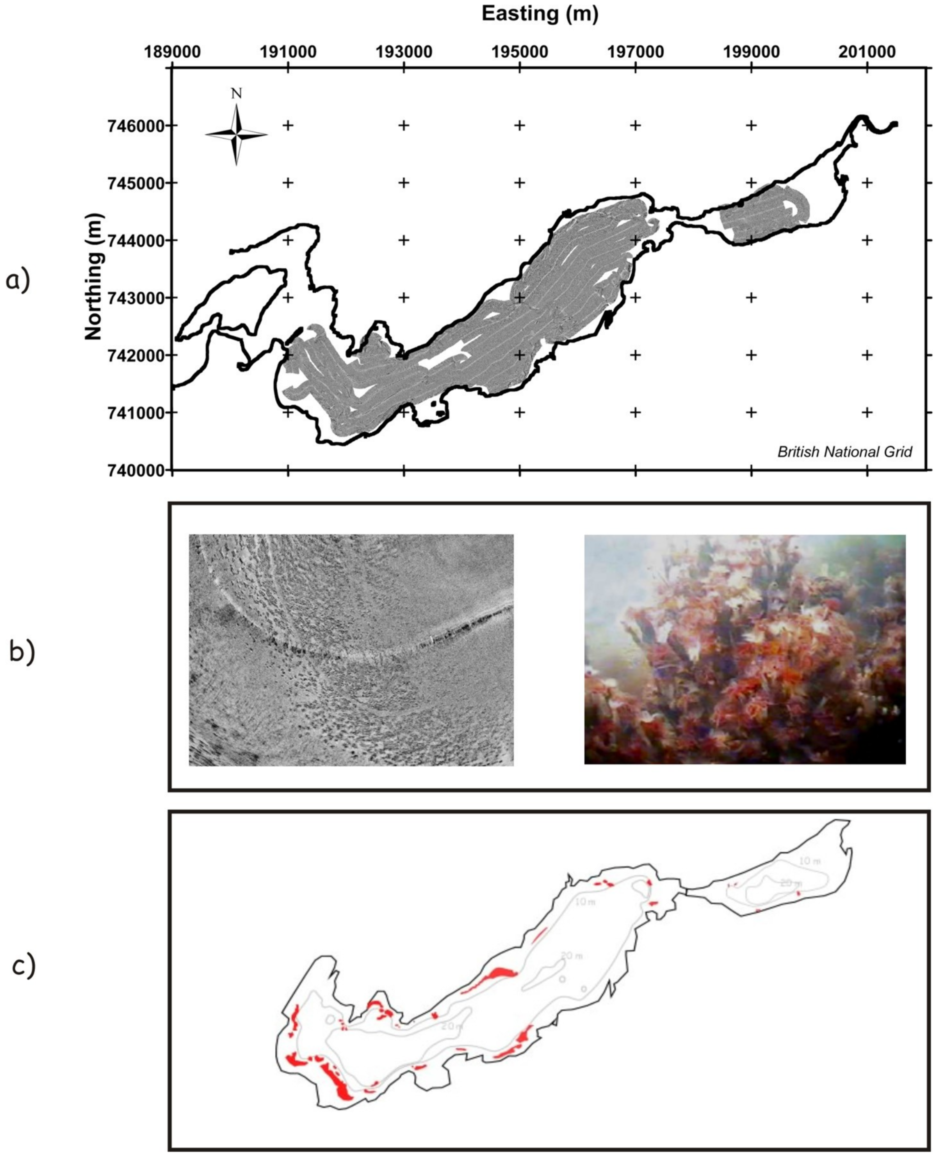

Figure 7. Detection of *Serpula vermicularis* facies in the Loch Creran. a) Sidescan sonar mosaic of the Loch Creran, b) Corresponding acoustic imagery and underwater observations, c) Reef distribution of *S. vermicularis* in the Loch Creran.

However, localised modification of reef cover, caused for instance by anthropogenic damage, can be easily delimited by sidescan sonar. The method facilitates the broadscale mapping of the major reef areas within the loch. It provides a faster approach to monitoring reef distribution than observational techniques such as drop-down video and diving, although such techniques are required for groundtruthing the sonar mapping. Sonar also aids in the identification of areas where quantitative monitoring of reefs is appropriate for conservation monitoring purposes (Moore et al., 2009).

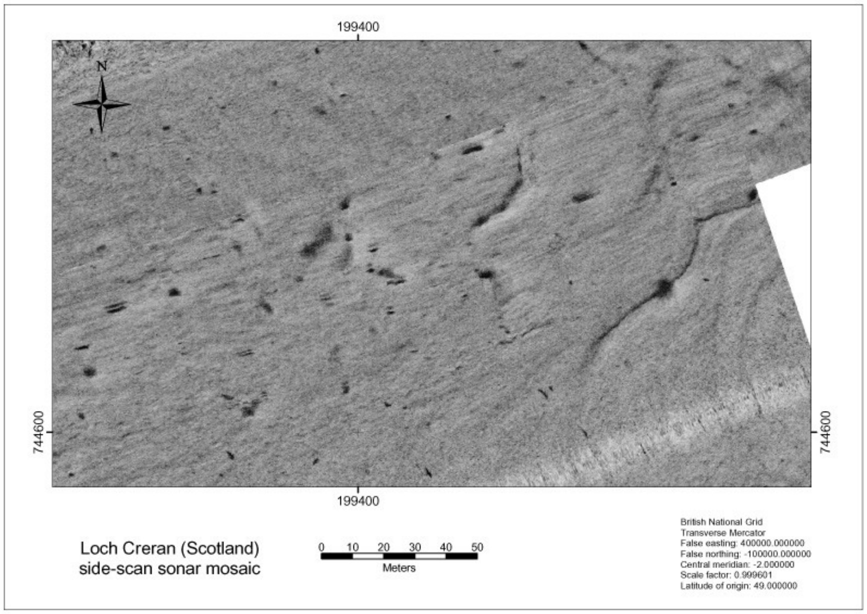

Figure 8. Detail of an acoustic image showing a Scampi/Norwegian lobsters facies (black patches are aggregated holes of *Nephrops norvegicus*) in the upper basin of Loch Creran.

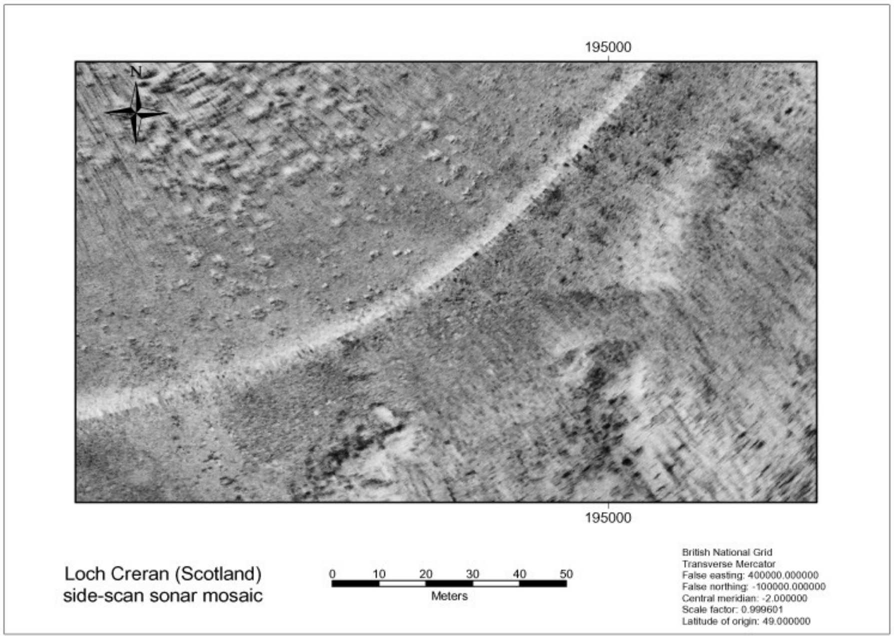

Figure 9. Detail of an acoustic image showing Serpulid facies (in the upper part of the image).

3. MONITORING THE DISTRIBUTION OF *ZOSTERA MARINA* BEDS

Zostera marina is a well distributed marine flowering plant species in the North Atlantic and forms extensive communities. This seagrass, also known as eelgrass, is found in shallow coastal areas typically on sheltered sandy substrata to a maximum depth of about 10 m. *Z. marina* grow in dense and extensive beds (meadows). The complex structure of these meadows contains a large number of sensitive biological systems that are extremely important to the coastal ecosystems. The beds create a productive habitat that provides shelter and food for a wide variety of plant and animal species. Seagrass beds are the main contributor to the biological diversity of the coasts because a very high number of species (eggs, juveniles and adults) colonise the whole meadows. The enclosed volume of water between the leaves (up to 1.8 m high) of the meadow plants contribute floating POM (Particulate Organic Matter) to the sediment and accumulate into the matrix of rhizomes. The dense root networks stabilize the substratum and reduce coastal erosion. Leaves produce high levels of oxygen (up to 17 $l/d^{-1}/m^{-2}$) and organic detritus when they fade in winter. Moreover, a great part of the seagrass biomass production is exported to the deeper water and becomes usable for the communities of invertebrate, fish and birds (geese and seaducks). Consequently, damage to the meadows influences the entire ecosystem. Several large *Zostera marina* beds are currently in expansion such as the beds from the Chausey archipelago (Godet et al., 2008) ; others are in a state of regression, due to anthropogenic coastal activities. The ecological importance and the vulnerability of this habitat therefore make them a priority for monitoring effort.

3.1. Presentation of the *Zostera marina* Meadows of North Brittany (France)

The meadows studied in this work are located in the Chausey archipelago and in the Bay of Lancieux (Figure 10). In these areas, the optimal habitat conditions of eelgrass correspond to shallow subtidal waters down to about 4 m depth. The eelgrass beds of Chausey and of the Bay of Lancieux are radically different. The eelgrass beds of Chausey archipelago correspond to numerous scattered patches (1 m^{-2} to up to 50 ha) whereas the beds in the bay of Lancieux correspond to a single patch that is more or less fragmented. The development of the *Z. marina* beds was particularly important between 1992 (178.2 ha) and 2002 (343.2 ha) in Chausey when the extent of the beds increased by 92% (Godet et al., 2008). The extension of the beds continued from 2002 to 2008, for the whole archipelago except an area where dredging activities have destroyed a part of the eelgrass bed. The situation of the eelgrass beds of the Bay of Lancieux is very different because of the remarkable spatial stability of the beds (approximately 60 ha since a score of years). It is the widest single seagrass beds of the coast of Saint-Malo. The *Z. marina* beds are located between the eastearn part of the island of Hébihens and the coast of Lancieux, the most sheltered area of the bay. However, the eelgrass beds are continuously finely scored due to fishing activities (e.g. bivalve dredging). They are modelled both by the swell and the tidal currents. For the purpose of detecting changes in the *Zostera* habitat, one of the most important parameter to monitor is the distribution and the extent of the *Zostera* coverage. When using sidescan sonar in these experimental areas (Lancieux, Chausey), it was possible to clearly differentiate between *Zostera* beds and sandy bottom and the beds and algae-covered rock.

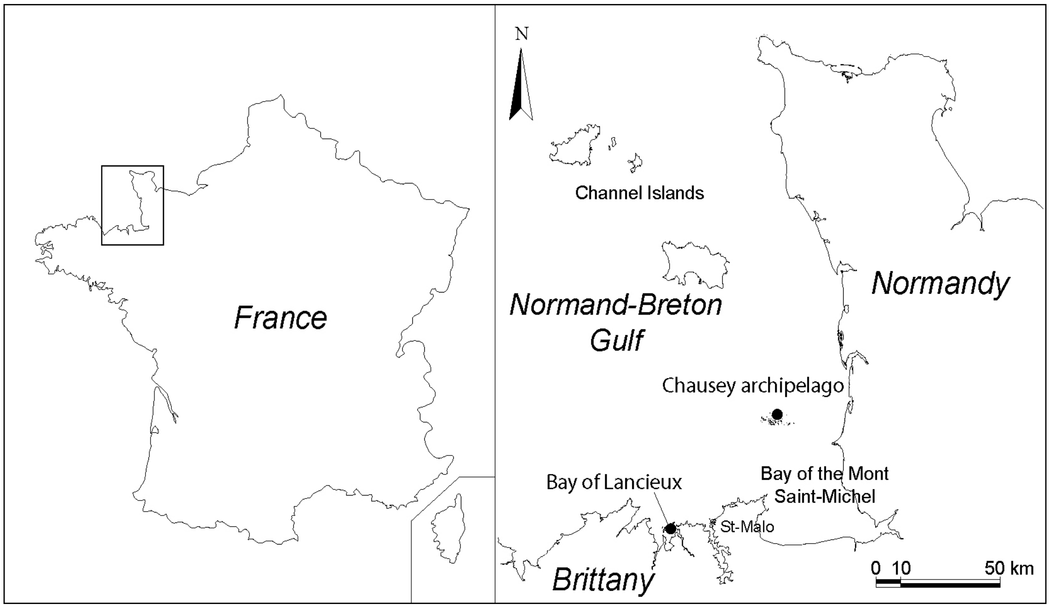

Figure 10. Location map of the Chausey archipelago and the Bay of Lancieux

3.2. Image Recording and Processing

The side-scan system used in this work is an Edge Tech 272 TD, which can emits simultaneously two beams, each with a different frequency (100 and 500 kHz). The *Zostera marina* vegetation are generally sufficiently large and extensive to be detected only with the 100 kHz band. For this present work we used a maximum slant range of 100 m per channel on each side of the towfish transducer. The pixel resolution was 50 cm. By using navigation and depth data from the boarding computer log system, several geometric corrections of the data are carried out automatically. This process eliminates the distortions caused by the movements of the sea due to the waves which disturb the speed of the boat and the slant of the beam. The system create isometric images and records the digital data on CD.

Image enhancement processes were then carried out to improve the interpretation and the identification of the features in the digital images. Several mosaics were constructed from all sonar tracks with Isis Sonar® and DelphMap® softwares. The mosaics were imported of the DelphMap platform and were processed by the ERmapper® software.

Some non-supervised classification based on the K-means algorithm and minimum-distance classifier give interesting results and help to map the outline of the seagrass beds.

3.3. Results and Discussion

The following images were selected to illustrate classic features and image geoprocessing.

Figure 11 is an extracted sub-scene corresponding to the main channel of the Chausey archipelago named “the Sund”.

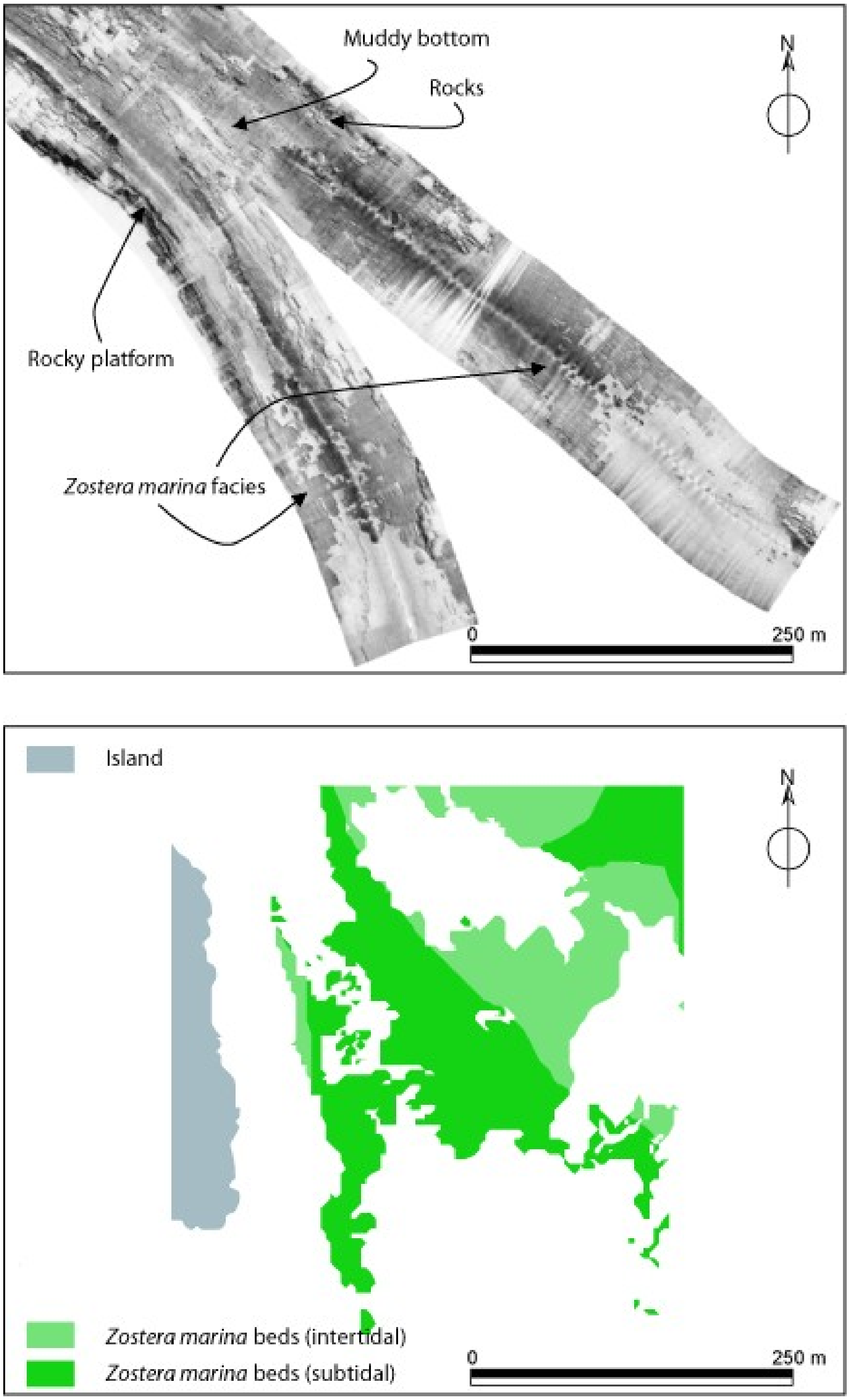

Figure 11. Location map of the sidescan sonar sub-scene mosaic in the 'Sund' of Chausey.

This image was acquired under excellent conditions. Without any image enhancement, it is possible to easily map the outline of the eelgrass beds, as shown in figure 11. The technique used is exactly the same one that is used for classical photo-interpretation.

Figure 12 shows a mosaic of a *Zostera marina* bed on a flat sandy bottom located in the Bay of Lancieux (North Brittany) (Fig 14 A). The image enhancement process differentiates well the cover and density of *Zostera* vegetation with tones of dark grey that contrast with the clear grey tones of the sediment (Fig 13, below) (Reed and Hussong, 1989). In this bay, the plants have long leaves (>1m) and a deep rhizome structure (25cm deep) that appears as a well-defined topographic feature. The spatial distribution pattern is defined as a "leopard peeling" which corresponds to circular spot cleared of vegetation. It is possible to identify the traces of dredging due to the scallop trawlers (Figure 13, upper image).

Firstly we applied an image enhancement for the best differentiation of the cover of *Zostera* from the sandy bottom (Figure 14 B). Then, we applied a transformation of the histogram (stretching) of the whole image (Figure 14 C) in order to improve the contrast of the image and eliminate the pixels corresponding to the sediment. A good result was given when we applied a non-supervised classification based on the K-means algorithm and minimum-distance classifier (Figure 14 D). This algorithm enhance only the dense areas of eelgrass, while the sparse vegetation is blurred. The image differentiate well between the vegetation (percentage of cover related to the density) with tones of red (pure pixels of *Zostera* vegetation) and yellow (mixed pixels of low density of *Zostera* vegetation and sediment) that contrast with the blue tones of the sandy bottom. We can note the noise in the image generated by the 100 kHz band. However, the definition of the meadow-structure is better than that of the 500 kHz image. The post-classified image is shown in the Figure 14 E where, green and blue tones correspond to *Zostera* vegetation and yellow tones to the sediment.

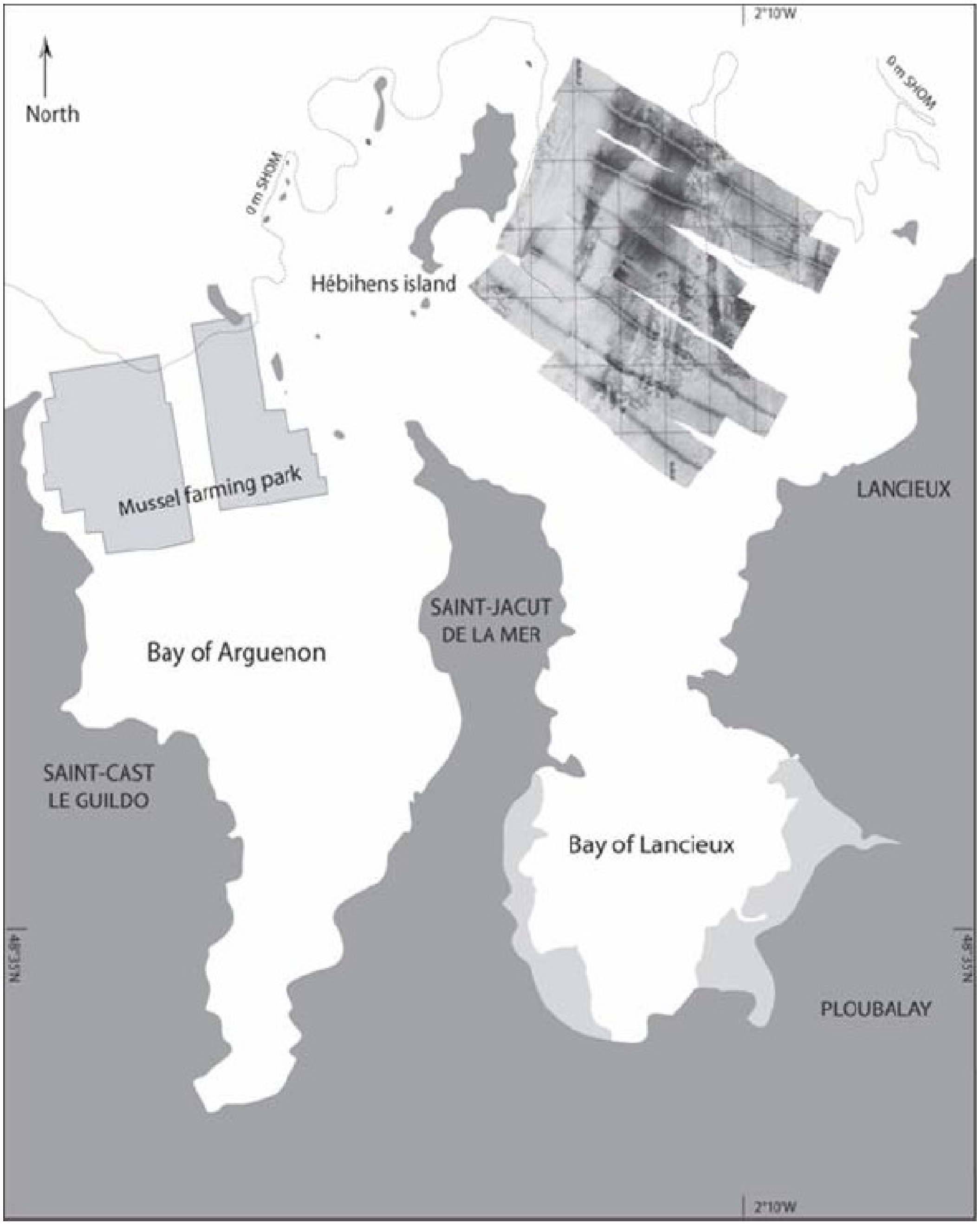

Figure 12. Sidescan sonar mosaic of the Bay of Lancieux.

This image allows a clear interpretation mainly due to the strong structure of the vegetation (leaves up to 1 m high). The Figure 15 show the final map of the *Zostera* beds of the Bay of Lancieux.

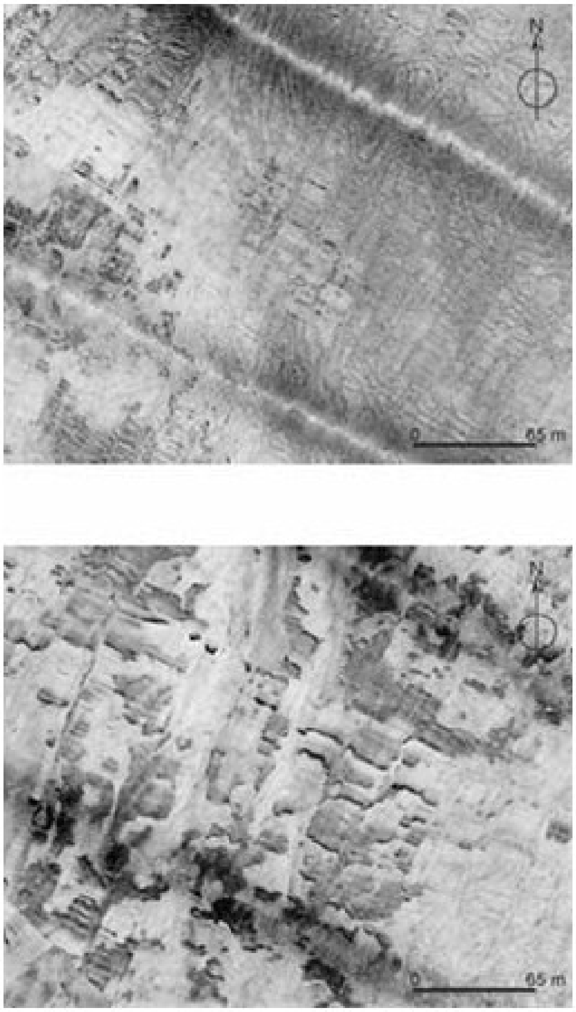

Figure 13. Zooms of the sidescan sonar image

CONCLUSION

This chapter demonstrated that sidescan sonar is an extremely valuable tool for studying, surveying, quickly mapping, monitoring and identifying submarine features such as Serpulid reefs or phanerogam meadows. It will become a powerful instrument for future cartographic purposes. Several processes (e.g. geometric corrections, noise reducing filters, unsupervised classification, image enhancement) made visual observation and interpretation by observers easier and more accurate. Although the 100 kHz images contained more noise, they gave more information than those given by the 500 kHz channel which are more specific to sedimentary studies. Underwater surveys that use sidescan sonar images are a cost-effective solution to the problem of monitoring shallow water benthic features in coastal areas.

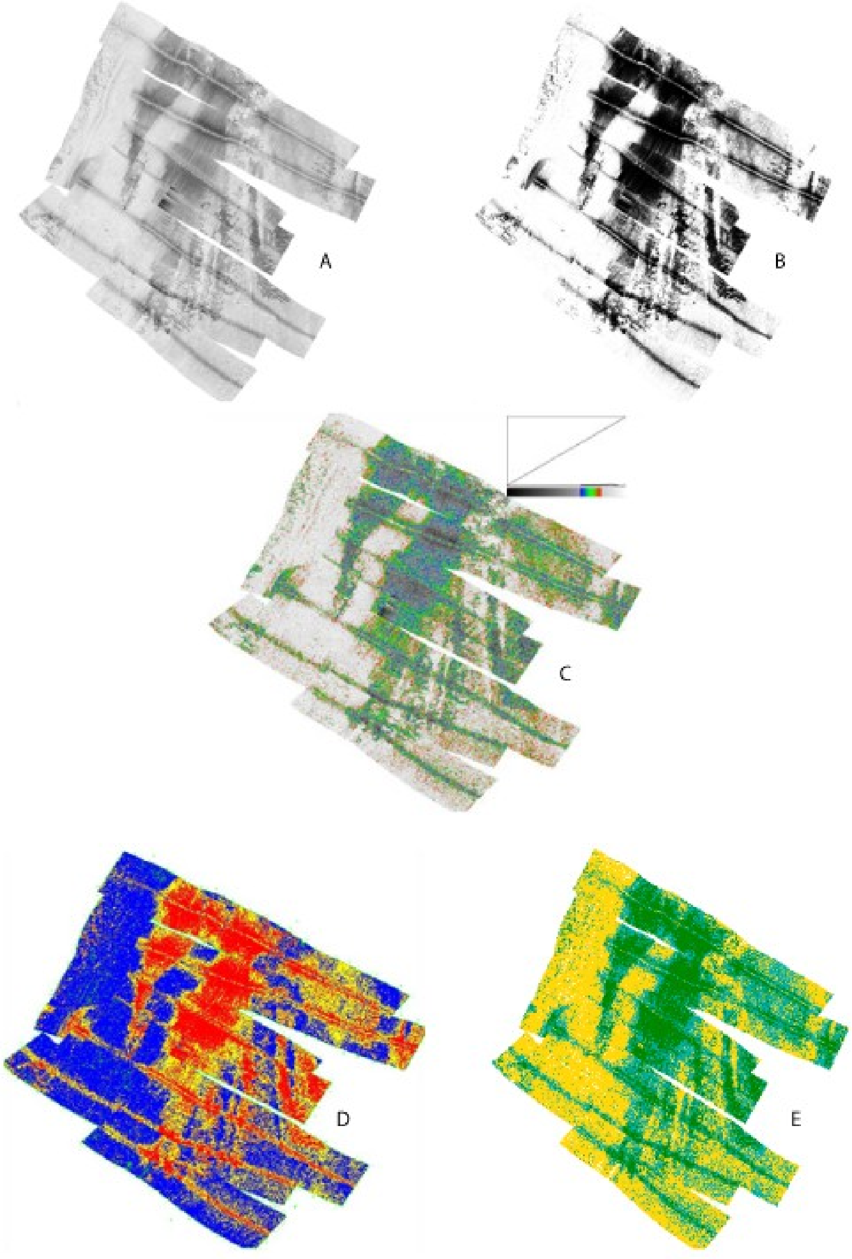

Figure 14. Steps of geoprocesses used in the sidescan sonar image of the Bay of Lancieux, a) sidescan sonar image, b) enhanced image, c) contrast equalization, d) non-supervised K-means algorithm, e) post-classified image

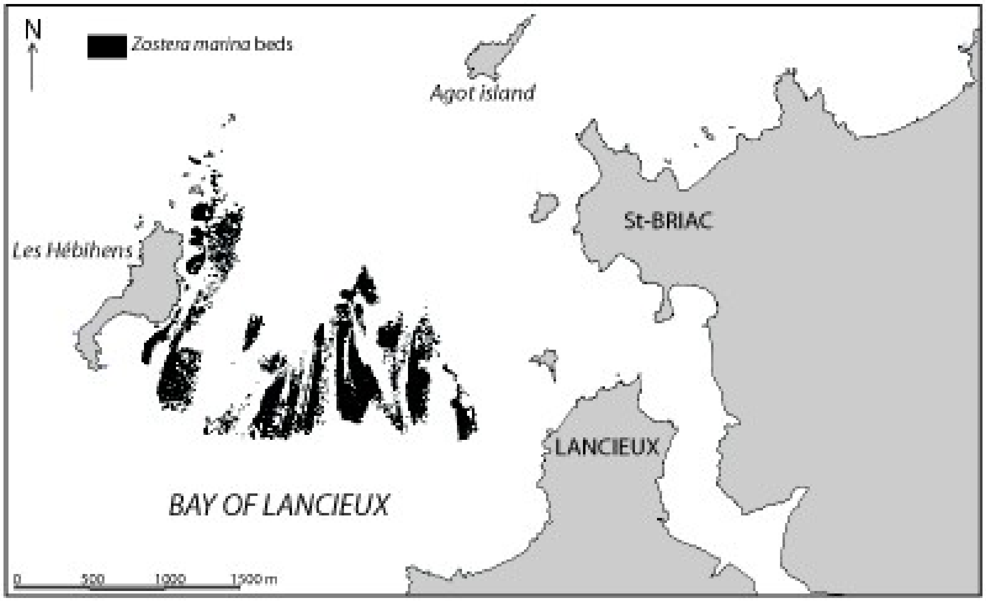

Figure 15. Map of the distribution of the *Zostera marin*a beds in the Bay of Lancieux.

ACKNOWLEDGEMENTS

We gratefully thank the following people for assistance with the fieldworks: Franck Lelong (CNRS, Caen), Dr C.G. Moore (Heriot-Watt University, Edinburgh), E. Poizot (Intechmer/CNAM, Cherbourg), Dr J.-M. Rousset (Ecole Centrale de Nantes), Dr A. Stepanian (Université de Basse-Normandie, Caen). We especially thank Amelia Curd (MNHN) for improving the English of this manuscript.

REFERENCES

Blondel, P., Murton, B.J. 1997. *Handbook of seafloor sonar imagery*. Chichester, UK: John Wiley and Sons/Praxis Publishing, 314 p.

Bosence, D.W.J. 1973. Recent serpulid reefs, Connemara, Eire. *Nature,* 242:40-41.

Brown, C.J., Cooper, K.M., Meadows, W.J., Limpenny, D.S., Rees, H.L. 2002. Small-scale mapping of sea-bed assemblages in the Eastern English Channel using sidescan sonar and remote sampling techniques. *Estuarine, Coastal and Shelf Science*, 54:263-278.

Brown, C.J., Hewer, A.J., Meadows, W.J., Limpenny, D.S., Cooper, K.M., Rees, H.L. 2004. Mapping seabed biotopes at Hastings Shingle Bank, eastern English Channel. Part 1. Assessment using sidescan sonar. *Journal of the Marine Biological Association of the United Kingdom*, 84:481-488.

Brown, C.J., Mitchell, A., Limpenny, D.S., Robertson, M.R., Service, M., Golding, N. 2005. Mapping seabed habitats in the Firth of Lorn off the west coast of Scotland: evaluation and comparison of habitat maps produced using acoustic ground-discrimination system, *RoxAnn*, and sidescan sonar. *ICES Journal of Marine Science*, 62:790-802.

Chavez, P.S. 1986. Processing techniques for digital sonar images from GLORIA. *Photogrammetric Engineering and Remote Sensing*, 52(8):1133-1145.

Clarke, J.H., Mayer, L.A., Wells, D.E. 1996. Shallow-water imaging multibeam sonars: a new tool for investigating seafloor processes in the coastal zone and on the continental shelf. *Marine Geophysical Researches*, 18:607-629.

Cochrane, G.R., Lafferty, K.D. 2002. Use of acoustic classification of sidescan sonar data for mapping benthic habitat in the Northern Channel Islands, California. *Continental Shelf Research*, 22:683-690.

Degraer, S., Moerkerke, G., Rabaut, M., Van Hoey, G., Du Four, I., Vincx, M., Henriet, J.-P., Van Lancker, V. 2008. Very-high resolution side-scan sonar mapping of biogenic reefs of the tube-worm *Lanice conchilega*. *Remote Sensing of Environment*, 112:3323-3328.

Foster-Smith, R.L., Brown, C.J., Meadows, W.J., White, W.H., Limpenny, D.S. 2004. Mapping seabed biotopes at two spatial scales in the eastern English Channel. Part 2. Comparison of two acoustic ground discrimination systems. *Journal of the Marine Biological Association of the United Kingdom*, 84:489-500.

Freitas, R., Rodrigues, A.M., Quintino, V. 2003. Benthic biotopes remote sensing using acoustics. *Journal of Experimental Marine Biology and Ecology*, 285-286:339-353.

Godet, L., Fournier, J., van Katwijk, M., Olivier, F., Le Mao, P., Retière, C. 2008. Before and after wasting disease in common eelgrass *Zostera marina* along the French Atlantic coasts: a general overview and first accurate mapping. *Diseases of Aquatic Organisms*, 79(3):249-255.

Kendall, M.S., Jensen, O.P., Alexander, C., Field, D., McFall, G., Bohne, R., Monaco, M.E. 2005. Benthic mapping using sonar, video transects, and an innovative approach to accuracy assessment: a characterization of bottom features in the Georgia Bight. *Journal of Coastal Research*, 21(6):1154-1165.

Kennish, M.J., Haag, S.M., Sakowicz, G.P., Tidd, R.A. 2004. Side-scan sonar imaging of subtidal benthic habitats in the Mullica River-Great estuarine system. *Journal of Coastal Research*, SI(45):227-240.

Kenny, A.J., Cato, I., Desprez, M., Fader, G., Schüttenhelm, R.T.E., Side, J. 2003. An overview of seabed-mapping technologies in the context of marine habitat classification. *ICES Journal of Marine Science*, 60:411-418.

Komatsu, T., Igarashi, C., Tatsukawa, K., Sultana, S., Matsuoka, Y., Harada, S. 2003. Use of multi-beam sonar to map seagrass beds in Otsuchi Bay on the Sanriku coast of Japan. *Aquatic Living Ressources*, 16:223-230.

Kostylev, V.E., Todd, B.J., Fader, G.B.J., Courtney, R.C., Cameron, G.D.M., Pickrill, R.A. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. *Marine Ecology Progress Series*, 219:121-137.

Malthus, T.J., Mumby, P.J. 2003. Remote sensing of the coastal zone: an overview and priorities for future research. *International Journal of Remote Sensing*, 24(13):2805-2815.

Mc Rea, J.E., Greene, H.G., O'Connell, V.M., Wakefiled, W.W. 1999. Mapping marine habitats with high resolution sidescan sonar. *Oceanologica Acta*, 22(6):679-686.

Miller, R.L., Swan, F.S., Cheng, C.F. 1991. Digital preprocessing techniques for GLORIA II sonar images. *Geo-Marine Letters*, 11:23-31.

Moore, C.G., Bates, C.R., Mair, J.M., Saunders, G.R., Harries, D.B., Lyndon, A.R. 2009. Mapping serpulid worm reefs (Polychaeta: Serpulidae) for conservation management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 19:226-236.

Moore, C.G., Saunders, G.R., Harries, D.B. 1998. The status and ecology of reefs of *Serpula vermicularis* L. (Polychaeta: Serpulidae) in Scotland. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 8:645-656.

Pasqualini, V., Pergent-Martini, C., Clabaut, P., Pergent, G. 1998. Mapping of *Posidonia oceanica* using aerial photographs and side scan sonar : application of the Island of Corsica. *Estuarine, Coastal and Shelf Science*, 47:359-367.

Pasqualini, V., Clabaut, P., Pergent, G., Benyoussef, L., Pergent-Martini, C. 2000. Contribution of side scan sonar to the management of Mediterranean littoral ecosystems. *International Journal of Remote Sensing*, 21(2):367-378.

Piazzi, L., Acunto, S., Cinelli, F. 2000. Mapping of *Posidonia oceanica* beds around Elba Island (western Mediterranean) with integration of direct and indirect methods. *Oceanologica Acta*, 23(3):339-346.

Poloczanska, E.S., Hughes, D.J., Burrows, M.T. 2004. Underwater television observations of *Serpula vermicularis* (L.) reefs and associated mobile fauna in Loch Creran, Scotland. *Estuarine, Coastal and Shelf Science,* 61:425-435.

Pratson, L.F., Edwards, M.H. 1996. Introduction to advances in seafloor mapping using side-scan sonar and multibeam bathymetry data. *Marine Geophysical Researches*, 18:601-605.

Reed, T.B. IV, Hussong, D. 1989. Digital image processing techniques for enhancement and classification of SeaMARC II Side Scan Sonar Imagery. *Journal of Geophysical Research*, 94(B6):7469-7490.

Sauriau, P.-G., Pichocki-Seyfried, C., Walker, P., De Montaudouin, X., Palud, C., Héral, M. 1998. *Crepidula fornicata* L. (Mollusca, Gastropoda) in the Marennes-Oléron Bay : side-scan sonar mapping of subtidal beds and stock assessment. *Oceanologica Acta*, 21(2):353-362.

Siljeström, P., Moreno, A., Rey, J. 1995a. Seafloor characterization through side scan sonar image processing. *International Journal of Remote Sensing*, 16(4):625-632.

Siljeström, P., Rey, J., Moreno, A. 1995b.Characterization of phanerogam communities (*Posidonia oceanica* and *Cymodocea nodosa*) using side-scan-sonar images. *ISPRS Journal of Photogrammetry and Remote Sensing*, 51:308-315.