Bed roughness over vegetated beds:
sonar imaging techniques and effect on unidirectional currents

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ABSTRACT

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ABSTRACT

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS
SCHOOL OF OCEAN & EARTH SCIENCES

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BED ROUGHNESS OVER VEGETATED BEDS: SONAR IMAGING TECHNIQUES AND EFFECT ON UNIDIRECTIONAL CURRENTS.

By Alice Lefebvre

Small scale roughness of the seafloor is of direct relevance to a range of interests, including boundary layer hydrodynamics, sediment transport and high-frequency acoustic scattering. Despite its importance, only few studies have quantitatively resolved seafloor height at the relevant scales. In particular, characterisation of roughness over vegetated beds is needed to better understand hydrodynamics and sediment transport in the coastal zone.

A new Benthic Roughness Acoustic Device (BRAD) has been developed to define micro-topographical roughness through high-resolution imagery of the seabed. BRAD, composed of a profiling sonar – the Sediment Imager Sonar (SIS) – and a motor, both mounted on a frame, enables measurements of the seabed elevation over an area of 1.7 m². A threshold method was established to detect the seabed from the SIS raw data. Laboratory deployments were carried out in order to assess the system accuracy over known targets and its ability to discriminate sediment sizes. Field deployments at 6 sites enabled the imaging of a variety of seabed types; in particular bioturbated fine sand and mud, seagrass canopies, gravelly sand and ripple fields. Spectral analysis applied on the seabed elevations was used to characterise roughness type.

Seagrasses are flowering plants that have adapted to the submerged marine environment. They develop extensive underwater meadows in coastal areas around the world, forming complex, highly productive ecosystems. The SIS was used together with a towed video camera system to survey a seagrass (Zostera marina) bed in Calshot, UK. A method was developed to assess Z. marina presence from the SIS data and its results were tested against video data. The SIS proved to be a useful tool for seagrass surveying and the use of the SIS and the video yielded a preliminary map of the seagrass bed.

Seagrass canopies exert strong effects on water flow inside and around them. The influence of Zostera marina canopies on flow, turbulence, roughness and sediment movement was evaluated through laboratory experiments. Numerous runs were carried out in an annular and a straight, recirculating flume using live Z. marina and a mobile sand layer. Flow was greatly decelerated inside the canopy while turbulence was increased. The Turbulent Kinetic Energy was observed to be maximal at the canopy/water interface. This was hypothesised to be related to the canopy ‘wavy’ motion. Sediment movement was observed within the canopy as scour around the stems. Ripples formed downstream of the canopy at velocities lower than the sediment threshold of motion. Intermittent turbulence associated with the burst phenomenon is thought to be responsible for this.
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Declaration of Authorship

I, Alice Lefebvre, declare that the thesis entitled “BED ROUGHNESS OVER VEGETATED BEDS: SONAR IMAGING TECHNIQUES AND EFFECTS ON UNIDIRECTIONAL CURRENTS” and the work presented in it are my own. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at the university;
- where any part of this work has been submitted for a degree or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I had contributed myself;
- parts of this work has been published as:

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Signed:

Date:
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Notations

c sound velocity (m s\(^{-1}\))
d distance between 2 along-beam measurements (m)
f frequency (s\(^{-1}\))
k\(_b\) bed roughness (mm)
r distance between start and end ranges (m)
t period (s)
t\(_s\) time to do a sweep (s)
u, v, w instantaneous velocities (x, y, z-directions)
u', v', w' instantaneous velocity fluctuations (x, y, z-directions)
$\bar{u}, \bar{v}, \bar{w}$ mean velocities (x, y, z-directions)
v velocity of the SIS along the track (mm s\(^{-1}\))
x distance along transverse axis (m)
y distance along range axis (m)
z elevation along vertical axis (cm)
z\(_0\) roughness length (mm)
B intensity of the backscatter
B\(_{\text{max}}\) maximum backscatter along a beam
F diameter of the footprint (cm)
L wavelength (m)
N number of sample along a beam
P water depth (m)
Q relative intensity of the backscatter
R range (distance from SIS head) (m)
R\(_0\) range at nadir (m)
S water salinity
T water temperature (°C)
TKE\(_{\text{horiz}}\) horizontal Turbulent Kinetic Energy (J m\(^{-3}\))
TKE\(_{\text{vert}}\) vertical Turbulent Kinetic Energy (J m\(^{-3}\))
U\(_{\text{rms}}\) rms turbulence (%)
U\(_*\) shear velocity (cm s\(^{-1}\))
\( \bar{U} \) resultant velocity (cm s\(^{-1}\))

\( V \) voltage of the power supply (V)

\( W \) average backscatter along a beam 0.3 to 0.5 m under the SIS

\( Z \) distance from SIS height (m)

\( \alpha \) grazing angle (°)

\( \beta \) incidence angle (°)

\( \gamma \) spectral exponent (power-law slope)

\( \delta \) solid angle (°)

\( \theta \) beam angle (°)

\( \kappa \) von Karman’s constant

\( \lambda \) wavenumber (m\(^{-1}\))

\( \rho \) density of water (g m\(^{-3}\))

\( \tau_0 \) bed shear stress (Pa)

\( \omega \) spectral strength (power-law intercept) (m\(^4\))

\( \Delta r_x \) theoretical transverse resolution (cm)

\( \Delta r_y \) theoretical range resolution (cm)

\( \Delta r_z \) theoretical vertical resolution (cm)
CHAPTER 1.  GENERAL INTRODUCTION
1.1. **Seabed Roughness**

The bottom of the sea presents asperities and irregularities, holes or mounts of various sizes, which gives it an uneven surface. The extent to which the seabed deviates from a perfectly planar surface, and thereby modifies the overlying fluid flow, defines the seabed roughness. It encompasses a wide range of spatial scales, from grain size to basin-wide features. Larger-scale roughness (10 to $10^4$ m) is traditionally studied in the fields of geology and geophysics. Features include mid-ocean ridges (Hayes and Kane, 1991), fault systems and tectonic plates (Audin et al., 2008), regional bathymetry (Micallef et al., 2009) and coral reefs (Nunes and Pawlak, 2008). Smaller scale features ($10^{-3}$ to 10 m) studied in the fields of benthic ecology, hydrodynamics, sediment transport and acoustic modelling include wave and current ripples (Ashley, 1990), biological features such as trails, burrows, tubes, craters and mounds created by biota activity (Wright et al., 1997) and ultimately grain size features (Soulsby, 1997, Figure 1). While larger features can be stable over tens to thousands of years (Jackson and Richardson, 2007), smaller features, such as sand ripples and biogenic features, are constantly being altered by hydrodynamics and biological activity, which create or destroy small relief on the seafloor (Guillén et al., 2008). Small-scale roughness in turn affects hydrodynamics, and thereby biological activity and sediment transport, by modifying flow friction on the bottom (Grant and Madsen, 1986). Small-scale roughness of the seafloor is therefore of direct relevance to a range of interests such as boundary layer dynamics (Grant and Madsen, 1986), sediment transport (Soulsby, 1997), acoustic scattering (Jackson and Briggs, 1992) and habitat classification (Kenny et al., 2003). Seabed roughness can be defined as either the force of resistance of the bed on the flow (hydraulic roughness) or as the physical variations in seabed elevation (topographic roughness).

1.1.1. **Hydraulic roughness**

From a hydraulic point of view, bed roughness defines the frictional force that the bed exerts on the flow (Grant and Madsen, 1982). Hydraulic roughness is used to evaluate bed shear stress – the frictional force that the flow applies on the seabed - and hence is an essential parameter in boundary layer dynamics and sediment transport calculations (Grant and Madsen, 1986; Soulsby, 1997). Bed roughness ($k_b$) can be estimated from bed physical
parameters and is generally defined as the sum of three components (Grant and Madsen, 1982; Van Rijn, 1993; Li and Amos, 1998):

(1) grain or Nikudarse roughness $k_g$, produced by skin friction forces acting on the non-moving bed material. It is commonly calculated as $k_g = 2.5 \, d_{50}$ where $d_{50}$ is the median grain diameter (Soulsby, 1997);

Figure 1.1: Examples of seafloor roughness: A. fresh-storm generated ripples in medium sand in 19 m water depth; B. a fine sand with biogenic features such as mounds, trails and track marks; C. a sand dollar destroying small 10 cm wavelength ripples; D. a highly bioturbated muddy sand seafloor with many examples of biogenic features such as fresh mounds, trails and tracks; E. a shallow water ooid sand with a mixture of ripple types; F. a field of 30 to 40 cm wavelength ripples in ooid (carbonate) sands from the Ocean Cay, Bahama Islands; G. carbonate hard ground which is nearly devoid of sediment and covered with sponges and corals; H. a shelly seafloor with sea urchins. Note that hydrodynamically induced roughness tends to be anisotropic whereas biologically induced roughness tends to be isotropic (from Jackson and Richardson, 2007).
(2) bedform roughness $k_f$, generated by pressure forces acting on the bedforms. Several expressions have been proposed relating bedform roughness to ripple height and length (e.g. Grant and Madsen, 1982; Nielsen, 1992; Li, 1997); and

(3) transport-related roughness $k_t$, created by the drag forces acting on moving sediment grains in the near-bed transport layer. Several expressions have been proposed to describe this mechanism (Grant and Madsen, 1982; Nielsen, 1992; Van Rijn, 1993). However, there are still uncertainties in defining transport-related roughness (Howman and Van Rijn, 1999).

In addition to these three components of bed roughness, flora and fauna activity interact with the overlying fluid to create a fourth type of bed roughness, the biogenic roughness. Mounds and burrows built by benthic organisms add roughness to the seabed (Briggs, 1989; Wheatcroft, 1994), while vegetation and animals that extend into the flow (seagrasses, bivalves) act as roughness elements (Green et al., 1998; Thompson et al., 2004). Biogenic roughness $k_{bi}$ is a function of, but not equivalent to, the relief of the roughness element themselves (Wright et al., 1997; Stephan and Gutknecht, 2002; Guillén et al., 2008).

### 1.1.2. Topographical roughness

Topographical roughness characterises variations in seabed elevation. Quantitative characterisation of small-scale topographical roughness is of direct relevance for (Akal and Hovem, 1978):

(1) investigation of the character, magnitude and distribution of bottom roughness related to grain size, bedforms and biological activity (Briggs et al., 2005);

(2) classification of quantitative roughness characteristics of the seafloor for different physiographic regions (Nunes and Pawlak, 2008); and

(3) application to different acoustic scattering and propagation theories (Richardson et al., 2001).

In the absence of other topographical features, variations of the seafloor height are defined by sediment nature, size and sorting. A bed made of well-sorted sand will have smaller height variations, hence a smaller topographical roughness, than a bed made, for
example, of unsorted boulders. Topography created by sediment characteristics is of small scale, typically of the order of $10^{-3}$ to $10^{-2}$ m and is usually isotropic, i.e. without any preferential direction. Bedforms (such as sand ripples) develop under the action of waves and currents, creating new topographical variations which have dimensions and orientations that are a function of bottom sediment size, current and wave directions and intensities (Soulsby, 1997). Bedform roughness usually has a bigger scale than sediment roughness (typically $10^{-1}$ to 10 m in length, $10^{-2}$ to $10^{-1}$ m in height) and is anisotropic, i.e. it has a preferential direction (Ashley, 1990). In the absence of sediment transport by waves or currents, the sediment surface is continuously being modified by the locomotion and/or feeding activity of animals that both live on (epifauna) and within (infauna) the sediment, creating a biogenic roughness (Wheatcroft, 1994; Lyons et al., 2002; Guillén et al., 2008). Biogenic roughness is generally isotropic and has a scale of $10^{-2}$ to $10^{-1}$ m (Jackson and Richardson, 2007). It is created by animals activity, but also by submerged vegetation growing on the seabed and in particular seagrass beds (Gambi et al., 1990).

### 1.2. *ZOSTERA MARINA*

Seagrasses are flowering plants that have adapted to the submerged marine habitat (Philips and Meñez, 1988). They cover about 0.1 – 0.2% of the global ocean (Duarte, 2002) and develop extensive underwater meadows on muddy or sandy substrates (den Hartog, 1970) forming complex, highly productive ecosystems. Seagrass beds play a key role in coastal ecosystems by stabilising bottom sediments with their roots (den Hartog, 1970), by attenuating near-bed currents and waves (Gambi et al., 1990; Fonseca and Cahalan, 1992) and by promoting sedimentation and reducing erosion (Leonard and Luther, 1995). They also provide shelter and refuge for adult animals (Connolly, 1994), serve as nurseries for juvenile fish (Horinouchi, 2007) and supply food for herbivores which graze on live seagrass and consume epiphytic algae that grow on seagrass leaves (Heck and Valentine, 2006). The infauna and epifauna of seagrass beds also serve as prey for larger invertebrates and fish (Pihl et al., 2006). Furthermore, seagrass beds have high rates of primary production (Hasegawa et al., 2007) and are an important source of organic matter (Gacia et al., 2003). They can be used to assess the health of coastal and estuarine communities (Short and Burdick, 1996; Austoni et al., 2007) and to trace metal
contamination (Lafabrie et al., 2008) or chemical constituents (Lewis et al., 2007). Recently, a decline of seagrass beds has also been used to assess the effect of infrastructure development on the coastal ecosystem (Freeman et al., 2008).

There are approximately 48 species of seagrasses found in shallow coastal areas of the world (Dawes, 1998). *Zostera marina* L., or eelgrass, is one of the four species in the genus *Zostera*, order Potamogetonales. It is a flowering plant with dark green, flat, ribbon-shaped leaves shooting from a creeping rhizome that binds the sediment (Figure 2, Dawes, 1998). It forms extensive submarine meadows, with a natural range of leaf lengths from < 10 cm to over 3 m (Fonseca and Cahalan, 1992).

![Figure 1.2: Zostera marina or eelgrass. The clonal plant consists of a rhizome and short shoots with clusters of roots (from Dawes, 1998).](image)

*Zostera marina* is widely distributed in both the northern Pacific and the northern Atlantic, and is the dominant species in the latter (Short et al., 2007). It is essentially a sublittoral species which penetrates to some extent into the intertidal zone. It occurs predominantly in sheltered places, on gravel mixed with coarse sand (den Hartog, 1970), but preferably on fine sand with carbonaceous remains and non-calcerous rock fragments.
(Bradley and Stolt, 2006). It is a euryhaline species occurring from fully marine to brackish water (Philips and Meñez, 1988). Eelgrass plants are often found with a great number of epiphytic fauna and flora and higher levels of biodiversity are found in Zostera marina beds than in the surrounding bare sand (Hirst and Attrill, 2008). Red algae such as Audouinella and Ceramium, or the green algae Enteromorpha have been reported to occur in eelgrass beds (Johnson et al., 2005). Primary production by attached algae can represent between 22 and 61% of productivity in Zostera beds (Hemminga and Duarte, 2000), with a shift in the major primary producer from eelgrass in spring and early summer to epiphytic algae in late summer and autumn (Hasegawa et al., 2007). Gastropods such as Hydrobia or Litorina, as well as copepods, are significantly associated communities of the Zostera assemblage (Boström and Bonsdorff, 1997).

The water depth reached by Zostera marina depends greatly on the light intensity and hence all factors influencing the penetration of light, such as water clarity, tidal range, degree of wave action and bottom type, affect the maximum depth eelgrass plants are found (den Hartog, 1970). The species is essentially subtidal, most often found at a depth of 7 - 10 m where the water is clear (Philips and Meñez, 1988) but it can also be found in smaller patches in the intertidal zone (den Hartog, 1970; Hirst and Attrill, 2008). The plants grow vegetatively in waters between 10°C and 15°C, while between 15°C and 20°C, generative shoots are produced (den Hartog, 1970). The ‘wasting disease’ destroyed most of the Atlantic Zostera beds between 1930 and 1940. It was caused by a fungus creating small brown spots on the leaves, which eventually become detached (Muehlstein, 1989). Repeated defoliation due to the fungus finally exhausted the plants, resulting in their death. The decline of Zostera marina caused a marked decrease in the number of organisms dependent on this plant for food or shelter (fishes, molluscs and crustaceans); in particular, Brent geese numbers reduced as a result of shortage as Z. marina (den Hartog, 1970). More recently, a decline of eelgrass beds has occurred from the occasional development of a green algae blanket above the bed, a phenomena which leads to anoxic conditions and seagrass mortality (den Hartog, 1994; Holmer and Nielsen, 2007). Although natural loss in Zostera marina beds occurs, increasing anthropogenic activities have been shown to result in seagrass decline. Housing development and nitrogen loading (Short and Burdick, 1996), reclamation of mudflats for waterfront development (Park et al., 2009) or eutrophication due to herbicides (Nielsen and Dahllöf, 2007) have been reported to create disturbance and loss in Zostera marina beds. Because seagrass ecosystems are in decline in many areas of
the world (Short and Burdick, 1996), conservation and restoration programmes have developed (Fonseca et al., 2000). Several techniques have subsequently been established for transplantation of *Zostera marina* plants (Orth et al., 1999; Lee and Park, 2008). However, prior to any replanting initiatives, existing seagrass beds need to be mapped and monitored in order to assess their evolution. Furthermore, interaction between currents and seagrass canopies needs to be further investigated in order to understand the complex relationship between hydrodynamics and benthic ecology.

1.3. **OBJECTIVES AND THESIS STRUCTURE**

1.3.1. **Thesis aims and objectives**

This thesis aims to investigate roughness of a variety of seabed types through sonar imaging techniques and to study the effect of seagrass canopies on currents, bed roughness and sediment mobilisation. To do so, this thesis was constructed around 3 main axes:

1. Definition of micro-topographical roughness of the seafloor through high-resolution acoustic imaging. Despite the importance of bed micro-topography in studies of near-bottom flow and sediment transport, only a few studies have quantitatively resolved seafloor micro-topography at small scales (e.g. Briggs, 1989; Wheatcroft, 1994; Lyons et al., 2002). Although sonar systems are frequently used for seabed detection, small-scale topographic roughness is usually defined by stereo-photography (e.g. Akal and Hovem, 1978; Richardson et al., 2001). These systems are effective but have limitations, such as the small areas possible to investigate or the difficulty in imaging a seagrass canopy. The first objective of this research project was to develop a method to quantitatively define bed roughness through high-resolution imaging of the seabed using a new acoustic system - the Benthic Roughness Acoustic Device (BRAD).

2. Application of a profiling sonar for seagrass mapping. Preservation, restoration or creation of seagrass beds are increasingly recognised as essential for the sustainable management of the coastal environment (Yap, 2000; Short et al., 2007). Therefore it is of growing importance to map and monitor seagrass beds in order to assess their state and protect them (Kirkman, 1996). Mapping of seagrass beds may also help defining hydrodynamic processes and sediment transport in the coastal zone (Koch et al., 2006).
The second aim of this thesis was to develop the application of a profiling sonar - the Sediment Imager Sonar (SIS) - for seagrass mapping.

(3) Investigation of the influence of *Zostera Marina* canopies on unidirectional flow, bed roughness and sediment mobilisation. Seagrass plants extend above the bottom and modify flow within and around them (Fonseca et al., 1982; Gambi et al., 1990). The benthic boundary layer and sediment transport are thereby affected by the presence of a seagrass canopy (Madsen et al., 2001). Although the influence of seagrass canopies on the flow has been studied in flumes (e.g. Fonseca et al., 1982; Fonseca and Koehl, 2006), it has never been studied in an annular flume, which allows one to examine, amongst other, the influence of vegetation patch length as well as facilitating measurements of velocity upstream, within and downstream of seagrass beds. This is particularly important as turbulence structure in and around submerged vegetation is still poorly understood (Madsen et al., 2001). Furthermore, flume experiments with live seagrass plants and a mobile sand layer enable the study of sediment mobilisation processes within and around seagrass beds, a technique rarely used prior to this study. The third objective of this thesis was to investigate flow intensity, turbulence, roughness and sediment mobilisation inside and around *Zostera marina* beds of different patch lengths and shoot densities.

1.3.2. Thesis structure

The main body of this thesis (Chapters 2 to 4) is based on the three aims presented above. Chapter 2 deals with defining bed roughness through BRAD measurements. After a review of the techniques available to measure seabed elevation, with special interest on sonar techniques, BRAD is described. The methodology developed to reconstruct seabed elevation from BRAD raw data and characterise bed roughness is then detailed. The results of BRAD lab-testing and field deployments to date are next presented, with special emphasis on seabed roughness characterisation from BRAD images. The results of this chapter will be presented at the Underwater Acoustic Conference in June 2009 and published in the conference proceedings (see Appendix 1).

Chapter 3 deals with the application of the SIS to map seagrass beds. This chapter is adapted from a paper published in *Estuarine, Coastal and Shelf Science* (Lefebvre et al.,...
2009) presented in Appendix 2. It will also be presented at the Underwater Acoustic Conference in June 2009. The sonar, which was used on BRAD, was tested for seagrass detection over a *Zostera marina* bed in Calshot and the results obtained from it were compared with data obtained from a video camera system. The novel use of the instrument and processing method are described in detail in this Chapter.

Chapter 4 presents laboratory experiments carried out to investigate the influence of *Zostera marina* canopies on flow, bed roughness and sediment mobilisation. Boundary layer dynamics and the effect of submerged vegetation canopies on flow and sediment transport are first reviewed. The methods used in this study are then presented. Results from experiments in 2 flumes are presented and analysed.

A fifth chapter summarises the main findings of this work and concludes the thesis.
CHAPTER 2. DEFINING MICRO-TOPOGRAPHICAL ROUGHNESS OF THE SEAFLOOR THROUGH HIGH-RESOLUTION ACOUSTIC IMAGING
2.1. **INTRODUCTION**

The topography of the seabed, or bed roughness, both reflects and influences diverse hydrodynamic and biological processes. For instance, the size and sorting of seabed sediment can indicate the direction of sediment transport (Gao and Collins, 1992). On the other hand, it will also have an influence on the reduction of flow towards the bed and hence on sediment transport (Soulsby, 1997). Bedform dimensions can show the direction and strength of the flow (Ashley, 1990) and in return alter bed shear stress and therefore the flow itself (Nielsen, 1992). Seagrass distribution is influenced by current strength (Fonseca and Kenworthy, 1987) but seagrass canopies also influence the flow by current reduction and turbulence increase (Gambi et al., 1990). Precise measurements of the seabed topography, bedform dimensions, macrophyte height, biota abundance, bioturbation intensity and sediment motion are needed to define bed roughness (Thorne and Hanes, 2002). Although high-resolution acoustic instruments can be used to measure the elevation of the seabed at a centimetric scale (e.g. Jetté and Hanes, 1997; Bell and Thorne, 1997b) they have been used principally to study ripple dimensions and migration rather than provide specific measurements to define bed roughness. A new acoustic system has been developed at the National Oceanography Centre, Southampton (NOCS), UK, the Benthic Roughness Acoustic Device (BRAD). This innovative system provides high-resolution acoustic measurements of the seabed elevation over a 1.7 m² area; these measurements are collected specifically to characterise topographical roughness.

The aim of this chapter was to develop methods to define bed roughness through high-resolution imaging of the seabed using BRAD. To do so, the specific objectives were to:

1. develop an algorithm to calculate and fully represent seabed elevations and backscatter intensities from raw data acquired using BRAD;
2. calibrate BRAD under controlled conditions using objects of various shapes and a range of sediment sizes;
3. image various bed types having different sediment characteristics, bedform features and biological attributes in order to acquire BRAD data on a range of natural roughnesses; and
investigate the relationship between statistical and spectral parameters of seabed elevations recorded using BRAD data and bed roughness character, such as sediment size, bedforms dimensions or biological activity.

2.2. BACKGROUND

2.2.1. Seabed imaging techniques

Over the last three decades, the most common solutions adopted for seabed imaging have been direct measurements, optical imaging techniques or acoustical imaging techniques (Kenny et al., 2003, Table 2.1). Direct measurement is usually done by divers tracing the seabed profile onto a gridded sheet (Briggs, 1989). This method is especially useful in conditions where the optical quality of the water is poor, but is severely limited by wave conditions, the accuracy of measurement that can be achieved and the relatively small areas investigated. Benthic grabs are also often used to collect seabed samples at a location (Kenny et al., 2003). They enable an assessment of sediment size and bottom type. However, they give only localised data and the depth or morphology of the seabed cannot be studied from grab samples. Optical techniques comprise photographs, stereo-photographs and video of the seabed. Digitised photographs of the seabed taken at regular intervals can be used for seabed classification and to assess ripple dimensions and migration rates (Li and Amos, 1998). However, seabed elevations of the seabed cannot be produced from the photographs so bed roughness can only be assessed qualitatively and not quantitatively, except in the case of a ripple field where height can be calculated from the shadow created by ripple crests (Li and Amos, 1998).

Stereo-photography can be used to create three-dimensional images of the seabed by taking two photographs of the same area from 2 perspectives a few centimetres apart. Quantitative measurements of seabed elevation can be derived from such images and used to define bed roughness (Briggs, 1989; Wheatcroft, 1994; Briggs et al., 2001; Lyons et al., 2002). Cameras are usually easily deployable but data quality is limited by optical transparency of the water column imposed both by ambient light and turbidity levels (Greenwood et al., 1993). Underwater video camera systems (Norris et al., 1997; McDonald et al., 2006) provide a direct observation of the seabed and have proved to be a good technique for habitat mapping (Short et al., 2007). Although detailed descriptions of
bottom type can be obtained over large portions of the seabed, data quality is limited by water clarity and seabed elevations cannot be derived from the video footage. Acoustic techniques (seismic, sidescan sonar, echosounder or multibeam) on the other hand, can rapidly provide information about the nature and elevation of a large portion of the seabed (e.g. Traykovski et al., 1999; Collier and Brown, 2005). Such data can be used to image and classify the seabed, from shallow to deep water (Kenny et al., 2003). It is such a technique that is explored further in this chapter.

### Table 2.1: Area of seafloor mapped (per unit of effort) versus resolution for different sensing, acoustic and sampling systems (from Kenny et al., 2003).

SSS: Side Scan Sonar, MBS: Multi-Beam Sounder, AGDS: ground-discriminating single-beam echosounders.

<table>
<thead>
<tr>
<th>System</th>
<th>Area mapped km$^2$ h$^{-1}$</th>
<th>Horizontal resolution (m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Chirp’ SSS</td>
<td>10</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>High-energy broad bandwidth pulse sonar</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Substrata characterization from backscatter data</td>
</tr>
<tr>
<td>MBS</td>
<td>5</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Swath width depends on frequency used</td>
</tr>
<tr>
<td>SSS</td>
<td>3.5</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Substrata characterization from backscatter data</td>
</tr>
<tr>
<td>Synthetic aperture sonar</td>
<td>3</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Swath width depends on frequency used</td>
</tr>
<tr>
<td>AGDS</td>
<td>1.5</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Valid for normal beam surface coverage only</td>
</tr>
<tr>
<td>High-resolution sub-bottom profiler</td>
<td>0.8</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Narrow-beam sub-bottom surface coverage</td>
</tr>
<tr>
<td>Video camera</td>
<td>0.2</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Allows mega-epibenthos identification</td>
</tr>
<tr>
<td>Benthic grab/core sampling</td>
<td>0.003</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Quantitative data on macro- and meio-fauna</td>
</tr>
<tr>
<td>Sediment profile camera</td>
<td>&lt;0.001</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Sediment/water interface inspections</td>
</tr>
<tr>
<td>X-ray photography</td>
<td>&lt;0.001</td>
<td>$10^3$ $10^2$ $10$ $1$ $10^1$ $10^2$ $10^3$ $&lt;10^3$</td>
<td>Geochemical and physical inspections</td>
</tr>
</tbody>
</table>

### 2.2.2. Acoustic systems principles

Acoustic systems use travel times and acoustics intensities of sound waves reflected off the seabed to determine depths to the seafloor and seabed properties (Blondel and Murton, 1997). A short pulse or ‘ping’ of acoustic energy is transmitted from the equipment and travels out through the water. When the sound wave encounters an object in the water,
waves are reflected, transmitted and scattered. The energy scattered back can be recorded by a receptor and the time delay between the transmission of the pulse and the reception of the echo is a measure of the distance of the object (Tucker, 1966). The distance between the source and the object, the range \( R \) in metres, is a function of the time delay (2-way travel time \( t \) in s) and the sound velocity \( c \) in m s\(^{-1}\):

\[
R = \frac{c \cdot t}{2} \tag{2.1}
\]

Sound velocity in water depends on salinity \( S \), temperature \( T \) in °C and depth \( P \) in m of the water through which the sound travels; it can be approximated with the expression (Mackenzie, 1981):

\[
c = 1448.96 + 4.591 \cdot T - 5.304 \times 10^{-2} \cdot T^2 + 2.374 \times 10^{-4} \cdot T^3 + 1.340 \cdot (S-35) + 1.630 \times 10^{-2} \cdot P + 1.675 \times 10^{-7} \cdot P^2 - 1.025 \times 10^{-2} \cdot T \cdot (S-35) - 7.139 \times 10^{-13} \cdot TP^3 \tag{2.2}
\]

The amount of energy scattered back to the source – the backscatter - is a function of the contrast in acoustic impedance – media density times speed of sound - between the 2 media (Tucker, 1966). A strong acoustic echo in the water column can be created by phenomena such as bubbles, sediment, fish, the seabed or submerged vegetation. Because the seabed is usually the medium with the highest impedance contrast to water, it reflects most of the energy and creates a ‘peak’ in the echo monitored by a receiver. The intensity of the backscatter from the seabed is influenced primarily by (Katsnelson and Petnikov, 2001):

1. surface roughness or scattering strength, which is related to sediment characteristics (mean size, sorting, shape, material, Figure 2.1a). Coarser sediment or rougher surface will usually exhibit a stronger backscatter than finer sediment or a smoother surface (Blondel and Murton, 1997);
2. refraction, which is a function of the angle of incidence on the seafloor (Figure 2.1b). For small angles of incidence (beam normal to a flat seafloor), high levels of energy are returned to the sensor head whereas for poor angles of incidence (\( \beta \) close to 90°), low amounts of energy are returned to the sensor head (Fish and Carr, 1990); and
3. attenuation with distance from beam source. At greater beam angles, the sound travels longer in the water column before reaching the seabed and is therefore more attenuated than at lower beam angles (Blondel and Murton, 1997). Most sonars
incorporate a time-varying gain (TVG) to amplify the backscattered signal according to its arrival time, which is related to the distance the beam has travelled in the water. As attenuation is a complex function of the beam width, it is usually determined empirically for each sensor (Blondel and Murton, 1997).

Since seabed scattering strength is related to sediment characteristics and surface roughness, backscatter intensity from the seabed can be used for seabed classification and habitat mapping (Ehrhold et al., 2006). If sediment is in suspension in the water column, a proportion of the sound is scattered from it, creating a strong backscatter in the water column. The intensity of this backscatter is related to the amount of particles in suspension therefore profiles of relative turbidity can be derived from sonar backscatter data (Thorne and Hanes, 2002). In the same way, if submerged vegetation, such as seagrass, is present in the water column, high backscatter is usually detected above the seabed (Sabol et al., 2002). This can be used to map vegetation presence, canopy thickness and shoot density from acoustic data (e.g. Komatsu et al., 2003; Warren and Peterson, 2007).

![Figure 2.1](image.png)

**Figure 2.1:** a. Acoustic scattering is influenced by the geometry of seafloor imaging, and by the intrinsic character of the seafloor (composition, roughness, volume properties), at scales comparable to the acoustic wavelength (from Blondel and Murton, 1997); b. definitions of some parameters.

### 2.2.3. Sonar system types

Several types of sonars, including single beam echosounders, multi beam sonars and side scan sonars, have been developed to measure bathymetry and seafloor characteristics at different scales (Kenny et al., 2003, Table 2.1). Single beam echosounders send a single
acoustic beam towards the seafloor immediately beneath the transducer. They are mainly used to measure water depth under the boat for navigational purpose and for fish finding (e.g. Wille, 2005). Multi-beam sonars emit simultaneously many beams of sound creating a fan-beam pattern and hence insonify large portions of the seabed on each side of the boat. They are usually used for extensive or deep-sea bathymetric surveys (e.g. Smoot, 1985). Side scan sonars emit fan-shaped pulses and produce an image of the echo intensity of the seabed on each side of the boat. They are generally used for seabed classification and archaeological surveys (e.g. Quinn et al., 2005; Ehrhold et al., 2006).

Most acoustic techniques efficiently classify large (1 to 10³ m) portions of the seabed (Table 2.1). However, rare are those which provide high-resolution (10⁻³ to 10⁰ m) information on ripple dimensions, seagrass height or biological features (Thorne and Hanes, 2002). This is mainly due to the fact that such sonars are usually fixed to the side of a boat or towed behind it in order to survey a large area of the seabed. This causes navigational inaccuracies and noisiness in the backscattered signal and prevent good quality, high-resolution data being collected (Goff et al., 2000). Some acoustic systems have been specifically designed to measure seabed morphology to centimetre resolution. To date, high-resolution seabed imaging systems reported are one of three types (Thorne and Hanes, 2002):

- a single beam echosounder measuring seabed elevation while travelling along a frame, e.g. the HRRTS II (High Resolution Remote Tracking Sonar) developed by Greenwood et al. (1993);
- a multi-transducer linear array which measures seabed elevation along a profile, e.g. the MTA (Multiple Transducer Array) used by Jetté and Hanes (1997); and
- a single transducer which radially rotates to detect the height of the seabed along a transect, e.g. the sand ripple profiler used by Bell and Thorne (1997a, 1997b).

Although these systems have been applied to measure bedform dimensions, they have not been used in the presence of seagrass or over bioturbated seabeds. Furthermore, the profilers to date operate only along a single transect and therefore do not image in three dimensions (3D). As a result, errors in ripple wavelengths would result if the transect were not orthogonal to ripple direction and the bed 3D geometry can not be defined (Thorne and Hanes, 2002).
2.2.4. Acoustic shadows and slope smoothing

Systems used for high-resolution seabed imaging have inherent drawbacks that need to be taken into account when analysing the data they produce. Acoustic shadowing and slope smoothing are two examples. An acoustic shadow is an area through which sound waves fail to propagate due to obstruction by topography (Fish and Carr, 1990, Figure 2.2a). At greater beam angles (beams further from nadir, see Figure 2.1b), an object protuding from the seabed (for example a rock) will block the sonar beam and create an area of no data - or acoustic shadow - behind it. In the same way, in the case of a depression in the seabed,
only one edge of the depression will be imaged as some of the acoustic energy will be obstructed by the leading edge of the depression. The size of the acoustic shadow is a function of the bed slope angle and orientation, the object dimensions and the beam angle. An object further from the source, i.e. imaged at a high beam angle, will produce a bigger shadow than an object close to the source. A small angle between 2 consecutive beams helps to reduce acoustic shadowing as data are collected behind the object as soon as the beam is not obstructed.

The depth is computed from sonar data as the first strong acoustic return from the seabed. If the footprint area is sloping, the first strong acoustic return will often be higher than the average depth over the footprint (Blondel and Murton, 1997, Figure 2.2b). As a result, the accuracy of the system will decrease as the change in seabed elevation over the footprint area increases and steep slopes will be smoothed. The error in slope computation will increase with increasing sweep angle as both the footprint and the angle of incidence increase. Error in slope computation is a well-known effect of acoustic systems and usually creates ripple smoothing (Green and Boon, 1988; Jetté and Hanes, 1997).

2.2.5. Quantitative characterisation of topographic roughness

High-resolution measurement of seabed elevation is only the first step in the analysis of topographic roughness. A statistical or spectral characterisation of the bed elevation is then required to quantitatively discriminate between the different types of roughnesses (Akal and Hovem, 1978). Statistical measures, such as standard deviation, root mean square (rms), variance, skewness and kurtosis of seabed elevation distribution can be used as indices of seabed roughness (Fox and Hayes, 1985, Table 2.2). In particular, the rms of the distribution may help to define topographical roughness as it shows the dispersion of seafloor feature height (e.g. Briggs, 1989; Wheatcroft, 1994). Wheatcroft (1994) studied the roughness presented by a number of seabed elevation profiles acquired by stereo-photography. He found that current ripples had large rms-height whereas smoothed scour-pitted beds showed small rms-height values; rms-heights of bioturbated beds were variable and appeared to depend on the previously-produced physical bed configuration.
Table 2.2: Definition of traditional statistical measures. $x_i$ are values of the seabed elevations, $n$ is the total number of values.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Formula</th>
<th>Measure of</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>sum of the values divided by the number of values</td>
<td>$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$</td>
<td>average</td>
</tr>
<tr>
<td>variance</td>
<td>average of the squared distance of the values from the mean</td>
<td>$\text{var} = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2$</td>
<td>dispersion</td>
</tr>
<tr>
<td>standard deviation</td>
<td>square root of variance</td>
<td>$\sigma = \sqrt{\text{var}}$</td>
<td>dispersion</td>
</tr>
<tr>
<td>rms</td>
<td>square root of the mean of the squares of the values</td>
<td>$\text{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} x_i^2}$</td>
<td>dispersion</td>
</tr>
<tr>
<td>IQR</td>
<td>difference between the third and first quartiles (Q)</td>
<td>$\text{IQR} = Q_3 - Q_1$</td>
<td>dispersion</td>
</tr>
<tr>
<td>MAD</td>
<td>absolute difference between the values and the mean</td>
<td>$\text{MAD} = \frac{1}{n} \sum_{i=1}^{n}</td>
<td>x_i - \bar{x}</td>
</tr>
<tr>
<td>skewness</td>
<td>third moment about the mean divided by cube of standard deviation</td>
<td>$\text{Skewness} = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^3$</td>
<td>asymmetry</td>
</tr>
<tr>
<td>kurtosis</td>
<td>fourth moment about the mean divided by standard deviation power 4</td>
<td>$\text{Kurtosis} = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^4$</td>
<td>‘peakness’</td>
</tr>
</tbody>
</table>

Although traditional statistical measures provide a quantification of the seabed elevation variability and therefore enable a distinction between different roughnesses, it does not provide any information on size, spacing and direction of seabed features. Several authors have therefore used directional power spectra of seabed elevation distribution to quantify variability in seabed relief (see Jackson and Richardson, 2007 for a review). In particular, two-dimensional (2D) seabed roughness power spectral density functions give wavelength content and preferential orientation of the seabed relief which can be used to quantitatively classify seabed roughness (Akal and Hovem, 1978).

Spectral analysis allows the description of a signal in the frequency domain rather than in the conventional time domain. Its principles state that any time series of a signal $s(t)$ can be decomposed into a sum of sinusoids, each one being defined by its frequency ($f$ in s$^{-1}$, the inverse of period ($t$) in s), amplitude ($A$) and phase ($\phi$) (Jenkins and Watts, 1968). One of the specific forms of Fourier analysis is the Discrete Fourier Transform (DFT). It decomposes an input discrete signal in time (i.e. finite sequence of real or complex numbers) into a sum of sinusoidal components by determining the amplitude, phase and spectral energy of each frequency. It is defined as:
\[
S(f) = \int_{-\infty}^{+\infty} s(t)e^{-i2\pi f t} dt
\]  

(2.3)

where \(S(f)\) is the signal in frequency \(f\). The DFT can be computed efficiently in practice using a Fast Fourier Transform (FFT) algorithm. The FFT yields the power spectral density (also referred to as Height of the Spectral Density Level, HDSL) as a function of frequency. High values of spectral density for a given frequency indicate a periodic or semi-periodic component in the time series (Jenkins and Watts, 1968). The method, developed for time-series, can be applied to spatial series, e.g. identification of large-scale oceanic waves from a satellite-based dataset (Cipollini et al., 2001). The ‘spatial frequency’ \(\lambda\) is then called wavenumber (\(m^{-1}\)) and the period \((L = 1 / \lambda)\) is named wavelength (m).

While one-dimensional (1D) analysis should be sufficient for isotropic roughness, which by definition is the same in every direction, it can be very limiting in the study of anisotropic roughness (e.g. a ripple field) as a profile has to be selected perpendicularly to the bedform direction in order to compute correct dimensions (Lyons et al., 2002). Even in the case of ‘isotropic’ roughness the results of the analysis may be dependant on the direction of the selected profile (Richardson et al., 2001). To overcome the limitation of 1D spectral analysis, some authors have applied a 2D DFT to images of seabed elevations (e.g. Akal and Hovem, 1978; Richardson et al., 2001; Lyons et al., 2002). This method is extremely powerful in the case of anisotropic roughness and provides recognition of bedform wavelength and direction without having to rely on correct positioning of a profile (Cazenave et al., 2008). The 2D Fast Fourier Transform, used to analyse 2D signals, is a logical extension of the 1D FFT:

\[
S(u,v) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} s(x,y)e^{-i2\pi(ux+vy)} dxdy
\]  

(2.4)

The 2D spectrum obtained from a ripple field usually shows anisotropy in spectral power associated with ripple directions (Figure 2.3).
The roughness spectral power calculated from an elevation profile of natural seabed usually presents a logarithmic decay with frequency and so a power-law regression line can be fitted to the spectral power in log-log space (Jackson and Richardson, 2007). From a 1D dataset, the power-law can be fitted directly on the roughness spectrum in the frequency space (e.g. Briggs et al., 2001). From a 2D spectrum, a ‘slice’ can be taken through the 2D spectrum and a power-law regression fitted on the roughness power spectrum thereby calculated (Figure 2.3c). The power-law regression fitted to the power spectrum \( P(f) \) has the form:

\[
P(f) = \omega f^{-\gamma}
\]  

(2.5)
where $\gamma$ (slope of the power-law) is called the spectral exponent and $\omega$ (y-intercept at a spatial frequency of $10^0$) is called the spectral strength (Jackson and Richardson, 2007). $\gamma$ and $\omega$ can be used to model high-frequency acoustic scattering (e.g. Jackson et al., 1996). As a result, several studies have characterised seabed roughness using power-law regressions fitted on roughness power spectra calculated from seabed elevations acquired with stereo-photography (e.g. Berkson and Matthews, 1984; Briggs, 1989; Richardson et al., 2001; Lyons et al., 2002). The total roughness of seabed elevation integrates the power of each frequency under the power-law fit (Jackson and Richardson, 2007). The spectral exponent ($\gamma$) characterises the spectral spatial frequency roll-off, i.e. the relative strength of high and low-frequencies (Briggs et al., 2001). For natural, random sediment surfaces, it has been found in almost all cases to be between 2 and 4 (Jackson and Richardson, 2007, Table 2.3). Higher values of $\gamma$, i.e. a steeper slope, imply a strong power of low frequencies compared to high-frequencies, whereas lower $\gamma$ values show a less steep slope and therefore less power contained at the low frequencies compared to high frequencies. The spectral offset (usually given as $\log(\omega)$ and therefore with units of cm$^3$ or cm$^4$ instead of dB) gives the strength of the power-law exponent. It generally has values between $10^{-4}$ and $10^{-2}$ m although it is highly variable (Table 2.3).

Despite the fact that a considerable effort has been put into determining the behaviour of the roughness spectrum over a wide range of bed types and spatial frequencies, few generalisations can be made confidently about the values of $\gamma$ and $\omega$ for the purpose of characterising bed roughness or predicting acoustic scattering (Briggs and Ray, 1997). Briggs et al. (2001) concluded that biogenic roughness was characterised by strong high-frequency fluctuations (created by small wavelength features such as surface trails and feeding pits). Little high-frequency variations but significant low-frequency fluctuations (large wavelength features, e.g. ripple crests and troughs) characterised hydrodynamic roughness. Furthermore, the lack of large roughness features or the presence of bioturbation was shown to result in a high spectral strength ($\omega$) and conversely, large roughness features, such as ripples, had a lower spectral strength (Briggs and Ray, 1997). Therefore, it seems that sites where seabed roughness is constructed by hydrodynamic processes generally present a higher slope than roughness dominated by bioturbation (i.e. hydrodynamic roughness has more power at small wavelengths but less power at high wavelengths than biogenic roughness), which usually present less steep slope but a higher
intercept. This is, however, a very general rule and studies have shown that it is extremely hard to predict bed roughness from spectral exponent and strength (Briggs and Ray, 1997).

### Table 2.3: Seafloor roughness measured from a variety of sediment types in shallow water sites.

Sediments are arranged in order of decreasing grain size (increasing phi units). Anisotropic roughness measurements have been measured crest-to-crest (c-c) and along-strike (a-s). Measurements techniques (meas. tech.) comprises diver-operated 35-mm stereo cameras, remote 70-mm cameras or a manual trace on Mylar by divers. Only selected sites are presented here and the whole table can be found in Jackson and Richardson (2007).

<table>
<thead>
<tr>
<th>Site</th>
<th>d&lt;sub&gt;90&lt;/sub&gt; (ø)</th>
<th>Type</th>
<th>rms (cm)</th>
<th>Meas. tech.</th>
<th>Slope (10&lt;sup&gt;-3&lt;/sup&gt; m&lt;sup&gt;4&lt;/sup&gt;)</th>
<th>Intercept</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kings Bay/Lynch site</td>
<td>0.9</td>
<td>hash</td>
<td>0.42</td>
<td>35 mm</td>
<td>1.47</td>
<td>5.34</td>
<td>Stanic et al., 1989</td>
</tr>
<tr>
<td>Mission Bay/ coarse</td>
<td>0.95</td>
<td>coarse sand</td>
<td>2.30</td>
<td>trace</td>
<td>2.46</td>
<td>5.70</td>
<td>Richardson et al., 1983</td>
</tr>
<tr>
<td>Panama City 1993</td>
<td>0.98</td>
<td>coarse sand</td>
<td>0.52</td>
<td>35 mm</td>
<td>2.12</td>
<td>1.98</td>
<td>Jackson et al., 1996a</td>
</tr>
<tr>
<td>Charleston/ coarse</td>
<td>1.44</td>
<td>med sand</td>
<td>0.26</td>
<td>&quot;</td>
<td>2.05</td>
<td>0.08</td>
<td>Briggs et al., 1986</td>
</tr>
<tr>
<td>SAX04 (c-c)</td>
<td>1.47</td>
<td>rip. med sand</td>
<td>1.81</td>
<td>&quot;</td>
<td>2.99</td>
<td>0.14</td>
<td>Unpublished data</td>
</tr>
<tr>
<td>SAX04 (c-c)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.09</td>
<td>trace</td>
<td>2.69</td>
<td>0.23</td>
<td>&quot;</td>
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<tr>
<td>SAX04 (a-s)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>0.86</td>
<td>&quot;</td>
<td>2.4</td>
<td>0.28</td>
<td>&quot;</td>
</tr>
<tr>
<td>Panama City 1998</td>
<td>1.65</td>
<td>med sand</td>
<td>0.65</td>
<td>35 mm</td>
<td>2.1</td>
<td>2.12</td>
<td>Briggs et al., 1986</td>
</tr>
<tr>
<td>Charleston/ fine</td>
<td>1.88</td>
<td>&quot;</td>
<td>0.36</td>
<td>&quot;</td>
<td>2.5</td>
<td>0.09</td>
<td>Briggs et al., 1986</td>
</tr>
<tr>
<td>Charleston/ fine (c-c)</td>
<td>1.97</td>
<td>rip. med sand</td>
<td>0.37</td>
<td>35 mm</td>
<td>2.29</td>
<td>0.08</td>
<td>Briggs et al., 1986</td>
</tr>
<tr>
<td>Charleston/ fine (a-s)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>0.36</td>
<td>&quot;</td>
<td>1.33</td>
<td>0.54</td>
<td>&quot;</td>
</tr>
<tr>
<td>Montauk Point</td>
<td>2.04</td>
<td>fine sand</td>
<td>0.28</td>
<td>&quot;</td>
<td>2.72</td>
<td>0.03</td>
<td>Richardson et al., 1983</td>
</tr>
<tr>
<td>Quinault Range (c-c)</td>
<td>2.94</td>
<td>rip. fine sand</td>
<td>1.65</td>
<td>70 mm</td>
<td>2.67</td>
<td>0.33</td>
<td>Jackson and Briggs, 1992</td>
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<tr>
<td>Quinault Range (a-s)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.19</td>
<td>&quot;</td>
<td>2.92</td>
<td>0.28</td>
<td>&quot;</td>
</tr>
<tr>
<td>Tirrenia Italy</td>
<td>3.72</td>
<td>v. fine sand</td>
<td>0.83</td>
<td>35 mm</td>
<td>3.01</td>
<td>0.25</td>
<td>Briggs et al., 2002</td>
</tr>
<tr>
<td>Mission Bay/ fine</td>
<td>3.77</td>
<td>fine sand</td>
<td>0.93</td>
<td>trace</td>
<td>2.17</td>
<td>1.23</td>
<td>Richardson et al., 1983</td>
</tr>
<tr>
<td>Lower FL Keys</td>
<td>6.62</td>
<td>carb. s-s-clay</td>
<td>0.65</td>
<td>35 mm</td>
<td>2.29</td>
<td>2.09</td>
<td>Jackson et al., 1996a</td>
</tr>
<tr>
<td>Juan de Fuca site 4</td>
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<td>glacial till</td>
<td>0.48</td>
<td>70 mm</td>
<td>3.35</td>
<td>0.20</td>
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</tr>
<tr>
<td>Eel River</td>
<td>7.17</td>
<td>clayey-silt</td>
<td>0.21</td>
<td>&quot;</td>
<td>3.28</td>
<td>0.06</td>
<td>Richardson et al., 2002</td>
</tr>
<tr>
<td>Orcas Island</td>
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<td>clayey sand</td>
<td>0.40</td>
<td>35 mm</td>
<td>3.23</td>
<td>0.05</td>
<td>Self et al., 2001</td>
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<tr>
<td>Eckernforde Bay</td>
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<td>siltty clay</td>
<td>0.37</td>
<td>&quot;</td>
<td>2.42</td>
<td>0.30</td>
<td>Jackson et al., 1996a</td>
</tr>
</tbody>
</table>
2.3. SYSTEM DESCRIPTION AND METHODOLOGY

2.3.1. The system

a. **BRAD design and settings**

The Benthic Roughness Acoustic Device is composed of a profiling sonar – the Sediment Imager Sonar (SIS) - and a small driver motor mounted on a frame (Figure 2.4). BRAD frame is made of aluminium and is 2 m long, 1 m high and 0.94 m wide. A computer is connected to the SIS and provides real-time display and recording of the data.

The SIS is a derivative of the Image Profiling Sonar 1640/2640 produced by Marine Electronics Ltd. (Guernsey). It is a single-beam profiling sonar with a rotating head, emitting a pencil-beam sound wave (beam width angle 1.8°) at a frequency of 1.1 MHz.
The sonar beam is swept at right angles to the sonar body and sweeps can be of any angle to a full 360° with beams every 0.9°. The SIS cannot be operated autonomously and so is connected to a computer and a power supply (17 – 24 Volts DC). The motor, which drives the SIS back and forth along the frame, is connected to a power supply with a 10 metre-long cable, limiting deployments to depths shallower than about 6 m. By convention, the water is sand. Data are displayed and recorded by the Sediment Imager Control Software® (Figure 2.5). The following settings are adjustable with the Sediment Imager Control Software:

- start range (m): distance from the sonar head where data collection begins;
- end range (m): distance from the sonar head where data collection ends;
- sweep angle (°): arc-length of the sweep;
- transmit pulse (µs): duration of the emitted sound source;

![Figure 2.5: Images produced by the Sediment Imager Software. The line of high backscatter is produced by the seabed and the high backscatter around 0 m is produced by the sensor head. Settings which can be adjusted are shown on the right-hand side.](image-url)
- **mute pulse** (µs): time after which the receiver begins to listen for backscatter (should be set to twice the transmit pulse value);
- **sample interval** (µs): time between subsequent measurements along a beam (should be set to half the transmit pulse value). It is used by the software together with the speed of sound to calculate the number of samples along the beam \( N \). The distance between two measurements along a beam \( d \) is then given by:

\[
    d = r / N
\]  

(2.6)

where \( r \) is the distance between the start range and the end range; and
- **speed of sound** (m s\(^{-1}\)): the value for the speed of sound can be adjusted to a value calculated using measurements of temperature and salinity made on site and applying Equation 2.2.

Echograms (backscatter intensity along beams) are recorded for each sweep (.img file) and converted to ASCII image intensity (.xyz file) with specially written software (Sediment Imager Converter 1.0 provided by Marine Electronics Ltd). The data available after conversion are beam angle \( \theta \) (in degrees), distance from SIS \( R \) in m and backscatter \( B \), dimensionless). The backscatter intensity values are given in relative integer values (0 to 255, linear). For simplicity, hereafter the intensity of the backscatter may be called backscatter. The SIS does not incorporate a time-variable gain (TVG) circuit or software correction and therefore no correction of the attenuation of sound with distance from the source is applied during data collection.

On BRAD, the SIS is fixed to be down-looking at 0.88 m above the bed and is slowly advanced along the length of the frame by the motor while in sweeping mode. The settings of the SIS used on BRAD are summarised in Table 2.4. Sweeps are made in an arc of 90° centred about nadir, so that data are acquired 45° each side of the vertical (total of 101 beams per sweep). Two bars are currently located at the bottom of the frame to increase stability and provide a fixed reference in the image.

BRAD can be deployed by 3 people from an anchored boat or a pontoon in water depths ranging from 1 m to 6 m. The maximum area of the seabed which can be surveyed in a single deployment is 1.7 m\(^2\).
**b. Theoretical spatial resolution consideration**

BRAD was developed for high-resolution seabed mapping and bed roughness investigations. It is therefore essential to assess the system resolution along the 3 axes: x-axis (transverse resolution), y-axis (range resolution) and z-axis (vertical resolution).

Transverse resolution ($\Delta r_x$) is the minimum distance between two objects parallel to the line of travel that are evident on the sonar as separate objects (Quinn et al., 2005). Here, the theoretical transverse resolution is the distance between 2 points on the x-axis, which assuming a flat bed is:

$$\Delta r_x = \tan \theta_x R_0 - \tan \theta_{n-1} R_0$$  \hspace{1cm} (2.7)

where $\theta (°)$ is the beam angle of beam $n$ and $R_0$ is the distance from the SIS head to the bed at nadir (see Figure 2.1b). On BRAD, $R_0$ is constant and equal to 88 cm. Beams are scanned every 0.9° from beam angles going from -45° to 45° about the vertical. Thus the transverse resolution is greatest at nadir (1.4 cm) and least at 45° on each side (2.7 cm, Table 2.5).

**Table 2.5: Theoretical resolutions and footprint size as a function of beam angle.**

<table>
<thead>
<tr>
<th>Beam angle ($\theta^{°}$)</th>
<th>Transverse resolution ($\Delta r_x$ cm)</th>
<th>Footprint diameter ($F$ cm)</th>
<th>Vertical resolution ($\Delta r_z$ cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.4</td>
<td>2.8</td>
<td>0.37</td>
</tr>
<tr>
<td>15.3</td>
<td>1.5</td>
<td>3.0</td>
<td>0.36</td>
</tr>
<tr>
<td>30.6</td>
<td>1.9</td>
<td>3.7</td>
<td>0.32</td>
</tr>
<tr>
<td>45.0</td>
<td>2.7</td>
<td>5.5</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Range resolution ($\Delta r_y$) is the minimum distance between two objects perpendicular to the line of travel that are displayed on the sonar as separate objects (Quinn et al., 2005). On BRAD, the SIS sweeps the bed while it moves along the frame at a constant speed. The resulting data track appears to zigzag across the bed (Figure 2.6). The distance between 2
points on successive lines depends on the speed of travel of the SIS along the frame. The velocity of the SIS along the length of the frame, \( v \) (mm s\(^{-1}\)) is a function of the voltage of the power supply applied to the motor \( V \) (V) and has been empirically determined to be (\( n = 21, R^2 = 0.88 \)):

\[
v = 0.033V
\]  

(2.8)

This relationship is valid for power supply voltage from 13 to 23 V. The distance between 2 points of 2 consecutive sweeps at nadir (\( x = 0 \)) \( \Delta r_y \) is then:

\[
\Delta r_y = \frac{v}{t_s}
\]  

(2.9)

where \( t_s \) is the time to complete a sweep (17 s using settings summarised in Table 2.4). A motor voltage of 14 V yields a velocity of 0.46 mm s\(^{-1}\) and a \( \Delta r_y \) of 0.8 cm at \( x = 0 \).

The acoustic footprint of the sonar - the area over which the sound beam will insonify the seabed - also needs to be taken into account in defining spatial resolution since the size of the footprint may have a significant impact when imaging seabed with sharp relief. The diameter of the footprint \( F \) is defined by:

\[
F = \tan(\theta - \delta / 2)R_0 - \tan(\theta + \delta / 2)R_0
\]  

(2.10)

where \( \delta \) is the solid angle (\( \delta = 1.8^\circ \)). Like the transverse resolution, the diameter of the footprint increases with beam angle, from 2.8 cm at nadir to 5.5 cm at 45\(^\circ\) of the vertical (Table 2.5). Due to the small angle between 2 consecutive measurements and the slow

Figure 2.6: SIS tracks on the seabed. The y-axis is exaggerated compared to the x-axis for illustrative purpose.
velocity of the sonar along the frame, the system theoretical range and transverse resolutions are smaller than the sonar footprint. This enables a certain degree of overlap between beam coverage, thereby reducing the effects of acoustic shadowing and slope smoothing.

Vertical resolution ($\Delta r_z$ in cm) is a function of the beam angle and the distance between 2 adjacent points on a beam. Assuming a speed of sound of 1500 m s$^{-1}$, a sample interval of 5 $\mu$sec yields an along beam resolution ($d$) of 0.375 cm in the measurement of backscatter intensity ($r = 2$ m, $N = 533$, see Equation 2.6). The theoretical vertical resolution can be defined as:

$$\Delta r_z = d \cos(\theta)$$  \hspace{1cm} (2.11)

The theoretical vertical resolution varies from 0.26 cm at 45° from vertical to 0.37 cm at nadir (Table 2.5). The vertical resolution is therefore higher at high beam angles than at nadir. At high beam angles, however, the acoustic footprint is bigger, the transverse resolution is lower and phenomena such as slope smoothing and acoustic shadowing are increased. Thus, the best quality data are acquired at low beam angles (towards the nadir) and data quality decreases towards higher beam angles.

2.3.2. Data processing

The ASCII files containing the range ($R$), beam angle ($\theta$) and backscatter ($B$) values obtained after transformation by the Sediment Imager Converter® are processed in several steps to produce the final files and images. The different stages of processing comprise: bed detection, raster interpolation and computation of statistical and spectral parameters.

a. Bed detection

The aim of this first step in data processing is to produce a single file containing the (x, y, z) positions and the associated backscatter intensity of the seabed at a site imaged with BRAD. The processing includes the detection of the seabed depth along each beam of each sweep ($Z$) and computation of its associated (x, y) horizontal co-ordinates, the translation of the origin of the vertical axis from the sonar head to the theoretical depth of the bed to
produce the seabed elevation \( z \) and the correction of backscatter intensities from the attenuation of backscatter with distance from the source. The steps taken to arrive to this result are detailed below.

1. Firstly, data points are converted from polar \( (R, \theta) \) to cartesian \( (x, Z) \) co-ordinates - \( x = R \cos(\theta) \) and \( Z = R \sin(\theta) \). The origin of the cartesian co-ordinate system is the sensor head so that the depth of the seabed is around \( Z = -0.88 \) m (Figure 2.7). When collecting data, the SIS is rarely looking directly downwards due to difficulty in fixing it on the frame (see position of the bed on Figure 2.5). A small correction (6 to 8° depending on the site) is therefore applied to the beam angle value before conversion from polar to cartesian co-ordinates to ensure the bed is horizontal.

Figure 2.7: Representation of all the points in a sweep. The bed can be recognised by its strong backscatter; the data retained for processing are indicated by the black box. Beam angles have already been corrected so that the bed is horizontal.
Thereafter, data ‘cleaning’ is undertaken (Figure 2.7): the points closer than 0.3 m to the sensor head (in the near field region and thus directly influenced by the presence of the head, i.e. red colour around the sensor head) or beyond 1.1 m of the sensor head (falling 25 cm below the bed level) are removed as they are not used in further analyses.

For each beam of each sweep,

- the maximum backscatter ($B_{\text{max}}$) is found;
- the average backscatter 0.5 to 0.3 m under the head ($W$) is calculated;
- a quantity $Q$ is calculated from the backscatter intensity along a beam. $Q$ is the relative intensity of the backscatter normalised to the maximum backscatter value:

\[
Q(Z) = \frac{B(Z) - W}{B_{\text{max}} - W}
\]  

(2.12)

where $B(Z)$ is the backscatter at depth $Z$ along a beam;
- the first point along the beam where $Q(Z)$ is greater than 0.8 is defined as the depth of the bed (Figure 2.8). For high-frequency acoustic systems, the depth of the seabed is usually situated above the highest backscatter and therefore, threshold methods are often used to detect the seabed (e.g. Greenwood et al., 1993; Jetté and Hanes, 1997). It was initially attempted to calculate the depth of the seabed using backscatter intensities along a beam. However, this method often gave inaccurate results as the threshold values to be used to correctly discriminate the seabed were found to be dependant on the intensity of the maximum backscatter along the beam and backscatter intensity in the water column, which vary from beam to beam (in particular with beam angle). To address this problem, the intensity of the backscatter along a beam was initially normalised to the intensity of the beam maximum backscatter ($B_{\text{max}}$). Thereafter, the intensity of the average backscatter in the water column ($W$) was subtracted from the backscatter intensities and from the maximum backscatter. The quantity thereby calculated $Q$, has values of on average 0 in the water column and 1 at maximum (Figure 2.8) and is not influenced by variations of average backscatter intensities in the water column and maximum backscatter. The threshold value of 0.8 was found by trial and error; and

- the backscatter intensities and (x) co-ordinates associated with the point satisfying the threshold condition are computed; the position along the frame (y) is calculated from the motor velocity (Equation 2.8), the time to complete a sweep ($t_s$) and the beam number.

After these steps, the dataset consists a grid of the depth of the seabed with (x, y, Z) co-ordinates and associated backscatter for each beam of each sweep.

(4) The average of the $W$ values per sweep ($\overline{W}$) is then calculated; $\overline{W}$ can be used as a measure of relative turbidity in the water column during the time the sweep was recorded (Thorne and Hanes, 2002).

(5) The seabed elevation ($z$) is computed as the depth of the seabed under the sensor head ($Z$) plus the height of the SIS (0.88 m) and is given in cm:

$$z = 100 (Z + 0.88)$$

(2.13)
(6) As the SIS does not incorporate a TVG, a correction of backscatter attenuation with distance from the source has to be applied on the bed backscatter data. Since the SIS is fixed on a frame, the distance travelled by the acoustic wave before reaching the seabed is dependant on beam angle (Figure 2.9a). The relationship between the absolute magnitude of the beam angle and the backscatter ($|\theta|$, backscatter) is calculated using a linear regression applied to all bed backscatter intensities of a given site (Figure 2.9b). The trend is subsequently removed from the backscatter data. The relationship between the absolute magnitude of the beam angle and the bed backscatter usually has a low correlation coefficient ($R^2$ is typically between 0.1 and 0.2). This is due to the large number of points for each site (around 15 000) and the high scatter in backscatter intensities created, for example, by the seabed characteristics (e.g. sediment size and sorting, bed slope or flora presence). However, as the p-value is usually very small ($< 0.00001$), the probability of obtaining a result at least as extreme as the one that is actually observed is very low and the null hypothesis can be considered true.

(7) If the seabed is particularly soft i.e. a muddy seabed, the feet of BRAD may sink into the sediment during deployment. Feet differential settling induces an artificial slope in the data. If this occurs, the data must be de-trended to remove this effect. A regression is applied on the x and y-axes and the trend so defined is removed from the bed elevation data.
(8) A final visual control of the data is carried out before saving the data. If a point is ‘ambiguous’ - that is, considered as a false return from the water column for example - it is removed. As the sites are usually observed visually prior or during deployment, any object protruding from the seabed (e.g. shells or rocks) and therefore creating high bed elevations, is identified and can be differentiated from a false return.

(9) The final data set is saved as an ASCII file containing the (x, y, z) co-ordinate of the bed elevation values for each beam of each sweep and the associated bed backscatter and corrected bed backscatter intensities. Between 150 and 200 sweeps, each composed of 101 beams, are recorded per site and hence each site comprises a matrix of around 15 000 data points of bed elevation and backscatter values.

**Special case: site over a seagrass canopy**

When a sound wave reaches submerged vegetation, such as a seagrass canopy, some of the acoustic energy is reflected from the seagrass back to the source, creating a strong backscatter above the bed (Sabol et al., 2002). Along beams recorded while BRAD was deployed over a seagrass canopy, a high backscatter response was seen from both the seabed and the seagrass canopy and can be differentiated from ambient noise (Figure 2.10). In that case, the first point satisfying the threshold condition may be either a reflection from the seabed or from the seagrass canopy. As the SIS is situated at a height of 0.88 m, the seabed can be seen as a high backscatter at around $Z = -0.88$ m and the top of the canopy is situated at $Z > -0.88$ m. Several methods were tested to compute both the height of the seabed and the height of the canopy. The method used here assumes that the bed under the canopy is relatively flat and situated no more than 4 cm above the theoretical depth of the bed ($Z = -0.88$ m). Along a beam, the depth of bed is computed as the first point where $Z < -0.84$ and $Q(Z) > 0.8$ (Figure 2.10). The height of the seagrass is calculated as the first point where $Z > -0.84$ and $Q(Z) > 0.6$; if no points satisfy the condition, no value is recorded. The threshold value for seagrass detection is lower than for the bed detection (0.6 and 0.8 respectively) because the backscatter intensity on the canopy was found to be variable and often (but not always) lower than the bed backscatter.
The processing method described for bed detection over bare seabed is applied to data collected over a seagrass canopy apart from the depths of the bed and the seagrass canopy, which are computed as detailed above. Two files are produced from processing of data acquired over a seagrass canopy: (1) bed elevation and backscatter values and (2) canopy height and backscatter values.

**b. Interpolation**

The second step in data processing is to interpolate elevation values and backscatter intensities to create a regular grid from which the bed elevation and backscatter intensities images are created. This step also enables to generate a file with the same grid for all sites and therefore reduces bias which might appear during further analysis. To do so, the ASCII files created during the first step of data processing are imported into ArcMap on a user-made co-ordinate system (plane projection conserving distances, origin of the system as...
indicated on Figure 2.4, metric system). The Kriging method (Oliver and Webster, 1990) is used to interpolate bed elevation values and backscatter intensities in order to generate a continuous data set in a grid format - a raster - with a cell size of 0.01 m. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface (Childs, 2004). This assumption can be considered true in the case of seabed elevation where sharp variations in seabed elevation rarely occur at a centimetre scale. The interpolation slightly smooths the data, but as it takes into account the correlation between the different neighbouring points, it also reduces the scatter. Several values have been tested to determine which cell size should be used for the interpolation. To interpolate data at a small cell size results in high interpolation between 2 data points, which may produce inaccurate seabed elevations. By contrast, interpolation on a large cell size smoothes seabed elevations and therefore may remove small-scale variations; it also produces a poorer display. The raster cell size (1 cm) was chosen to be slightly smaller than the horizontal resolution (approximately 1 to 3 cm). Each cell contains on average 0.8 data points, i.e. some cells are interpolated between data points but most cells contain at least one data point. Images of bed – and seagrass, if present – elevations and backscatter intensities are created in ArcGIS and the interpolated data are then exported as an ASCII file to be processed further.

c. Statistics and spectral analysis

The third processing step is to calculate statistical parameters on elevation values and backscatter intensities and to spectrally analyse elevation values. Statistical parameters are computed from the interpolated data of bed elevation – and canopy height if present - and backscatter intensity. In order to reduce bias due to dataset size, a constant number of points needs to be analysed for each site. The extent of data considered is dictated by the smallest dataset available. Presently, the analysis is performed on a rectangle of 90 cm along the transverse axis and 125 cm along the range axis. The average elevation is subtracted from each elevation value and the statistics summarised in Table 2.2 are calculated from the bed elevation and backscatter intensity distributions. Nominally, the statistical parameters calculated are: root mean square (rms), interquartile range (IQR), median absolute deviation (MAD), standard deviation (stdev), skweness and kurtosis. The mean corrected backscatter intensity of each site is also calculated.
At present, two methods are used for spectral analysis. The first method (method 1) was
developed by Cazenave et al. (2008) to calculate bedform direction, wavelength and height
from high-resolution (decimetric) swath data. The processing methodology is summarised
in this section and the reader should refer to the original paper (Cazenave et al., 2008) for a
complete discussion of the technique. At each site, a square box of data points is extracted
from the whole dataset. The size of the box depends on the initial length of data available
in the x-axis (typically 120 cm); if the stabilising bars are at the bottom, the data retained
for the analysis exclude the bars, which constitute artificial roughness element and would
bias the results. First, the dataset mean elevation is subtracted from each point and the
origin of the system is translated to the left bottom corner of the image (Figure 2.11a,
example of a synthetic ripple field under random noise). A 2D Fast Fourier Transform is
then applied to the seabed elevation data. By definition, the smallest frequency spacing \( \Delta \lambda \)
on which it is sensible to compute the DFT is the inverse of the signal duration, \( \Delta \lambda = 1 / (n \times D) \),
where \( D \) is the horizontal distance between 2 consecutive data points and \( n \) is the total
number of sample points (Jenkins and Watts, 1968); to compute the DFT on a finer
frequency spacing does not convey any additional information. The DFT is therefore
computed with a frequency spacing of about 0.8 m\(^{-1}\) (\( D \) is 0.01 m after interpolation and \( n \)
is typically 120 in x and y directions).

Although the data are detrended, large-scale features (long wavelengths i.e. low
frequencies) are still present and will contain high power in the DFT, which may mask the
higher frequencies that are of interest (Cazenave et al., 2008). They can be ‘cut off’, i.e.
artificially put at low values. Using method 1, all the spatial frequencies smaller than 3.3
m\(^{-1}\) (wavelength bigger than 0.30 m) are given low power spectrum values. The spectrum
is then normalised to the highest power value and plotted against x and y-frequencies
(Figure 2.11b).

Peaks in the spectrum show the most significant wavelength and amplitude components in
the input data, i.e. ripples wavelength and direction if present. If no bedforms are present in
the site analysed, the peaks show the amplitude and wavelength of features on the seabed.
The output of a Fourier transform comprises positive and negative components hence the
spectrum has two peaks which mirror each other. For ease of understanding, only the peaks
in the positive part of the plot are used to interpret the results. A threshold value of 66%
(2/3) of the maximum power is used in order to distinguish significant peaks from
background noise. The direction and spatial frequency of the peaks satisfying the threshold condition are calculated and plotted against x and y frequencies (Figure 2.11c).

![Figure 2.11: a. Synthetic seabed elevation showing a ripple field (wavelength 10 cm, direction 120° and amplitude 1 cm) and random noise; b. 2D spectrum showing 2 clear peaks (negative and positive components) associated with the ripple field; the frequencies which have been cut off are visible as deep blue in the middle of the spectrum; c. the blue points show peaks with power superior to 2/3 of the spectrum maximum power; \( \gamma_1 \) is the angle between the y-axis and the direction of the peak, \( \gamma_2 = \gamma_1 \pm 90^\circ \) indicates the bedform direction. The black circle shows the bedform spatial frequency (inverse of wavelength). The method calculated a bedform wavelength of 9.5 cm, direction of 119° and amplitude of 0.95 cm, showing good correspondence with input data.]

If peaks are separated by less than 5°, they are assumed to belong to the same bedform field and so the average direction and wavelength of those points are calculated. The peak orientation is given in degrees as the angle from the vertical to the peak value (\( \gamma_1 \) on Figure 2.11c). If the orientation of the frame is known, the direction of the bedforms to north can
be given. However, frame direction was not recorded for the datasets analysed in this study, so peak directions are given as the angle from the y-axis. Bedform direction is normal to peak direction ($\gamma_2 = \gamma_1 \pm 90^\circ$, Figure 2.11c). The bedform wavelength is calculated as the inverse of the peak spatial frequency. At present, the program uses the rms roughness as an estimate of the bedform amplitude.

The second method used in this study to spectrally analyse the data was used by Lyons et al. (2002) to characterise the 2D roughness of a rippled bed imaged with digital photogrammetry. The processing method is summarised here and the reader should refer to the original paper (Lyons et al., 2002) for a more detailed description. The first step is the same as the previous method; that is, to subtract mean elevation and translate the origin of a square box taken out of the original dataset. The second step is to multiply the data by a tapering function. Bias, or spectral leakage, is a common problem in nonparametric spectral estimations and is caused by the finite size of data segments used for analysis (Jenkins and Watts, 1968). Data tapering is often used to mitigate bias effects. While reducing bias, data tapering also causes a reduction of resolution, or a smoothing effect, in the spectral estimate (Figure 2.12). As in the original paper (Lyons et al., 2002), a DPSS (Discrete Prolate Spheroidal Sequences) taper is used (see Percival and Walden, 1993 for a complete discussion of DPSS). The dataset is then padded with zeros to yield 256 ($2^8$) rows and columns resulting in an artificially increased frequency resolution of around 0.47 m$^{-1}$. A 2D FFT is next applied to the seabed elevations. In order to accentuate the energy at lower frequencies, the spectrum is given in logarithmic form:

$$S = 10 \log_{10} (|s|^2)$$  \hspace{1cm} (2.14)

where $s$ is the spectrum output of the 2D FFT and $S$ the spectrum power in dB. Using method 2, frequencies smaller than 2 m$^{-1}$ (wavelength larger than 0.5 m) are cut off. ‘Slices’ are then taken through the 2D roughness spectrum in one degree steps from $0^\circ$ to $180^\circ$. Each slice through the 2D roughness spectrum is a 1D representation of the 2D roughness spectrum in a particular orientation, but it is not the same as the 1D roughness spectrum roughness estimated from a 1D profile (see Briggs et al., 2005 for a discussion of 1D and 2D datasets). A power-law regression is fitted on the spectrum of slices taken along and at $90^\circ$ to the peak having the most energy (computed with method 1) and on the spectrum calculated from the average of all the slices (e.g. Figure 2.3c). The slope and intercept (at 10$^6$) of the power-law regression lines are then calculated.
2.3.3. Sediment analysis

Sediment samples collected on sites are analysed in the sediment dynamics lab at NOCS, University of Southampton. They are first wet sieved to separate them according to their grain diameter $\phi$ into mud ($\phi < 63 \, \mu m$) and sand and gravel ($63 \, \mu m > \phi$). Each fraction is dried in the oven over night at 50°C and weighed to determine their dry weight.

The mud fractions are analysed using a Coulter LS 130 Laser Diffraction Size Analyser, that measures grain size distribution from 0.4 to 1000 $\mu m$. The method uses the forward scattering of a laser beam by particles from the properties of the diffraction pattern that is produced (Hoey, 2004). The sand fraction is dried in the oven at 380°C over night to burn off organic matter and is re-weighed. The samples are then dry sieved by mechanical shaking for 15 min with a series of standard test sieves with successively smaller mesh sizes decreasing by 0.5 phi steps, from -1 phi (2 mm) to -4 phi (16 mm).

The weights from the Coulter Sizer and dry sieving are then combined in order to generate a complete particle size distribution (PSD). Statistic parameters are calculated following definition by McManus (1988).
CHAPTER 2

2.4. BRAD LABORATORY TESTS

2.4.1. Introduction and objectives

BRAD was tested in a controlled environment using facilities at NOCS. The tank used in this study was free of the presence of currents and waves, which in the field could create bubbles, of gradient in temperature or salinity, which would affect the speed of sound and of sediment suspension that would influence the backscatter response. The clear, still-water of the tank ensured that testing of shape recognition and backscatter response of BRAD to grain size could be verified against objects of known shapes and sediment of known grain size. The objectives of BRAD lab-testing were to:

(1) test the data processing method;
(2) compare the vertical and horizontal resolutions with the theoretical values;
(3) validate the motor velocity equation and examine the differences between the same sites scanned in opposite directions and at different velocities; and
(4) investigate the relationship between backscatter and sediment size.

Table 2.6: Summary of BRAD test deployments; by convention, SIS direction is positive when the SIS is travelling away from the motor.

<table>
<thead>
<tr>
<th>Deployment</th>
<th>Voltage applied to motor (V)</th>
<th>Motor velocity (mm s⁻¹)</th>
<th>SIS direction</th>
<th>Targets</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>0.46</td>
<td>+</td>
<td>1 - 8</td>
<td>Shape recognition, resolution</td>
</tr>
<tr>
<td>2a</td>
<td>14</td>
<td>0.46</td>
<td>-</td>
<td>3, 4, 9, 10</td>
<td>Shape recognition, resolution, ripples imaging, influence of direction, influence of velocity</td>
</tr>
<tr>
<td>2b</td>
<td>14</td>
<td>0.46</td>
<td>+</td>
<td>3, 4, 9, 10</td>
<td>Shape recognition, resolution, ripples imaging, influence of direction, influence of velocity</td>
</tr>
<tr>
<td>2c</td>
<td>17</td>
<td>0.56</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>14</td>
<td>0.46</td>
<td>+</td>
<td>11 – 13 + sediment</td>
<td>Shape recognition, backscatter sensibility, influence of velocity and direction</td>
</tr>
<tr>
<td>3b</td>
<td>20</td>
<td>0.66</td>
<td>-</td>
<td>11 – 13</td>
<td>Shape recognition, backscatter sensibility, influence of velocity and direction</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>0.46</td>
<td>+</td>
<td>sediment</td>
<td>Backscatter response to sediment size</td>
</tr>
</tbody>
</table>

2.4.2. Laboratory deployments settings

BRAD was deployed over 2 days in the acoustic test tank in the National Marine Facilities Division Workshop at NOCS. The test tank, filled with freshwater, is 5 m long, 4 m wide, 2 m deep and equipped with a crane. Different targets and sediment types were
positioned on the floor beneath BRAD, which then scanned the water column and targets. To facilitate deployment, objects and sediment were placed in trays, which often did not stay horizontal during the deployment process and so the targets were moved from their initial position inside the trays. As a result, the precise positions of targets during deployment could not be recorded. A total of 4 deployments were undertaken (Table 2.6). Objects tested included fossilised ripples on a rock slab, sand peel, standard shaped objects in lead, a ship model containing both wood and metal, and different sediment types such as sand, gravel and shells (Table 2.7).

Table 2.7: Description and sizes of the targets used during BRAD test deployments.

<table>
<thead>
<tr>
<th>Target</th>
<th>Material</th>
<th>Size (cm)</th>
<th>Height (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plastic and sand</td>
<td>3.8 diameter</td>
<td>4</td>
<td>Plastic tube filled with fine sand ($d_{50} = 0.2$ mm)</td>
</tr>
<tr>
<td>2</td>
<td>Metal</td>
<td>6 x 5</td>
<td>3</td>
<td>Metal L bracket</td>
</tr>
<tr>
<td>3</td>
<td>Lead</td>
<td>19 x 3.8</td>
<td>3.8</td>
<td>Rectangle shape made of lead</td>
</tr>
<tr>
<td>4</td>
<td>Lead</td>
<td>3.8 x 3.8</td>
<td>3.8</td>
<td>Square shape made of lead</td>
</tr>
<tr>
<td>5</td>
<td>Lead</td>
<td>6.4 x 6.4</td>
<td>6.4</td>
<td>Square shape made of lead</td>
</tr>
<tr>
<td>6</td>
<td>Lead</td>
<td>12.8 x 6.4</td>
<td>6.4</td>
<td>Rectangle shape made of lead</td>
</tr>
<tr>
<td>7</td>
<td>Lead</td>
<td>11.5 x 3.8</td>
<td>3.8</td>
<td>Rectangle shape made of lead</td>
</tr>
<tr>
<td>8</td>
<td>Solidified sand</td>
<td>33 x 31</td>
<td>2</td>
<td>Sand peels: sand from a core solidified with epoxy</td>
</tr>
<tr>
<td>9</td>
<td>Rock</td>
<td>21 x 23</td>
<td>5</td>
<td>Rock slab with fossilised bedforms</td>
</tr>
<tr>
<td>10</td>
<td>Rock</td>
<td>40 x 25</td>
<td>2.5</td>
<td>Rock slab with fossilised ripples (5.2 cm long, less than 1 cm high)</td>
</tr>
<tr>
<td>11</td>
<td>Rock</td>
<td>25 x 13</td>
<td>7.5</td>
<td>Rock slab with fossilised ripples (3.5 to 5 cm long, less than 1 cm high)</td>
</tr>
<tr>
<td>12</td>
<td>Rock</td>
<td>28 x 15</td>
<td>4.5</td>
<td>Rock slab with fossilised ripples (5.5 cm long, less than 1 cm high)</td>
</tr>
<tr>
<td>13</td>
<td>Wood and metal</td>
<td>54 x 12</td>
<td>6 (wood) + 3 (weights)</td>
<td>Ship model in wood with 2 metal weights on top</td>
</tr>
</tbody>
</table>

The data collected during these 2 days were processed using the methods detailed in section 2.3.2. The height of the trays used to contain the targets created acoustic shadows beyond the edges (Figure 2.13). When the whole image was interpolated, the steep gradients created by the sides of the trays were smoothed; the bottom of the tray next to the side thus appeared higher than it was in reality. To avoid that effect, the inside of the trays
were interpolated separately from the remaining image. The Natural Neighbour method was used to interpolate the data rather than the Kriging method. The Natural Neighbour method uses only the points directly around the interpolated points and hence it conserves the heights of the initial points and reduces deformation caused by the sharp edges imaged during the testing. Although it was impossible to measure the exact positions of the targets, the objects tested were measured and photographed individually prior to immersion and during deployment. All photos contained a scale and so it was possible to compare target dimensions from photos and BRAD results. During deployments of trays filled with sediment, the sediment had a tendency to collect on one side of the tray and creating bed slopes. Deployment procedures meant that it was not possible to measure the slope, only to detect the direction of the slope.

Figure 2.13: Input points and interpolated image of test 1. Acoustic shadows created by the container result in the inability to image directly around the sides of the tray. Also distortions can be seen at the corners of the tray.
2.4.3. Results

a. Deployment 1

The first deployment consisted of a tray containing 8 targets of different sizes and shapes scanned at a motor speed of 0.46 mm s\(^{-1}\). The objective of this first deployment was to test BRAD shape recognition and accuracy. To do so, the images constructed from BRAD data were compared to target photographs (Figure 2.14). Five distinct shapes, out of the 8 targets, were identified on the image. Targets 2 and 3 as well as 6 and 7 were side by side, hence they appeared as one object on the image. Targets 5 and 8 were separated by a few centimetres but were still imaged as one object, probably due to the narrow space between them (5 to 15 cm) and perturbations created by the sound reflected back from the lead. The targets’ actual dimensions were compared to those calculated from the images (Table 2.8). All the targets appeared bigger in the image than they were in reality, on average 20% longer and wider and 30% higher than measured. The higher objects were more distorted and appeared proportionally wider, certainly due to acoustic shadowing. By contrast the dimensions of smaller objects, e.g. Target 8, which had smaller vertical dimensions than the targets in lead, were better evaluated. Target 1 was a plastic tube 3.8 cm in diameter filled with sand. Although the dimensions of the object were the same as those of the footprint, which made it difficult to image correctly, the reconstructed image showed a circular shape, only slightly bigger than actual due to shadowing and interpolation smoothing. Linear regression applied to the measured dimensions against the reconstructed ones shows a good correlation between the 2 datasets (Figure 2.15). The y-intercept is equal to 1.63 cm suggesting than objects smaller that 1.63 cm can not be discriminated by BRAD. This agrees well with theoretical values (see Table 2.4). Furthermore, the linear regression slope of 0.94 suggests that the difference between measured and reconstructed values decreases with increasing object height.

Overall, the shapes were discriminated, i.e. square objects appeared square. However, slopes were smoothed, as expected. Target 2, a piece of metal bent into an L shape, appeared on the image as a cube. The bend was high in the middle and the object was only slightly bigger than the footprint and so the slope could not be recorded from the acoustic data, which explains why the object appeared as a cube.
Figure 2.14: Photo of BRAD deployment 1, with associated schematic and elevation images in 2D and 3D perspectives.
Table 2.8: Comparison of target dimensions measured and reconstructed using BRAD.

NaN = dimensions which could not be clearly determined.

<table>
<thead>
<tr>
<th>Target</th>
<th>Measured (real) Dimension (cm)</th>
<th>Measured (real) Height (cm)</th>
<th>Reconstructed (BRAD) Dimension (cm)</th>
<th>Reconstructed (BRAD) Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.8</td>
<td>4 cm</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>6 x 5</td>
<td>3</td>
<td>7 x NaN</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>19 x 3.8</td>
<td>3.8</td>
<td>20 x 4.2</td>
<td>4.8</td>
</tr>
<tr>
<td>4</td>
<td>3.8 x 3.8</td>
<td>3.8</td>
<td>6.2 x 3.8</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>6.4 x 6.4</td>
<td>6.4</td>
<td>7 x NaN</td>
<td>7.5</td>
</tr>
<tr>
<td>6</td>
<td>12.8 x 6.4</td>
<td>6.4</td>
<td>15 x 11</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>11.5 x 3.8</td>
<td>3.8</td>
<td>NaN</td>
<td>NaN</td>
</tr>
<tr>
<td>8</td>
<td>33 x 31</td>
<td>2</td>
<td>33 x 32</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 2.15: Measured versus reconstructed horizontal dimensions (blue) or vertical dimensions (black). The linear regression line applied to the data is also shown with its equation and correlation coefficient

\[ y = 0.94x + 1.63 \]

\[ R^2 = 0.98 \]

\[ p < 0.0001 \]

b. Deployment 2

During a second deployment, a tray was scanned back and forth at a motor speed of 0.46 mm s\(^{-1}\) and once more at 0.56 mm s\(^{-1}\). The targets imaged during this deployment were rock slabs of fossilised ripples (Targets 9 and 10), standard geometric shapes in lead (Targets 3 and 4) and sediment (not shown here, but results used during analysis of deployment 4). The objectives of this second deployment were (1) to test if the ripples could be imaged correctly despite their small dimensions and if the method developed to calculate ripples dimensions (method 1) could be tested and (2) to determine if changes in scanning direction and motor velocity influenced the results.
The three images constructed from BRAD data show similar results (Figure 2.16). The horizontal dimensions were similar for all three images, indicating that the relationship between current voltage on the motor, motor velocity and distance between 2 sweeps was valid and predictable. Moreover, the direction of travel of the SIS had no impact on the final produced image. A higher motor speed did not result in a loss of accuracy; the ripples were seen as well if not better when the bed was scanned with a motor speed of 0.56 mm s\(^{-1}\) instead of 0.46 mm s\(^{-1}\). Targets elevations calculated from the three different runs were in good agreement; less than 10% differences in height were detected between the three runs.

The floor was clearly detected on all three images when the distance between Targets 9 and 10 was more than 3 cm, i.e. the distance separating the objects had similar dimensions as the average size of the footprint (3.5 cm). Target 4 was situated at less than 1 cm from Target 8 and between 2 and 5 cm from Target 9. As a consequence of the small distance between the targets, they appeared joined in the images.

Targets 9 and 10 were slabs of rock with fossilised bedforms. Bedforms on Target 9 were irregular, sinuous, sharp-crested ripples (see photo on Figure 2.16). As the ripples did not present a regular wavelength, a spectral analysis would not reveal any preferential frequency and no processing was applied to this dataset to characterise bedform dimensions. On Target 10, the fossilised ripples had a measured wavelength of 5.2 to 5.8 cm and a height of nearly 1 cm. Despite their small dimensions, the ripples could be clearly recognised on all three images. Due to the small area over which the ripples were imaged and the small number of ripples, method 1 applied on the data did not give significant results. Ripple dimensions were therefore computed using a method adapted from Dr Neumeier (Matlab codes, http://neumeier.perso.ch/index.html) to compute wave parameters.

Profiles were created with ArcGIS across the bedforms (Figure 2.16). Smoothing of the crests could be observed due to the inherent difficulty to image steep slopes with acoustics systems. Ripple wavelengths were calculated by averaging the distance between 2 adjacent maxima (ripple crests). Ripple height was computed as the average height difference between minima (ripple troughs) and maxima. Overall, the computed dimensions agreed well with the actual measurements, although they appeared to be slightly bigger (wavelength 5.5 cm) for the fastest motor velocity than the slowest (wavelength 6 cm). However, this difference is small and BRAD proved its ability to image ripples.
Figure 2.16: BRAD images from deployment 2 with associated ripple profiles. On the profiles, the y-axis is exaggerated compared with the x-axis.
c. Deployment 3

A third deployment was undertaken to image Targets 11, 12 and 13 at a motor speed of 0.46 and 0.66 mm s\(^{-1}\). Targets 11 and 12 were rock slabs of fossilised ripples and Target 13 was a ship model made of a piece of oblong wood with 2 metallic disks on top. The objectives of the deployments were to test ripple imaging and assess if the density differences between metal and wood causes a difference in backscatter.

There were good similarities between the images scanned at different traversing velocities (Figure 2.17). Although the overall target shapes could be recognised in the images, the ripples on both Targets 11 and 12 could not be discriminated and the targets were seen as flat. Ripples on Target 11 were around 2 mm high, which is less than the effective vertical resolution on BRAD. Thus, it is not surprising that they were not imaged correctly. On the other hand, ripples on Target 12 had a wavelength of 5.5 cm and a height of about 1 cm. Hence, they should have been imaged, as the ripples on Target 10, having similar dimensions, were imaged during the previous deployment. Ripples on Target 12 were very sharp-crested, which might explain why they could not be identified on the images. Furthermore, acoustic perturbations created by the metallic disks might have influenced the detection of the objects next to them. The overall shape of Target 13 was correctly imaged; the two metallic disks on top of the wood however, did not show any relief and could not be clearly identified either by their elevation or backscatter. This may be due to strong reflections off the target surface and backscatter saturation on the metal. No clear difference in backscatter was seen between the metal, the wood and the rock samples (Figure 2.17d). The scatter of backscatter values on each material was found to be higher than the overall difference in backscatter between the objects.

d. Deployment 4

A fourth deployment was carried out over trays filled with gravel, sand and shells of different size and scanned at a motor speed of 0.46 mm s\(^{-1}\). The objective of this deployment was to investigate the relationship between backscatter intensity and sediment size. Some of the trays had also been scanned during deployments 2b, 2c and 3a in order to provide data with different settings.
Figure 2.17: BRAD images from deployment 3. a. bed elevation of the bed scanned at + 46 mm s$^{-1}$; b. 3D view of the same bed; c. bed elevation of the bed scanned at − 0.66 mm s$^{-1}$; d. backscatter intensity of the bed scanned at + 0.46 mm s$^{-1}$.
The shape of the trays and targets inside them were clearly identified from the elevation data (Figure 2.18a). On the backscatter images, the sides of the trays (in plastic) had a lower backscatter than the sediment and thus could be easily discriminated (Figure 2.18b). The correction for backscatter diminution with increasing grazing angle seemed to be valid. Before correction, the backscatter was highest at nadir and decreased towards the sides (Figure 2.18b); after correction, the backscatter remained unchanged at nadir whereas to the sides of the image, it was higher than before correction and has the same intensity as at nadir (Figure 2.18c). It was noticed that when a flat shell was present in the tray scanned, a high backscatter was seen in the whole water column when the sound was strongly reflected off the shell (Figure 2.19). However, this phenomenon did not seem to affect the bed elevation data.

Figure 2.18: Images of BRAD deployment 4. a. bed elevation; b. backscatter; c. corrected backscatter. The sediments imaged during this deployment comprised sand (S1 and S2), gravel (G1) and shells (Sh). See Table 2.9 for more details.
Table 2.9 summarises the results of the statistics calculated from backscatter intensities together with sediment characteristics and run settings. No significant difference in mean backscatter was found between the different grain sizes since the distributions standard deviations were always bigger than the differences in means. However, when the same settings were used to image different sediment sizes, gravel always had a slightly higher average backscatter than sand (Figure 2.20); yet, the high standard deviation meant that the relationship was not significant. If settings, such as motor velocity, scan direction or size of the area investigated, were changed, the backscatter distribution was greatly affected, e.g. a higher motor velocity resulted in a lower mean backscatter for all grain sizes. It is therefore concluded that the range of sediment tested here could not be interpreted on the basis of their backscatter response alone as settings had an important influence on backscatter intensities. However, if two sediment sizes were investigated with the same settings, a higher average backscatter implied coarser sediment.

Figure 2.19: Intensity of the backscatter for sweep 20, deployment 2a, showing the high backscatter created by reflection off a shell. Bed position is also shown.
Table 2.9: Summary of backscatter statistics and associated grain sizes from BRAD calibration, see Figure 2.18 for sediment position.

Stdev = standard deviation; rms = root mean square; IQR = interquantile range; MAD = mean absolute deviation. Direction: positive is travelling away from the motor.

<table>
<thead>
<tr>
<th>deployment</th>
<th>2b</th>
<th>2c</th>
<th>3a</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>run settings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>motor velocity (mm s(^{-1}))</td>
<td>0.46</td>
<td>0.66</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>direction</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>mean depth (cm)</td>
<td>8.12</td>
<td>9.49</td>
<td>8.08</td>
<td>9.45</td>
</tr>
<tr>
<td>sediment name</td>
<td>S1</td>
<td>G1</td>
<td>S1</td>
<td>G1</td>
</tr>
<tr>
<td>median grain diameter (mm)</td>
<td>0.21</td>
<td>9.32</td>
<td>0.21</td>
<td>9.32</td>
</tr>
<tr>
<td>sorting</td>
<td>0.39</td>
<td>0.33</td>
<td>0.39</td>
<td>0.33</td>
</tr>
<tr>
<td>backscatter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>223</td>
<td>226</td>
<td>209</td>
<td>211</td>
</tr>
<tr>
<td>stdev</td>
<td>13.0</td>
<td>13.5</td>
<td>13.5</td>
<td>14.1</td>
</tr>
<tr>
<td>rms</td>
<td>5.6</td>
<td>5.5</td>
<td>6.2</td>
<td>6.1</td>
</tr>
<tr>
<td>IQR</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>MAD</td>
<td>10.3</td>
<td>10.5</td>
<td>10.6</td>
<td>11.0</td>
</tr>
<tr>
<td>number of elements</td>
<td>1621</td>
<td>1717</td>
<td>1134</td>
<td>1181</td>
</tr>
</tbody>
</table>

Figure 2.20: Average backscatter for different types of sediment with associated standard deviations. See Table 2.8 for sediment characteristics.
2.4.4. Discussion

The deployments carried out in the acoustic test tank were performed to test BRAD response to different settings, shapes and types of material. The horizontal resolution of BRAD was found to depend on the relative height of the objects, the sharpness of the edges and the distance between the targets. The system detection limit was calculated to be around 2 cm, i.e. features with horizontal dimensions smaller than 2 cm will not be discriminated using BRAD. Furthermore, the acoustic shadows created by objects protruding from the floor made small objects appear bigger than they actually were. Acoustic shadowing also meant that some objects could not be imaged because they were under a bigger object shadow. In addition, if a rapid change in bed elevation occurred at the scale of the acoustic footprint, the first strong acoustic echo was recorded as the depth of the bed and therefore, steep slopes were smoothed. This is a well-known effect of high resolution acoustic instruments (Green and Boon, 1988; Greenwood et al., 1993) and is inherent to them. Due to the combination of shadowing, slope smoothing and interpolation smoothing, sharp edges of objects will in general appear distorted. However, sharp edges are rarely encountered in the field so are not considered a significant problem in this study.

Small fossilised ripples on the surface of rock slabs were successfully imaged with BRAD, except when ripple wavelengths were too small to be discriminated or perturbations produced by nearby objects prevented correct imaging. Correct imaging of ripples with centimetre height confirms BRAD sub-centimetre vertical accuracy. Profiles created over the ripples were used to define ripple dimensions. Although the troughs and crests were smoothed, the dimensions calculated from BRAD agreed well with the measurements. Similar smoothing of ripples has been reported for other high-resolution acoustical seabed imagery (Green and Boon, 1988; Greenwood et al., 1993; Jetté and Hanes, 1997; Bell and Thorne, 1997a; 1997b). In those studies, ripple crests and troughs were smoothed as observed on elevations reconstructed from BRAD data.

No loss of accuracy was recorded by varying the motor velocity. A motor velocity of 0.46 mm s\(^{-1}\) did not give any more information than 0.56 mm s\(^{-1}\) but took 10 minutes longer to scan the bed. Therefore, a motor velocity of 0.56 mm s\(^{-1}\) (power supply voltage of 17 V) is advised to be used in future surveys. Backscatter intensity, on the other hand, was found to be sensitive to motor velocity. The highest motor velocity resulted in the lowest average backscatter. It is therefore advised to keep a constant motor velocity for all
deployments in order to facilitate backscatter comparison. The images were the same when scanned backwards or forwards. Direction of imaging therefore did not affect data quality and do not need to be taken into account.

No significant difference in backscatter was found between different material types. The metal, wood and rock were clearly imaged as separate targets, but it was impossible to determine material type from the backscatter intensity alone. This is coherent with results from studies performed with side scan sonars (e.g. Quinn et al., 2005), which showed that targets of different materials could not be identified clearly out-of-context based only on backscatter response. In this laboratory study, no direct relationship was found between sediment size and backscatter intensity. However, if two sites were imaged with the same settings, a higher average backscatter indicated coarser sediment. These results are in general agreement with acoustic theory where coarser sediment showed higher backscatter (e.g. Goff et al., 2000; Collier and Brown, 2005). Nevertheless, the standard deviation of the backscatter distribution was always higher than the difference between the average backscatter. Moreover, changes in motor velocity or sample size had more effect on the average backscatter than changes in sediment size. This might be due to the small size of the sample examined here; backscatter intensities averaged over a whole image produced by BRAD might show better results. However, BRAD backscatter intensities should be analysed with care and should not be compared if BRAD settings are changed between measurements.

A threshold method was chosen to detect the seabed, a method frequently used for seabed detection in high-resolution acoustic data (e.g. Greenwood et al., 1993; Jetté and Hanes, 1997). The threshold method developed here uses a coefficient \( Q \) calculated using the maximum backscatter along a given beam and the average backscatter 0.3 to 0.5 m from the SIS head. This coefficient therefore facilitates the removal of the influence of seabed characteristics, water column backscatter intensities and beam angle. The method established to process BRAD data does not require a complicated algorithm to model the bed echo as do other methods (Bell and Thorne, 1997a; 1997b) and thus data processing is faster than if the bed echo was modelled for the 15 000 beams recorded at each site. Although the bed detection method was found to be generally accurate, some false returns were detected in the test deployments. It was decided not to check the tests files for false return since strong variations in height were created by the trays and targets and could not
be easily differentiated from false returns. In the field however, steep changes in bed elevations are rarely encountered, or if seen, are likely to be localised, for example shells or small rocks protruding from the seabed. These rare events may be taken into account during data checks so false returns can be differentiated from ‘real’ higher elevations and removed.

2.4.5. **Summary of BRAD laboratory test**

The Benthic Roughness Acoustic Device developed at NOCS has been successfully tested in a control tank. A range of targets and sediment types were scanned and data were processed using an algorithm developed specifically to analyse BRAD data. A number of conclusions can be drawn from BRAD lab test:

1. the algorithm developed to process the data was successfully validated;

2. the system was found to image correctly various shapes however shadowing and interpolation resulted in smoothing of geometric forms and shadowing meant that a loss of accuracy occurred when objects protruded from the seabed;

3. small ripples were imaged and ripple dimensions calculated from BRAD images agreed well with measurements;

4. vertical resolution was confirmed to be sub-centimetre and horizontal resolution to be in the order of 2 cm at nadir, decreasing with increasing beam angle;

5. it was concluded that a motor velocity of 0.56 mm s\(^{-1}\) was optimum as it gave adequate resolution and took 10 min less time than at 0.46 mm s\(^{-1}\); and

6. targets could not be differentiated on the basis of backscatter alone; however, when several grain sizes were scanned within the same bed, bigger grain sizes yielded higher backscatter.
2.5. **FIELD DEPLOYMENT**

2.5.1. **Introduction and objectives**

Stereo-photography has been used to characterise bed roughness from 1D and 2D high-resolution seabed elevation data (e.g. Wheatcroft, 1994; Lyons et al., 2002; Briggs et al., 2005). Stereo-photography is a good method to produce images of seabed elevation, however, the field of view is often small and water turbidity can limit data quality. Acoustic systems have the potential to produce high-resolution images (2D) of the seabed elevation. To date, however, high-resolution acoustic systems produce only profiles of seabed elevation (1D) which were used principally to study ripple dimensions (e.g. Bell and Thorne, 1997a; 1997b). As discussed previously, this can be limiting as roughness is a spatially-varying parameter and the direction of the profile can have an important effect on the resulting analysis (Richardson et al., 2001). It is therefore considered an advance to be able to produce 2D images of seabed elevation through high-resolution acoustic measurements. Bed roughness has been characterised from stereo-photography using spectral analysis (e.g. Akal and Hovem, 1978; Briggs, 1989; Briggs et al., 2005). To date, spectral analysis has not been used on high-resolution 2D images of seabed elevation produced from acoustic data. In this study, we intend to test the application of spectral analysis on seabed topography computed from BRAD.

The seabed types investigated during previous studies using stereo-photography ranged from smooth beds (e.g. Wheatcroft, 1994) to ripple fields (e.g. Lyons et al., 2002) and bioturbated beds (e.g. Briggs et al., 2001). Although numerous seabed types have been examined, no studies have shown measurements of seagrass canopy elevation and morphology in conjuncture with seabed elevation, possibly due to system limitations (difficulty in imaging a moving canopy and the bed under the canopy with stereo-photography). As the acoustic pulse penetrates the vegetation, the elevation of both the canopy and the seabed can be computed from BRAD data. It is therefore possible to characterise the morphology and roughness of a seagrass canopy and the bed beneath it. BRAD had been successfully calibrated and tested in the lab. The second series of tests was carried out in the field to acquire data and characterise roughness of different seabed types.
The objectives on BRAD field deployments were to:

1. image a variety of seabed types and roughnesses using BRAD;
2. test the algorithms developed to process BRAD data on measurements collected under a range of field conditions; and
3. define natural bed roughness through statistical and spectral analysis of seabed elevation and backscatter values collected with BRAD.

2.5.2. Field deployments settings

BRAD was deployed over a selection of bed types in Venice Lagoon, Italy, in September 2007 (Sites 1 to 4, Figure 2.21a and Table 2.10) and in Calshot, UK, in September 2008 (Sites 5 and 6, Figure 2.21b and Table 2.10). Sites in Venice Lagoon were in very shallow water (1 to 2 m water depth during deployment, e.g. Figure 2.22) and in slightly deeper water in Calshot (4 to 5.6 m water depth during deployment). Site 1 was inside the lagoon, over shelly fine sand, and Site 2, a few meters away from Site 1, was over a *Zostera marina* canopy. Site 3, also inside the lagoon, was over a bioturbated muddy bed. Site 4 was over rippled fine sand outside Chioggia inlet. Site 5 was over a
**CHAPTER 2**

*Zostera marina* canopy and Site 6 was over a mixture of fine sand and granules with brown algae (*Ceramium* spp) attached on the seafloor. These sites were selected for the variety of roughnesses they presented, from bioturbated beds to a ripple field, from seagrass canopies to mixed sand/gravel sediment.

Table 2.10: Position and description of the BRAD field deployments, co-ordinates are in WGS 84.

- *T* = temperature, *S* = salinity. Depth is the average water depth during deployment.

<table>
<thead>
<tr>
<th></th>
<th>longitude (E)</th>
<th>latitude (N)</th>
<th>depth (m)</th>
<th>motor velocity (mm s⁻¹)</th>
<th>T (°C)</th>
<th>S (°C)</th>
<th>sound velocity (m s⁻¹)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>12°15'59''</td>
<td>45°17'42''</td>
<td>1.1</td>
<td>0.50</td>
<td></td>
<td>1500</td>
<td></td>
<td>Fine sand with bivalve shells (such as oysters)</td>
</tr>
<tr>
<td>Site 2</td>
<td>12°15'59''</td>
<td>45°17'42''</td>
<td>1</td>
<td>0.50</td>
<td></td>
<td>1500</td>
<td></td>
<td>Fine sand covered with seagrass <em>Zostera marina</em></td>
</tr>
<tr>
<td>Site 3</td>
<td>12°16'10''</td>
<td>45°18'08''</td>
<td>2</td>
<td>0.50</td>
<td></td>
<td>1500</td>
<td></td>
<td>Mud with shells and bioturbation (holes ~2cm in diameter)</td>
</tr>
<tr>
<td>Site 4</td>
<td>12°18'04''</td>
<td>45°14'21''</td>
<td>1.4</td>
<td>0.46</td>
<td></td>
<td>1500</td>
<td></td>
<td>Fine sand with wave ripples, and some molluscs shells.</td>
</tr>
<tr>
<td>Site 5</td>
<td>-1°19'14''</td>
<td>50°48'14''</td>
<td>5.6</td>
<td>0.53</td>
<td>19</td>
<td>34</td>
<td>1518</td>
<td>Fine sand covered with seagrass <em>Zostera marina</em></td>
</tr>
<tr>
<td>Site 6</td>
<td>-1°19'50''</td>
<td>50°47'51''</td>
<td>4</td>
<td>0.53</td>
<td>19</td>
<td>35</td>
<td>1519</td>
<td>Fine sand and gravel with brown algae</td>
</tr>
</tbody>
</table>

![Figure 2.22: BRAD deployed at Site 2, Venice Lagoon, Italy.](image)

Motor
SIS
Stabilising bars
In Venice Lagoon, BRAD was deployed manually by 3 people from a small boat. In Calshot, it was deployed by 2 people from the R.V. Bill Conway using an A-frame, which greatly facilitated deployment. At each site, a grab sample was taken to establish seabed type prior to anchoring the boat. Thereafter, BRAD was deployed and salinity and temperature in the water column were recorded using a YSI 30 (conductivity-temperature probe); the corresponding speed of sound was calculated using Equation 2.2 and input into the SIS software. During data collection, a diver verified instrument position, took notes on any visible features, measured bedforms dimensions if present and took photographs where possible (in good water clarity).

Water temperature and salinity were not available during deployments in Venice Lagoon so sound velocity was set at 1500 m s\(^{-1}\) for the 4 deployments. The average temperature and salinity in Venice Lagoon during September modelled by Solidoro et al., (2004) was 20 to 25\(^\circ\)C and 32 to 34 respectively. Using a sound velocity of 1500 instead of 1518.1 m s\(^{-1}\) (temperature 20\(^\circ\)C, salinity 32) or 1533.3 m s\(^{-1}\) (temperature 25\(^\circ\)C, salinity 34) would cause the bed to be seen with the same geometry but 1 to 2 cm higher than it should be (assuming a flat seabed at 0.88 m from the SIS). The use of an inaccurate speed of sound translated the bed by 1 or 2 cm but did not deform it therefore it should not influence roughness measurements, since site mean depth was subtracted before statistical or spectral analysis.

During deployments in Venice Lagoon, the stabilising bars on BRAD, usually at the bottom of the frame, were fixed at a height of 0.5 m above the bed (Figure 2.22). The bars placed at such a height limited the acoustic field of view. As a result, beams with an angle larger than 33\(^{\circ}\) from the vertical were removed for the 4 sites imaged in Venice Lagoon. Therefore, a total 75 beams were analysed for Sites 1 to 4 instead on 101 when the bars were placed at the bottom of the frame (Sites 5 and 6).
2.5.3. Results

a. Site 1

The sandy bed imaged at Site 1 was relatively flat and no identifiable bedforms were noticed during the visual observation of the seabed. Razor clam shells (Solenidae), other bivalve shells (e.g. Cardiidae, Veneridae, Ostreidae) and anemones were observed on the seabed. The sediment collected at Site 1 was principally sandy (85.3%) with a fraction of mud (10.4%) and shell debris (4.3%, Table 2.11). The median grain diameter was classified as fine sand (d$_{50}$ of 0.17 mm) and the sediment distribution was moderately sorted, symmetrical to negatively skewed and leptokurtic (Table 2.12). At the beginning of the acquisition, a small elevation from the bed was seen for a few sweeps on the acoustic images. During visual observation, a cluster of 3 oysters and an anemone, around 10 cm high, were found on the seabed (Figure 2.23).

<table>
<thead>
<tr>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
<th>Site 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud</td>
<td>Sand</td>
<td>Gravel</td>
<td>Shells debris</td>
<td>classification</td>
<td></td>
</tr>
<tr>
<td>10.4%</td>
<td>85.3%</td>
<td>0.0%</td>
<td>4.3%</td>
<td>muddy sand</td>
<td></td>
</tr>
<tr>
<td>11.3%</td>
<td>85.3%</td>
<td>0.0%</td>
<td>3.4%</td>
<td>muddy sand</td>
<td></td>
</tr>
<tr>
<td>72.2%</td>
<td>24.8%</td>
<td>0.0%</td>
<td>3.0%</td>
<td>sandy mud</td>
<td></td>
</tr>
<tr>
<td>1.1%</td>
<td>98.7%</td>
<td>0.0%</td>
<td>0.2%</td>
<td>sand</td>
<td></td>
</tr>
<tr>
<td>9.1%</td>
<td>90.9%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>sand</td>
<td></td>
</tr>
<tr>
<td>4.3%</td>
<td>69.1%</td>
<td>26.6%</td>
<td>0.0%</td>
<td>gravelly sand</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
<th>Site 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>median (phi)</td>
<td>median (mm)</td>
<td>classification</td>
<td>sorting</td>
<td>Skewness</td>
<td>Kurtosis</td>
</tr>
<tr>
<td>2.52</td>
<td>0.17</td>
<td>fine sand</td>
<td>moderately sorted</td>
<td>-0.09</td>
<td>symmetrical</td>
</tr>
<tr>
<td>Site 2</td>
<td>2.54</td>
<td>0.17</td>
<td>fine sand</td>
<td>moderately sorted</td>
<td>-0.15</td>
</tr>
<tr>
<td>Site 3</td>
<td>5.02</td>
<td>0.03</td>
<td>silt</td>
<td>poorly sorted</td>
<td>0.04</td>
</tr>
<tr>
<td>Site 4</td>
<td>3.16</td>
<td>0.11</td>
<td>very fine sand</td>
<td>well sorted</td>
<td>0.03</td>
</tr>
<tr>
<td>Site 5</td>
<td>2.48</td>
<td>0.18</td>
<td>fine sand</td>
<td>poorly sorted v. poorly sorted</td>
<td>-0.03</td>
</tr>
<tr>
<td>Site 6</td>
<td>1.95</td>
<td>0.26</td>
<td>fine sand</td>
<td>2.15</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

Table 2.11: Percentage by weight of the different fractions for each sample and classification from the Folk diagram (Soulsby, 1997).

Table 2.12: Summary of statistical parameters (phi units) of the particle size distribution of the seabed sediments for the four sites and their description according to McManus (1988).
Figures 2.24a and 2.24b show the seabed elevation at Site 1 reconstructed from BRAD data in 2D and 3D views. The feature formed by the oysters and anemones is clearly visible at the bottom of the image. The dimensions of this feature calculated from the acoustic data agreed well with the dimensions measured on site (10 cm high, around 10 cm wide). A ridge, about 2.5 cm high, crosses the image from the top-left corner to the bottom-right corner. This feature was not evident during the visual observation on site. No other noticeable features were distinguished in the acoustic data and the floor was relatively plane (around 7 cm of difference was evident between the highest and lowest points, discounting the shell).

The two-dimensional roughness spectrum is presented on Figure 2.24c. Only spectra computed using method 2 are shown here. Spectra calculated using method 1 are essentially the same but not corrected for spectral leakage and displaying normalised power; they are presented in Appendix 3. The 2D spectrum estimated from seabed elevations at Site 1 is substantially isotropic i.e. it does not present any pronounced directionality in 2D spectral frequency space, indicating that the seabed elevations were also isotropic. Five significant peaks were recognised using method 1 that were diagnostic of features with wavelengths from 15.5 to 24.3 cm and directions from 7 to 170° (blue stars in Figure 2.24d, direction of features perpendicular to the black lines). The fact that 5 significant peaks were identified highlights the isotropy of the relief at this site; there was no preferential directionality or frequency of the seabed elevations.
Site 2 was situated only a few metres away from Site 1 and therefore, sediment collected at this site present the same distribution as at Site 1 (Tables 2.11 and 2.12), mainly sandy with fractions of mud and shells. The seabed at Site 2 was covered with *Zostera marina* and associated algae (e.g. *Ulva lactuca* and *Rhodophyta* spp). Epiphytes

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**Figure 2.24:**

a. Seabed elevation at Site 1 in 2D view, the black rectangle marks the extent of the data used for spectral analysis; b. seabed elevation at Site 1 in 3D view; c. 2D spectrum estimated from the elevation field at Site 1 (method 2); d. significant peaks (power > 2/3 maximum power) computed using method 1; the red line shows the direction of the peak with the maximum energy; feature directions are perpendicular to the lines shown on the graph.

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**b. Site 2**

Site 2 was situated only a few metres away from Site 1 and therefore, sediment collected at this site present the same distribution as at Site 1 (Tables 2.11 and 2.12), mainly sandy with fractions of mud and shells. The seabed at Site 2 was covered with *Zostera marina* and associated algae (e.g. *Ulva lactuca* and *Rhodophyta* spp). Epiphytes
(algae and molluscs) were observed on the seagrass. The method detailed in section 2.3.2 for a site occupied over a seagrass canopy was used to process the data and both the seabed and canopy elevations were computed from the raw data.

The reconstructed seabed elevation at Site 2 is presented in 2D and 3D views in Figures 2.25a and 2.25b. A small depression can be observed at the bottom of the image (Figure 2.25a, black circle) and was found to be the footprint of someone involved in the deployment (site carried out in very shallow water, see Figure 2.23). This showed that the method used to separate seagrass canopy and seabed was effective, as the footprint was recognised beneath the seagrass canopy. Apart from the footprint, the bed was essentially flat and presented a depth variation of only 3 cm from the lowest to the highest point. However, in the case of a site imaged over a seagrass canopy, the height of the seabed is limited to 4 cm above the average seabed depth during data processing, which biased the data. At some positions, the differentiation between seagrass shoots and seabed was difficult to make. This is probably due to the fact that seagrass shoots and sediment present a small impedance difference and therefore create similar backscatter intensities, which make them difficult to distinguish.

The spectral analysis was performed on a matrix of data taken away from the footprint, as this feature constitutes an artificial bedform and should not be taken into account for analysis. The 2D roughness spectrum was essentially isotropic (Figure 2.25c) and seven significant peaks were recognised from method 1, showing features with wavelengths from 21 to 27.5 cm and directions from 29 to 153° (Figure 2.25d). The seabed elevations at Site 2 therefore did not show any clear directionality or significant spatial periodicity and can be regarded as isotropic.

Figures 2.26a and 2.26b present the reconstructed canopy elevation at Site 2 in 2D and 3D views. The canopy surface was found to be uneven and irregular. It had an average height above the bed of 19.5 cm (standard deviation of 4.9 cm) which varied from about 5 to 35 cm above the bed, indicating strong canopy height variations. The canopy 2D spectrum was significantly less isotropic than the bed spectrum and only 2 significant peaks were recognised from method 1 (Figure 2.25c). The peak with the maximum energy showed features at 0° from the y-axis, i.e. in the SIS direction of travel. This peak was probably an artefact of data collection (see also the horizontal leakage still apparent on Figure 2.26c). Although only 2 peaks were found, indicating a certain degree of
anisotropy, the spectra also shows that high frequencies (small wavelengths) contain a lot of power, which is consistent with the observed shape of the canopy, i.e. strong height variations of the canopy at a small scale.

Figure 2.25: a. Seabed elevation at Site 2 in 2D view, the black rectangle marks the extent of the data used for spectral analysis; b. seabed elevation at Site 2 in 3D view; c. 2D spectrum estimated from elevation field at Site 2 (method 2); d. significant peaks (power > 2/3 maximum power) computed using method 1; the red line shows the direction of the peak with the maximum energy; feature directions are perpendicular to the lines shown on the graph.
Site 3 was located in Venice Lagoon, in slightly deeper water than Sites 1 and 2 (around 2 m water depth during deployment) over bioturbated mud. By contrast to sediment collected at Sites 1 and 2, the sediment at Site 3 was principally muddy (72.2%) with a fraction of sand (24.8%, Table 2.11). The median grain diameter (0.03 mm) was classified

Figure 2.26: a. Canopy elevation at Site 2 in 2D view, the black rectangle marks the extent of the data used for spectral analysis; b. canopy elevation at Site 2 in 3D view; c. 2D spectrum estimated from elevation field at Site 2 (method 2); d. significant peaks (power $> 2/3$ maximum power) computed using method 1; the red line shows the direction of the peak with the maximum energy; feature directions are perpendicular to the lines shown on the graph.

c. **Site 3**

Site 3 was located in Venice Lagoon, in slightly deeper water than Sites 1 and 2 (around 2 m water depth during deployment) over bioturbated mud. By contrast to sediment collected at Sites 1 and 2, the sediment at Site 3 was principally muddy (72.2%) with a fraction of sand (24.8%, Table 2.11). The median grain diameter (0.03 mm) was classified
as silt and the sediment distribution was poorly sorted, symmetrical and mesokurtic (Table 2.12). Visual description was limited by poor water clarity and it was not possible to take good quality underwater photographs. Bivalve shells, anemones and a few small algae were observed on the seafloor, which was predominantly flat. A large number of bioturbation holes, around 2 cm in diameter and deeper than 6 cm, were also seen. Unfortunately it was not possible to observe the organisms making these holes and hence their origin is unknown.

Since the bioturbation holes had the same dimensions as the SIS footprint, the bed around the holes created the strongest echo along the beam and therefore the holes could not be detected using the algorithm developed for bed detection. However, after close inspection of the backscatter data, a higher backscatter was observed around 10 cm below the bed on some sweeps (Figure 2.27a). This strong backscatter was attributed to the reflection of the sound wave off the bottom of the holes or of the biota within the holes. Although it was not the highest backscatter along the beam, it could clearly be discriminated from ambient noise (Figure 2.27b).

![Figure 2.27: a. Backscatter intensity along sweep 20, Site 3, together with the position of the bed (blue dots) and of a hole bottom (yellow dots); b. backscatter intensity along beam 15, sweep 20, Site 2, showing the method to calculate hole depth.](image)
Therefore, it was hypothesised that a bioturbation hole was present in the seabed when a high backscatter was seen around 10 cm below the depth of the bed. Several threshold backscatter intensities and depths were tested to allow holes detection. It was concluded that holes could be recognised by the last backscatter greater than 155, from a depth of 7 cm beneath the maximum backscatter of the sweep (Figure 2.27b). The locations and depths of bioturbation holes were integrated with the bed data and the whole image of Site 3 seabed elevation constructed (Figure 2.28a and 2.28b).

Figure 2.28: a. Seabed elevation at Site 3 in 2D view, the black rectangle marks the extent of the data used for spectral analysis; b. seabed elevation at Site 3 in 3D view; c. 2D spectrum estimated from elevation field at Site 3 (method 2); d. significant peaks (power > 2/3 maximum power) computed using method 1; the red line shows the direction of the peak with the maximum energy; feature directions are perpendicular to the lines shown on the graph.

Therefore, it was hypothesised that a bioturbation hole was present in the seabed when a high backscatter was seen around 10 cm below the depth of the bed. Several threshold backscatter intensities and depths were tested to allow holes detection. It was concluded that holes could be recognised by the last backscatter greater than 155, from a depth of 7 cm beneath the maximum backscatter of the sweep (Figure 2.27b). The locations and depths of bioturbation holes were integrated with the bed data and the whole image of Site 3 seabed elevation constructed (Figure 2.28a and 2.28b).
The seabed at Site 3 was predominantly flat, except for some raised areas probably associated with algae tufts, and presented elevations varying from -2.5 to 2.2 cm. Sixteen holes were detected in the image (area of 1.7 m²). Their depths varied from 7.5 cm to 15 cm (average 12 cm) below the mean depth of the seabed and were smoothed slightly during interpolation.

The 2D spectrum computed from seabed elevations at Site 3 was the most isotropic of the roughness spectra presented in this study (Figure 2.28c). The spectrum does not exhibit any directionality in the frequency space. Furthermore, high power values can be seen at high spatial frequencies, i.e. at small wavelengths (see the extent of green and pale blue in Figure 2.28c compared to other spectra, as well as the lack of red colours). The obvious isotropy of the spectra indicates that seabed roughness at Site 3, characterised by biota activity, is isotropic. Furthermore, the strong power contained in the high frequencies shows the dominance of small wavelength roughness at this site, whereas the low power contained by low frequencies highlights the lack of large wavelength features. Six significant peaks were calculated from method 1 - indicating that several preferential directions were found in the spectrum, another sign of isotropy - with wavelengths varying from 14.4 to 26.0 cm and direction going from 45 to 172°.

d. **Site 4**

Site 4 was occupied outside Venice Lagoon, north of Chioggia inlet (Figure 2.21a) over a wave-ripple field. Unlike sediment taken inside the lagoon, sediment collected at Site 4 was largely composed of well-sorted sand (98.7%) with a median grain diameter of 0.11 mm (fine sand) and a very small fraction of mud (1.1%, Table 2.11). The sediment distribution was symmetrical and mesokurtic (Table 2.12). This sediment sample differs from previous ones due to the fact that it was sampled outside the lagoon, where sand is reworked and sorted by wave action. The seabed at Site 4 was covered by symmetrical, sharp-crested, wave ripples with bifurcations of the crest lines (Figure 2.29). Ripple dimensions, approximately measured during dives, show a wavelength of around 10 cm and a height of roughly 1 cm.
Seabed elevations reconstructed at Site 4 are presented on Figures 2.30a and 2.30b. The reconstructed ripple field shows sharp-crested, symmetrical bedforms, with occasional bifurcations, which agrees well with on-site descriptions. Correct reconstruction of the bedforms confirms the sub-centimetre vertical resolution in the field, as ripples with 1 cm amplitude were successfully imaged. The 2D spectrum computed from the seabed elevations at Site 4 clearly shows the anisotropy associated with the ripple field (Figure 2.30c). As expected, only 1 significant peak (2 peaks mirror each other in the spectrum) was computed from method 1 (Figure 2.30d). Wavelength and direction of the bedforms calculated using method 1, specifically designed to compute bedform dimensions, were 10.7 cm and 34° respectively. Ripple height (rms of the height distribution) was calculated to be 1.2 cm.

The seabed elevation at Site 4 is presented in Figure 2.31a together with lines showing the direction and wavelength of the significant peak calculated from method 1. The very good correspondence between the image and the direction and spacing calculated from method 1 illustrates the effectiveness of the method developed by Cazenave et al. (2008) to calculate bedform dimensions from 2D seabed elevations. A profile taken perpendicular to the ripple direction (calculated using method 1) shows regular sharp-crested ripples (Figure 2.31b). Although some smoothing is seen, especially on ripple crests, there is a good correspondence between BRAD images and observed ripples.
Figure 2.30: a. Seabed elevation at Site 4 in 2D view, the black rectangle marks the extent of the data used for spectral analysis; b. seabed elevation at Site 4 in 3D view; c. 2D spectrum estimated from elevation field at Site 4 (method 2), notice the peak in power associated with the ripple field; d. significant peaks (power > 2/3 maximum power) computed using method 1; the red line shows the direction of the peak with the maximum energy; feature directions are perpendicular to the line shown on the graph.
e. Site 5

Site 5 was occupied off Calshot beach (Figure 2.21b) over a *Zostera marina* canopy. Sediment collected on site was a poorly sorted sand, which contained a fraction of mud (9.1%) and had a median grain diameter of 0.11 mm (Tables 2.11 and 2.12). The PSD was negatively skewed and extremely leptokurtic. The sediments collected at Sites 2 and 5, i.e. sites imaged over a *Z. marina* canopies, were surprisingly similar despite the fact that they came from very different locations (Venice Lagoon and Calshot). This is probably showing the seagrass preference for fine sands and the possible subsequent retention of fine sediment due to current reduction inside the canopy (den Hartog, 1970). The water depth during deployment at Site 5 was the greatest of all deployments (5.6 m). Due to strong boat movement in relatively deep water, a first deployment had to be stopped after a few sweeps due to lack of cable. The frame was then redeployed and data collection was carried out. However, it had to be stopped again before the SIS had travelled the entire length of the
frame, hence a reduced length of the image. Visual observation showed the canopy to be sparse and, although shoot density was not counted, the seagrass bed imaged in Calshot was observed to be significantly less dense than the canopy imaged at Site 2, Venice Lagoon. Furthermore, a steady current led to greater bending of the shoots than in Venice, where bending was observed to be small. The top of the canopy in Calshot was measured during deployment to be situated approximately 10 to 15 cm above the bed.

The reconstructed seabed elevations at Site 5 are presented in Figure 2.32a and 2.32b in 2D and 3D views. The stabilising bars, situated at the bottom of the frame during this deployment, are clearly recognisable as higher elevations at -0.5 and +0.5 m along the x-axis. The stabilising bars were moved from the middle to the bottom of the frame between deployments in Venice Lagoon and Calshot in order to act as a reference on the seabed and because they were reducing the field of view. The bars appear straight and their reconstructed height agrees well with measurements (4 cm). However, the bar on the left side appears to be better imaged than the one on the right side. This might be due to the fact that the SIS was not looking at nadir (a correction of 7.5° had to be applied for the bed to be horizontal) due to difficulty in positioning it correctly on the frame. Because the SIS was not looking vertically down, the bar on the right was imaged at a higher beam angle than the left bar and therefore with less precision, due to bigger footprint and stronger acoustic shadows. Furthermore, the bars can be difficult to differentiate from seagrass plants because of the height of the bars and the method used to calculate seabed and canopy heights. The algorithm developed to discriminate a seagrass canopy from the seabed specifies that the seabed is found within 4 cm of the theoretical height of the seabed (0.88 m under the SIS head). As the bars were 4 cm high, they were at the height limit of seabed detection and might sometimes have been automatically detected as part of the seagrass canopy rather than considered as seabed elevation.

The bed under the canopy at Site 5 was more irregular than the bed imaged under the canopy at Site 2. A depression, around 3 cm lower than the bed around it, can be seen in the middle of the image, at around 1 m along the y-axis (black circle on Figure 2.32a). It is thought that this depression was created by one of the frame foot during the first deployment.
The 2D spectrum showed anisotropy roughly along the y-axis (Figure 2.32c). Four peaks were calculated using method 1 with wavelengths varying from 15.5 to 25.9 cm and directions ranging from 57 to 90° (Figure 2.32d). Apart from the main peak, situated at 0°, the directions and intensities of the 3 remaining peaks were grouped between 57 and 79° in direction and 15.5 to 17.2 cm wavelength, suggesting that they belong to the same feature. This confirms the anisotropy of the spectrum despite the fact that 4 peaks were found.

Figure 2.32: a. Seabed elevation at Site 5 in 2D view, the black rectangle marks the extent of the data used for spectral analysis; b. seabed elevation at Site 5 in 3D view; c. 2D spectrum estimated from elevation field at Site 5 (method 2); d. significant peaks (power > 2/3 maximum power) computed using method 1; the red line shows the direction of the peak with the maximum energy; feature directions are perpendicular to the lines shown on the graph.
Figures 2.33a and 2.33b present the reconstructed canopy elevation at Site 5 in 2D and 3D views. The canopy height imaged in Calshot presents a different morphology to the one imaged in Venice Lagoon. The canopy was significantly lower with an average elevation above the bed of 8.5 cm and a maximum height of 17.2 cm. The standard deviation of the canopy height was 2.0 cm, showing the relative flatness of the canopy. These measurements agree well with the height and morphology of the canopy observed on site.

Figure 2.33: a. Canopy elevation at Site 5 in 2D view, the black rectangle marks the extent of the data used for spectral analysis; b. canopy elevation at Site 5 in 3D view; c. 2D spectrum estimated from elevation field at Site 5 (method 2); d. significant peaks (power > 2/3 maximum power) computed using method 1; the red line shows the direction of the peak with the maximum energy; feature directions are perpendicular to the lines shown on the graph.

Figures 2.33a and 2.33b present the reconstructed canopy elevation at Site 5 in 2D and 3D views. The canopy height imaged in Calshot presents a different morphology to the one imaged in Venice Lagoon. The canopy was significantly lower with an average elevation above the bed of 8.5 cm and a maximum height of 17.2 cm. The standard deviation of the canopy height was 2.0 cm, showing the relative flatness of the canopy. These measurements agree well with the height and morphology of the canopy observed on site.
The canopy spectrum was relatively anisotropic (Figure 2.33c). Four significant peaks were calculated using method 1 (Figure 2.33d). Two of them were probably due to artefacts in the data collection method (features at 0 and 90°). The two remaining peaks have wavelengths of 20.8 and 29.4 cm and directions of 63 and 72°.

\[ \text{f. Site 6} \]

Site 6 data were collected shortly after Site 5, further south off Calshot beach, in an area without seagrass (Figure 2.21). By contrast to the other sites imaged with BRAD, sediment collected at Site 6 contained a significant amount of gravel (Table 2.11). The gravel, which represented nearly 30% of the sample, was composed of rounded flint granules (between 2 and 4 mm size). The PSD of the sediment collected at that site was bimodal, with a mode of fine sand and a second one of gravel. As a result, the distribution was very poorly sorted, negatively skewed and very platykurtic (Table 2.12). This site was the only one so far acquired above gravelly sand. Furthermore, numerous brown algae (\textit{Ceramium} spp) were noticed on the seafloor during visual observation, whereas other sites were carried out either over bare sediment or above seagrass canopies.

The reconstructed seabed elevations at Site 6 are presented in Figures 2.34a and 2.34b in 2D and 3D views. As for Site 5, the stabilising bars are clearly visible as lines of higher elevation at -0.5 and +0.5 m along the x-axis. Here again, the bar on the left side seem better imaged than the one on the right side. Sites 5 and 6 were collected the same day and the SIS was not moved between the 2 deployments, so it seems to reinforce the hypothesis that the difference in imaging the bars was due to beam angle rather than created by the method used for detecting seagrass canopies. Nevertheless, the bars were imaged correctly (i.e. they appear straight and around 4 cm above the seabed), giving confidence in the system accuracy and the processing method.

The 2D roughness spectrum was relatively anisotropic although a large amount of energy was found at high frequencies (small wavelengths, Figure 2.34c). Even though 4 significant peaks were calculated using method 1, showing a certain degree of isotropy, the peaks were grouped around the same direction (74 to 117°) and with wavelength varied between 17 and 29 cm, indicating that these peaks might be associated with the same feature.
Figure 2.35 presents the average backscatter 0.5 to 0.3 m under the head per sweep ($\bar{W}$), which is related to relative turbidity in the water column, for the 6 sites under investigation in this study. As each sweep was recorded in 17 seconds, the relative

**g. Average backscatter intensities**

Figure 2.35 presents the average backscatter 0.5 to 0.3 m under the head per sweep ($\bar{W}$), which is related to relative turbidity in the water column, for the 6 sites under investigation in this study. As each sweep was recorded in 17 seconds, the relative
turbidity can be presented as a function of sweep number or time. At Sites 3, 5 and 6, the
turbidity was relatively low and constant (average backscatter 84, 94 and 90 and standard
deviation 3, 2 and 4 respectively) apart from the beginning or end of deployments where
\( W \) shows higher values. This shows that turbidity at those sites was relatively low and
constant except when sediment was put in suspension by deployment or recovery
disturbance. \( W \) at Sites 1 and 2 shows numerous along-line variations although with small
intensities. This might be due to the fact that those sites were carried out in very shallow
water. The turbidity in the water column was higher and more variable at Site 4 (average
97 and standard deviation 12) than at all the other sites and showed some localised peaks in
turbidity. Divers were present during this deployment and disturbed sediment while diving
to observe the system, creating those peaks in turbidity.

Figure 2.35: Average backscatter in the water column at the 6 sites investigated in this study. The 2 x-
axis are equivalent with one sweep completed in 17 sec.
Figure 2.36 presents the average backscatter on the seabed for each site as a function of the sediment median grain diameter (phi scale). Sites 2 and 5 had a lower backscatter on the seabed than other sites with similar median grain diameter due to the presence of the seagrass canopy, which was attenuating the sound beam before it reached the seabed. A regression line was therefore fitted through the averaged backscatter at Sites 1, 3, 4 and 6 and excluding Site 2 and 5. A good correlation was found between the average backscatter on the seabed and the median grain diameter in phi scale ($R^2 = 0.89$) although the limited number of sites means the significance was not high (p-value of 0.05). During field deployment, the average backscatter on the seabed was therefore found to increase with increasing grain size.

### h. Statistical and spectral characterisation

A summary of the statistical parameters calculated from elevation and backscatter data are presented in Table 2.13. Mean depth under the SIS head was smaller for Sites 1 to 4, as expected since sound velocity was left at 1500 m s$^{-1}$. The rms was found to be the highest for the canopy imaged at Site 2, as the canopy presented strong height variations and was smallest at Site 4. No definite trend was found between any of the parameters calculated from elevation, backscatter intensity, bed morphology or roughness.
Table 2.13: Summary of statistics calculated on elevation and backscatter data. For Sites 2 and 5, values are given for bed (b) and canopy (c) data. Definition of statistics parameters can be found in Table 2.2. Mean elevation refers to the mean depth under the SIS head.

<table>
<thead>
<tr>
<th>Site</th>
<th>Elevation</th>
<th>Backscatter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>Site 2b</td>
<td>Site 2c</td>
</tr>
<tr>
<td>mean</td>
<td>-0.86</td>
<td>-0.85</td>
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<tr>
<td>rms</td>
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<td>0.85</td>
</tr>
<tr>
<td>IQR</td>
<td>1.3</td>
<td>0.8</td>
</tr>
<tr>
<td>MAD</td>
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<td>0.61</td>
</tr>
<tr>
<td>skewness</td>
<td>0.94</td>
<td>-1.61</td>
</tr>
<tr>
<td>kurtosis</td>
<td>8.25</td>
<td>6.51</td>
</tr>
<tr>
<td>Site 2</td>
<td>Site 2b</td>
<td>Site 2c</td>
</tr>
<tr>
<td>mean</td>
<td>220</td>
<td>212</td>
</tr>
<tr>
<td>rms</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>IQR</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>MAD</td>
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<td>5</td>
</tr>
<tr>
<td>skewness</td>
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<td>0.23</td>
</tr>
<tr>
<td>kurtosis</td>
<td>4.41</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Table 2.14: Slope and intercept of the power-law regression line at all sites investigated in this study going through (1) the spectrum average over all slices, (2) along the main feature direction (main peak found with method 1) and (3) normal to the feature direction. The intercept has units of m^4, the slope is dimensionless.

<table>
<thead>
<tr>
<th>Site</th>
<th>Feature direction (°)</th>
<th>(1) average slices slope</th>
<th>intercept</th>
<th>(2) along feature direction slope</th>
<th>intercept</th>
<th>(3) normal to feature direction slope</th>
<th>intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>79</td>
<td>3.10</td>
<td>0.0021</td>
<td>2.73</td>
<td>0.0005</td>
<td>3.44</td>
<td>0.0089</td>
</tr>
<tr>
<td>Site 2 bed</td>
<td>127</td>
<td>4.13</td>
<td>0.0902</td>
<td>4.17</td>
<td>0.0950</td>
<td>3.53</td>
<td>0.0070</td>
</tr>
<tr>
<td>Site 2 canopy</td>
<td>180</td>
<td>3.53</td>
<td>0.6258</td>
<td>3.22</td>
<td>0.3389</td>
<td>2.70</td>
<td>0.0395</td>
</tr>
<tr>
<td>Site 3</td>
<td>45</td>
<td>3.47</td>
<td>0.0275</td>
<td>3.43</td>
<td>0.0273</td>
<td>3.52</td>
<td>0.0301</td>
</tr>
<tr>
<td>Site 4</td>
<td>34</td>
<td>4.33</td>
<td>0.2596</td>
<td>4.20</td>
<td>0.0950</td>
<td>4.47</td>
<td>0.3988</td>
</tr>
<tr>
<td>Site 5 bed</td>
<td>90</td>
<td>3.88</td>
<td>0.4506</td>
<td>3.16</td>
<td>0.0429</td>
<td>3.05</td>
<td>0.0216</td>
</tr>
<tr>
<td>Site 5 canopy</td>
<td>72</td>
<td>3.87</td>
<td>0.3591</td>
<td>3.55</td>
<td>0.0955</td>
<td>3.42</td>
<td>0.0242</td>
</tr>
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<td>Site 6</td>
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<td>0.0436</td>
<td>4.32</td>
<td>0.1527</td>
<td>4.21</td>
<td>0.0528</td>
</tr>
</tbody>
</table>

Table 2.14 summarises the slope and intercept values calculated from the power-law fit on (1) the average slices through the spectrum (2) along the main feature direction and (3) normal to the main feature direction. The main feature direction was taken as the direction of the most significant peak found using method 1. Slope values varied between 2.70 (normal to feature at Site 2 canopy) and 4.47 (normal to main feature, i.e. crest to crest at Site 4). Intercept values varied between 0.0005 m^4 (along main feature at Site 1) and 0.6258 m^4 (average at Site 2 canopy). Slope and intercept values were found to vary within the same range for all sites between the average slices and along or normal to the direction of the most significant peak and no correlation could be found between the slope calculated from the average of the slices and from the slices along or across the main feature.
Slope and intercept values can be used to assess the importance of high-frequency (small-scale) compared with low-frequency (big-scale) topographic variations (i.e. roughness) at each site and between sites. For instance, Site 3 (bioturbated mud) and Site 4 (ripple field) present very different roughnesses and a graph of the slices and associated power-law fits enable a better understanding of their relative roughness (Figure 2.37a). As the spectrum at Site 3 was isotropic, the average of all slices may be used to assess its roughness, whereas the slice taken perpendicular to the ripple field is used for Site 4 in order to assess the roughness associated with the ripples. Topographic roughness can be thought of as the power contained under the lines. This implies that Site 3 comprises more roughness at high-frequencies (small-scales) while Site 4 presents more roughness at lower frequencies (larger scales). This is coherent with seabed morphology: seabed at Site 3 was characterised by small-scale roughness stemming from bioturbation, whereas the seabed imaged at Site 4 showed a bigger scale roughness created by the ripples. Similarly, small-scale roughness was apparent at Site 1 (fine sand with evidence of biological activity due to the proximity of seagrass patches) whereas larger-scale roughness was higher at Site 6 (gravelly sand), probably due to the gravel fraction present in the sediment distribution (Figure 2.37b). Therefore, BRAD data are coherent with the general concept that the slope value of the power-law fit give an indication of the relative importance of small-scale compared to large-scale roughness, i.e. steeper slopes were found at sites characterised by larger-scale roughness (ripple field and coarse sediment) whereas a less important slopes were seen at sites with smaller-scale roughness (bioturbated seabed and seagrass canopies).
At Site 5, the seabed and the canopy present very similar roughnesses (slopes of 3.88 and 3.87 and intercepts of 0.4506 and 0.3591 m$^4$ respectively for the average slices) whereas at Site 2, the relative roughnesses of the bed and the canopy differs significantly (slopes of 4.13 and 3.53 and intercepts of 0.0902 and 0.6258 m$^4$ respectively for the average slices). In particular, the canopy at Site 2 presents a strong small-scale roughness, as it can be seen from the high intercept value and relatively low slope. The differences in spectral roughness may be explained by differences in the canopy morphology: the canopy at Site 2 was characterised by strong irregularities at a small-scale hence has a high roughness whereas the canopy at Site 2 was relatively flat hence has a lower roughness.

In order to assess the coherence of the data presented here to previously collected data, they were compared to seafloor roughness measured from a variety of sediment types in shallow coastal sites by Kevin Briggs and presented in Jackson and Richardson (2007). These slope and intercept values were calculated from profiles of seabed elevations (i.e. 1D) acquired by stereo-photography. To allow comparison, they were converted to 2D data in metre units following the methodology described by Jackson and Richardson (2007, p 478, 479). The spectral slopes calculated in the present study were on the whole coherent with spectral slopes compiled by Jackson and Richardson (2007) although they were situated in the upper range of Briggs’ data (Figure 2.38). The intercept of our data and theirs differ markedly; the intercept values calculated from BRAD data are 10 to $10^3$ times higher than the intercept calculated from 1D stereo-photography. In Figure 2.38, it can be seen that slope and intercept values are very variable and it is difficult to predict spectral values from seabed types. For instance, crest-to-crest rippled sand is hypothesised to present the highest spectral slope due to the relative importance of the small-frequencies compared to the high-frequencies (Briggs et al., 2005). However, spectral slopes of crest-to-crest rippled beds vary from 3 to 4 and isotropic mud and sand may have stronger spectral slopes than rippled beds, illustrating the difficulty of giving a general rule to estimate roughness from spectral slope and intercept (Briggs and Ray, 1997).
Six sites with various roughness types including ripple fields, bioturbated sediments, gravelly sand and *Zostera marina* canopies, were imaged during BRAD field-deployments. Seabed elevations - and if present, canopy heights - were successfully reconstructed from the raw data. However, the system cannot perfectly record the seabed and suffers limitations inherent to high-resolution acoustic systems including: (1) stochastic variability in acoustic scattering, i.e. a certain degree of randomness is to be expected in sound response (Greenwood et al., 1993); (2) smoothing of steep gradients (Green and Boon, 1988; Greenwood et al., 1993); (3) acoustic shadowing (Bell and Thorne, 1997a); and (4) loss of accuracy at higher beam angle due to the increased footprint (Bell and Thorne, 1997b). The small footprint of the SIS mounted on BRAD (2.8 cm to 5.5 cm) together with the small angle between 2 consecutive beams (0.9°) allowed the detection of small features and the reduction of acoustic shadowing and error in slope computation. The high vertical resolution of BRAD (sub-centimetre), theoretically estimated and tested in the lab, was
confirmed by the accurate imaging of small (1 cm amplitude) wave ripples at Site 4. The horizontal accuracy, calculated to be in the order of 2 to 3 cm, is consistent with field results, where small features, such as shells, holes and a footprint, were correctly imaged. However, it should be kept in mind that measurements taken at low beam angle (close to nadir) are of better quality than those recorded at higher beam angle (further from vertical), since the sonar footprint and acoustic shadowing increase with increasing beam angle.

BRAD presents advantages compared to previous high-resolution sonars used for seafloor imaging, in particular the recording of backscatter intensity continuously from the sonar head to the sub-bottom and the ability to produce 3D images of the seafloor. Most high-resolution acoustic systems record (or use) only the depth of the seabed and not the backscatter intensity in the water column (e.g. Greenwood et al., 1993; Jetté and Hanes, 1997). Using BRAD, backscatter intensities are recorded along each beam. This presents several benefits, including the possibility to image seagrass canopies, map bioturbation holes and provide information on relative turbidity. If calibrated, backscatter intensity near the seabed could provide information on suspended sediment concentration (Thorne and Hanes, 2002). At present, such a study has not been carried out, but variations of $\overline{W}$ at Site 4 created by divers showed that the system is able of detecting variations in suspended sediment concentration.

Height of seagrass canopies was reconstructed from 2 sites imaged with BRAD, Site 2 in Venice Lagoon and Site 5 in Calshot. Although imaging of seagrass canopies and subsequent evaluation of canopy height is valuable in studies of hydrodynamics above and with seagrass beds, no study so far has imaged seagrass canopies at such a high-resolution. The results obtained with BRAD hence cannot be compared with results from other instruments. The two canopies exhibited very different morphology: the canopy imaged in Venice Lagoon (average height above the seabed of 19.5 cm) showed strong small-scale height variations whereas the canopy imaged in Calshot was noticeably shorter (average height of 8.5 cm) and flatter. Site 2 was recorded at the end of an ebb flow in a microtidal lagoon (1 m range) and Site 5 was recorded in the middle of an ebb phase during spring tide in a macrotidal zone (4 m range). It can therefore be assumed that currents were stronger during collection of Site 5 than of Site 2. During the canopy visual examination, it was also noticed that shoot density in Venice Lagoon was significantly higher than in Calshot. Bending in *Zostera marina* canopies has been observed to increase with
increasing current velocity (Fonseca et al., 1982) and decreasing shoot density (pers. obs.). As currents were stronger and the canopy was sparser in Calshot than in Venice Lagoon, the plants were certainly bending more, explaining the morphological differences observed between the canopies imaged at the 2 sites.

Bioturbation holes were successfully imaged at Site 3 although their size was comparable to the sonar footprint. Unfortunately, it was not possible to identify the fauna creating these holes. Numerous animals create burrows for feeding or protection (Barnes et al., 2001) such as polychaetes worms (e.g. *Arenicola marina*), shrimps (e.g. *Upogebia pusilla*) or bivalves (e.g. *Tapes philippinarum*). BRAD enables a non-intrusive mapping of burrows distribution, which might be of interest for biologists studying benthic fauna, for instance, distribution and ecological impact of burrows (Benoit et al., 2004).

To date, all acoustic systems designed specifically to measure seabed elevation at high-resolution ($10^{-3}$ to $10^0$ m) take measurements along a transect (e.g. Greenwood et al., 1993; Jettè and Hanes, 1997; Bell and Thorne, 1997a). This is very limiting as seabed morphology varies in three dimensions. BRAD therefore presents an improvement on previous systems as it enables mapping of seabed elevation in 2 dimensions, i.e. produces 3D images of the seabed. This is particularly important in studies of sand ripples, since bad positioning of an instrument measuring along a transect could lead to erroneous measurements of ripple dimensions (Thorne and Hanes, 2002). Seabed elevation collected at the ripple field site and spectrally analysed following the method developed by Cazenave et al. (2008) proved to be particularly valuable to determine ripple direction, wavelength and height. Ripple dimensions are an essential parameter to calculate bedform-induced hydraulic roughness (Grant and Madsen, 1982; Grant and Madsen, 1986). Method 1 applied to data from a rippled seabed imaged with BRAD provides a straightforward and precise dataset for computation of these parameters. Furthermore, other ripple characteristics, such as the presence of bifurcations and 3D structures, can be recognised from the seabed reconstruction.

Average backscatter intensity showed good correlation with sediment size in phi scale at the site despite poor correlation observed during the laboratory tests. In the field, backscatter intensities were on average over 15 000 data points whereas averaged backscatter was calculated on significantly smaller datasets in the lab (616 to 1717 points). This possibly explains the better correlation found from field measurements. However, as
the correlation between median grain size and average backscatter was carried out at 4 sites only, a greater number of sites with a variety of grain sizes need to be analysed to confirm the trend.

Statistical and spectral analyses were carried out on seabed and canopy elevations. Statistical parameters did not show any significant relationship to seabed types, as observed from previous research (Wheatcroft, 1994). Spectral analysis, on the other hand, was found to enable statistical characterisation of micro-topography and roughness types, as was suggested by Jackson and Richardson (2007). In particular, the method developed by Lyons et al. (2002) enabled an estimation of the 2D roughness spectra from the seabed and canopy elevations. The spectrum shape allows a description of the degree of isotropy of the seabed elevations, giving a first indication of roughness type. As observed by other authors (Briggs et al., 2005; Jackson and Richardson, 2007), biogenic roughness in this study was characterised by isotropic spectra whereas bedform roughness was distinctively anisotropic. Topographic roughness was further defined by the fitting of power-law regressions to slices of the spectra. The slices were used to assess the relative importance of low and high-frequencies of roughness power. For instance, the slice taken normal to the ripple crests showed the highest slope due to the dominance of large scales in defining bedform roughness. By contrast, sites characterised by biogenic activities (Sites 1, 2, 3 and 5) presented significantly smaller slopes since biological activity is often responsible for destroying large-scale roughness and constructing small scale roughness (Jackson and Richardson, 2007). This agrees well with results from Briggs (1989) and Briggs et al. (2001). They observed that bioturbated sites, characterised by a combination of weak low-frequency roughness and strong high-frequency roughness, accounted for the smallest slope values; fresh ripple beds resulted in the steepest slopes due to the coincidence of large low-frequency roughness and small high-frequency roughness.

The spectral analysis method, initially developed to define roughness of the seabed, was also applied to the canopy elevation. However, care should be taken in drawing conclusions from this analysis. Seagrass canopies often develop a wavy motion under the action of waves and currents (Ackerman and Okubo, 1993). These oscillations mean that the canopy is not a static surface but rather a mobile volume, which makes them extremely difficult to image. Nevertheless, images of the canopy elevation reconstructed from BRAD data are thought to constitute a good representation of the average canopy heights during
deployments. Similarly, it is questionable whether spectral analysis can be applied to the canopy elevation in order to characterise the canopy roughness since the canopy is a dynamic volume. Nevertheless, spectral analysis was applied to canopy elevation and presented interesting results. The spectra of the 2 canopies imaged with BRAD showed that the canopies presented notably different roughnesses. Roughness over the *Zostera marina* bed imaged in Calshot was small and comparable to seabed roughness at the same site. By contrast, the canopy imaged in Venice Lagoon exhibited a significantly higher topographic roughness, especially at high-frequencies. These differences in spectral roughness, showing the difference in topographic roughness created by dissimilarities in plant bending, may be of importance when analysing hydraulic roughness over seagrass canopies.

In the present study, slope and intercept values were found to vary within the same range for all sites between the average slices and along or normal to the direction of the most significant peak. This is against the general agreement that in the case of an anisotropic spectrum, the slopes and intercepts of the power-law fit do not depend on the slice direction (Briggs, 1989; Jackson and Richardson, 2007) although it is consistent with results from Richardson et al. (2001).

The comparison of the data from the present study to previous work showed that the slope and intercept values calculated herein are higher than those computed from 1D stereo-photography. It seems that our data are shifted compared to the line formed by Briggs’ data. Several reasons might explain the discrepancy observed in Figure 2.38. Previous seabed imaging was carried out from stereo-photography (optical system) whereas BRAD uses a profiling sonar (acoustic system) to do so. Further to the intrinsic distinctions between the methods used to record seabed elevations, the dimensions of the seabed under investigation were notably different; Briggs recorded profiles 0.5 to 2.1 m-long (Briggs and Ray, 1997) whereas BRAD images used to estimated spectral roughness covered areas between 1 and 1.2 m². The systems resolutions were also markedly different; 2 to 3 cm horizontal resolution with BRAD and around 1 mm horizontal resolution for Briggs data (Briggs, 1989). It has been shown that slope and intercept computations were sensitive to length of record and spacing between points (Briggs et al., 2001; Briggs et al., 2005), so it is likely that the dissimilarities in extent of the seabed that was imaged and the
system resolutions are responsible for some of the discrepancy observed between BRAD and Briggs data.

2.6. CONCLUSIONS AND PERSPECTIVES

2.6.1. Summary

This chapter reported on the development and first testing of the Benthic Roughness Acoustic Roughness. BRAD is now ready to be used; the algorithms needed to process the data have been successfully developed and tested on data collected in the lab and in the field.

The system can image an area of 1.7 m² in 50 minutes. It continuously records backscatter along beams (total of 101 beams per sweep, 150 to 200 sweeps per site) from the sonar head to a 2 m range. Along each beam, the seabed is detected using a threshold method. When present, the height of the canopy is also detected using a threshold method. Seabed and canopy elevations are interpolated to a regular grid (0.01 m) to produce the final images.

Lab tests were performed to evaluate the accuracy and limitations of the system. Sharp edges and slopes were smoothed and acoustic shadowing occurred, especially at higher beam angles. The horizontal resolution has been established to be around 2 to 3 cm (a function of beam angle) while the vertical resolution is sub-centimetre.

Field deployments enabled imaging of natural seabed types with a variety of roughnesses. Six sites were imaged, including seagrass canopies, bioturbated sediment and ripple fields. Seabed elevations and canopy height when present were successfully reconstructed from BRAD data.

Statistical and spectral analyses were applied to the seabed and canopy elevation data. Statistical parameters did not show any correlation to seabed type. By contrast, spectral analysis provided a valuable method to characterise topographic roughness. The spectra estimated from seabed elevations showed the degree of isotropy of the seabed topography. Bedform roughness was seen to present a strong anisotropy in the bedform direction and
the 2D spectrum was used to calculate the average direction, wavelength and height of the bedforms. In the case of biogenic roughness, the spectra were essentially isotropic.

Power-law regressions fitted on slices taken through the spectra were used to further characterise roughness. A high slope showed a strong influence of the small frequencies compared to high frequencies and was thought to be characteristic of bedform roughness. A smaller slope implied a stronger influence of high frequencies and therefore of stronger influence of biogenic roughness.

2.6.2. Recommendations for future work

Further work is needed to test BRAD. Imaging ripples with known variable dimensions in the fashion of Green and Boon (1988) would assess the capacity of BRAD to accurately reproduce ripples. Additional tests are also needed to evaluate the minimum size that can be detected, which has not been specifically estimated in the present study. In addition, the effect of sediment in suspension in the water column should be further tested. Sediment put in suspension will create a strong backscatter above the bed and under high turbidity the bed may be difficult to differentiate from sediment in suspension. The threshold over which the bed cannot be recorded accurately due to sediment concentration should be assessed.

The two-dimensional spectral analysis of seabed elevation data collected with BRAD proved to be a good tool to define topographical roughness. More research is needed to fully comprehend the influence of seabed elevation variations on diverse processes such as hydrodynamics and sediment movement. In particular, a better characterisation of temporal variations of topographical roughness is required. A catalogue of natural roughnesses imaged with BRAD and characterised through spectral analysis should be constructed. Moreover, further research should aim at related topographical roughness as described through spectral analysis of BRAD images and hydraulic roughness, often needed to compute hydrodynamics and sediment transport rates.
CHAPTER 3. USE OF A HIGH-RESOLUTION PROFILING SONAR AND A TOWED VIDEO CAMERA TO MAP A ZOSTERA MARINA BED, SOLENT, UK
3.1. INTRODUCTION

Seagrasses develop extensive underwater meadows forming complex, highly productive ecosystems which provide shelter and refuge for adult animals (Connolly, 1994), nurseries for juvenile fish (Horinouchi, 2007) and a supply of food for herbivores (Heck and Valentine, 2006). They represent a form of biogenic roughness of the seabed (Thompson et al., 2004) which attenuate currents and waves (Gambi et al., 1990; Fonseca and Cahalan, 1992). Thereby, they promote sedimentation and reduce erosion (Leonard and Luther, 1995). Furthermore, seagrass beds have high rates of primary production (Hasegawa et al., 2007) and are an important source of organic matter (Gacia et al., 2003). They can be used to assess the health of coastal and estuarine communities (Short and Burdick, 1996; Austoni et al., 2007) and to trace metal contamination (Lafabrie et al., 2008) or chemical constituents (Lewis et al., 2007). Seagrass beds can therefore serve as “coastal canaries”, global biological sentinels, with large-scale losses reported worldwide showing the increasing anthropogenic influences on the coastal ecosystems (Orth et al., 2006).

As a consequence of their strong ecological role, preservation, restoration or creation of seagrass beds are increasingly recognised as being essential for the sustainable management of the coastal environment (Yap, 2000; Short et al., 2007). Therefore it has become a growing concern to accurately map and monitor seagrass beds in order to assess their state and protect them (Kirkman, 1996). Mapping the extent and density of seagrass beds may also help in evaluating hydrodynamics and sediment transport in the coastal zone (Koch et al., 2006), as well as carbon and nutrient fluxes (Mateo et al., 2006; Romero et al., 2006).

Several techniques have been used to detect seagrass beds and estimate seagrass density, ranging from physical sampling to optical or acoustic techniques. Physical sampling, e.g. divers or beach surveys, provides accurate localised data but is labour-intensive and time-consuming. Optical techniques include satellite imagery, aerial surveys and towed underwater camera systems. Satellite and aerial techniques are often the preferred methods for seagrass mapping of intertidal areas because they cover large areas but these methods have limitations including cost, image distortion, tidal stage, water colour, cloud cover and turbidity (Vis et al., 2003). Underwater video camera systems provide direct observation of the seabed and have proved to be a good technique for
surveysing seagrass beds (Norris et al., 1997; McDonald et al., 2006). Video systems can give a record of macroalgae species composition and abundance as well as a description of the non-vegetated seabed. However, the data quality is limited by water clarity and boat speed (Short et al., 2007). Moreover, detailed interpretation of the video is time-consuming and subject to individual observer bias (Crawford et al., 2001).

Acoustic systems such as side scan sonars, echosounders or multibeam sonars can be used to measure the amount of acoustic energy scattered by plants as a proxy for seagrass abundance. The use of these techniques is growing as they facilitate more quantitative and spatially-referenced studies of submerged vegetation abundance (Warren and Peterson, 2007; Winfield et al., 2007). A density contrast between an object and seawater usually produces a strong backscatter response in the water column. This can be created by several phenomena, such as bubbles, suspended sediment, fish, the seabed or submerged vegetation (Katsnelson and Petnikov, 2001). As seagrasses have air-filled tissues (Sculthorpe, 1967), the density contrast between the plants and seawater creates a strong acoustic echo which can be used to assess seagrass canopy presence (Warren and Peterson, 2007). Echosounders, usually employed in bathymetric surveys, have been used to map submerged vegetation and canopy height (Sabol et al., 2002; Tegowski et al., 2003; Valley et al., 2005) but these instruments only acquire data on a single narrow track. Side scan sonars can be used to map seagrass distribution and detect lateral variations in seagrass coverage (Siljeström et al., 1996; Pasqualini et al., 1998), although accuracy decreases with increasing range (Kenny et al., 2003). However, side scan sonars do not provide bathymetric information or measure canopy height and accurate positioning can be difficult to compute. Multibeam sonars are able to map seagrass distribution in 3 dimensions and acquire data on canopy height (Komatsu et al., 2003). Although multibeam sonars rapidly produce a large quantity of data, the swath width of multibeam sonar depends on water depth therefore the efficiency of surveying decreases in shallow areas and the cost of the instrument may be prohibitive.

*Zostera marina* L. is the dominant seagrass species in the northern Atlantic (Short et al., 2007). It is a flowering plant with dark green, flat, ribbon-shaped leaves shooting from a rhizome (Dawes, 1998) and forms extensive submarine meadows on muddy or sandy substrates developing in subtidal (0-10 m), sheltered water (den Hartog, 1970). Leaf length varies from less than 10 cm to over 3 m and leaf width is usually between 2 and 10 mm.
\(Z.\ marina\) plants are often shelter to a great number of epiphytic fauna and flora and higher levels of biodiversity are found in \(Z.\ marina\) beds than in the surrounding bare sand (Hirst and Attrill, 2008). The distribution and dynamics of \(Z.\ marina\) and \(Zostera\ noltii\) (a smaller species of \(Zostera\)) have been described in several harbours (Portsmouth, Langstone and Chichester) in the Solent, UK (Tubbs and Tubbs, 1983; den Hartog, 1994). \(Z.\ marina\) occurs mainly in sublittoral beds around the low-water mark of spring tides and in large eulittoral beds on mudflats where it is often associated with \(Z.\ noltii\). \(Zostera\) beds in the Solent play an important ecological role because these seagrasses are the favoured food of Brent Geese (\(Branta\ bernicla\)) and Wigeon (\(Anas\)), which consume their leaves and rhizome in autumn and early winter (Tubbs and Tubbs, 1983). However, these ecosystems have been poorly studied up till now.

A survey has been undertaken off Calshot beach, in the Solent, UK, to investigate the extent and structure of a \(Zostera\ marina\) meadow that had not been previously mapped. This survey combined a profiling sonar, the Sediment Imager Sonar (SIS) and a towed seabed video sledge system. The objectives of the survey were:

1. to test the use of the SIS for seagrass surveying against the video camera system and
2. to map and characterise the seagrass bed surveyed in Calshot.

3.2. MATERIAL AND METHODS

3.2.1. Survey area

Calshot spit is situated in the West Solent, at the mouth of Southampton Water, on the south coast of England (Figure 3.1). The spit is an important recreational area for local residents with an outdoor activity centre, sailing club and beach huts. Car ferries, linking Southampton to Cowes on the Isle of Wight, pass close to the spit. The largest oil refinery in the UK is situated at Fawley only 4 kilometres north-west of Calshot. Recent morphological evolution of the spit shows that it has been stable for the last 125 years (Lobeck, 1995). The beach, off which the survey was undertaken, is composed of gravel (flint) with sandy patches. The tidal range varies from 2 to 4 m for mean neap and spring tides respectively; due to sheltering by the Isle of Wight, waves are generally small. All depths in this study are given compared to Chart Datum (CD) which is approximately the
level of Lowest Astronomical Tide. The intertidal zone on the beach is situated between 0 and +4 m CD, however zones situated between 0 and +1 m are exposed only during low water at spring tides. *Zostera marina* had been noted on Calshot beach during extreme low tides but the extent of the meadow was unknown.

![Figure 3.1: Geographical location of the survey area.](image)

### 3.2.2. Beach and diver surveys

Shore and divers surveys were conducted in the survey area shortly before the boat survey in order to measure shoot densities and maximum leaf length. On the 24th and 31st July 2007, measurements were made at 20 locations by SCUBA divers along 2 transects at right angles to the shore. At each location, 15 - 30 replicates were conducted by 2 divers using a 30 x 30 cm quadrat. Locations of the divers’ surface marker buoy were recorded by the support vessel (equipped with a Trimble DGPS) with an accuracy of around 5 m. Due to extreme low-water on the 2nd and 3rd August 2007, beach transects were possible and were conducted perpendicular to the beach from low water inshore at 10 m intervals (Vince, 2007). At each of the 17 locations, measurements of shoot density and maximum leaf length were taken over 10 replicate 30 cm x 30 cm quadrats. Beach positions were recorded by handheld Garmin GPS (accuracy 5 m).
3.2.3. Instrumentation used during the boat survey

a. The sonar system

The Sediment Imager Sonar described in the preceding chapter as part of the Benthic Roughness Acoustic Device was used in this study. During the survey, the instrument was facing the bow so that sweeps were perpendicular to the boat’s direction of travel. The sweep angle was 46.8° centered downward, so beams with a beam angle of 0° were recording backscatter just under the instrument, beams with a negative beam angle were surveying on the port side of the SIS head and beams with a positive beam angle were surveying on the starboard side of the instrument. The pulse duration was fixed to 40 µs and the measurement range was limited to 6 m along which 396 measurements of backscatter were recorded, yielding a vertical resolution of 1.5 cm, i.e. backscatter intensity recorded every 1.5 cm along a beam. Because the sweep angle was fixed, the horizontal distance over which an entire sweep was recorded depended on water depth, i.e. the deeper the water, the longer the area of seabed surveyed during a sweep; for example, the total of length of bed surveyed in a sweep varied from 1.5 to 4 m for water depths under the SIS varying from 1.75 to 4.6 m.

b. The video system

The video system is composed of a downward-facing video camera (Divecam-550C from Bowtech Products Ltd, Aberdeen, UK) and a light source mounted on a specially designed aluminium sledge (Craig, 2006). The video camera is a miniature, high-definition (550 TV lines) colour CCD camera (PAL format, 25 frames per second) with a scanning speed of 50 Hz. Illumination is provided by a 50 W array of high intensity white LEDs. The sledge is towed approximately 20 m behind the vessel with a Kevlar cored multi-conductor cable, typically at a speed of 1 to 2 knots to allow good quality images (blurring becomes unacceptable at speeds above 2 knots). With the camera held at approximately 50 cm above the bottom, the field of view averages an area of about 50 x 70 cm. The height of the sledge can vary slightly (± 20 cm) with boat speed. A 12 volts power supply for the lights and camera is provided through the towing cable in which the composite video signal also returns. Boat location is recorded with the onboard differential GPS (Trimble, submetre resolution) and is overlaid on the video signal. The analogue composite video signal is viewed onboard and recorded at the highest possible resolution to hard disc; it is subsequently copied onto a DVD for play-back.
3.2.4. The survey

A survey was undertaken on 12th September 2007 onboard the R.V. Bill Conway around high tide during spring tide. During the survey, the SIS was fixed 94 cm below the waterline to a downrigger mounted on the starboard side of the boat while the camera system was towed around 20 m behind the boat (Figure 3.2a). The SIS was positioned around 22 m in front and 2 m on the starboard side of the camera the instruments were therefore not always surveying identical seabed locations (0 to 2 metres lateral difference depending on water depth, Figure 3.2b). A monitor and a computer in the cabin gave real-time displays of the video and SIS images. Waves were small (less than 20 cm high) and the weather was sunny with light winds. Four lines parallel to the shore were surveyed in 3.5 hrs at a speed of 1 to 2 knots. Lines were about 1.5 km-long and were spaced 50 to 100
m apart. The total length of the surveyed lines was 6.5 km encompassing an area of 44.6 ha.

Salinity and temperature profiles were measured on site prior to survey using a YSI 30 probe. The average salinity recorded was 34.8 and the average temperature was 18.3°C, yielding a sound velocity of 1516 m s\(^{-1}\) which was entered into the SIS software to compute correct depth from the 2-way travel time. The profiles of temperature and salinity suggested a well-mixed water column (less than 5% changes in salinity and temperature with depth) and therefore no correction was needed for a change in speed of sound with depth.

3.2.5. Data processing

   a. Video data

   The video was replayed at half speed to allow adequate time for observations to be made. Every 2 to 3 seconds, the video was paused and relative Zostera density, algae abundance, seabed type, time and position were logged (Table 3.1). A semi-quantitative density scale was established to evaluate seagrass coverage (Zostera density, ZosD) ranging from 0 where no seagrass was seen, to 4 in the case of a continuous seagrass canopy. Presence and abundance of algae (algae index AlgI) was ranked from 0 (no algae) to 2 (abundant algae). In this study, the term algae is used to designate macroalgae such as Enteromorpha spp, Ulva lactuca, Halurus flosculosus or Ceramium spp. Planktonic species, which are hard to distinguish on the video, were not considered. Bottom type (BoType) was assigned the value 1 when the seabed was covered with sand, 2 in case of a mix of gravel and sand and 3 when the seafloor was covered with gravel. When the seagrass canopy occupied the whole image and prevented seabed observation, no value was put in the bottom type rating. During the survey, ripples were observed on the seabed and were allocated a BoTyp value of 0.5, in order to be differentiated from other bottom types. An observation every 2 seconds on the video translates to a data point every 2 to 4 m over the seabed.
Table 3.1: Definition of ratings used to describe the variables calculated from the video data.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zostera density (ZosD)</td>
<td>0</td>
<td>no seagrass</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>sparse coverage (only a few shoots within several video frames)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>patchy coverage (patches of seagrass and sand or intermediate density)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>dense seagrass but seabed visible (&lt; 100% cover)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>continuous seagrass canopy (100% cover)</td>
</tr>
<tr>
<td>Algae index (AlgI)</td>
<td>0</td>
<td>no algae</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>algae present</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>abundant algae</td>
</tr>
<tr>
<td>Bottom Type (BoTyp)</td>
<td>0.5</td>
<td>sandy sediment with small ripples</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>sandy sediment</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>mix sand/gravel</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Gravel</td>
</tr>
</tbody>
</table>

**b. SIS data**

The SIS was sweeping over the bed perpendicularly to the direction of travel. It was hence recording data over a line going 4 to 10 m in the direction of boat travel and 1 to 3 m towards one side of the instrument (negative beam angles to the left, positive to the right) before changing direction and recording another sweep; overall the track of the data was therefore in a zigzag (Figure 3.2b). A sweep, recorded in about 10 seconds, was composed of 52 beams, therefore beams were recorded every 5 to 13 cm depending on boat speed and water depth (beam rate of 5.2 beam s\(^{-1}\), boat speed of 1 to 2 knots and water depth under the SIS between 2 and 5 m). If all of the points in a sweep were used to assess seagrass distribution then a very high-resolution dataset could be achieved; however changes in seagrass density at the centimetre scale meant that backscatter values would be highly variable from one point to the next. Moreover, the lateral extent of the data (1 to 3 m) would be hard to represent compared to the length of the lines (1.5 km) and would have to be averaged for an overall analysis. Therefore, most of the processing was done on 5 averaged beams in the middle of the sweep in order to reduce variability and produce a single data point per sweep, i.e. one point every 4 to 10 m, the same resolution as video data. Because beams with angles at ±1.8° from the vertical were averaged, the average beam angle was 0°, i.e. the average beam was perpendicular to the flat seabed, thereby reducing the need to apply a correction for beam angle. The backscatter data of those 5 averaged beams were processed in several steps in order to calculate the depth of the bed, the Seagrass Index (SI) used to assess seagrass presence and, if present, the height of the canopy (Figure 3.3).
Firstly the depth of the bed was computed as the depth of the maximum backscatter. A sharp contrast in acoustical impedance at the sediment/water interface defines the bed as the strongest acoustic scatterer of a given beam (Warren and Peterson, 2007). Hence the depth of the strongest backscatter usually denotes the depth of the seabed. This depth was corrected for the height of the tide during the survey and the depth of the SIS under the boat in order to provide bathymetric data along the survey lines. Secondly, the value of the maximum backscatter, i.e. the backscatter on the seabed, was recorded. Backscatter intensity from side scan sonar data has been shown to be related to the mean size of bottom sediments on the phi scale (Collier and Brown, 2005). Although sediment size was not assessed in this study, bottom type was identified on the video images and therefore areas of sand and gravel were distinguished. A relationship was therefore sought between

Figure 3.3: Backscatter intensity of the 5 averaged beams as a function of depth from SIS head for a sweep over a. bare seabed and b. a seagrass canopy. The depth of the bed (dark grey line) is coincident with the depth of maximum backscatter (black dot on the line bed). The Seagrass Index (SI) is the average backscatter 10 to 15 cm above the bed (average backscatter of the points in the black rectangle) and the height of the canopy (CH) is the first point where the backscatter is above a threshold value. In Figure 3a, the SI was 93 yielding a SIs of 0.1 i.e. no or little seagrass; no point satisfied the threshold condition for the canopy height which therefore was 0. In Figure 3b, the SI was 177 yielding a SIs of 3.9 i.e. dense seagrass canopy; the first point satisfying the threshold condition for canopy height is situated 17 cm above the bed, so CH = 17 cm. See section 3.1 for details of SIs and P, calculation.
backscatter on the seabed and bottom type, especially in areas with little or no seagrass plants. Thirdly, the Seagrass Index was calculated by averaging the intensity of the backscatter 10 to 15 cm above the seabed (black rectangles on Figure 3.3). When present, submerged vegetation usually produces a strong backscatter immediately above the bottom to a height that depends on canopy height (Sabol et al., 2002). The Seagrass Index was used to discriminate seagrass canopies from bare seabed, i.e. low SI corresponding to bare seabed (Figure 3.3a) and high SI indicating dense vegetation (Figure 3.3b). Fourth, the height of the canopy (CH) was computed as the height above the bed where the backscatter was greater than a given threshold value. An adequate threshold value was found to be the ambient backscatter in the water column at a distance of 1.0 to 1.4 m from the SIS plus 60 yielding to a backscatter threshold value of around 150 depending on the backscatter in the water column (see lines ‘threshold value for CH’ on Figure 3.3).

The last quantity calculated for each sweep was the ‘patchiness’ (P). As the SIS swept the seabed perpendicularly to the boat track, it provided data on the lateral extent of the canopy. An attempt to measure the patchiness, defined here as the percentage of the seabed fully occupied by seagrass plants during a sweep, was computed as the percentage of beams in a sweep where the SI was superior to a threshold value (backscatter of 120). Calculation of the depth of the bed and SI were the same along a beam as for the 5 averaged beams, i.e. the depth of the bed was recorded as the depth of the maximum backscatter and SI was the average backscatter 10 to 15 cm above the bed. A P of 0 indicates that no seagrass was recorded on the whole sweep and a P of 1 shows that a dense canopy was recorded on the whole sweep. As all the beams in a sweep were used to calculate P, full advantage was taken of the lateral extent of the seabed survey using the SIS. This parameter could not have been calculated using data from a single beam echosounder.

Parameter calculations and threshold values were found empirically by trial and error. Several heights of averaging and threshold values for SI and P parameters were tested against results from video data. Averaging the backscatter 10 to 15 cm above the bed was found to be the best method to detect presence of Zostera marina and is intuitively understandable considering that the top of the canopy is situated around that height. The threshold value used to calculate the height of the canopy was tested against SIS images.
and backscatter intensity along a beam, where the height of the canopy was clearly visible as a stronger backscatter above the bed (see Figure 3.3).

c. **Dataset alignment**

Data points collected with the two instruments were not coincident; video observations were made every 2 to 4 m whereas SIS data points were approximately every 4 to 10 m depending on boat speed. Furthermore, the video camera was around 23 m behind the SIS and 2 m on its port side. The two datasets had to be merged to enable comparison of parameter values. Data processing and analysis were done in Matlab and plotting with ArcGIS. Firstly, co-ordinates were transformed from geographic to projected system and corrected from the layback of the video (around 25 m depending on the depth) and the SIS (2 m) to the DGPS antenna. Thereafter, the values of the parameters calculated from the video were interpolated every metre (in order to achieve a regular grid and therefore the same number of video points around each SIS point) and averaged 5 m around each SIS data point. Averaging video parameters around SIS points reduces uncertainty due to variations in the height of the camera above the bed and the lateral difference between the location where the camera and SIS were recording the seabed, which could not be corrected. This averaging exercise was done in order to obtain coincident points from the SIS and video data and therefore be able to compare the 2 datasets; in the future however, it is not necessary to do so if the aim of the survey is to assess seagrass presence and density without comparing datasets obtained from 2 systems. Statistical parameters, such as mean and standard deviation of the variables and correlation coefficients between the parameters, were calculated using Matlab. The data were then imported into arcMAP and rasters (cell size of 5 m) calculated using the Natural Neighbour interpolation.

### 3.3. **RESULTS**

#### 3.3.1. **Comparison of instruments**

A total of 1007 sweeps, each composed of 75 beams, was recorded during the 3 hours of the camera survey. In each sweep, the seabed was clearly recognisable by its strong backscatter (Figure 3.4a). Where seagrass was present, a strong backscatter was observed above the bottom, which was weaker than the bottom return but stronger than ambient
noise. Seagrass could be detected either over the whole length of the sweep (Figure 3.4b) or only parts of it where the seagrass bed was patchy (Figure 3.4c).

The correspondence was good between *Zostera* Density (ZosD) calculated from the video data and patchiness (P) computed from the SIS data (Figure 3.5a, $R^2 = 0.61$, $n = 1007$, $p < 0.001$). The correlation was not as strong between Seagrass Index (SI) and ZosD (Figure 3.5b, $R^2 = 0.44$, $n = 1007$, $p < 0.001$). In order to compare the 2 datasets, SI and P were scaled to the video data values. Most of the points with an SI inferior to 85 or P inferior to 0.05 had low ZosD values (on average 0.4 and 0.3 respectively), indicating that no seagrass or only a few shoots were observed on the video for such points and these can be assigned a value of 0. Points with SI greater than 180 or P greater than 0.85 had high ZosD values (on average 3.4 and 3.1 respectively) indicating that the seagrass canopy was seen on the video and that these points could be attributed a value of 4. Based on the above, SI and P were scaled as followed:

$$SI_s = 4 \times \frac{SI - 85}{180 - 85}$$  \hspace{2cm} (3.1)

$$P_s = 4 \times \frac{P - 0.05}{0.85 - 0.05}$$  \hspace{2cm} (3.2)

Figure 3.4: Examples of SIS sweeps over a. bare seabed; b. continuous seagrass canopy; c. patchy seagrass. Distance along the x-axis refers to the horizontal distance along the sweep. The strongest backscatter denotes the seabed. A backscatter higher than ambient noise above the bed indicates the presence of seagrass. The seabed is seen to be undulating due to boat movements with waves. The horizontal distance covered by the sweep is a function of seabed depth, hence the difference in the extent of seabed (in red) and water column (in blue) seen on each sweep.
In doing so, SI, and P have the same range as ZosD, and the values of SI and P of a given point can be interpreted following the description of ZosD as summarised in Table 3.1, i.e. SI or P of 0 shows an area with no or very little seagrass, whereas SI or P greater than 3 can be classified as a dense canopy (see Figure 3.3). The correlation coefficients between SIS data (P and SI) and video data (ZosD) remained the same after scaling (Figure 3.5c and 3.5d).

![Figure 3.5: The relationship between seagrass coverage estimated from the video (ZosD) and from the SIS data: a. P (R\(^2\)=0.61); b. SI (R\(^2\)=0.44); c. P scaled with Equation 3.2 (R\(^2\)=0.61); d. SI scaled with Equation 3.1 (R\(^2\)=0.44). On all graphs the regression line associated with R\(^2\) is shown; each graph contains 1007 points and p-values were always < 0.001.](image)

Along the survey lines, there was general agreement between the video and SIS evaluations of seagrass density; P, SI, and ZosD showed the same trends and intensity ranges (Figures 3.6a and 3.6b). Only at some locations, e.g. around 4500 m along the line, P predicted a canopy less dense than ZosD. SI showed similar trends to ZosD and P, but
had more along-line scatter. Seagrass canopy height (CH) was found to be between 0.1 and 0.2 m (Figure 3.6c). The video system could not produce quantitative data for canopy height and so assessment of accuracy was not possible for this parameter. However, canopy height, which is dependant on current speed and seagrass density (Gambi et al., 1990) was observed during dives and found to be between 0.15 and 0.3 m. It thus appears that CH calculated from the SIS data was a good approximation of the measured height of the canopy.

Figure 3.6: Comparison of the different parameters computed from video and SIS data. The shaded areas show zones with little or no seagrass. a. seagrass density calculated from SIS data, P (grey) and from video data, ZosD (black); b. seagrass density SI, calculated using SIS data; c. canopy height CH estimated from SIS data; d. algae abundance AlgI described from video data; e. bottom type BoTyp rated from video data; f. backscatter intensity on the seabed, bed back, calculated from SIS data; g. average backscatter in the water column, water.
The algae abundance parameter (AlgI) did not correlate with seagrass density evaluated from the SIS data, \( P_s \) or \( S_{I_s} \) \((R^2 = 0.03\) and \( p < 0.001\) for both parameters). Furthermore, when AlgI was greater than 1.5 and ZosD was 0, i.e. significant quantities of algae seen on the video but no seagrass, both the scaled patchiness \( P_s \) and Seagrass Index \( S_{I_s} \) had values below 0.5, i.e. no seagrass or only few shoots were present (Figure 3.6d). This suggested that \( S_{I_s} \) and \( P_s \) were not influenced by algae presence.

Seabed backscatter did not show the same along-line variations as bottom type assessed from the video, BoTyp (Figure 3.6e and Figure 3.6f). Furthermore, backscatter on the seabed exhibited strong point to point variations. Acoustic attenuation is affected, amongst others, by sound travel distance, turbidity in the water column and presence of submerged vegetation (Katsnelson and Petnikov, 2001). Results indicated that backscatter on the seabed was weakly correlated with depth during the survey \((R^2 = 0.3)\) and that it was not correlated with average backscatter in the water column \((R^2 = 0.06)\) or Zostera Density \((R^2 = 0.01)\). A relationship was sought between bottom type and bed backscatter in areas with no or little seagrass \((ZosD < 1)\) by averaging the bed backscatter for each bottom type (Figure 3.7). The average backscatter on the seabed was found to be the lowest on sandy bottom (179), intermediate on mixed sand and gravel (190) and highest on areas of gravel (198). However, the standard deviations of each distribution (20, 21 and 23 respectively), were higher than the difference in average values therefore reflecting the high variability of the backscatter on the seabed. As the scatter in the bed backscatter data was very high, this parameter could not be used to determine bottom type, even in areas with little or no seagrass.

![Figure 3.7: Average backscatter on the seabed as a function of the 4 bottom types recognised from the video data. The vertical black lines show the standard deviation.](image)
3.3.2. Description of the survey area and seagrass distribution

The combination of direct measurements by beach and diver surveys and remote sensing with SIS and video systems produced a valuable dataset with which to map the survey area. The video and SIS systems offered the opportunity to rapidly classify a large portion of seabed whereas direct measurements, although time-consuming, provided shoot densities and leaf length measurements unavailable with remotely acquired data. The maximum average shoot density encountered was 150 shoots m$^{-2}$. However, individual shoot densities in a quadrat were often higher, reaching a maximum of 500 shoots m$^{-2}$. Seagrass was rarely encountered as a dense continuous meadow and more frequently as small (decimetres) patches with locally high densities. Maximum leaf length varied from 20 to 90 cm with an average of 33 cm (average standard deviation 18 cm).

The only seagrass species recognised on the video was *Zostera marina*. Densities varied from very sparse (a few shoots seen during the 2 - 3 seconds assessed) to a dense meadow (only a dense *Z. marina* canopy seen on the image). Frequently, algae (*Enteromorpha* spp, *Ulva lactuca*, *Halirus flosculosus* or *Ceramium* spp.) and epiphytes were also seen. The sediment varied from fine sand to mixed sand/gravel and gravelly beds. Shells were often seen on the bottom although never formed an extensive mat. At some locations, small sand ripples were observed. These were aligned with the camera track, hence parallel to the shore. Ripple dimensions could not be precisely assessed due to the lack of a scale on the video image and the varying depth of the camera sledge above the bed. It was estimated that they had a wavelength of 5 to 10 cm and a height of about 1 cm.

Quantitative maps of the different parameters calculated using SIS and video data were produced from the GIS raster. The survey area was thereafter classified according to parameter values as described in Table 3.2.
Eight regions with distinct characteristics were recognised from this classification (Table 3.3 and Figure 3.7).

Zone 1: seagrass meadow. Around 4 hectares of the survey area were categorised as a seagrass meadow with an average ZosD of 3.1 and a $P_s$ of 2.4. This zone also comprised the locations with the highest densities counted from the beach and diving surveys ranging from 110 to 145 shoots m$^{-2}$. The average canopy height was 12 cm and the maximum leaf lengths from beach and diving surveys were between 40 and 80 cm. The difference between the maximum leaf length and the canopy height might be explained by the bending of the canopy (Fonseca et al., 1982) and the variations in leaf length within the canopy since during the surveys, only the maximum length was recorded. BoTyp was on average 1.0 in this zone, indicating that bottom sediment was sandy.

Zone 2: patchy seagrass. The edges of the seagrass meadow were much patchier with an average ZosD of 2.1 and $P_s$ of 1.7 on sandy sediment (average SedI of 0.7). Beach and intertidal surveys showed densities of between 80 and 110 shoots m$^{-2}$ with a strong standard deviation over the quadrats measured at the same location (around 60 shoots m$^{-2}$).

Zone 3: sparse seagrass. Around the patchy seagrass was an area of sparse seagrass with an average ZosD of 1.2 and $P_s$ of 0.9. The sediment was sandy (average BoTyp 1.0) and algae was often present but not abundant (average AlgI of 0.5). The two direct measurements performed in this area recorded a shoot density of about 50 shoots m$^{-2}$.

![Table 3.2: Parameters values used to classify the survey area.](image-url)
Figure 3.8: a. Location of the survey lines and the 8 zones defined in the text; b. interpolated bathymetry and scaled Seagrass Index (SI) along the survey lines; c. interpolated Zostera Density (ZosD) raster and algae abundance (AlgI) values along the lines; d. interpolated Bottom type (BoTyp) raster and scaled patchiness (Ps) values along the lines. Refer to Table 3.2 for definitions of the parameter values. Aerial photos (2001, ortho-rectified) are courtesy of the Channel Coastal Observatory (www.channelcoast.org).
Zone 4: mixed sand and gravel. An area with mixed sand and gravel (average BoTyp 1.7) without seagrass (average ZosD and Pₕ of 0.1) was found in the southern region of the survey.

Zone 5: algae. In the middle of the mixed sand and gravel area was found an area characterised by abundant algae (average AlgI of 1.5) and no seagrass (average ZosD and Pₕ of 0.0) on a sandy bottom with some gravel (average BoTyp of 1.3).

Zone 6: ripples. In the middle of a sandy intertidal flat was found an area with small sand ripples (average BoTyp of 0.5) and very few seagrass plants (average ZosD of 0.3).

Zone 7: bare sand. Small portions of the survey area (11%) were characterised by bare sand (average BoTyp of 1.0, ZosD of 0.5, Pₕ of 0.2 and AlgI of 0.3).

Zone 8: gravel. The most southern part of the survey was characterised by bare gravel (average BoTyp of 2.7). No seagrass was seen in this region (average ZosD and Pₕ of 0.0) and very few algae were present (average AlgI of 0.3).

Table 3.3: Average and standard deviation of the variables calculated from the video and SIS data for the 8 zones defined in the survey area. Back is the backscatter on the seabed, the other parameters are described in Table 3.1 and section 2.5.2.

<table>
<thead>
<tr>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Seagrass meadow</td>
<td>Patchy seagrass</td>
<td>Sparse seagrass</td>
<td>Sand/gravel</td>
<td>Algae</td>
<td>Ripples</td>
<td>Sand</td>
<td>Gravel</td>
<td></td>
</tr>
<tr>
<td>Area (ha)</td>
<td>4.07</td>
<td>12.77</td>
<td>12.11</td>
<td>4.96</td>
<td>3.02</td>
<td>1.44</td>
<td>4.93</td>
<td>2.91</td>
<td>44.59</td>
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<tr>
<td>Area (%)</td>
<td>9</td>
<td>28</td>
<td>26</td>
<td>11</td>
<td>7</td>
<td>3</td>
<td>11</td>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>-0.3±0.4</td>
<td>-0.4±0.5</td>
<td>-0.4±0.8</td>
<td>-1.1±0.6</td>
<td>-0.7±0.5</td>
<td>0.7±0.1</td>
<td>0.2±0.9</td>
<td>-0.7±0.4</td>
<td>-0.5±0.7</td>
</tr>
<tr>
<td>ZosD</td>
<td>3.1±0.4</td>
<td>2.1±0.4</td>
<td>1.2±0.4</td>
<td>0.1±0.2</td>
<td>0.0±0.1</td>
<td>0.3±0.1</td>
<td>0.5±0.2</td>
<td>0.0±0.1</td>
<td>1.3±1.0</td>
</tr>
<tr>
<td>Pₕ</td>
<td>2.4±0.4</td>
<td>1.7±0.4</td>
<td>0.9±0.3</td>
<td>0.1±0.1</td>
<td>0.0±0.0</td>
<td>0.0±0.1</td>
<td>0.2±0.2</td>
<td>0.0±0.0</td>
<td>1.0±0.8</td>
</tr>
<tr>
<td>SIs</td>
<td>2.6±0.6</td>
<td>1.8±0.5</td>
<td>1.0±0.4</td>
<td>0.2±0.2</td>
<td>0.2±0.2</td>
<td>0.2±0.1</td>
<td>0.3±0.2</td>
<td>0.1±0.2</td>
<td>1.1±1.0</td>
</tr>
<tr>
<td>CH</td>
<td>0.12 ±0.03</td>
<td>0.08 ±0.03</td>
<td>0.04 ±0.02</td>
<td>0.01 ±0.01</td>
<td>0.01 ±0.01</td>
<td>0.01 ±0.00</td>
<td>0.01 ±0.00</td>
<td>0.05 ±0.05</td>
<td></td>
</tr>
<tr>
<td>AlgI</td>
<td>0.3±0.2</td>
<td>0.5±0.2</td>
<td>0.5±0.3</td>
<td>0.9±0.3</td>
<td>1.5±0.2</td>
<td>0.1±0.1</td>
<td>0.3±0.3</td>
<td>0.3±0.3</td>
<td>0.6±0.4</td>
</tr>
<tr>
<td>BoTyp</td>
<td>1.0±0.0</td>
<td>1.0±0.1</td>
<td>1.0±0.1</td>
<td>1.7±0.4</td>
<td>1.3±0.2</td>
<td>0.5±0.0</td>
<td>1.0±0.1</td>
<td>2.7±0.2</td>
<td>1.2±0.6</td>
</tr>
<tr>
<td>back</td>
<td>192±7</td>
<td>186±7</td>
<td>181±8</td>
<td>189±12</td>
<td>191±15</td>
<td>183±9</td>
<td>180±11</td>
<td>197±15</td>
<td>186±11</td>
</tr>
</tbody>
</table>
The classification of the survey area showed that the gravel zone was free of seagrass. Amongst the survey points recognised as seagrass (ZosD or P_s > 1), 98% had a BoTyp smaller than 1.5 indicating that *Zostera marina* in Calshot was found only on sand and was absent from gravel zones. Furthermore, *Z. marina* was found to prefer depths of between -1 and +0.5 m CD (80% of the distribution, Figure 3.9) and was seldom found at depths below -1.5 m CD (3% of the distribution). Around 10% of the points recognised as *Z. marina* were situated between +0.5 and +0.93 m CD, which was the upper limit of the survey due to boat limitations. However, beach surveys and aerial photos indicated that *Z. marina* plants can be found on Calshot beach up to +1.5 m CD. In total, 35% of the points recognised as *Z. marina* were found within the lowest intertidal zone.

### 3.4. DISCUSSION

The results show that it is possible to use SIS data to predict seagrass abundance and canopy height through P_s, SI_s and CH and that these parameters were not affected by the presence of algae. The SIS has therefore proved a reliable tool to detect seagrass, giving estimates of canopy height and density as well as measures of bathymetry. The video system provided continuous visual observation of the seabed and therefore was used to identify seagrass and algae species and abundance and to assess bottom type.
Agreement between the 2 instruments was very good; seagrass density evaluated from the video was better correlated with the parameter initially calculated to measure patchiness $P_s$ than to the one specifically used for seagrass detection $S_{IS}$ ($R^2$ of 0.61 and 0.44 respectively). The correlation between $S_{IS}$ and $ZosD$ increased significantly if the parameters were averaged every 4 values, i.e. a data point every 30 m ($R^2 = 0.71, n = 248, p < 0.001$); the correlation between $P_s$ and $ZosD$ also increased after averaging ($R^2 = 0.79, n = 248, p < 0.001$). Averaging allowed data comparison over a larger area and removed any high-resolution spatial variations. A better correlation between averaged parameters therefore indicates that the values of $ZosD$, $S_{IS}$ and $P_s$ were greatly influenced by local variations in seagrass densities and/or location offset between the portions of the seabed surveyed by the 2 different systems. This effect is probably exacerbated by the patchiness of the seabed surveyed.

The Seagrass Index ($SI$) was calculated from 5 beams over the 52 beams contained in a sweep and hence covers 0.3 to 0.8 m of the seabed. The patchiness $P$, on the other hand, was calculated from the data of an entire sweep i.e. a line of 4 to 10 m in the boat direction and 0.5 to 1.5 m to each side of the instrument depending on water depth. Therefore, $SI$ specified the presence and abundance of seagrass at a precise location whereas $P$ showed an average of seagrass cover between two points. As the video data were averaged 5 metres around the SIS data points, they were also assessing seagrass cover between two points. This certainly explains the fact that $P$ showed a better correlation with video data than $SI$ did. In future surveys, it would be preferable to use $ZosD$ or $P$ to classify the area in terms of seagrass densities and to use $SI$ to assess seagrass presence at a precise location.

The SIS does not integrate any time-variable gain (TVG) to account for transmission loss. This implies that the diminution of backscatter with distance from the transducer head is not taken into account during data acquisition (Katsnelson and Petnikov, 2001) and should be corrected during data processing. However, the scatter in the backscatter data was large and as a result there was no significant relationship between distance from the SIS head and backscatter intensity. No correction was therefore applied during processing to account for this phenomenon. Depth variations during the survey were small (depth under the SIS ranging from 1.5 to 4.4 m with an average 2.9 m and a standard deviation 0.7 m); the small depth variations may explain why the lack of TVG did not influence the SIS...
data collected during this survey. However, if depth variations are high during a future survey, a correction of diminution of backscatter with distance from the source might need to be applied.

Correct calculation of canopy presence and height from SIS data is strongly dependant on the correct computation of the depth of the seabed. In the present study, the bed was always found to constitute the highest backscatter of a given beam (used to calculate $P$) or of the 5 averaged beams in the middle of the sweep (used to calculate SI and CH); this might be explained by the relatively low shoot densities encountered in Calshot. However, if the maximum backscatter is found in the seagrass canopy, bathymetry, SI, CH and $P$ will be incorrectly calculated. This might happen in the case of high shoot densities, e.g. *Zostera marina* bed described by Cabello-Pasini et al. (2003) with densities of 1400 shoots m$^{-2}$; other seagrass species might also create a stronger backscatter than those observed in our study and therefore the maximum backscatter might be found within the seagrass canopy rather than on the seabed. As this is the first time the SIS has been used to survey a seagrass canopy, it is not possible to determine the influence of seagrass species on backscatter at present, but care will have to be taken in further studies to ensure consistency of bed depth along a sweep.

The processing methodology used to calculate SI, $P$ and CH from the SIS data was found empirically by trial and error. The threshold values and heights of averaging worked for the survey presented here, however, they will probably need to be changed for other surveys, depending on environmental conditions and seagrass species surveyed. For example, the height where the backscatter is averaged to calculate SI might have to be different in the case of a smaller seagrass species. Moreover, threshold values might need to be adjusted due to water turbidity.

Overall, seagrass densities calculated from the video ($\text{ZosD}$) and the SIS ($P_s$ and $\text{SI}_s$) had similar intensities. At some locations however, $P_s$ had smaller values than $\text{ZosD}$. This discrepancy could have been caused by errors in estimating seagrass density either from the video or from the SIS data. Video interpretation is a time-consuming activity and clearly subject to interpreter bias (Crawford et al., 2001). Density evaluation could have been wrongly evaluated due to poor visibility (high turbidity in the water column) or variations in the height of the sledge above the bed revealing more or less of the seagrass bed and therefore affecting observer classification. The SIS acoustically detected the
changes in seagrass densities. As the SIS does not incorporate a TVG, water depth variations during the survey might have had an influence on the backscatter intensity from the seagrass and led to inaccurate estimations of seagrass density. A weak correlation ($R^2 = 0.35$) was found between water depth during the survey and $P_s$ greater than 1, i.e. points with a seagrass canopy. However, correcting for this relationship did not reduce the discrepancy sometimes observed between video and SIS data.

The abundance of benthic invertebrates is generally higher in a *Zostera marina* bed than in adjacent bare sand (Boström and Bonsdorff, 1997; Hirst and Attrill, 2008). Shelled benthic fauna has a higher density than the surrounding water and therefore produces a strong backscatter echo (Sauriau et al., 1998). Variations in backscatter intensity within a seagrass canopy could hence be related to invertebrate density. Epiphyte loading has potentially an influence on backscatter intensity in a seagrass bed. This effect has not been studied and has yet to be tested. Although shelled fauna may play a role in seagrass detection, the plants are thought to be acoustically identified mainly by their air-filled tissues (Sculthorpe, 1967) which produce a density contrast with seawater and create a strong acoustic echo (Sabol et al., 2002; Warren and Peterson, 2007). Variations in gas production may therefore also account for some of the differences encountered between video and SIS estimations of seagrass density. This effect also needs to be studied in more detail.

Parameters calculated from acoustic data ($SI_s$ and $P_s$) were related to seagrass densities and were not affected by the presence of algae. Algae lack vascular tissues and most of the species noted during the survey were very thin foliose or filamentous, thus unlikely to produce as strong an acoustic return as the seagrass. Besides, $SI$ was calculated by averaging the backscatter 10 to 15 cm above the bed, which was found to be the height of the highest backscatter on the seagrass. Most algae have smaller dimensions and should not produce a strong echo at this height. Algae might present a problem in mapping and identifying smaller seagrasses (e.g. *Zostera noltii*) which have the same dimensions as most algae observed in this area.

The survey presented here aimed to test the instruments’ capabilities to detect seagrass and assess the extent of the seagrass bed in Calshot. The spacing between survey lines was large (50 to 100 m) and therefore, parameter values were highly interpolated between the lines, especially compared to the interpolation between 2 consecutive points (separated by
4 to 10 m). This can result in incorrect spatial distribution of the parameters between the survey lines. In future surveys aimed at mapping seagrass beds, line spacing should be smaller (less than 50 m) in order to reduce errors which might arise from highly interpolated data. Despite the uncertainties due to the large interpolation applied, the dataset produced by the beach, diver and boat surveys was used to describe the *Zostera marina* bed in Calshot as some characteristics were little or not affected by interpolation.

The seagrass bed was characterised by small patches of seagrass in the lower intertidal area and a small area with a higher density canopy around the -1 m depth line. Seagrass densities (150 shoots m\(^{-2}\)) were low compared to those reported in some locations e.g. 1400 shoots m\(^{-2}\) in Baja California, Mexico (Cabello-Pasini et al., 2003) or in New Jersey, USA (Bologna, 2006) but related well to densities described in other locations e.g. 100 shoots m\(^{-2}\) in Woods Hole, USA (Worcester, 1995) or between 60 and 500 shoots m\(^{-2}\) in the Baltic Sea (Boström and Bonsdorff, 1997). Few *Zostera* beds have been described in the south coast of England. Tubbs and Tubbs (1983) summarised the spatial distribution of *Zostera* in the Solent. They described sublittoral beds of *Zostera marina* occurring on relatively exposed shores on firm sand from about 1 m below to 1 m above CD; the beds are thus mostly permanently submerged, though the upper margins may be exposed at extreme low-water spring tides. Flowering stem densities varied from 25 to 75 shoots m\(^{-2}\) and leaf length reached 30 cm. More recently, Hirst and Attrill (2008) described a *Z. marina* bed in Devon, on the south coast of England, which is exposed at extremely low water. The seagrass coverage was sparse in the intertidal zone, ranging from a few shoots to patches up to 1.6 m across, and more continuous into the subtidal zone. The *Zostera* bed mapped in Calshot, where the patchy, low density seagrass bed was exposed during extreme low water and a more continuous bed was found in the subtidal down to −1.5 m CD, therefore is in line with descriptions by previous authors in the same area (Tubbs and Tubbs, 1983; Hirst and Attrill, 2008). However the only seagrass recognised in Calshot was *Z. marina*, unlike in Langstone Harbour where *Zostera noltii* and *Z. marina* occurred in homogeneously mixed patches (den Hartog, 1994).
3.5. CONCLUSIONS AND PERSPECTIVES

3.5.1. Summary

The use of both a video camera sledge and a high-resolution profiling sonar during the survey facilitated the evaluation of the SIS for seagrass detection and a preliminary mapping of the seagrass bed in Calshot. The advantages of the camera system were direct observations of the seabed, the possibility of flora identification and bottom type classification. However, data processing was time-consuming and subject to observer error. The SIS has proved to be a useful tool for seagrass surveying. An algorithm to analyse the data was developed and tested. The Seagrass Index (SI) was calculated as the average backscatter 10 to 15 cm above the bottom of 5 beams averaged in the middle of a sweep and the patchiness (P) as the percentage of beams in a sweep where the average backscatter 10 to 15 cm above the bottom were higher than a threshold value. It was possible to estimate seagrass abundance using SI and P. Furthermore, the SIS was used to estimate canopy height and accurately measure depth of the seabed. On the other hand, the backscatter on the bottom showed too much scatter to be used for bottom type determination.

The combination of the two systems provided a valuable dataset with which to study a seagrass bed in Calshot, which was complimented by direct measurements during beach and diver surveys. The survey area has been classified according to seagrass density, algae abundance and bottom type. Eight regions were distinguished, comprising areas of bare gravel, bare sand, rippled sand, mixed sand and gravel, sparse seagrass, patchy seagrass and dense seagrass meadow. Seagrass was found only on sandy bottoms and at depths shallower than -1.5 m CD. Around 35% of the seagrass was distributed in the lower intertidal zone where it formed small patches. Four hectares of the survey area were classified as dense meadow with average densities of 150 shoots m\(^{-2}\) and reaching local maxima of 500 shoots m\(^{-2}\).

3.5.2. Recommendations for future work

The work presented here report on the first evaluation the use of the SIS for seagrass surveying. The instrument needs to be tested further. In particular, the accuracy of the
system should be assessed over vegetation having different morphology than *Zostera marina*, such as *Posidonia*, which form a thick matte on the seabed or *Zostera noltii*, which is notably smaller than *Z. marina*. This would enable an evaluation of the system’s sensitivity to seagrass type. It would also be valuable to assess the system capacity to detect changes in seagrass density over beds with higher shoot density than in Calshot. Further research is needed to confirm the correct estimation of canopy height from SIS data. To do so, seagrass beds with a known canopy height, determined for instance by divers, should be surveyed and the results compared. Furthermore, the system should be tested under different survey conditions, such as water temperature and salinity, turbidity or boat speed. Specifically, the threshold values might need to be adjusted to environmental conditions. The effect of shelled benthic fauna on backscatter intensity has been poorly studied until now. More research is needed to understand the influence biota may have on sonar data used to survey seagrass beds. Moreover, the changes of gas production with time and/or seagrass species should be further investigated.

The area described here should also be periodically surveyed in order to assess the evolution of the seagrass bed with time. This would allow a detection of any perturbation to the system. The seagrass bed described here, easy to access due its shallow depth, could also be used to study the complex interactions between seagrass canopies, hydrodynamics, sediment movement and biological activity.
CHAPTER 4.

LABORATORY INVESTIGATIONS ON THE INFLUENCE OF ZOSTERA MARINA CANOPIES ON UNIDIRECTIONAL FLOW, BED ROUGHNESS AND SEDIMENT MOBILISATION.
4.1. **INTRODUCTION**

4.1.1. **Boundary layer dynamics**

The flow of a current in the sea is usually accompanied by the formation of a turbulent boundary layer adjacent to the seabed (Grant and Madsen, 1986). This is a region of frictionally retarded flow which is characterised by a spatial and temporal randomness of the velocity field (Heathershaw, 1988). In this region, the horizontal mean flow adjusts from zero at the bed to its maximum value away from the bed, in the free-stream (Figure 4.1). Throughout this layer, turbulent energy levels and shear stresses also change, decreasing from maximum values near the bed to zero at the outer edge of the boundary layer. The bed shear stress, or bottom friction, is the frictional force exerted on a unit area of the seabed by the current flowing over it (Soulsby, 1997). The total bed shear stress ($\tau_0$) acting on the bed is made up of contributions from the skin friction produced by (and acting upon) the sediment grains, the form drag produced by the pressure field associated with the flow over ripples and/or larger features on the bed and the sediment-transport contribution caused by momentum transfer to mobilise the grains (Soulsby, 1997).

![Figure 4.1: The velocity profile for steady current flow over a bed showing current shear (length of arrow proportional to velocity) in the boundary layer (after Open University, 2000).](image)

In a turbulent, steady flow, current speed usually presents a logarithmic profile and may be described by the Karman-Prandtl Law of the Wall:

$$
\bar{U}(z) = \frac{U_*}{\kappa} \ln \left( \frac{z}{z_0} \right)
$$

(4.1)
where $\bar{U}(z)$ is the mean current speed at elevation $z$ above the bed, $\kappa$ is the von Karman’s constant, $z_0$ is the roughness length and $U_*$ is the friction velocity. The von Karman’s constant is usually taken as 0.4 (Soulsby, 1997) but its value may vary due to suspension of material (Yalin, 1972). The bed shear stress $\tau_0$ is related to the friction velocity by:

$$\tau_0 = U_*^2 \rho$$

(4.2)

where $\rho$ is the density of water. The roughness length $z_0$ has been related to bed roughness $k_b$ by the expression (Nielsen, 1992):

$$z_0 = \frac{k_b}{30}$$

(4.3)

Empirical relationships have been determined between bed roughness and mean grain size, bedform dimensions or suspended sediment concentration (Grant and Madsen, 1982; Nielsen, 1992). The effect of submerged vegetation on bed roughness, however, has been poorly studied and is rarely accounted for.

### 4.1.2. Flow modifications inside submerged vegetation canopies

Just as terrestrial plant communities modify air flow around themselves and within their canopy (Ni, 1997; Shen and Leclerc, 1997), in marine environments, submerged vegetation exerts strong effects on water flow inside and around them and thereby modifies boundary layer dynamics (Gacia et al., 1999; Stephan and Gutknecht, 2002). The effect of submerged vegetation on the flow has been studied for river-growing plants such as grasses, sedges and willows (Jarvela, 2002; 2005), as well as for a range of seagrass species such as *Zostera marina* (Fonseca and Fisher, 1986; Gambi et al., 1990; Ackerman and Okubo, 1993; Peterson et al., 2004), *Zostera novazelandica* (Heiss et al., 2000) or *Posidonia* (Gacia et al., 1999) and seaweeds, e.g. kelp (Jackson and Winant, 1983). General results can be drawn from those studies, however it should be kept in mind that specific plant morphology plays an important role in flow modification inside and around a canopy and therefore there may be significant differences between submerged vegetation
types. The most obvious and accepted effect of submerged vegetation is a reduction of the flow velocity inside the canopy (Fonseca et al., 1982; Gambi et al., 1990; Heiss et al., 2000; Peterson et al., 2004; Jarvela, 2005) where it is generally found to be nearly constant (Neumeier and Amos, 2006). Variations in current velocity within the canopy were observed to result from variations in plant density, e.g. diminution of flow intensity where a large amount of plant is found (Leonard and Luther, 1995) or slight increase in flow intensity due to reduced friction exerted by the stems of the plants compared to the leafy part (Verduin and Backhaus, 2000). It is generally admitted that flow reduction inside the canopy increases with increasing vegetation density (Leonard and Luther, 1995; Peterson et al., 2004; Leonard and Croft, 2006). However, several studies (Fonseca et al., 1982; Fonseca and Fisher, 1986; Gambi et al., 1990) found no influence of shoot density on flow structure within the canopy.

Turbulence inside submerged vegetation canopies is not well understood (Madsen et al., 2001). In studies using a variety of techniques in flumes and in the field, the presence of submerged vegetation compared to surrounding unvegetated areas and above the canopy has caused an increase (Gambi et al., 1990; Fonseca and Koehl, 2006), decrease (Ackerman and Okubo, 1993; Leonard and Croft, 2006) or had no effect (Worcester, 1995) on turbulence intensities. Independent of turbulence intensities within the canopy, a turbulence maximum is generally found to occur at the water/canopy interface (Gambi et al., 1990; Ghisalberti and Nepf, 2002; Leonard and Croft, 2006; Neumeier and Amos, 2006).

Vegetation relative submergence, i.e. the height of the water column occupied by the vegetation canopy, is an essential parameter in defining the influence of vegetation on the flow. Friction at the canopy/water interface has been found to increase with increasing relative submergence of the seagrass (Fonseca and Fisher, 1986; Koch, 1999) and longer plants were seen to cause greater reduction of the flow inside the canopy (Fonseca and Fisher, 1986; Jarvela, 2002; Thompson et al., 2004). The shape of the vegetation also affects the obstruction to currents inside the canopy (Fonseca and Fisher, 1986; Leonard and Luther, 1995). For instance, longer plants were found to create higher oscillation amplitudes and therefore produce more turbulence (Stephan and Gutknecht, 2002). Plant flexibility was shown to have a strong impact on the effect of vegetation on the flow as a more flexible canopy will compress more under currents than a less flexible canopy and
will therefore impact the flow in a different manner (Jarvela, 2002; Shi and Hughes, 2002; Jarvela, 2005).

Knowledge of flow structure within submerged vegetation canopies is essential since current intensity is expected to influence seagrass distribution and physiology as well as affecting the organisms living within these canopies (Fonseca and Kenworthy, 1987). Flow reduction within seagrass beds has been shown to increase food supply for suspension-feeders (Heck and Valentine, 2006), enhance larval recruitment, growth and survival (Eckman, 1987) and provide sheltered water for juvenile organisms (Horinouchi, 2007). It is also likely to affect sediment deposition and resuspension (Terrados and Duarte, 2000). Turbulence in submerged vegetation canopies may enhance CO₂ and nutrient supply, potentially helping the plants to develop (Koch, 1994) and influence sediment transport (Koch, 1999). Further research is therefore needed to characterise turbulence in and around these canopies (Madsen et al., 2001).

4.1.3. Roughness length and bed shear stress

The flow above the canopy generally presents the classic logarithmic profile described by the Law of the Wall (Gambi et al., 1990; Stephan and Gutknecht, 2002; Neumeier and Amos, 2006) so the vegetation is often considered as a form of macro-roughness of the boundary layer (Peterson et al., 2004; Thompson et al., 2004; Jarvela, 2005). Only few studies found that the flow above the canopy did not fit a logarithmic relationship (e.g. Shi and Hughes, 2002) and it has been reported that the flow structure within and just above a canopy more closely resembles a mixing layer than a boundary layer (Ghisalberti and Nepf, 2002).

If measurements of velocity along a depth profile above the vegetation canopy fit the logarithmic profile, roughness length ($z₀$) and shear velocity ($U_s$) can be computed through the Law of the Wall by fitting a linear regression of $\bar{U}(z)$ to $\ln(z)$:

$$\ln(z) = \frac{\kappa}{U_s} \bar{U}(z) + \ln(z₀)$$ 

(4.4)
Shear velocity can thereafter be used to calculate bed shear stress using Equation 4.2. Shear velocity (and by extension, bed shear stress) is usually seen to increase with increasing distance into seagrass beds and upstream velocity (Gambi et al., 1990) although plant flexibility strongly influences flow structure and therefore the shear velocity (Shi and Hughes, 2002). Few studies investigated roughness length over seagrass canopies, since even under relatively stable flume conditions, roughness height may be unstable and difficult to predict (Fonseca et al., 1982). Roughness length calculated over submerged vegetation canopies varied from a few millimetres (Shi and Hughes, 2002) to the height of the canopy itself (Neumeier and Amos, 2006).

Assessing the influence of submerged vegetation canopy on roughness length and bed shear stress would help to improve understanding of water movement in areas where seagrass canopies are found. Many models have been developed to simulate hydrodynamics in the coastal zone (e.g. Umgiesser et al., 2004; Ferrarin et al., 2008) in order to, for example, assess residence time (Cucco and Umgiesser, 2003) or compute sediment transport rates (Coraci et al., 2006). Although many models use a roughness length to account for bed friction (e.g. Neumeier and Amos, 2006), roughness lengths over vegetated areas has been poorly studied till now. In particular, a better understanding of the effect of submerged vegetation characteristics (species, shoot density, patch size) on bed shear stress and roughness length is needed.

4.1.4. Sediment movement

Seagrass beds are generally thought to stabilise bottom sediment by increasing the threshold of motion inside the canopy (Fonseca and Fisher, 1986; Fonseca, 1989; Thompson et al., 2004). In fact, it has been shown that seagrass beds tend to protect the sediment from erosion by shifting flow intensity from the sediment surface to the top of the meadow (Koch, 1999). Particle resuspension is therefore usually reduced in a seagrass meadow compared to unvegetated seabeds (Terrados and Duarte, 2000). However, flow and turbulence intensification near the bed where stem density is lower can result in resuspension of sediment even at low current velocities (Koch, 1999). As current velocity is decreased and waves are attenuated in a seagrass canopy (Fonseca et al., 1982; Fonseca and Kenworthy, 1987), the sediment carrying capacity is also diminished and
sedimentation occurs (Figure 4.2). As a result, fine particles are trapped inside the canopy (Bos et al., 2007) and seagrass beds usually exhibit a higher silt content that surrounding bare areas (De Falco et al., 2000). Although seagrass canopies increase particle trapping, studies have shown that their main effect is to decrease re-suspension rates (Gacia et al., 1999; Gacia and Duarte, 2001) and thereby to stabilise bottom sediment.

After studying plant physiology, den Hartog (1970) suggested that *Zostera marina* beds stabilise the bed with their roots but have a limited sediment-fixing capacity because the rhizome does not seem to be able to grow in a vertical direction. Recent studies showed that annual *Z. Marina* beds trap fine sediment during the growing season but that the accumulated sediment is released during winter (Bos et al., 2007). However, mobilisation processes are still not clearly defined and might be of importance to evaluate sediment transport within the canopy and by extension in the coastal zones where seagrass canopies are present.

**4.1.5. Objectives**

Complex interactions are found between submerged vegetation canopies, associated water movement and resulting sediment dynamics (Figure 4.3). Precise knowledge of flow behaviour around and inside seagrass systems can aid in evaluating the influence of seagrass canopies on boundary layer dynamics and is therefore of direct relevance when
studying hydrodynamics, sediment transport and benthic ecology inside and around submerged vegetation (Madsen et al., 2001).

\[ \text{Zostera marina} \] is the dominant seagrass species in the North Atlantic (Short et al., 2007). \textit{Z. marina} beds are encountered principally in shallow water, low energy environments, such as lagoons and sheltered coastal areas where they play an important ecological role (den Hartog, 1970). They can be found as continuous meadows or as small patches (Hirst and Attrill, 2008) and it is unknown whether seagrasses have the same influence on flow modification in these different configurations. In particular, flow structure downstream of the canopy is very poorly understood, possibly due to flume limitations. Several studies have investigated the effect of \textit{Zostera marina} on the flow in flumes (e.g. Fonseca et al., 1982; Fonseca and Koehl, 2006) and few in the field (e.g. Worcester, 1995). However, flume studies with real seagrass and a mobile sand layer are very rare (e.g. Gambi et al., 1990) whereas they may help to understand re-mobilisation processes within and around submerged vegetation.

The aim of this study was to investigate flow intensity, turbulence, roughness and sediment mobility inside and around \textit{Zostera marina} beds of different lengths and densities. Experiments were undertaken in an annular flume (the Lab Carousel) and a

Figure 4.3: Conceptual model of the interactions between water movement, sediment and submerged vegetation; a. when or where submerged vegetation is sparse, current velocity is affected only slightly, sediment resuspension is relatively high and turbidity and light attenuation are also high; b. by contrast, when or where submerged vegetation is abundant, currents are strongly attenuated, leading to reduced sediment resuspension, turbidity and light attenuation (after Madsen et al., 2001)
straight re-circulating flume. The straight flume enabled characterisation of the flow within and above canopies of various structures whereas the Lab Carousel was used to investigate the flow upstream, within and downstream of seagrass beds. These experiments were carried out using live Z. marina plants and a mobile sand layer. The specific objectives of this chapter were to:

1. characterise the structure of flow and turbulence intensity inside an ‘infinite’ canopy for different densities and velocities (Lab Carousel);
2. investigate the effect of patch size on velocity and turbulence upstream, inside and downstream of a canopy (Lab Carousel);
3. characterise the structure of the flow and turbulence intensity inside and above canopies of different densities, velocities and patch size (recirculating flume);
4. calculate bed shear stress and bed roughness upstream and above the canopy (recirculating flume); and
5. identify sediment movement within the range of velocities and densities tested in both flumes.

4.2. METHODS

4.2.1. Assessment of field conditions

The purpose of a flume is not only to simulate realistic field conditions near the seabed, but also to simplify them so that flow characteristics can be summarised in a small number of parameters (Nowell and Jumars, 1987). These parameters should also be comparable to flow and sediment characteristics found in nature. However, a flume cannot reproduce exactly the flow in the field and limitations inherent to flume design will impact lab-based measurements. Those limitations are discussed throughout the chapter. Prior to lab experiments, hydrodynamic conditions and seagrass bed characteristics were assessed in Calshot, UK, in order to reproduce similar conditions in the flume.

Seagrass densities were counted at low water on Calshot beach (N50°48′20″, W01°19′17″) over 4 quadrats (30 cm side) during preliminary work (26/10/2007). Shoot densities were relatively low (between 100 and 300 shoots m⁻²) but the count was undertaken at the end of autumn when shoots density is usually lower than in summer.
(pers. obs.) and in the intertidal area where densities are lower than in deeper water (Lefebvre et al., 2009). As higher densities were counted in the subtidal area and are often encountered elsewhere (e.g. Bologna, 2006), it was decided to carry out experiments with densities varying between 300 and 750 shoots m$^{-2}$. This also allows comparison with other studies on the influence of $Zostera marina$ canopies on the flow e.g. Fonseca et al. (1982) who tested shoot density of 400, 1000 and 1600 shoots m$^{-2}$ and Gambi et al. (1990) who characterised flow structure through canopies with densities varying from 400 to 1200 shoots m$^{-2}$.

The experiments conducted in this study comprised a mobile sand layer, which, in order to realistically reproduce sediment movement in the flume, should be comparable to sediment found in the field. Sediment samples were collected within the seagrass bed in Calshot (N50°48’20’’, W01°19’17’’) and analysed following the method described in section 2.3.3. The sediment sample collected on the beach was composed of 8% mud and 92 % sand and the median grain diameter was 0.18 mm (fine sand). In the lab, clean sand was sieved and put together in proportions made to reproduce the distribution of the sediment collected in Calshot (Figure 4.4) though without the mud fraction (grain size smaller than 63 µm) as it cannot be used in the recirculating flume. A significant proportion of mud in sediment changes the sediment properties, as the sediment becomes more cohesive (Dyer, 1986). However, a small mud fraction (3 to 15%) has been shown not to affect sediment properties significantly (Mitchener and Torfs, 1996).

![Figure 4.4: Particle size distribution of the sediment collected in Calshot (black) and of those put in the flume (blue). The dashed lines show the class frequency and the bold lines the cumulative frequency.](image-url)
To assess hydrodynamic conditions in the seagrass bed, an Autonomous Benthic Lander (ABL) was deployed off Calshot beach, near (but not within) the seagrass bed during the survey presented in Chapter 3, on the 15th September 2007 (spring tide). The ABL deployed was equipped with an electromagnetic current meter (EMCM, situated 23 cm above the bed), a pressure sensor (46 cm above the bed) and an Optical Backscatter Sensor (OBS, 41 cm above the bed) held on a frame. The ABL was deployed for 2 hours and 45 minutes during the flood and the following slack water, autonomously taking measurements (2 Hz frequency) every 30 minutes during bursts lasting for 8 min 32 sec. The EMCM was used to monitor horizontal flow velocity and direction, the pressure sensor to assess water depth above the sensor and the OBS to detect relative turbidity. A spectral analysis was performed on the data collected during the deployment using the instrument software. Average values for each burst were thereby calculated: water depth, current intensity and direction, relative turbidity and wave direction, significant period, significant height and energy. The water depth at the deployment site varied from 2.7 and 4.4 m (Figure 4.5). The currents were minima at the beginning of the deployment with a velocity of 0.07 m s\(^{-1}\) and reached a maximum of 0.25 m s\(^{-1}\) at the beginning of high water. The significant wave height was always smaller than 0.18 m and on average 0.12 m with a mean period of 2.4 seconds. Turbidity level showed a low correlation to flow velocity (R\(^2\))

Figure 4.5: Results from ABL deployment on the 15/09/2007: a. water depth (black) and relative turbidity (blue); b. currents velocity (black) and direction (blue); c. significant wave height (Hs, black) and period (Tz, blue).
= 0.17) and no correlation to wave height ($R^2 < 0.001$). The hydrodynamics at the site were therefore dominated by current action and wave action was very small.

### 4.2.2. Lab Carousel

A series of experiments were conducted in the Lab Carousel at NOCS, UK, in order to investigate flow structure inside a *Zostera marina* canopy. The Lab Carousel (Thompson et al., 2006) is an annular flume constructed of smooth acrylic with a diameter of 2 m, a workable channel width of 0.15 m and a maximum water depth of 0.45 m. A current is generated within the channel by means of a rotating lid, fitted with 8 equidistant paddles. The speed of rotation of the lid is controlled by an E-track AC inverter motor controller. Velocity measurements were taken using an ADV (Acoustic Doppler Velocimeter) from Nortek, the Vectrino Velocimeter. The instrument uses the Doppler effect to measure current velocity in three dimensions (defined in the Lab Carousel as tangential ($x$), radial ($y$) and vertical ($z$)). A short pulse is transmitted from the transducer and the Doppler shift introduced by the reflection from particles suspended in the water 5 cm under the transducer is used to calculate water velocity. Velocity measurements can be taken 1 to 16 cm above the bed; above that height, the paddles would impact the instrument. During the experiments, the flume was filled with artificial seawater (AquaOne) of a salinity of 34 and a temperature of 19°C ($\pm 1{}^\circ$C). Temperature and salinity were measured prior to each run and input into the ADV software to enable correct computation of sound velocity, used by the software to calculate water velocity. Eight artificial bed sections, made of acrylic and drilled with holes, were placed on the bed of the flume.

Vertical and horizontal velocity profiles were measured prior to experiments with seagrass in order to assess flow conditions in the flume. These profiles (hereafter referred to as bare sand profiles) were carried out with the false bed sections inserted into the flume and covered with the sand previously described. No significant differences were found along the working section apart from profiles directly downstream of an EMCM positioned within the channel, which resulted in a small velocity reduction and an increase in turbulence (especially at the lowest velocity tested) 10 to 15 cm above the bed (Figure 4.6).
Forty-six runs were carried out in the Lab Carousel to test the effect of patch length and shoot density on the flow (Table 4.1). The first 16 runs were carried out with the entire flume covered with seagrass ('infinite' length canopy) at 4 densities (300, 450, 600 and 750 shoots m$^{-2}$) and 4 free-stream velocities (10, 15, 20 and 25 cm s$^{-1}$) chosen to reflect field conditions at Calshot, UK. In the next series of experiments, 12 runs were undertaken measuring velocity profiles upstream, inside and downstream of a 2.25 m-long patch (Patch a, Figure 4.7 and Table 4.2) at two free-stream velocities (10 and 20 cm s$^{-1}$) and one shoot density (750 shoots m$^{-2}$). The remaining 16 runs were carried out measuring velocity profiles upstream, inside and downstream of a 1.2 m-long patch (Patch b, Figure 4.7 and Table 4.2) at two free-stream velocities (10 and 20 cm s$^{-1}$) and one shoot density (750 shoots m$^{-2}$). Flow velocity was controlled by lid rotation speed and therefore free-stream velocity refers to the average velocity recorded during bare sand runs for a given lid rotation speed. During bare sand runs, no sediment movement was observed at 10 or 15 cm s$^{-1}$, very little movement was seen at 20 cm s$^{-1}$ (a few grains moved but no bedforms were visible after an hour-long run) and ripples formed at 25 cm s$^{-1}$ (wavelength 10 cm and height around 1 cm).

Table 4.1 Details of the different runs undertaken in the Lab Carousel (see Table 4.2 for positions of velocity measurements along the patches).

<table>
<thead>
<tr>
<th>Run number</th>
<th>Patch name</th>
<th>Free-stream velocities (cm s$^{-1}$)</th>
<th>Shoot density (shoots/m$^2$)</th>
<th>Number of positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 16</td>
<td>Infinite</td>
<td>10, 15, 20 and 25</td>
<td>300, 450, 600 and 750</td>
<td>1</td>
</tr>
<tr>
<td>17 – 29</td>
<td>Patch a</td>
<td>10 and 20</td>
<td>750</td>
<td>6</td>
</tr>
<tr>
<td>30 - 46</td>
<td>Patch b</td>
<td>10 and 20</td>
<td>750</td>
<td>8</td>
</tr>
</tbody>
</table>
Zostera marina plants were collected on Calshot beach (N50°48’18”, W001°19’17”) during low water on spring tides. Plants were immediately transported to the lab, cleaned of epiphytes and measured (Table 4.3). The plants were randomly (i.e. no geometrical pattern) fixed on the predetermined sections (Figure 4.8a). The sections with the plants and if necessary empty sections were put in the flume at the preset positions and covered with 2 cm of clean sand ensuring a levelled bed (Figure 4.8b). Due to the curved shape of the flumes, secondary flows usually develop in annular flumes (Maa, 1990; Amos et al., 1992). In the Lab Carousel, that phenomenon affected the canopy shape and it was observed that the canopy was more compressed towards the exterior of the channel than towards the interior. This means that it was not possible to record the canopy height in the middle of

<table>
<thead>
<tr>
<th>Name</th>
<th>distance from the beginning (m)</th>
<th>distance from the end (m)</th>
<th>Name</th>
<th>distance from the beginning (m)</th>
<th>distance from the end (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1a</td>
<td>-0.5</td>
<td>-2.75</td>
<td>p1b</td>
<td>-0.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>p2a</td>
<td>-0.12</td>
<td>-2.37</td>
<td>p2b</td>
<td>-0.2</td>
<td>-1.4</td>
</tr>
<tr>
<td>p3a</td>
<td>0.22</td>
<td>-2.03</td>
<td>p3b</td>
<td>0.13</td>
<td>-1.07</td>
</tr>
<tr>
<td>p4a</td>
<td>0.98</td>
<td>-1.27</td>
<td>p4b</td>
<td>0.57</td>
<td>-0.63</td>
</tr>
<tr>
<td>p5a</td>
<td>2.03</td>
<td>-0.22</td>
<td>p5b</td>
<td>0.9</td>
<td>-0.3</td>
</tr>
<tr>
<td>p6a</td>
<td>2.4</td>
<td>0.15</td>
<td>p6b</td>
<td>1.25</td>
<td>0.05</td>
</tr>
<tr>
<td>p7b</td>
<td>1.65</td>
<td>0.45</td>
<td>p7b</td>
<td>1.65</td>
<td>0.45</td>
</tr>
<tr>
<td>p8b</td>
<td>2</td>
<td>0.8</td>
<td>p8b</td>
<td>2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 4.2: Positions of velocity measurements along Patches a and b.

Figure 4.7: Positions of the measurements for Patch a and Patch b, the green areas represent areas covered with a Zostera canopy, the yellow of bare sand.
the channel. However, it was estimated that most profiles were completed entirely within the canopy. The different bed configurations were done by adding and removing sections, changing ADV position and removing plants from sections. If any bedforms had developed during a run, the bed was levelled prior to a subsequent run.

Table 4.3: Characteristics of the plants fixed in the flumes.

<table>
<thead>
<tr>
<th></th>
<th>Infinite</th>
<th>Patch a</th>
<th>Patch b</th>
<th>Recirculating flume</th>
</tr>
</thead>
<tbody>
<tr>
<td>date of collection</td>
<td>22/03/2008</td>
<td>06/05/2008</td>
<td>18/05/2008</td>
<td>23/06/2008</td>
</tr>
<tr>
<td>number of plants measured</td>
<td>100</td>
<td>37</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>total number of plants fixed</td>
<td>648</td>
<td>231</td>
<td>122</td>
<td>238</td>
</tr>
<tr>
<td>leaves length (cm)</td>
<td>23.8 ± 7.4</td>
<td>25.4 ± 7.6</td>
<td>27.4 ± 12.2</td>
<td>28.4 ± 11.0</td>
</tr>
<tr>
<td>leaves width (mm)</td>
<td>3.4 ± 1.2</td>
<td>3.6 ± 1.4</td>
<td>3.7 ± 1.7</td>
<td>4.0 ± 1.6</td>
</tr>
<tr>
<td>number of leaves per shoot</td>
<td>4.2 ± 0.9</td>
<td>4.1 ± 1.1</td>
<td>4.2 ± 1.0</td>
<td>4.4 ± 0.8</td>
</tr>
</tbody>
</table>

Figure 4.8: Photographs of Zostera marina plants in the annular flume; a. fixed on a section; b. with the bed covered with sand.

Vertical profiles of velocity were measured starting 1 cm above the bed and in increments of 1 cm throughout the canopy to a height of 16 cm above the bed. At some heights above the bed (around 9 – 11 cm), the ADV experienced a phenomenon of resonance which resulted in poor quality data. An entire velocity profile consisted of 10 to 13 measurements during which the instantaneous velocities were recorded for 3 min at 25 Hz.

In straight recirculating flumes, the entrance conditions as well as the exit conditions can affect the nature of the flow in the test section, which usually limits the extent of the flow that can be investigated (Nowell and Jumars, 1987). Annular flumes offer the advantage of not presenting entrance or exit conditions so the flow can be measured in any
section of the flume and in particular upstream, within and downstream of a seagrass canopy. Furthermore, as the flow is continuous, ‘infinite’-length flows can be studied. On the other hand, the flume curvature creates a secondary circulation, which increases the radial component of the flow (Maa, 1990; Amos et al., 1992). This influences lateral flow structure and, as explained before, the canopy is thereby more compressed on the outer part of the channel than on the inner part. A further limitation is created by the fact that flow movement is forced by the paddles from the top of the flume. This creates a wavy motion and increases turbulence at the top of the water column. However, measurements were collected 1 to 16 cm above the bed over the 40 cm total water depth, leaving 24 cm to dissipate paddle effect. Moreover, instantaneous velocities were recorded for 3 min in order to average out the wavy motion induced by the paddles.

4.2.3. Long flume

Another set of experiments was conducted in a recirculating flume at NOCS, UK, to characterise flow structure inside and above Zostera marina canopies. The recirculating flume (Paphitis and Collins, 2001a; 2001b) has a rectangular cross-section 5 m long, 0.3 m wide and 0.45 m deep with glass-sided walls and an open top. The water is pumped from the reservoir tanks and after passing through an adjustable gate valve, it goes into a constant-head inlet tank. From there, the water flows through a honeycomb-like structure into the working section and over an adjustable tail gate, into the discharge tank. The water is directed to the reservoir tank through a draft tube and then back into the inlet tank. The flow can be controlled by lowering the tail gate and/or opening the gate valve. Lowering the tail gate accelerates the flow but also decreases water level whereas opening the gate valve increases water level and flow. It is not possible to precisely measure the volume of water pumped through the gate valve so free-stream velocity is here controlled by the tail gate position and water level in the flume.

Vertical and horizontal profiles were taken prior to the experiments with seagrass in order to assess the flow conditions through the flume. To do so, the sections were first inserted on the flume bed. The first 25 cm of the flume surface were then covered with gravel in order to enhance the development of a fully rough-turbulent flow (Nowell and Jumars, 1987). The sand described previously and used in the Lab Carousel was thereafter
laid on the remaining surface. No significant differences were found along the working section (Figure 4.9). In total, ten runs were carried out in the recirculating flume (Table 4.4) to characterise flow structure within and above the canopy (runs 1 and 2), shoot density (runs 3 to 6) and patch width (runs 7 to 10) on the flow. For each run, velocity profiles were measured in the cross-section centre in 5 positions along the flume (0.75, 1.40, 2.00, 2.60, 3.25 m) resulting in measurements to be taken upstream, inside and downstream of the seagrass canopy for the 5 configurations tested (Figure 4.10).

Zostera marina plants were collected on Calshot beach during low water on the 23rd June 2008. Plants were immediately transported to the lab, cleaned of epiphytes and measured (Table 4.3). The plants were randomly fixed on 2 sections (0.5 and 1 m in length, 0.3 m in width, 1 cm high). The sections with the plants and plain sections were then put in the flume at the preset positions and covered with 2 cm of sand so that the entire bed of the flume was covered with sediment. Water depth in the flume was maintained at 40 cm (as in

<table>
<thead>
<tr>
<th>Run number</th>
<th>Free-stream velocity (cm s⁻¹)</th>
<th>Patch length (m)</th>
<th>Patch width (m)</th>
<th>Shoot density (shoots m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 2</td>
<td>10 and 20</td>
<td>1.5</td>
<td>0.3</td>
<td>750</td>
</tr>
<tr>
<td>3 and 4</td>
<td>10 and 20</td>
<td>1</td>
<td>0.3</td>
<td>750</td>
</tr>
<tr>
<td>5 and 6</td>
<td>10 and 20</td>
<td>0.5</td>
<td>0.3</td>
<td>450</td>
</tr>
<tr>
<td>7 and 8</td>
<td>10 and 20</td>
<td>0.5</td>
<td>0.3</td>
<td>750</td>
</tr>
<tr>
<td>9 and 10</td>
<td>10 and 20</td>
<td>0.5</td>
<td>0.15</td>
<td>750</td>
</tr>
</tbody>
</table>

Figure 4.9 Velocity (a) and turbulence (b) profiles at free-stream velocities of 5 cm s⁻¹ (blue) and 20 cm s⁻¹ (black) along 4 position in the recirculating flume (position relative to the flume entrance). Velocity profiles are very similar at all positions. Turbulence increased slightly from the beginning to the end of the flume but remains small.
the Lab Carousel) and the canopy bent to a height of 12 to 18 cm above the bed, resulting in 30 to 40% of the water depth occupied by the canopy (Figure 4.11). The bed was levelled after a run if any bedforms developed. The different seagrass configurations were obtained by adding and removing sections and plants in sections. The flume was filled with freshwater as saltwater would damage the flume. When not in use, plants were kept in a tank filled with seawater to help conserve them. Water temperature varied from approximately 18°C to 23°C as the water warmed when it was recirculated in the flume. Water temperature was entered in the ADV software prior to measurements to define the correct sound velocity, used by the ADV software to compute water velocity.

Figure 4.10: Schematic of run settings in the recirculating flume, the width of the flume has been doubled compared to the length to ease representation. The green sections show the positions of the seagrass, the yellow area were covered with sand and the first 25 cm (black and white tiles) were covered with gravel. P1 to P5 show the position of velocity measurements.
Velocities in the recirculating flume were measured using the same ADV used in the Lab Carousel. The instrument was mounted on a bracket that was raised or lowered to the preset position above the bed (Figure 4.11). Where relevant, the average height of the canopy was recorded within the canopy (±1 cm as the canopy was moving). During bare sand runs and at the first profile (P1, before the canopy), velocity was measured at 1, 2, 3, 5, 11, 15, 20, 25, 30 and 34 cm above the bed. At profiles with a seagrass canopy, velocities were measured starting 1 cm above the bed and at vertical increments of 2 cm inside the canopy. At the canopy/water interface, measurements were taken every cm for 4 measurements. Above the canopy, velocities were measured at 20, 25, 30 and 34 cm above the bed. Measurements of profiles situated after the canopy were taken at increments of 2 cm up to the height of the canopy at the last position with a canopy, then in increments of 5 cm up to 34 cm above the bed. An entire velocity profile consisted of 10 to 13 measurements during which the instantaneous velocities were recorded at 25 Hz for 1 min.

The recirculating flume provided measurements of velocity above the canopy, which were not possible in the Lab Carousel. Furthermore, the height of the canopy was easily measured and therefore velocity measurements were taken at a higher vertical resolution (every cm) at the canopy/water interface. The recirculating flume is also wider than the Lab Carousel, so different patch widths were tested. However, the entrance and exit conditions limited the length of the flow that could be investigated. At the flume entrance, the honeycomb-like structure and the 25 cm-long gravel section ensured that a fully rough
flow developed relatively rapidly so the first profile could be taken 75 cm downstream of
the flume entrance. At the flume exit, a hydraulic jump occurred just upstream of the gate,
resulting in an acceleration of the top layer (5 to 10 cm, going directly above the tail gate)
compared to the bottom one (30 to 35 cm, obstructed by the tail gate). In order to reduce
the influence of the exit condition, the last profile was taken 1.75 m upstream of the tail
gate. Finally, because the precise volume of water pumped through the gate valve could
not be measured, the same flow could not be perfectly reproduced between runs. This
imprecision was reduced by keeping a constant water level in the flume and adjusting the
gate valve opening and the tail gate position in order to produce the chosen water velocity.

4.2.4. Data processing

Instantaneous velocities in the x-direction ($u$) can be expressed as the sum of the mean
velocity ($\bar{u}$) and the instantaneous velocity fluctuation ($u'$): $u = \bar{u} + u'$. Velocity can be
decomposed in the same way in the two other directions, $v$ (y-direction) and $w$ (z-
direction). High-frequency (25 Hz) measurements of velocity were recorded for 3 minutes
in the Lab Carousel and 1 min in the recirculating flume. Measurements were longer in the
Lab Carousel in order to damp the influence of the paddles on current velocity. From the
high-frequency data, measurements with a correlation coefficient lower than 85% (i.e.
oisy data, Nortek, 2004) or outliers were eliminated. The mean resultant velocity ($\bar{U}$) and
turbulence intensity ($U_{rms}$) were thereafter calculated for each measurement following the
definitions summarised in Table 4.5. In order to evaluate the effect of canopy morphology
on both horizontal and vertical turbulence, the Turbulent Kinetic Energy (TKE) was used
for the horizontal component ($\text{TKE}_{\text{horiz}}$) and the vertical component ($\text{TKE}_{\text{vert}}$). $U_{rms}$ and
TKE are both measures of the flow turbulence.

Mean velocities were also normalised in order to compare velocity reduction for
different free-stream velocities. In the Lab Carousel, for each position and each flow
treatment, the mean velocity was normalised by the mean velocity at the same position and
same flow treatment over bare sand. In the recirculating flume, for each position within the
test patch and for each flow treatment, the mean velocity was normalised by the mean
velocity at profile P1 at the same flow treatment.
The Law of the Wall was used for profiles recorded in the recirculating flume to evaluate roughness length \( z_0 \) and shear velocity \( U_* \). Profiles within the canopy were segregated into those elevations above the canopy and those inside it. Least-square regression of \( \ln(z) \) on \( \overline{U}(z) \) was used to calculate \( U_* \) and \( z_0 \) for profiles upstream and above the canopy (Equation 4.4).

### Table 4.5: Formulas of mean velocity, turbulence intensity, total Turbulent Kinetic Energy (TKE), the horizontal TKE (TKE\(_{\text{horiz}}\)), the vertical TKE (TKE\(_{\text{vert}}\)) and the normalisation applied to the high-frequency measurements. \( \rho \) is the water density and over-bars denote burst-averaged means.

<table>
<thead>
<tr>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \overline{U} = \sqrt{u'^2 + v'^2 + w'^2} )</td>
<td>Mean velocity (m s(^{-1}))</td>
</tr>
<tr>
<td>( U_{\text{rms}} = \frac{\text{rms}U'}{\overline{U}} \times 100 )</td>
<td>Turbulence intensity (%)</td>
</tr>
<tr>
<td>( TKE = \frac{1}{2} \rho (u'^2 + v'^2 + w'^2) )</td>
<td>TKE (J m(^{-3}))</td>
</tr>
<tr>
<td>( TKE_{\text{horiz}} = \frac{1}{2} \rho (u'^2 + v'^2) )</td>
<td>TKE(_{\text{horiz}}) (J m(^{-3}))</td>
</tr>
<tr>
<td>( TKE_{\text{vert}} = \frac{1}{2} \rho (w'^2) )</td>
<td>TKE(_{\text{vert}}) (J m(^{-3}))</td>
</tr>
<tr>
<td>( \text{Lab Carousel: } \overline{U}(z) - \overline{U}<em>{\text{ws}}(z) \text{ and } U</em>{\text{ws}} ) is the mean velocity during bare sand runs</td>
<td>Normalisation</td>
</tr>
<tr>
<td>( \text{Recirculating flume: } \overline{U}(z) - \overline{U}_1 \text{ and } U_1 ) is the velocity at the first profile (upstream of the seagrass)</td>
<td></td>
</tr>
</tbody>
</table>

### 4.3. Results

#### 4.3.1. Lab Carousel

Profiles of velocity, turbulence and horizontal and vertical TKE collected in the Lab Carousel are presented in this section. No error bars are plotted on the velocity profiles. As the instantaneous velocities were collected at 25 Hz for 3 min, each point represents an average value calculated over 4500 data points and the standard errors were therefore too small to be distinguished on the graphs. As discussed previously, the height of the canopy is not indicated on the profiles as it was difficult to determine an average canopy height in the middle of the flume. Overall, it was noticed that canopy height decreased with increasing free-stream velocity. The difficulty to precisely measure canopy height at the
ADV head position resulted in an ambiguity of whether some measurements were taken inside or outside the canopy.

**a. ‘Infinite’ canopy**

In the case of an ‘infinite’ canopy, the current velocity was always lower inside the canopy than during bare sand runs (Figure 4.12, first column). By contrast, turbulence and TKE were always greater inside the canopy than during bare sand runs (Figure 4.12 second, third and forth columns). Furthermore, at all velocities, the current was most strongly decelerated and turbulence and TKE were greatest for the highest shoot densities tested (750 shoots m⁻²) than for the lowest (300 shoots m⁻²). For example, at the lowest shoot density and velocity tested (average free-stream velocity of 10.2 cm s⁻¹ and turbulence of 9.6%), the average velocity along the profile was 7.5 cm s⁻¹ on average (with a minimum of 6.3 cm s⁻¹) and the turbulence was 20.1% on average (with a maximum of 23.5%). At the highest shoot density, the same free-stream velocity was reduced to 4.6 cm s⁻¹ on average along the profile (with a minimum of 2.6 cm s⁻¹) and the turbulence increased to 34.5% on average (with a maximum of 43.4%). On some profiles, 2 zones can be distinguished: at the bottom of the profiles was a zone of greatly reduced velocity and very high turbulence, whereas at the top of the profiles was a zone of faster flow and higher turbulence. This was particularly evident at the highest velocity and shoot density tested, where the flow had, on average, a velocity of 3 cm s⁻¹ and a turbulence of 80% for the bottom 3 cm, and a velocity of 20 cm s⁻¹ and a turbulence of 20% from 4 cm to 16 cm above the bottom. This stratification appeared at the highest density and free-stream velocity tested but was less evident at the lowest density and free-stream velocity. Furthermore, the difference in velocity and turbulence between the 2 layers increased and the transition height decreased with increasing free-stream velocities. The horizontal and vertical TKE were always greater inside the canopy than during bare sand runs (Figure 4.12, third and fourth columns). They increased with increasing free-stream velocity and were greatest for the highest shoot density tested.

The vertical TKE increased with increasing height above the bed and increasing free-stream velocity. This was due to the effects of the paddles on the flow, which created vertical water movement at the top of the water column. This effect increased with increasing free-stream velocity, i.e. increasing lid speed rotation, and was slowly dissipated towards the bottom of the flume. Nevertheless, vertical TKE was small compared to
horizontal TKE (less than half the intensity) and the effect of the paddle was clearly
discernible from the effect of the canopy, so could be taken into account.

Figure 4.12: Profiles of velocities (first column), turbulence (second column), TKE_{horiz} (third column) and TKE_{vert} (fourth column) for an infinite canopy with a shoot density of 300 shoots m^{-2} (crosses) and 750 shoots m^{-2} (dots) and without seagrass (blue) at free-stream velocities of 10 cm s^{-1} (first row), 15 cm s^{-1} (second row), 20 cm s^{-1} Hz (third row) and 25 cm s^{-1} (fourth row).
Measured velocities were normalised to free-stream values in order to compare velocity reduction at different flow magnitudes (Figure 4.13). Flow velocity reduction was generally greater at smaller free-stream velocities than at higher ones (e.g. around 30\% and 5\% for free-stream velocities of 10 cm s$^{-1}$ and 25 cm s$^{-1}$ respectively at a density of 300 shoots m$^{-2}$). However at high velocity and shoot density (Figure 4.13d), the stratification observed in the profiles meant that velocities were greatly reduced at the bottom (up to 80\%) and significantly less reduced at the top (approximately 20\%).

### b. Patch a

Velocity profiles were recorded at 2 positions upstream (p1a and p2a), 3 positions within (p3a to p5a) and 1 position downstream (p6a, situated 15 cm after the last plant stem but within the leaves due to plant bending with currents, see Figure 4.5) along Patch a (2.25 m-long) with a shoot density of 750 shoots m$^{-2}$, at 2 free-stream velocities (10 and 20 cm s$^{-1}$). Current intensity was reduced and turbulence increased at the 2 positions upstream of the patch compared to the free-stream velocity (Figure 4.14, first and second rows). For example, a free-stream velocity of 20.2 cm s$^{-1}$ was reduced to 14.4 cm s$^{-1}$ on average along the profile at position p2a; the turbulence was increased from 8 to 14\%. At twenty-two centimetres from the leading edge of the canopy (p3a), 2 zones could be differentiated within the profiles, with the bottom zone (approximately 1 to 10 cm above the bed) showing reduced velocities and increased turbulence intensities whereas the top 6 cm presented velocities and turbulence with the same values as upstream of the canopy.
Figure 4.14: Profiles of velocity (first column), turbulence (second column), $TKE_{\text{horiz}}$ (third column) and $TKE_{\text{vert}}$ (fourth column) at six positions upstream (yellow background), within (green background) and downstream (pale green background) of Patch a (see Table 4.2 for position details) at a free-stream velocity of 10 cm s$^{-1}$ (black) and 20 cm s$^{-1}$ (blue). The profiles with the stars were collected during bare sand runs.
One metre inside the canopy (p4a), the profile recorded at the lowest free-stream velocity did not show significant changes compared to the preceding profile, whereas at the highest free-stream velocity tested (20 cm s\(^{-1}\)), the differences between the 2 zones observed at the previous profile were accentuated. Velocity was reduced to 2 cm s\(^{-1}\) and turbulence increased to 65% in the bottom part of the profile; in the upper part velocities were equal or greater than upstream of the canopy and turbulence showed intensities between 10 and 30 %. Downstream of the canopy (but still within the leaves), velocities showed smaller intensities than during bare sand runs, but greater than upstream of the canopy. This shows that the influence of the canopy on the velocity was quickly dissipated. Turbulence however, stayed high at the last profile, especially near the bed (25 to 30%).

Overall, vertical TKE seems to be suppressed in the canopy whereas horizontal TKE was enhanced within the canopy (Figure 4.14, third and fourth rows).

c. **Patch b**

Velocity profiles were recorded at 2 positions upstream (p1b and p2b), 3 positions inside (p3b to p5b) and 3 positions downstream (p6a to p8b) of Patch b (1.2 m-long) with a shoot density of 750 shoots m\(^{-2}\), at 2 free-stream velocities (10 and 20 cm s\(^{-1}\), Figure 4.15).

As observed on measurements along Patch a, the velocity upstream of Patch b was reduced compared to free-stream velocity. However, the velocity of the first profile (p1b, 90 cm before the leading edge of the canopy) was slightly slower than along the second profile (p2b, 20 cm from the leading edge) with an average velocity along the profiles of 15.7 and 16.2 cm s\(^{-1}\) respectively for an average free-stream velocity of 20.2 cm s\(^{-1}\). At 13 cm from the leading edge of the canopy (p3b), 2 layers could be distinguished within the profiles: a bottom one characterised by low velocities and high turbulence and a top one with higher velocity and lower turbulence than upstream of the canopy (Figure 4.15, third row).
Figure 4.15: Profiles of velocity (first column), turbulence (second column), TKE_{horiz} (third column) and TKE_{vert} (fourth column) at eight positions upstream (yellow background), within (green background) and downstream (pale green and yellow background) of Patch b (see Table 4.2 for position details) at a free-stream velocity of 10 cm s^{-1} (black profiles) and 20 cm s^{-1} (blue profiles). The profiles with the stars were collected during bare sand runs.
The bottom layer was slowed by leaf obstruction whereas the ‘free’ upper layer was accelerated. The thickness of the 2 zones was dependant on free-stream velocity: at the lowest velocity tested, the bottom zone was 8 cm high, whereas it was only 3 cm high at the highest velocity tested. This phenomenon was observed again in the middle of the canopy, and was particularly evident at the highest velocity tested. It therefore appears that 2 boundary layers formed, one inside the canopy, with reduced velocity and increased turbulence and one at the canopy/water interface with an accelerated flow and decreased turbulence. However, it is uncertain if the top layer was really situated at the canopy/water interface as the canopy was certainly more than 3 cm high in the middle of the channel even at the highest free-stream velocity tested. These results were therefore affected by the curvature of the flow in the Lab Carousel and the resulting secondary circulation. At the last position inside the canopy (p5b), the profiles were more uniform than at previous profiles, with lower velocities and higher turbulence intensities than upstream of the canopy.

At the first position downstream of the canopy (p6b, situated 5 cm after the last stem but still covered by seagrass leaves), velocities were higher at the top of the profile. The bottom part of the profile however was still affected by the canopy and showed lower velocities and higher turbulence due to obstruction by the leaves. The flow acceleration coming from the top of the water column probably enables the top of the profiles to recover from the effect of the canopy quicker than the bottom part. At positions p7b and p8b (downstream of the canopy), the profiles were uniform with velocities and turbulence comparable to those recorded during bare sand runs.

Horizontal and vertical TKE were also affected by the canopy. Horizontal TKE was low upstream of the canopy (0.4 J m\(^{-3}\) on average at a free-stream velocity of 20 cm s\(^{-1}\)) and increased within the canopy (to around 0.6 J m\(^{-3}\) on average at the same free-stream velocity). It showed higher values at the transition of the 2 layers forming inside the canopy (up to 1.2 J m\(^{-3}\)). Its highest values (1.3 J m\(^{-3}\)) were found between 5 and 10 cm above the bed (profile p6b). Vertical TKE, though having lower intensities, generally followed horizontal TKE variations. The effect of the paddle, however, was seen as an increase in vertical TKE towards the top of the profile.
d. Patch length

Normalised velocity and turbulence were averaged at each profile and free-stream velocity. Results were plotted against the average normalised velocity and average turbulence of profiles within the ‘infinite’ canopy for equivalent shoot density and free-stream velocities (Figure 4.16).

![Figure 4.16: Normalised velocity and turbulence collected at a free-stream velocity of 10 cm s⁻¹ (in blue) and 20 cm s⁻¹ (in black) averaged per profile and plotted along the distance from the leading edge of Patch a and Patch b. Green background indicates the extent of the patch. The bold horizontal lines show the average values of normalised velocity and turbulence for an infinite canopy with the same shoot density and free-stream velocities as those tested for Patch a and Patch b.](image)

Velocities upstream of the canopies were reduced by 20 to 40% on average along the profiles for both patches. Flow reduction upstream of the canopies was greater for the longest patch, indicating that the length of the flume occupied by a seagrass canopy might play a role in flow reduction, i.e. the flow had more free space to develop in the case of the smallest patch that for the longest. For both patches, flows accelerated just before entering the canopy. Flows decelerated as soon as they entered the patch and generally showed lowest velocities in the middle of the canopy. At a free-stream velocity of 20 cm s⁻¹, averaged velocities were slightly lower than in the case of an ‘infinite’ canopy, whereas
they were still higher than the average value reached in an ‘infinite’ canopy for a free-stream velocity of 10 cm s$^{-1}$. Averaged velocities were found to increase from the middle towards the end of the canopy and flows immediately downstream of the canopy accelerated. Turbulence intensities showed opposite trends to velocities, being low upstream of the canopy, increasing along the canopy up to the middle of the patch and then decreasing towards the end of the canopy. Average turbulence intensities, however, stayed higher downstream of the canopy than upstream.

e. Sediment movement

The theoretical threshold depth-averaged current velocity $\overline{U}_{cr}$ for the sand used in this study was calculated from Soulsby (1997) which is valid for any non-cohesive sediment and water conditions for which $D_*$ > 0.1:

$$\overline{U}_{cr} = g \left( \frac{h}{d_{50}} \right)^{1/7} \left[ g (s - 1) d_{50} f(D_*) \right]^{1/2}$$  \hspace{1cm} (4.5a)

with $f(D_*) = \frac{0.30}{1 + 1.2D_*} + 0.055 [1 - \exp(-0.02D_*)]$  \hspace{1cm} (4.5b)

and $D_* = \left[ \frac{g (s - 1)}{\nu^2} \right]^{1/3} d_{50}$  \hspace{1cm} (4.5c)

where $g$ is the gravitational force (9.81 m s$^{-2}$), $s$ is the ratio of densities of sand and water (2.6), $h$ is the total water depth (0.4 m), $d_{50}$ is the median grain diameter (1.8 $10^{-4}$ m) and $\nu$ is the kinematic viscosity of water (1.2 $10^{-6}$ m$^2$ s$^{-1}$). This equation applied to the sediment used in this study yields a threshold current velocity of 26 cm s$^{-1}$. Hence, in theory, no sediment movement should occur during the experiments. However, it was noticed that sediment moved during the bare sand runs. The threshold of motion was therefore experimentally assessed in the Lab Carousel. Sediment movement was visible at a velocity of 20 cm s$^{-1}$ but was very slow (saltation). Ripples (wavelength 10 cm, height around 1 cm) formed at a velocity of around 23 cm s$^{-1}$. 

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During runs with an ‘infinite’ canopy, no sediment movement was seen at free-stream velocities of 10 to 20 cm s\(^{-1}\). At a free-stream velocity of 25 cm s\(^{-1}\), however, sediment movement was observed at the lowest densities (300 and 450 shoots m\(^{-2}\)) but rarely seen at the highest shoot densities (600 and 750 shoots m\(^{-2}\)). Sediment movement was observed mainly as scour around the shoots.

No sediment movement was seen during experiments with Patches a and b at a free-stream velocity of 10 cm s\(^{-1}\). At a free-stream velocity of 20 cm s\(^{-1}\), on the other hand, some sediment movement was observed within the canopy, especially around the shoots where scouring occurred. Furthermore, ripples developed downstream of the patches, from a few centimetres before the end of the stems to around 1 m downstream of the canopy (Figure 4.17). The ripples were 10 cm in wavelength and 1 cm in height. These ripples formed while the average velocity in the water column was under the sediment threshold of motion and noticeably under the velocity at which ripples formed during bare sand runs.

![Figure 4.17: Photograph of the ripples forming downstream of Patch a at a free-stream velocity of 20 cm s\(^{-1}\).]
4.3.2. Recirculating flume

a. Flow structure

Figure 4.18 presents measurements of velocity, turbulence and TKE along 5 profiles for the longest patch tested (1.5 m-long) in the recirculating flume. The first profile (P1), situated 50 cm upstream of the canopy, presents the classic Law of the Wall velocity profile; TKE and turbulence intensities were low throughout the water column. The second profile (P2) was situated 15 cm inside the canopy and experienced the shortest canopy height (6 cm) due to bending of the stalks. Along this profile and within the canopy, flow velocity decelerated while turbulence and TKE increased. Above the canopy, the profile showed values similar to those recorded upstream of the canopy.

At profile P3 (0.75 m inside the canopy), three zones can be distinguished. These correspond to those previously observed in Zostera marina canopies (Gambi et al., 1990): 'within canopy' zone, 'above canopy' zone and a transitional zone between these two. Within the canopy and close to the bed (0 to 8 cm above the bed at a free-stream velocity of 20 cm s\(^{-1}\)), flow intensity was reduced and nearly constant, turbulence was increased compared to upstream flow and TKE was small. Above the canopy (15 to 34 cm above the bed at a free-stream velocity of 20 cm s\(^{-1}\)), the flow was faster and the turbulence was equal or lower than at the same height upstream of the canopy and TKE was still small. Between these 2 zones, a transition zone was found, just under the top of the canopy (10 to 15 cm above the bed at a free-stream velocity of 20 cm s\(^{-1}\)), where flow accelerated quickly, turbulence decreased and the TKE was high. The fourth profile (1.35 m inside the canopy), also exhibited this structure in three zones, although the transition zone was at the height of the canopy/water interface instead of slightly under it as in the previous profile.

A fifth profile (P5) was taken 50 cm downstream of the canopy and 175 cm before the tail gate. Profiles downstream of the canopy showed the influence of the seagrass canopy, but were also obstructed by the tail gate. This means that the flow near the bed did not re-accelerate as easily as it would if it were not obstructed. Nevertheless, the turbulence was highest near the bed along this profile (up to 60% at the highest velocity tested) whereas its maximum was 35% within the canopy and 10% before or above the canopy. Furthermore, the TKE was also greatest here.
Figure 4.18: Profiles of velocity (first column), turbulence (second column), TKE\textsubscript{horz} (third column) and TKE\textsubscript{vert} (fourth column) at 5 positions upstream, within and downstream of the seagrass canopy (see Figure 3.6 for positions relative to canopy). Velocity profiles are shown for the 2 free-stream velocities tested (10 cm s\(^{-1}\) in black and 20 cm s\(^{-1}\) in blue), whereas turbulence, TKE\textsubscript{horz} and TKE\textsubscript{vert} are shown at a free-stream velocity of 20 cm s\(^{-1}\). Profiles carried out at a free-stream velocity of 10 cm s\(^{-1}\) can be found in the Appendix. Horizontal plain black or blue lines indicate the height of the canopy (± 1 cm) and dashed lines (appearing on profile downstream of the canopy) show the height of the canopy at the end of the canopy.
b. **Shoot density**

Figure 4.19 shows measurements of velocity, turbulence and TKE on 5 profiles upstream, within and downstream of a 1 m-long canopy for 2 shoot densities, 450 and 750 shoots m\(^{-2}\). Overall, the results described in the preceding section were replicated here; in particular, a decrease in flow intensity and an increase in turbulence were seen inside the canopy. An acceleration of the flow above the canopy and a high TKE near the top of the canopy were also observed. Dissimilarities were seen between the 2 densities tested. Along the second profile inside the canopy (P3), the flow was on average 10% lower within the canopy and consequently faster above the canopy (7% on average) at the highest shoot density than at the lowest. On the other hand, the turbulence was on average 7% higher inside the canopy and 1% lower above the canopy for the highest shoot density than for the lowest. Differences between the 2 shoot densities tested were most striking downstream of the canopy. The flow under the height of the canopy at profile P4 (35 cm downstream of the canopy) was on average 19% lower for the highest density than for the lowest; it was only 0.5% higher above the height of the canopy. Furthermore, the TKE at the water/canopy interface at high shoot density was twice those of the lowest. Therefore, it appears that the effect of shoot density played a role in flow structure within the canopy but this effect was greatest downstream of the canopy.

Profiles recorded at a free-stream velocity of 10 m \(s^{-1}\) present similar trends to those described for a free-stream velocity of 20 cm \(s^{-1}\) (Appendix 4).

c. **Patch width**

Figure 4.20 presents measurements of velocity, turbulence and TKE on 5 profiles upstream, within and downstream of a 0.5 m-long canopy for 2 patch widths, 30 cm (equal to the width of the flume) and 15 cm (half the flume width). Velocity profiles at the first position inside the canopy (P2, 15 cm from the leading edge) were very similar for both beds. Turbulence intensities and TKE also showed similar values for both beds except at the top of the profiles, where the wide bed showed higher values than the narrow bed (turbulence was 2 to 3 \%, TKE\(_{\text{horiz}}\) 0.1 J m\(^{-3}\) and TKE\(_{\text{vert}}\) 0.05 J m\(^{-3}\) higher in the 10 upper cm of the profile).
Figure 4.19: Profiles of velocity (first column), turbulence (second column), TKE\textsubscript{horiz} (third column) and TKE\textsubscript{vert} (fourth column) at 5 positions along the bed for run 4 (in black: 1 m-long patch, density 750 shoots m\textsuperscript{-2}, free-stream velocity 20 cm s\textsuperscript{-1}) and run 6 (in blue: 1 m-long patch, density 450 shoots m\textsuperscript{-2}, free-stream velocity 20 cm s\textsuperscript{-1}). Horizontal plain blue lines indicate the average height of the canopy and dashed lines (appearing on profile downstream of the canopy) show the height of the canopy at the end of the canopy. Profiles taken at a free-stream velocity of 10 cm s\textsuperscript{-1} can be found in Appendix.
Figure 4.20: Profiles of velocity (first column), turbulence (second column) $TKE_{\text{horiz}}$ (third column) and $TKE_{\text{vert}}$ (fourth column) at 5 positions along the bed for run 8 (in black: 0.5 m-long and 0.3 m-wide patch) and run 10 (in blue: 0.5 m-long and 0.15 m-wide patch); both patches had a density of 450 shoots m$^{-2}$ and a free-stream velocity of 20 cm s$^{-1}$ (profiles taken at a free-stream velocity of 10 cm s$^{-1}$ can be found in Appendix). Horizontal plain blue lines indicate the average height of the canopy and dashed lines (appearing on profile downstream of the canopy) show the height of the canopy at the end of the canopy.
At profile P3 (25 cm downstream of the canopy, just at the limit of the leaves), the velocity near the bed was reduced compared to the previous profile, indicating that even a relatively small patch of seagrass (0.5 m-long) has a significant effect on the flow. Downstream of the canopy, flow decelerated below the canopy level (11% on average at P4) and accelerated above it more (14% on average at P4) for the wide bed than for the narrow bed. Turbulence intensities were noticeably higher in the lower part of the profile (7% on average at P4) and slightly lower in the higher part (2% on average at P4) for the wide bed than for the narrow bed. For both bed configurations, TKE showed highest values just under the canopy/water interface downstream of the canopy. The wide bed showed TKE values 20 to 100% higher at the height of the canopy than the narrow bed. However, TKE values for the narrow bed were higher near the top of the profile than for the wide bed.

**d. Sediment movement**

No sediment movement was seen in the recirculating flume at a free-stream velocity of 10 cm s$^{-1}$. During bare sand runs, very little sediment movement was seen at a free-stream velocity of 20 cm s$^{-1}$. However, sediment movement was observed inside the canopy during runs with seagrass patches and at a free-stream velocity of 20 cm s$^{-1}$, especially as scour around the stems. Furthermore, small ripples formed downstream of the 0.5 and 1 m-long patches. The ripples were usually small and not well-defined. Nevertheless, they indicated sediment movement downstream of the canopy, even though the velocity was under the predicted threshold of motion. The most well-defined ripples formed during run 8, i.e. 0.5 m-long, 0.15 m-wide patch at a free-stream velocity of 20 cm s$^{-1}$.

**e. Roughness length and bed shear stress**

Shear velocity ($U_s$) and roughness length ($z_0$) values were calculated along the velocity profiles measured upstream and above the canopy (Table 4.6). Within and downstream of the canopy, flow departed from the classical log profile and so the Law of the Wall could not be applied. Of the 28 velocity profiles tested, 68% fitted the log-profile relationship with an $R^2 > 0.85$; all were significant at $p < 0.05$ and 86% at $p < 0.01$. Shear velocity calculated using the Law of the Wall was then used to calculate bed shear stress using Equation 4.2.
Shear velocity showed values varying between 0.39 and 2.59 cm s⁻¹ and increased with increasing distance from the leading edge of the canopy. Roughness length was smaller upstream of the canopy (inferior to 0.01 to 0.04 mm) than above the canopy (0.02 to 5.47 mm) where it was still significantly smaller than the height of the canopy (6 to 15 cm). The bed shear stress varied between 0.2 and 0.69 Pa and, for each run, was always smaller upstream of the canopy than above it. Roughness length and bed shear stress were found to increase exponentially with increasing distance from the leading edge (Figure 4.21).
Roughness length showed the same range for both free-stream velocities tested, whereas bed shear stress was around 20% greater at a free-stream velocity of 20 cm s\(^{-1}\) than at a free-stream velocity of 10 cm s\(^{-1}\). No significant difference in \(z_0\) was found between the different runs; the patch width and shoot density did not seem to influence roughness length or bed shear stress.

Figure 4.21: Roughness length \((z_0)\) and bed shear stress \((\tau_0)\) as a function of distance from the leading edge of the canopy at a free-stream velocity of 10 and 20 cm s\(^{-1}\) and associated best-fit line.
4.4. DISCUSSION

4.4.1. Limitations and advantages

All lab-based experiments have constraints imposed by flume design. Fonseca et al. (1982) carried out some of the first measurements of flow velocity through a Zostera marina canopy in a straight recirculating flume. They emphasised the fact that, although the plants occupied much of the water passage area, their influence caused a severe redirection of flow around the meadow. In experiments with submerged vegetation, deflection and acceleration of the flow generally occurs around the canopy since a constant flow is imposed in an area limited by the flume walls (Gambi et al., 1990, Figure 4.22). Furthermore, the water is forced to go through the canopy, which probably influences the results (Fonseca et al., 1982).

During experiments in the Lab Carousel, the current was created by eight paddles, which were fixed to the rotating flume lid. As the stirring was at the water surface, high turbulence was found there, which decreased downwards. This effect can be seen from the downward decrease of vertical TKE. This effect was minimised by taking measurements at least 25 cm below the water surface, at which depth most of the paddle effect was dissipated. However, it is likely that the paddle action caused the canopy to be more compressed in the Lab Carousel than it would have been in the field. Furthermore, flow forcing from the top of the water column is probably responsible for an accentuation of the velocity difference between ‘within’ and ‘above canopy’ zones. In particular, in the case of an ‘infinite’ canopy and at high velocity and shoot density, the near-bed flow (bottom 3 to 10 cm) was strongly decelerated compared to the top of the profiles. As water was forced...
from the top, the canopy was severely compressed. Two layers developed: one within the canopy with a reduced flow and the second one, above the canopy, with a skimming flow. This effect has been found in other studies (Thompson et al., 2004) but is thought to be more pronounced in the Lab Carousel due to the flow acceleration mechanism.

An additional drawback in the Lab Carousel was the difficulty to precisely determine canopy height in the middle of the channel and particularly at the ADV head position. This caused uncertainty on whether some measurements were taken inside or above the canopy. Because of this, velocity measurements collected in the Lab Carousel were not used to characterise flow structure above the canopy.

On the other hand, the Lab Carousel facilitated measurements to be taken upstream, within and downstream of the canopy without constraints created by entrance or exit conditions. Moreover, the use of an annular flume allowed the extent of the patches that were studied (1.2 m, 2.25 m and an ‘infinite’ canopy) to be longer than in most lab-based studies of flow in seagrass canopies; for example, Fonseca et al. (1982) used a 50 cm-long canopy and Gambi et al. (1990), Fonseca and Fisher (1986) and Fonseca et al. (2006) used a 1 m-long canopy.

In the straight, recirculating flume, instantaneous velocities were measured above the canopy as well as within it, facilitating the application of the Law of the Wall and the estimation of roughness lengths and shear velocities above the canopy. However, the tail gate limited the extent of the working section and had an influence on profiles taken downstream of the canopy since it constituted an artificial obstacle to the flow.

Instruments used to measure instantaneous current velocities usually affect the flow that is measured as they are positioned within the water column. In the present study, an ADV was used and vegetation had to be cut around its head to enable acoustical measurement of flow velocity. This means that a gap was artificially created in the vegetation around the ADV head. Other methods used to measure current velocity within seagrass canopies have included hot-film anemometry sensors (Gambi et al., 1990; Leonard and Luther, 1995), dye tracking (Worcester, 1995; Heiss et al., 2000) or electromagnetic current meters (Ackerman and Okubo, 1993; Fonseca and Koehl, 2006). These methods also have their limitations such as lower frequency sampling or measurements in 2 directions only. Furthermore, they are still intrusive and infer with the flow. ADV measurements of
velocity were taken 5 cm under the head, i.e. where the flow was not disturbed by the instrument, thereby reducing flow disturbance. The ADV also presents the advantage of recording water velocity in 3 directions at a sampling frequency of 25 Hz, which enables a characterisation of high-frequency turbulence. As a result, the ADV proved to be a suitable instrument for measuring velocity inside submerged vegetation, illustrated by the fact that it was used in many lab or field-based studies (e.g. Verduin and Backhaus, 2000; Ghisalberti and Nepf, 2002; Jarvela, 2005; Neumeier and Amos, 2006).

The present study used living seagrass plants in preference to artificial mimics. Plant replicates present the advantage of not deteriorating with time. However, mimics also have difficulty reproducing living plant flexibility and plant morphology (Ghisalberti and Nepf, 2002; Fonseca and Koehl, 2006). In particular, artificial blades are generally found to be more deflected than living seagrass, which results in a higher density of obstruction to the flow than would be expected with live seagrass (Fonseca and Koehl, 2006). In the set of experiments described here, live seagrass plants were fixed to flume sections using silicon; because the plants were uprooted, their general vitality decreased with time. This effect was noticed in other vegetation types fixed in flumes (Jarvela, 2002) and was expected to result in reduced flow resistance. Care was therefore taken to use healthy seagrass that was always kept in seawater and with natural light to help preservation. Furthermore, the plants were never used for longer than 5 days after being fixed. Since plants were collected between March and June, there was an increase of the average leaf length from the first set of experiments to the last one (from 23.8 to 28.4 cm, Table 4.3). However, canopy height was observed to be more dependent on current intensity than leaf length, probably due to the bending of the canopy by currents. Moreover, the standard deviation of the leaf length distribution was always higher than the difference in average leaf lengths, indicating large leaf length variations for each sample of seagrass collected. The variation of average leaf length is therefore thought not to affect the data collected in the present study.

Finally, this study examined the influence of seagrass beds on unidirectional flow. Waves were not considered whereas they may have a great influence in the field and certainly cause other flow patterns (Fonseca and Cahalan, 1992). The preliminary survey undertaken at Calshot indicated that hydrodynamics in that particular location on the day of the survey were dominated by currents and that wave action was weak. At other locations or other times however, waves might play a key role in hydrodynamics within
and around seagrass beds and the effect of combined waves and currents needs to be further investigated.

4.4.2. Flow structure

From the velocity measurements collected in the recirculating flume, 3 layers can be distinguished along the profiles: (1) within canopy layer, with low and relatively constant current velocity, high $U_{\text{rms}}$ turbulence and moderately high TKE; (2) transition zone, at the canopy/water interface, where current velocity increased, $U_{\text{rms}}$ turbulence decreased and TKE was high; and (3) above canopy layer, where current velocity was equal or greater than upstream of the canopy, and $U_{\text{rms}}$ turbulence and TKE were low.

Velocity profiles described in the present study are consistent with the results of other studies investigating flow structure within and above *Zostera marina* canopies. Fonseca et al. (1982) and Gambi et al. (1990) also found a reduced velocity within the canopy, a transition zone and an accelerated flow above the canopy. Other studies observed that flow within the canopy was correlated with plant morphology, e.g. Leonard and Luther (1995) within a *Spartina alterniflora* canopy, Koch (1999) within a *Thalassia testudinum* canopy and Verduin and Backhaus (2000) within a *Amphibolis antarctica* bed. This effect was not seen in the present work and velocities were found to be relatively constant within the canopy or increasing from the bed to the top of the canopy. This difference can be explained by the fact that velocity variations were related to plant morphology and were seen on vegetation that has a different anatomy to *Z. marina*.

In this study, $U_{\text{rms}}$ turbulence was always found to be higher within the canopy than upstream, above or downstream of the seagrass patch. This is coherent with results from other lab-based studies (Gambi et al., 1990; Fonseca and Koehl, 2006). Several authors found on the contrary a decrease of turbulence within the canopy (Ackerman and Okubo, 1993; Leonard and Croft, 2006; Neumeier and Amos, 2006). All these latter studies were carried out in the field, perhaps showing a difference in results to those in the lab. In flumes, the flow is constrained to go through the canopy and cannot be deflected to the sides, which may affect turbulence. Fonseca and Koehl (2006), however, demonstrated that turbulence was still high in a canopy which occupied only 1/3 of the flume width and in
the present study, high turbulence were seen within a canopy occupying only half of the flume width. Differences observed between lab and field studies may also come from limitations in data collection in the field, with a constantly changing current velocity due to tides, poor visibility or difficulty in positioning the instruments without affecting the measurements. More research is needed to establish why such differences are found.

Overall, an increase in $U_{rms}$ turbulence inside the canopy seems likely as the flow is obstructed by the plants stems and leaves, which results in fluttering and vortex shedding (Gambi et al., 1990; Ackerman and Okubo, 1993; Fonseca and Koehl, 2006). In this study, $U_{rms}$ turbulence was usually found to increase from the top of the canopy to the bed, where it was greatest. This can be explained by a high turbulence created near the bed by the stems, which constitute a solid obstacle to the flow and behind which vortices are created and shed. Higher in the canopy, flow is obstructed by the leaves, which are flexible and can therefore move with the flow, creating less turbulence than at the bottom.

In the experiments presented here, TKE was found to be highest around the canopy/water interface. Only few studies present TKE values within submerged vegetation canopies and most research carried out on flow velocity within *Zostera marina* canopies present only $U_{rms}$ turbulence (Fonseca et al., 1982; Gambi et al., 1990; Fonseca and Koehl, 2006). Leonard and Croft (2000) and Neumeier and Amos (2006) found an increase in TKE at the canopy/water interface of *Spartina alterniflora* canopies despite the fact that they observed a reduced TKE inside the canopy. According to turbulent flow theory, the major part of the TKE is contained in large-scale eddies, which continuously feed energy by an ‘energy cascade’ to smaller eddies (Mathieu and Scott, 2000). Leonard and Croft (2000) observed an increase of TKE at the canopy edge and hypothesised that it was related to the production of large-scale turbulence associated with wake formation when a flow first encounters the canopy. Similarly, the abrupt increase in total TKE observed in this study at the canopy/water interface suggests the presence of large-scale eddies on the canopy surface.

Submerged, flexible vegetation is likely to move under the influence of currents. Large-scale oscillatory movement of seagrass canopies have been described by Ackerman and Okubo (1993) and called monami (mo= aquatic, nami= waves). They hypothesised that the oscillations were created by the hydroelastical energy translated by the plants to the fluid. Canopy movement was observed in this study, although the amplitude and period of the
oscillations were not recorded. It is likely that the large-scale oscillations of the flow occurring at the canopy surface, indicated by the high values of TKE, are related to the canopy ‘wavy’ movement. Guisalberti and Nepf (2002) suggested that the canopy oscillations were created by Kevin-Helmholtz instabilities; these occur when the velocity difference across the interface between the two layers increase above a threshold limit.

This hypothesis is plausible since a strong velocity difference was found across the canopy top. Regardless of the processes responsible for the production of these oscillations, the high TKE values observed indicate that large-scale oscillations occur along the canopy surface. These large-scale eddies are then most likely disrupted by the vegetation to form high-frequency oscillations within the canopy as suggested by Madsen et al. (2001). This is consistent with the increase of turbulence and decrease in TKE observed with depth into the canopy. Near the bed, the stems constitute a solid obstacle to the flow and hence short-scale vortices are formed and shed, dissipating the energy to smaller scales, explaining the high turbulence and low TKE observed at the canopy base.

In the Lab Carousel, flow was observed to decelerate upstream of the canopy, reaching a minimum in the middle of the canopy and accelerating slightly before exiting the canopy. Profiles upstream of the canopy have usually been used to compare flow structure inside the canopy to upstream of it (Gambi et al., 1990; Fonseca and Koehl, 2006). No study has yet presented a comparison of flow upstream of a canopy to flow over bare sand in the manner of the present study, possibly due to flume limitation (use of straight, recirculating flumes). A reason for the reduced velocity upstream of the patch compared to bare sand runs may be that profiles upstream of the canopy were also downstream of it (because of the ‘infinite’ flow) and the flow did not have an infinite length to develop as it did during the bare sand runs. However, since the last profiles taken downstream of the canopy (around 3 m upstream of the first profile recorded upstream of the canopy) showed velocities greater than upstream of the canopy, this result also seems to indicate that the current intensity decreased before going through the canopy. It seems reasonable that the flow was slowed down before entering the canopy since the latter constituted an obstacle to the flow. Although this phenomenon was probably accentuated by flow constriction into the flume, it can be imagined that, in the field, the flow ‘feels’ the canopy and will be slowed down and deflected just upon entering a seagrass bed. The same analysis can be applied to flow acceleration before exiting the canopy. The flow appeared to ‘feel’ the end of the canopy (the end of the obstruction), so was accelerated. Deceleration prior the
canopy and acceleration before exiting the canopy were observed solely in the Lab Carousel as entrance and exit conditions prevented the observation of such phenomenon in the recirculating flume. They still need to be tested in the field where the flow is not constrained and wave action may also influence flow structure.

No study till now has presented profiles downstream of seagrass canopies. In the Lab Carousel, velocities were observed to recover relatively rapidly from the influence of the canopy and reached values slightly higher than upstream of the canopy within 20 to 50 cm downstream of the canopy. By contrast, turbulence intensities and TKE usually showed their highest values immediately downstream of the canopy. This may have effects on sediment mobilisation and is discussed later.

### 4.4.3. Density effects and width influences

It is generally accepted that flow reduction inside the canopy increases with increasing vegetation density (Leonard and Luther, 1995; Peterson et al., 2004; Leonard and Croft, 2006). However, some studies (Fonseca et al., 1982; Fonseca and Fisher, 1986; Gambi et al., 1990) found little or no influence of shoot density on flow structure within the canopy and they observed that the position along the bed had a stronger effect on flow velocity than shoot density. Those experiments were conducted in straight recirculating flumes using small seagrass beds, 0.5 m (Fonseca et al., 1982) to 1.0 m-long (Fonseca and Fisher, 1986; Gambi et al., 1990). Results from both the Lab Carousel and the recirculating flume clearly indicate an effect of shoot density on the flow. In particular, velocity reduction and turbulence increase were significantly greater within ‘infinite’ canopies of higher shoot density than at lower shoot density. The difference between the studies cited earlier and herein might come from the fact that we studied an ‘infinite’ canopy, where flow had time to stabilise, whereas they used small canopy beds. Shoot density influence was also tested in the recirculating flume, on a 1 m-long canopy. Within the canopy, only the TKE values showed significant differences between the 2 densities tested, with the dense bed having higher TKE values than the sparse bed. Velocity and turbulence intensities presented differences of only a few percent between the 2 densities within and above the canopy, which is consistent with studies from Fonseca et al. (1982) and Gambi et al. (1990). Downstream of the canopy on the other hand, significant differences were seen between
the 2 densities tested. Velocities were lower and turbulence and TKE were higher under the height of the canopy for the denser bed than for the sparser one. This is probably due to the fact that more water could go through the sparse bed than the dense one since less leaves were obstructing the flow and so the effect of the canopy was less strong downward of the canopy.

Fonseca and Koehl (2006) tested the effect of patch width on flow modification in the flume within an artificial *Zostera marina* canopy. They found that there was less current velocity reduction by the canopy as the width of the artificial seagrass bed was increased. They observed that increased canopy width significantly increased both within and above canopy velocities as more water was forced to pass through the seagrass canopy. The results collected in our study are not fully consistent with theirs. Patch width was tested on a 0.5 m-long patch in the recirculating flume. No significant differences were found between the 2 patch widths tested along the profile taken within the canopy (15 cm from the leading edge). Unlike Fonseca and Koehl (2006), where measurements were taken down to 95 cm from the leading edge of the canopy, here, the only profile taken within the canopy was situated at 15 cm from the leading edge. Some differences were observed downstream of the canopy: below the height of the canopy, deceleration was greater for the wide bed than for the narrow one; above the height of the canopy, velocity was higher for the wide bed than for the narrow one. It is probable that water was flowing with a higher velocity on the side of the canopy downstream of the narrow patch than of the wide patch, due to the free space left between the plants and the flume walls. This possibly explains that a higher velocity was recorded downstream of the narrow bed.

### 4.4.4. Roughness length, shear velocity and bed shear stress

Results from the recirculating flume showed that flow was generally found to follow a logarithmic profile above the canopy. Shear velocity and bed shear stress increased exponentially with position from the leading edge of the patch; both were higher for higher free-stream velocity but did not seem to be significantly correlated to patch length, density or width. This is consistent with results from Gambi et al (1990) who found that shear velocity above a 1-m long *Zostera marina* canopy increased significantly with increasing distance into the bed and free-stream velocity and slightly but not significantly with shoot
density. Furthermore, the values of shear velocity presented in their paper \(10^{-3} \text{ to } 10^{-1} \text{ m s}^{-1}\), although smaller, were in the same range as the values calculated in the present study \(10^{-2} \text{ to } 10^{0} \text{ m s}^{-1}\). Shi and Hughes (2002) calculated shear velocity and roughness length above 2 species of freshwater aquatic plants (Myriophyllum and Hydrilla) from profiles taken in a recirculating flume. They observed that shear velocity increased with increasing free-stream velocity and distance from the leading edge of the canopy, although differences in plant flexibility were found to strongly influence flow structure and therefore shear velocity.

In this study, roughness length \(z_0\) was found to increase with distance from the leading edge and was not affected by free-stream velocity intensity. Although \(z_0\) was higher above the canopy than above bare sand, its values stayed small \(10^{-4} \text{ to } 10^{-2} \text{ m}\). Roughness length in this study was far from equal to the height of the canopy as reported by Neumeier and Amos (2006) from field-based profiles carried out above a Spartina canopy (Table 4.7). Fonseca et al. (1982) concluded that under the relatively stable flume conditions, roughness height above a Zostera marina canopy was unstable and difficult to predict. Shi and Hughes (2002) found roughness length over a Hydrilla canopy to vary from 3 to 30 \(10^{-3}\) m. These are in the same range as roughness lengths calculated in the present study. However, they observed that the value of \(z_0\) mostly decreased with increasing flow range at each density and not with measurement position.

If submerged vegetation seemed to have little influence on the flow over the canopy, velocities and turbulence within the canopy were strongly affected by the vegetation presence. The canopy also had a strong impact on sediment movement, and it appears that sediment movement inside the canopy could not be estimated from threshold of motion and bed shear stress or shear velocity in the water column.

<table>
<thead>
<tr>
<th>Authors</th>
<th>(z_0)</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>Neumeier and Amos (2006)</td>
<td>35 to 233 mm</td>
<td>Velocity measurements over Spartina canopies in the field</td>
</tr>
<tr>
<td>Shi and Hughes (2002)</td>
<td>2.7 to 21.8 mm</td>
<td>Velocity measurements over Myriophyllum and Hydrilla canopies in a recirculating flume</td>
</tr>
<tr>
<td>Present study</td>
<td>0.02 to 5.47 mm</td>
<td>Velocity measurements over Zostera marina canopies in a recirculating flume</td>
</tr>
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</table>
4.4.5. Sediment movement

In the present study, sediment movement was observed in most runs inside and downstream of the canopy at a free-stream velocity of 20 cm s\(^{-1}\). It was especially evident downstream of the canopy as sand ripples formed. Sediment movement therefore occurred whereas velocity at those positions was greatly reduced and notably under the sediment threshold of motion determined over bare sand. On the contrary to velocity, turbulence was significantly higher where sediment movement was observed than over bare sand. Field and lab-based studies have shown that entrainment of sand grain is closely related to the turbulent ‘bursting’ process (Soulsby, 1983; Le Couturier et al., 2000). The structure of turbulent flow is regularly, but briefly, disrupted by intervals during which strong turbulent motions are generated. During those moments, the instantaneous velocity fluctuations \((u', v', \text{ and } w')\) deviate from the mean velocities \((\bar{u}, \bar{v}, \text{ and } \bar{w})\). Four types of motion are observed within these events, which constitute the ‘burst cycle’ (Kline et al., 1967): (1) ejections when \(u' < 0\) and \(w' > 0\); (2) sweeps when \(u' > 0\) and \(w' < 0\); (3) outward interactions when \(u' > 0\) and \(w' > 0\); and (4) inward interactions when \(u' < 0\) and \(w' < 0\). Sweeps in particular have been shown to generate most of the bedload movement over flat beds while ejections are thought to be responsible for sediment entrainment into suspension (Le Couturier et al., 2000). To assess if the bursting processes could be responsible for sediment movements observed within and downstream of the canopy in the Lab Carousel, the instantaneous Reynolds stresses were calculated for the first velocity measurements (1 cm above the flume bed) of the profiles measured along Patch a at a free-stream velocity of 20 cm s\(^{-1}\). The profiles show that the Reynolds stresses were lowest upstream of the patch, increased slightly when entering the canopy and were the highest just downstream of the canopy (Figure 4.23). The sweeps and ejections with a magnitude over 2 N m\(^{-2}\) are shown on the profiles downstream of the canopy (little or none were found on profiles upstream or within the canopy). Similar results were seen along Patch b. It therefore seems credible that burst events are responsible for sediment movement observed directly downstream of the canopy.
Figure 4.23: Instantaneous Reynolds stresses at a height of 1 cm above the bed along the 8 profiles upstream, within and downstream of Patch b (free-stream velocity of 20 cm s\(^{-1}\)). Bold numbers show the average Reynolds stresses (N m\(^{-2}\)) for each graph. For measurements downstream of the canopy, the major sweep (triangle) and ejection (diamond) events are indicated.
Our results thus confirm that sediment movement occurs within and downstream of seagrass beds. This is important for the estimation of sediment transport within and around seagrass canopies, in particular in the case of annual seagrass beds where a large number of plants die during winter. At such times, sediment which has not yet been consolidated by biological action may be more easily remobilised due to the increased turbulence around the reduced seagrass patches. This theory is consistent with results from Bos et al. (2007) who suggested that in annual beds, a yearly cycle occurs: sediment is trapped within the canopy during the seagrass growing season and then released during winter, when some of the plants die back. These processes may also play a role in the seabed relief often seen in seagrass beds, where seagrass patches present a raised bottom compare to adjacent areas (Fonseca, 1996). Even in the case of perennial seagrass, sediment movement created by increased turbulence may help in maintaining a balance between sediment trapping due to the dampening effect of the canopy and sediment mobilisation due to an increased turbulence. This agrees with the description of den Hartog (1970) who suggested that Zostera marina beds stabilise the bed with their roots but have a limited sediment-fixing capacity because the rhizome does not seem to be able to grow in a vertical direction. Although the work presented here confirms that sediment mobilisation may occur within and around seagrass beds, even at relatively low current intensity, it did not take into account the role of biota in stabilising or destabilising the sediment, whereas biological processes, in particular benthic fauna activity, are thought to play an important role in sediment movement in seagrass beds (Widdows et al., 2008).

4.5. CONCLUSIONS AND PERSPECTIVES

4.5.1. Conclusions

Lab-based experiments were conducted in an annular and a straight recirculating flume using live Zostera marina plants and a mobile sand layer. These experiments aimed to investigate the influence of Z. marina canopies on unidirectional flow, bed roughness and sediment mobilisation, with emphasis on flow structure upstream, within and downstream of patches of different lengths. To do so, numerous profiles of instantaneous velocities were measured along patches of various lengths and shoot densities and at different free-stream velocities. Flow structure was characterised by time-averaged velocity, turbulence
intensity and horizontal and vertical TKE. When velocity data were available above the canopy, they were fitted to the Law of the Wall profile and shear velocities and roughness lengths were calculated. Movements of the mobile sediment layer were assessed during runs. Although some limitations inherent to flume designs appeared, several conclusions can be drawn from this work:

(1) 3 layers can usually be distinguished in the water column:

- within canopy with low velocities, high turbulence and low TKE;
- transition zone around the height of the canopy, where velocities increased, turbulence decreased and TKE is high; and
- above canopy where velocities are equal or higher than free-stream velocities and turbulence and TKE are low.

(2) Shoot density was found to accentuate flow reduction and increase turbulence within the canopy, especially in the case of an ‘infinite’ canopy length.

(3) The enhanced TKE observed at the canopy/water interface suggests that large-scale oscillations develop at the canopy surface. These oscillations are probably related to canopy wavy motion, the so-called monami. Large-frequency turbulence is then broken down within the canopy and small-frequency turbulence is observed to take place near the bed.

(4) Flow velocity seems to be reduced before entering the canopy and to accelerate before exiting it. This implies that the canopy ‘feels’ flow obstruction.

(5) Flow above the canopy was generally found to follow a logarithmic profile. Shear velocity increased with increasing distance into the canopy and free-stream velocity. Roughness length was higher above the canopy than over bare sand, however, it was still small (mm to cm) compared to other studies. It also increased with increasing distance from the leading edge of the canopy but did not seem to vary with shoot density or patch width.

(6) Sediment movement was observed within and downstream of the canopy at positions where the average velocity was estimated to be under the threshold of motion. Sediment movement is thought to be initiated by turbulence and in particular through sweeps and ejections from the ‘burst phenomenon’. Therefore, on the contrary to the common idea that movement is reduced within seagrass beds, the present study suggests that mobilisation of the mobile sediment layer can happen
even at reduced velocities due to the high turbulence intensities encountered within and downstream of the canopy.

4.5.2. Recommendations for future work

The present study helped to better understand flow structure and sediment movement within and around *Zostera marina* beds. However, further research is needed to fully comprehend these processes. In particular, field measurements are necessary to validate the results observed in the flume. Turbulence structure within the canopy was found to differ in the flume and in the field and so additional research is needed to ascertain where the differences come from. Flow structure upstream and downstream of the canopy should also be further investigated to establish if the flow can ‘feel’ the canopy as it is hypothesised in this study. Roughness length measurements from the field are still required in order to determine roughness length variations over other type of plants and at different relative submergence. More importantly, the hypothesis of sediment mobilisation by bursting events needs to be further investigated in order to fully comprehend sediment movement to and from seagrass canopies. The role of biological activity, certainly of importance in seagrass beds, should also be considered in more details. Finally, studies looking at the influence of flow created by wave and currents are crucially needed as it is encountered most in reality.
CHAPTER 5. SUMMARY AND CONCLUSIONS
Although bed roughness is an essential parameter in studies of hydrodynamics, sediment transport and acoustic scattering, few studies characterise it at an adequate resolution. The aim of this thesis was to investigate bed roughness over vegetated beds with an emphasis on sonar imaging techniques and effect on unidirectional currents. The new high-resolution acoustic system (BRAD) presented in Chapter 2 enables the definition of small-scale topographic roughness over a variety of roughness types and in particular over seagrass canopies, a form of biogenic roughness of the seabed. The survey methodology described in Chapter 3 facilitates mapping of seagrass distribution and canopy height, which should help to define topographic roughness of the seabed at a larger-scale. Finally, the laboratory experiments carried out on Zostera marina canopies (Chapter 4) investigated hydrodynamic modifications and sediment movement within and around seagrass beds, thereby characterising roughness over seagrass canopies. Overall, the work presented here therefore improves our knowledge of bed roughness over vegetated beds and the processes affected by it, such as hydrodynamics and sediment movement.

5.1. High-resolution measurements of topographic roughness

The Benthic Roughness Acoustic Device was successfully developed and tested through lab and field-based deployments. A processing method was developed to enable high-resolution measurements of seabed and canopy elevations over an area of 1.7 m² at maximum. A threshold method is used to calculate the depth of the seabed - and the canopy if present – from the raw SIS data. Measurements carried out in the test tank were used to assess the system accuracy and its capacity to correctly discriminate various shapes and sediment types. The horizontal resolution was around 2 to 3 cm (a function of beam angle) while the vertical resolution was sub-centimetre.

Six sites were imaged in the field over a range of roughness types including seagrass canopies, bioturbated sediment and ripple fields. Two-dimensional roughness spectra estimated from the seabed and canopy elevations were used to characterise bed roughness. The spectra showed the degree of isotropy of the seabed topography, which is often a function of roughness type. Bedform roughness was seen to present a strong anisotropy in the bedform direction whereas in the case of biogenic roughness, the spectra were
essentially isotropic. The 2D spectrum of the ripple field was used to calculate the average direction, wavelength and height of the bedforms. Power-law regressions fitted on slices taken through the spectra were used to further describe roughness. A high slope of the power-law fit showed a strong influence of the small frequencies (large wavelengths) compared to high frequencies (small wavelengths) and was thought to be characteristic of bedform roughness. Smaller slopes implied a stronger influence of high frequencies, characteristic of biogenic roughness. A variety of sites should to be imaged with BRAD and defined through spectral analysis in order to construct a catalogue of natural roughnesses.

5.2. MAPPING OF BIOGENIC ROUGHNESS ELEMENTS

The survey carried out in Calshot using both a video camera sledge and a high-resolution profiling sonar (the SIS) was undertaken to evaluate the use of the SIS for seagrass detection and to undertake a preliminary mapping of the seagrass bed in Calshot. The camera system has the advantage of providing a direct observation of the seabed, which enabled flora identification and bottom type classification. However, data processing was time-consuming and subject to observer error. The SIS has proved to be a useful tool for seagrass surveying and an algorithm to analyse the data was developed and tested. The Seagrass Index (SI) was calculated as the average backscatter 10 to 15 cm above the seabed of 5 beams averaged in the middle of a sweep and the patchiness (P) as the percentage of beams in a sweep where the average backscatter 10 to 15 cm above the bottom were higher than a threshold value. It was possible to estimate seagrass abundance using SI and P. Furthermore, the SIS was used to estimate canopy height and accurately measure depth. On the other hand, the backscatter on the bottom showed too much scatter to be used for bottom type determination. The system needs to be tested with different seagrass species in order to assess the influence of seagrass morphology on SIS backscatter.

The survey area has been classified according to seagrass density, algae abundance and bottom type. The only seagrass recognised during the survey was Zostera marina. It was found only on sandy bottoms and at depth above -1.5 m CD. Around 35% of the seagrass was distributed in the lower intertidal zone where it formed small patches. Four hectares of
the survey area were classified as dense meadow with average densities of 150 shoots m$^{-2}$ and reaching local maxima of 500 shoots m$^{-2}$.

5.3. HYDRODYNAMICS AND ROUGHNESS IN SEAGRASS BEDS

Lab-based experiments were conducted in an annular and a straight recirculating flume using live *Zostera marina* plants and a mobile sand bed. Numerous profiles of instantaneous velocities were measured along patches of various lengths and shoot densities and at different free-stream velocities. Flow structure was characterised by mean velocity, turbulence and horizontal and vertical TKE. When velocity data were available above the canopy, they were fitted to the Law of the Wall profile and shear velocities and roughness lengths were calculated. Movements of the mobile sediment layer were assessed during runs. Limitations inherent to flume designs appeared, such as the secondary circulation in the Lab Carousel, which resulted in a compressed canopy, or the influence of the tail gate on flow downstream of the canopy, which limited the extent of the flow that could be measured.

The results showed that 3 layers can usually be distinguished in the water column: (1) within canopy with low velocities, high turbulence and low TKE; (2) a transition zone around the height of the canopy, where velocities increased, turbulence decreased and TKE was high; and (3) above the canopy where velocities were equal or higher than free-stream velocities and turbulence and TKE were low. Flow velocity was seen to be reduced before entering the canopy and accelerated before exiting it. The enhanced TKE observed at the canopy/water interface suggested that large-scale oscillations developed at the canopy surface. These oscillations were probably related to canopy wavy motion, the so-called monami. Large-frequency turbulence was then broken down within the canopy and small-frequency turbulence was observed to take place near the bed. Flow above the canopy was generally found to follow a logarithmic profile. Roughness length was higher above the canopy than over bare sand, however, it was still small (mm to cm) compared to other studies. It increased with increasing distance from the leading edge of the canopy but did not seem to vary with shoot density or patch width. Sediment movement was observed within and downstream of the canopy at positions where the average velocity was estimated to be under the threshold of motion. Sediment movement is thought to be
initiated by turbulence and in particular through sweeps and ejections from the ‘burst phenomenon’. Sediment mobilisation initiated by turbulence may play an important role in sediment balance within and around seagrass beds. More research is needed to confirm the results described here, in particular field-based measurements.
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Appendix 1: Conference paper

A NEW SYSTEM FOR SEAFLOOR CHARACTERISATION: BRAD, THE BENTHIC ROUGHNESS ACOUSTIC DEVICE

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Small scale ($10^{-2}$ to $10^{-1}$ m) roughness of the seafloor is of direct relevance to a range of interests, including boundary layer hydrodynamics, sediment transport and high frequency acoustic scattering. Methods for the quantification and characterisation of seafloor micro-topography for a range of natural roughness scales are therefore essential.

A new acoustic system has been developed at the National Oceanography Centre, Southampton (NOCS), UK, the Benthic Roughness Acoustic Device (BRAD). This system is used to define micro-topographical roughness of the seafloor through high-resolution acoustic imaging. BRAD is composed of a high-frequency profiling sonar, the Sediment Imager Sonar (SIS) and a small driver motor, both mounted on a frame.

BRAD measures high-resolution relief of the seabed over an area of 1.7 m\textsuperscript{2}. A two-dimensional spectral analysis is then applied on the seabed elevation data in order to characterise seafloor roughness. Three field deployments in areas with different bottom types (seagrass canopy, bioturbated mud and sandy ripples) are presented and discussed here. The seagrass canopy was successfully differentiated from the underlying bed, which presented an isotropic spectrum. The bioturbated seabed was also characterised by an isotropic roughness spectrum, while the ripple field roughness spectrum exhibited a strong anisotropy in the direction of the ripples. At each site, the slope and intercept of the power-law regression line fitted to “slices” taken through the 2D roughness spectrum were also used to characterise topographical roughness.

Keywords: bed roughness, high-resolution acoustic imagery
1. Introduction

Small-scale (10^{-2} to 10^{-1} m) roughness of the seafloor is of direct relevance to a range of interests such as boundary layer dynamics [1], sediment transport [2] and acoustic scattering [3]. Seafloor topography is influenced by both the nature of the sediment, such as grain size and sorting (grain roughness), and the contributions of several roughness producing mechanisms. Under the action of waves and currents, bedforms such as sand ripples develop, creating topographical variations (bedform roughness). In the absence of sediment transport by waves or currents, the sediment surface is continuously being modified by the locomotion and/or feeding activity of animals that live on and within the sediment creating biogenic roughnesses. Furthermore, the animals and plants living on the seafloor themselves constitute a relief of the seabed. While bedform roughness is usually anisotropic, i.e. it presents a preferential direction (function of wave and current directions), biological roughness is generally isotropic [3].

Despite the importance of bed roughness on near-bottom flow and sediment transport, only a few studies have quantitatively resolved seafloor height at the relevant scales. Traditionally, stereo-photography has been used to compute 1D or 2D high-resolution seabed elevation data used to spectrally characterise bed roughness [3-6]. Acoustic systems have the potential to produce high-resolution images of the seabed, which can then be used to study topographical roughness. To date, however, high-resolution acoustic systems produce only profiles of seabed elevation (i.e. 1D) which have been used principally to study ripple dimensions (e.g. [7]). This can be limiting as roughness is a spatially varying parameter and the direction of the profile can have an important effect on the resulting analysis [8].

A new acoustic system has been developed at the National Oceanography Centre, Southampton (NOCS), UK, the Benthic Roughness Acoustic Device (BRAD). This apparatus provides high-resolution acoustic measurements of seabed elevation over an area of 1.7 m^2. In this study, we test the application of spectral analysis to characterise topographical roughness from seabed elevations computed using BRAD.

2. System description and methodology

2.1. The system

The Benthic Roughness Acoustic Device is composed of a profiling sonar – the Sediment Imager Sonar (SIS) - and a small driver motor which are mounted on a frame (1.7 m long, 1 m high and 1 m wide) in aluminium (Fig. 1). During deployments, the SIS is down-looking at a height of 0.88 m above the bed. It is advanced along the length of the frame by the motor at a velocity of 0.56 mm s^{-1}. The SIS is a single-beam profiling sonar with a rotating head manufactured by Marine Electronics Ltd. (Guernsey). It emits a pencil-beam sound wave (beam width angle 1.8°) at a frequency of 1.1 MHz. The sonar beam is swept at right angles to the sonar body and sweeps are made in an arc of 90° (beams every 0.9°) centred about nadir so that data are acquired 45° each side of the vertical (total of 101 beams per sweep). Echograms (backscatter intensity along the beams) are displayed, recorded and converted to ASCII image intensity by the Sediment Imager Control Software®. The data available after conversion are beam angle (degrees), distance from transducer (m) and backscatter intensity (0 - 255). With a range of 2 m, a transmit pulse of 10 µsec and a sample interval of 5 µsec, the along-beam resolution is about 3.75 mm (dependant on the sound velocity in water). The horizontal resolution is a function of beam angle and varies from 2 to 3 cm.
Fig. 1: Schematic of the Benthic Roughness Acoustic Device (BRAD) developed at NOCS.

The SIS cannot be operated autonomously and so is connected to a power supply and a computer, which provides real-time display and recording of the data. BRAD can be deployed by 3 people from an anchored boat or a pontoon in water depths ranging from 1 to 6 m. The maximum area of the seabed that can be surveyed in a single deployment is 1.7 m$^2$ in a period of around 50 minutes.

2.2. DEM PRODUCTION

BRAD was deployed at three sites in Venice Lagoon, over a *Zostera marina* canopy (Site 1), bioturbated mud (Site 2) and rippled fine sand (Site 3). Digital elevation models (DEMs) of the seabed imaged with BRAD were created from the raw SIS data for each site. A threshold method was used to calculate the depth of the bed along each beam of each sweep. Seabed detection was initially tried using only the backscatter intensities along a beam. This method, however, often gave inaccurate results as the threshold values were found to be dependent on the intensity of the maximum backscatter and backscatter intensity in the water column, which vary from beam to beam (in particular with beam angle). To address this problem, a threshold using a quotient $Q$ was applied:

$$Q(Z) = \frac{B(Z) - W}{B_{\text{max}} - W}$$  \hspace{1cm} (1)

where $B(Z)$ is the backscatter intensity at the depth ($Z$) under the SIS head and $W$ is the average backscatter 0.3 to 0.5 m from the transducer head (Fig. 2a). $Q$ has values of on average 0 in the water column and 1 at maximum. The first point along the beam where $Q(Z)$ was greater than 0.8 was defined as the depth of the seabed (Fig. 2a). Beam angle and depth of the seabed were used to compute the $x$ co-ordinates associated with the points satisfying the threshold condition. The positions along the frame ($y$) were calculated from the motor velocity, the time to complete a sweep and the beam number. Finally, the seabed elevation ($z$)
was computed as the deviation from the theoretical depth of the seabed under the SIS head ($Z = -0.88$ m).

This processing was applied on datasets from Sites 2 and 3. Site 1, however, was undertaken over a seagrass ($Zostera marina$) canopy. When a sound wave reaches submerged vegetation, some of the acoustic energy is scattered from the vegetation back to the source, creating strong backscatter above the seabed [9]. Along the beams collected at Site 1, a high backscatter response was seen from both the seabed and the seagrass canopy and could be differentiated from ambient noise (Fig. 2b). Several methods were tested to allow computation of both the height of the seabed and the height of the canopy. The method used here assumes that the bed under the canopy was relatively flat and situated no more than 4 cm above the theoretical depth of the bed ($Z = -0.88$ m). Along a beam, the seabed depth was taken as the first point where $Z < -0.84$ and $Q(Z) > 0.8$ and the height of the seagrass was calculated as the first point where $Z > -0.84$ and $Q(Z) > 0.6$ (Fig. 2b). Seabed and canopy elevations of each site were thereafter interpolated over a regular grid (cell size of 0.01 m).

![Fig. 2: Values of relative intensity of the backscatter ($Q$) of a beam along the depth under the SIS head ($Z$). (a) Bare seabed. The maximum backscatter ($Q = 1$) is showed as a black dot. The depth of the seabed is indicated by the red line and red dot (first point where $Q > 0.8$). The rectangle shows the extent of the backscatter intensities averaged to calculate $W$. (b) Seagrass canopy. The canopy height (CH) is showed by the green line and green point (first point where $Q > 0.6$ and $Z > 0.84$ m). The depth of the bed is indicated by the red line and the red dot (first point where $Q > 0.8$ and $Z < 0.84$ m).](image)

### 2.3. Roughness Characterisation

Topographical roughness can be described through statistical parameters such as the root mean square (RMS) of the elevation distribution (e.g. [10]). Spectral analysis, however, proved to be more efficient as it characterises the variance of seabed topography as a function of spatial frequency [6]. A power-law can be fitted to the spectrum of a 1D profile or to a “slice” of a 2D spectrum in log-log space. The slope and intercept values of the regression line are often used by acoustic modellers to predict bottom scattering [11]. Spectral analysis was applied to the DEM using the methodology detailed by Lyons et al. (2002) to
characterise the 2D roughness of a rippled bed imaged with digital photogrammetry. DEMs were first multiplied by a tapering function (Discrete Prolate Spheroidal Sequences) to reduce spectral leakage, which is caused by the finite size of data segments used for analysis [12]. While reducing bias, data tapering also causes a reduction of resolution, or a smoothing effect, in the spectral estimate. The seabed elevations were then transformed to the spatial domain using a 2D Fast Fourier Transform. “Slices” were taken through the 2D roughness spectrum in one degree steps from 0° to 180°. Each slice through the 2D roughness spectrum is a 1D representation of the 2D roughness spectrum in a particular orientation, but it is not the same as the 1D roughness spectrum estimated from a 1D profile (see [3] for more details). In case of rippled seafloors, a power-law regression was fitted to slices taken in directions along and at 90° to the peak in the spectrum caused by the ripples. At the other sites, a power-law regression was fitted to the average of all the slices. The slope and intercept (at a spatial wavenumber of $10^0$) of the power-law regression lines were used to characterise bed roughness.

3. RESULTS

The first site imaged in Venice Lagoon consisted of a Zostera marina canopy. The seabed under the canopy was composed of fine sand with a small fraction of mud and shells. Fig. 3 presents the reconstructed seabed elevation at Site 2 and the 2D roughness spectrum computed from the seabed elevations. The spectrum was essentially isotropic; that is, the spectrum has a central peak without any pronounced directionality in 2D spectral frequency space [6]. The reconstructed canopy elevation at Site 1 is also shown on Fig. 3. The canopy had an average height above the bed of 19.5 cm (standard deviation of 4.9 cm). Its surface was found to be uneven and irregular (height varying between 5 and 35 cm above the bed).

Deployment at Site 2 was carried out inside Venice Lagoon over bioturbated mud. An important number of bioturbation holes, around 2 cm in diameter and deeper than 6 cm, were also seen. Unfortunately it was not possible to observe the organisms making these holes and hence their origin is unknown. The bioturbation holes could be recognised along certain beams as a strong backscatter below the bed. Seventeen bioturbation holes were counted within the 1.7 m$^2$ of seabed imaged. The 2D spectrum computed from seabed elevations at Site 2 was essentially isotropic (Fig. 4).

The isotropy of the spectra estimated from the seabed elevations at Sites 1 and 2 suggests that the seabed relief at these sites at the time of the imaging was weakly influenced by hydrodynamics, which usually creates directionality in the spectrum. Roughness at those sites was most likely created by biota activity, which is generally isotropic. Furthermore, the strong power contained in the high frequencies shows the importance of small scale roughness, whereas the low power contained by low frequencies highlights the lack of large wavelength features, further suggesting a predominance of biogenic roughness at these sites.

Site 3 was occupied outside Venice Lagoon over well-sorted fine sand. The seabed imaged was covered by symmetrical, sharp-crested, wave ripples (wavelength of approximately 10 cm and a height of around 1 cm) with numerous bifurcations. Seabed elevations reconstructed at Site 3 are presented on Fig. 5. The reconstructed ripple field shows sharp-crested and symmetrical bedforms, with occasional bifurcations, which agrees well with on-site description. The 2D spectrum computed from the seabed elevations at Site 3 clearly shows the anisotropy associated with the ripple field (Fig. 5) as well as the peak in power associated with the wavelength of the ripples.
Fig. 3: Top: seabed elevations at Site 1 and the isotropic 2D roughness spectrum estimated from the DEM (some spectral leakage can still be seen as horizontal lines along the spectrum). Bottom: 3D view of the canopy elevations over the seabed and slices through the 2D spectrum (45 and 135°) together with the power-law line fitted on the average of all the slices.

Fig. 4: Isotropic 2D roughness spectrum estimated from the seabed elevations at Site 2 and slices of the spectrum (45 and 135°) together with the power-law line fitted on the average of all the slices.
Slope ($\gamma$) and intercept ($\omega$) values calculated from the slices through the 2D spectra are summarised in Table 1, together with the median grain size diameter and RMS values of the seafloor elevation distribution at each site. The highest slope was calculated from the slice taken perpendicular to the ripple crest at Site 3, showing the importance of the low frequencies compared to the high frequencies for this case of bedform roughness. The smaller slope, which was calculated from the average of the slices computed from Site 2 spectrum, shows that biogenic roughness is characterised by a relatively stronger contribution of the high-frequencies compared to the low-frequencies (i.e. roughness at the bioturbated site is characterised by high spatial frequency fluctuations in sediment height), as has been described in other studies [11].

<table>
<thead>
<tr>
<th></th>
<th>$d_{50}$ ($\phi$)</th>
<th>Type</th>
<th>RMS (cm)</th>
<th>Slope</th>
<th>Intercept (m$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>2.54</td>
<td>fine sand</td>
<td>0.85</td>
<td>4.1</td>
<td>0.09022</td>
</tr>
<tr>
<td>Site 2</td>
<td>5.02</td>
<td>bioturbated silt</td>
<td>0.83</td>
<td>3.5</td>
<td>0.02750</td>
</tr>
<tr>
<td>Site 3 (c-c)</td>
<td>3.16</td>
<td>rippled v. fine sand</td>
<td>0.64</td>
<td>4.7</td>
<td>0.39884</td>
</tr>
<tr>
<td>Site 3 (a-s)</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>4.1</td>
<td>0.09497</td>
</tr>
</tbody>
</table>

**Table 1:** Summary of median grain diameter ($d_{50}$), seabed type, RMS height and slope and intercept of the power spectrum at each site imaged with BRAD. At Sites 1 and 2, slope and intercept values were calculated from the average of all the slices; at Site 3, they were computed from slices taken perpendicular (c-c) and parallel (a-s) to the ripple crests.

Slope and intercept values calculated in this study were compared with slope and intercept values compiled in [3]. To enable comparison, the values calculated from 1D seafloor elevations acquired with stereo-photography were transformed to 2D values in metre units following the method detailed in [3]. The slope and intercept values calculated from BRAD data were found to be higher than those of previous studies (3.5 and 0.0021 m$^4$ on average for a variety of roughness types). The reasons for such a difference are not fully understood, but might come from the difference in the systems used to image the seafloor (acoustical versus optical), the length of the seafloor analysed and the systems specific resolution.
4. CONCLUSIONS

The development and first use of BRAD, a new high-resolution acoustic system designed specifically for seafloor roughness characterisation, are presented here. The system was deployed at 3 sites in Venice Lagoon over a variety of bottom types (Zostera marina canopy, bioturbated silt and ripple field). The DEMs were successfully produced from BRAD raw data and the 2D roughness spectra estimated from the seabed elevations were used to characterise topographical roughness at each site. The roughness spectra clearly show the anisotropy of the ripple site and isotropy of the bioturbated seabeds. The slope and intercept values of slices through the spectra help in assessing the relative influence of small and high-frequencies on topographical roughness. A variety of sites should to be imaged with BRAD and characterised through spectral analysis in order to construct a catalogue of natural roughnesses.

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Use of a high-resolution profiling sonar and a towed video camera to map a *Zostera marina* bed, Solent, UK

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**Abstract**

Seagrasses are flowering plants that develop into extensive underwater meadows and play a key role in the coastal ecosystem. In the last few years, several techniques have been developed to map and monitor seagrass beds in order to protect them. Here, we present the results of a survey using a profiling sonar, the Sediment Imager Sonar (SIS) and a towed video sledge to study a *Zostera marina* bed in the Solent, southern UK. The survey aimed to test the instruments for seagrass detection and to describe the area for the first time. On the acoustic data, the bed produced the strongest backscatter along a beam. A high backscatter above the bottom indicated the presence of seagrass. The results of an algorithm developed to detect seagrass from the sonar data were tested against video data. Four parameters were calculated from the SIS data: water depth, a Seagrass Index (average backscatter 10–15 cm above the bed), canopy height (height above the bed where the backscatter crosses a threshold limit) and patchiness (percentage of beams in a sweep where the backscatter 10–15 cm above the bed is greater than a threshold limit). From the video, *Zostera* density was estimated together with macroalgae abundance and bottom type. Patchiness calculated from the SIS data was strongly correlated to seagrass density evaluated from the video, indicating that this parameter could be used for seagrass detection.

The survey area has been classified based upon seagrass density, macroalgae abundance and bottom type. Only a small area was occupied by a dense canopy whereas most of the survey area was characterised by patchy seagrass. Results indicated that *Zostera marina* developed only on sandy bottoms and was not found in regions of gravel. Furthermore, it was limited to a depth shallower than 1.5 m below the level of Lowest Astronomical Tide and present in small patches across the intertidal zone. The average canopy height was 15 cm and the highest density was 150 shoots m\(^{-2}\).

1. **Introduction**

Seagrasses are flowering plants that have adapted to the submerged marine environment. They develop extensive underwater meadows forming complex, highly productive ecosystems. Seagrass beds play a key role in coastal ecosystems by stabilising bottom sediments through their roots (den Hartog, 1970), by attenuating currents and waves (Gambi et al., 1990; Fonseca and Cahalan, 1992) and by promoting sedimentation and reducing erosion (Leonard and Luther, 1995). They also provide shelter and refuge for adult animals (Connolly, 1994), serve as nurseries for juvenile fish (Horinouchi, 2007) and supply food for herbivores which graze on live seagrass leaves and consume epiphytic algae that grow on seagrass leaves (Heck and Valentine, 2006). The infauna and epifauna of seagrass beds also serve as prey for larger invertebrates and fish (Pihl et al., 2006). Furthermore, seagrass beds have high rates of primary production (Hasegawa et al., 2007) and are an important source of organic matter (Gacia et al., 2003). They can be used to assess the health of coastal and estuarine communities (Short and Burdick, 1996; Austoni et al., 2007) and to trace metal contamination (Lafabrie et al., 2008) or chemical constituents (Lewis et al., 2007).

Preservation, restoration or creation of seagrass beds are increasingly recognised as being essential for the sustainable management of the coastal environment (Yap, 2000; Short et al., 2007). Therefore it has become a growing concern to accurately map and monitor seagrass beds in order to assess their state and protect them (Kirkman, 1996). Several techniques have been used to detect seagrass beds and estimate seagrass density, ranging from physical sampling to optical or acoustic techniques. Physical
Zostera marina (a smaller species of Z. marina) have been described in several harbours (Porstmouth, Langstone and Chichester) in the Solent, UK (Tubbs and Tubbs, 1983). However, these ecosystems have been poorly studied up till now.

The survey undertaken off Calshot beach, in the Solent, UK, combining a profiling sonar, the Sediment Imager Sonar (SIS) and towed seabed video sledge equipment investigated the extent and structure of a Zostera marina meadow that had not been previously mapped. The SIS dataset was used in a direct comparison of the video and sonar data and to map seagrass in a qualitative and a quantitative manner. The objectives of the survey were to test the use of the SIS for seagrass surveying against the video camera system and to map and characterise the seagrass bed.

2. Material and methods

2.1. Survey area

Calshot spit is situated in the West Solent, at the mouth of Southampton Water, on the south coast of England (Fig. 1). The spit is an important recreational area for local residents with an outdoor activity centre, sailing club and beach huts. Car ferries, linking Southampton to Cowes on the Isle of Wight, pass close to the spit. The largest oil refinery in the UK is situated at Fawley only 4 km north-west of Calshot. Recent morphological evolution of the spit shows that it has been stable for the last 125 years (Lobey, 1995). The beach, off which the survey was undertaken, is composed of gravel (flint) with sandy patches. The tidal range varies from 2 to 4 m for mean neap and spring tides respectively and due to sheltering by the Isle of Wight, waves are generally small. All depths in this paper are given compared to Chart Datum (CD) which is approximately the level of Lowest Astronomical Tide. The intertidal zone on the beach is situated between 0 and +4 m CD, however, zones situated between 0 and +1 m are exposed only during low water at spring tides. Zostera marina had been noted on Calshot beach during extreme low tides but the extent of the meadow was unknown.

2.2. Beach and diver surveys

Shore and divers surveys were conducted in the survey area shortly before the boat survey in order to measure shoot densities and maximum leaf length. On the 24th and 31st July, 2007, measurements were made at 20 locations by SCUBA divers along 2 transects at right angle to the shore. At each location, 15–30 replicates were conducted by 2 divers using a 30 × 30 cm quadrat. Locations of the divers’ surface marker buoy were recorded by the support vessel (equipped with a Trimble DGPS) with an accuracy of around 5 m. Due to extreme low water on the 2nd and 3rd August 2007 beach transects were possible and were conducted perpendicularly to the beach from low-water inshore at 10 m intervals (Vince, 2007). At each of the 17 locations, measurements of shoot density and maximum leaf length were taken over 10 replicate 30 cm × 30 cm quadrats. Beach positions were recorded by handheld Garmin GPS (accuracy 5 m).

2.3. Instrumentation used during the boat survey

2.3.1. The sonar system

The Sediment Imager Sonar is a derivative of the Image Profiling Sonar 1640/2640 produced by Marine Electronics Ltd. (Guernsey). It is a high frequency (1.1 MHz), single beam sonar (conical beam width angle 1.8°) with a rotating head (sweeps up to 360°, beams
every 0.9°) and records a high-resolution acoustic image of the seabed and the water column. Echograms are recorded for each sweep (.img file) and converted to ASCII image intensity (.xyz file) with specially written software (Sediment Imager Converter 1.0 provided by Marine Electronics Ltd). The data available after conversion are beam angle (degrees), distance from transducer (m) and backscatter (dimensionless). The backscatter intensity values are given in relative integer values (0–255, linear) and the SIS does not incorporate a time-variable gain (TVG) circuit or software correction. The sonar beam is swept at right angles to the sonar body and during the survey, the instrument was facing the bow so that sweeps were perpendicular to the boat’s direction of travel. The sweep angle was 46.8° centered downward, so beams with a beam angle of 0° were recording backscatter just under the instrument, beams with a negative beam angle were surveying on the left of the transducer head and beams with a positive beam angle were surveying on the right of the instrument. The pulse duration was fixed to 40 μs and the measurement range was limited to 6 m along which 396 measurements of backscatter were recorded, yielding a vertical resolution of 1.5 cm, i.e. backscatter intensity recorded every 1.5 cm along a beam. Because the sweep angle was fixed, the horizontal distance over which an entire sweep was recorded depended on water depth, i.e. the deeper the water, the longer the area of seabed surveyed during a sweep; for example, the total of length of bed surveyed in a sweep varied from 1.5 to 4 m for water depth under the transducer varying from 1.75 to 4.6 m.

2.3.2. The video system

The video system is composed of a downward facing video camera (Divecam-550C from Bowtech Products Ltd, Aberdeen, UK) and a light source mounted on a specially designed aluminium sledge (Craig, 2006). The video camera is a miniature, high definition (550 TV lines) colour CCD camera (PAL format, 25 frames per second) with a scanning speed of 50 Hz. Illumination is provided by a 50 W array of high intensity white LEDs. The sledge is towed approximately 20 m behind the vessel with a Kevlar cored multi-conductor cable, typically at a speed of 1–2 knots to allow good quality images (blurring becomes unacceptable at speeds above 2 knots). With the camera held at approximately 50 cm above the bottom, the field of view averages an area of about 50 × 70 cm. The height of the sledge can vary slightly (±20 cm) with boat speed. A 12 volts power supply for the lights and camera is provided through the towing cable in which the composite video signal also returns. Boat location is recorded with the onboard differential GPS (Trimble, submetre resolution) and is overlaid on the video signal. The analogue composite video signal is viewed onboard and recorded at the highest possible resolution to hard disc; it is subsequently copied onto a DVD for play-back.

2.4. The survey

A survey was undertaken on 12th September 2007 onboard the R.V. Bill Conway around high tide during spring tide. During the survey, the SIS was fixed 94 cm below the waterline to a downrigger mounted on the starboard side of the boat while the camera system was towed around 20 m behind the boat. The SIS was positioned around 22 m in front and 2 m on the starboard side of the camera, therefore the instruments were not always surveying identical seabed locations (0–2 m lateral difference depending on water depth). A monitor and a computer in the cabin gave real-time displays of the video and SIS images. Waves were small (less than 20 cm high) and the weather was sunny with light winds. Four lines parallel to the shore were surveyed in 3.5 h at a speed of 1–2 knots. Lines were about 1.5 km-long and were spaced 50–100 m apart. The total length of the surveyed lines was 6.5 km encompassing an area of 44.6 ha.

Salinity and temperature profiles were measured on site prior to survey using a YSI 30 probe. The average salinity recorded was 34.8 and the average temperature was 18.3 °C, yielding a sound velocity of 1516 m s−1 which was entered into the SIS software to compute correct depth from the 2-way travel time. The profiles of temperature and salinity suggested a well-mixed water column (less than 5% changes in salinity and temperature with depth) and therefore no correction was needed for a change in speed of sound with depth.

Fig. 1. Geographical location of the survey area.
2.5. Data processing

2.5.1. Video data

The video was replayed at half speed to allow adequate time for observations to be made. Every 2–3 s, the video was paused and relative Zostera density, algae abundance, seabed type, time, and position were logged (Table 1). A semi-quantitative density scale was established to evaluate seagrass coverage (Zostera density, ZosD) ranging from 0 where no seagrass was seen, to 4 in the case of a continuous seagrass canopy. Presence and abundance of algae (algae index AlgI) was ranked from 0 (no algae) to 2 (abundant algae). In this study, the term algae is used to designate macroalgae such as Enteromorpha spp, Ulva lactuca, Halurus flosculosus or Ceramium spp. Planktomic species, which are hard to distinguish on the video, are not considered. Bottom type (BoTyp) was assigned the value 1 when the seabed was covered with sand, 2 in case of a mix of gravel and sand and 3 when the seafloor was covered with gravel. When the seagrass canopy occupied the whole image and prevented seabed observation, no value was put in the bottom type rating. During the survey, ripples were observed on the seabed and were allocated a BoTyp value of 0.5, in order to be differentiated from other bottom types. An observation every 2 s on the video translates a data point every 2–4 m over the seabed.

2.5.2. SIS data

The SIS was sweeping over the bed perpendicularly to the direction of travel. It was hence recording data over a line going 4–10 m in the direction of boat travel and 1–3 m towards one side of the instruments (negative beam angles to the left, positive to the right) before changing direction and recording another sweep; overall the track of the data was therefore in a zigzag. A sweep, recorded in about 10 s, was composed of 52 beams, therefore beams were recorded every 5–13 cm depending on boat speed and water depth (beam rate of 5.2 beam s\(^-1\), boat speed of 1–2 knots). The seabed was occupied by seagrass plants, 2 and 5 in the direction of boat travel and 1–3 m towards one side of the instruments. The SIS was composed of the ambient backscatter in the water column at a distance of 1.0–1.4 m from the transducer plus 60 to a backscatter threshold value of around 150 depending on the seabed in the water column (see lines “threshold value for CH” on Fig. 2). When present, submerged vegetation produces a strong backscatter immediately above the bed where the backscatter intensity is higher than the backscatter threshold value.

First the depth of the bed was computed as the depth of the maximum backscatter. A sharp contrast in acoustic impedance at the sediment/water interface defines the bed as the strongest acoustic scatterer of a given beam. The depth of the strongest backscatter usually denotes the depth of the seabed. This depth was corrected for the height of the tide during the survey and the depth of the transducer under the boat in order to provide bathymetric data along the survey lines. Second, the value of the maximum backscatter, i.e. the backscatter intensity on the seabed, was recorded. Backscatter intensity from side-scan sonar data has been shown to be related to the mean size of bottom sediments on the phi scale. Although sediment size was not assessed in this study, bottom type was identified on the video images and therefore areas of sand and gravel were distinguished. A relationship was therefore sought between backscatter on the seabed and bottom type, especially in areas with little or no seagrass plants. Thirdly, the Seagrass Index was used to compute the depth of the seabed. The Seagrass Index was used to discriminate seagrass canopies from bare seabed, i.e. low SI corresponding to bare seabed and high SI indicating dense vegetation. In this study, height of the canopy was computed as the height above the bed where the backscatter intensity was greater than a threshold value. An adequate threshold value was found to be the ambient backscatter in the water column at a distance of 1.0–1.4 m from the transducer plus 60 to a backscatter threshold value of around 150 depending on the seabed in the water column (see lines “threshold value for CH” on Fig. 2). The last quantity calculated for each sweep was the “patchiness” (P). As the SIS swept the seabed perpendicularly to the boat track, it provided data on the lateral extent of the canopy. An attempt to measure the patchiness, defined here as the percentage of the seabed fully occupied by seagrass plants during a sweep, was computed as the percentage of beams in a sweep where the SI was superior to a threshold value (backscatter of 120). Calculation of the depth of the bed and SI were the same along a beam as for the 5 averaged beams, i.e. the depth of the bed was recorded as the depth of the maximum backscatter and SI was the average backscatter 10–15 cm above the bed. A P of 0 indicates that no seagrass was recorded on the whole sweep and a P of 1 indicates that a dense canopy was recorded on the whole sweep. As all the beams in a sweep were used to calculate P, full advantage was taken of the lateral extent of the seabed survey using the SIS. This parameter could not have been calculated using data from a single beam echosounder.

Parameter calculations and threshold values were found empirically by trial and error. Several heights of averaging and threshold values for SI and P parameters were tested against results from video data. Averaging the backscatter 10–15 cm above the bed was found to be the best method to detect presence of Zostera marina and is intuitively understandable considering that the top of the canopy is situated around that height. The threshold value used to calculate the height of the canopy was tested against SIS images and backscatter intensity along a beam, where the height of the canopy was clearly visible as a stronger backscatter above the bed (see Fig. 2).

2.5.3. Dataset alignment

Data points collected with the two instruments were not coincident; video observations were made every 2–4 m whereas SIS
data points were approximately every 4–10 m depending on boat speed. Furthermore, the video camera was around 23 m behind the SIS and 2 m on its port side. The two datasets had to be merged to enable comparison of parameter values. Data processing and analysis were done in Matlab® 7.6 and plotting with arcGIS® 9.2. First, co-ordinates were transformed from geographic to projected system and corrected from the layback of the video (around 25 m) and the SIS (2 m) to the GPS antenna. Thereafter, the values of the parameters calculated from the video were interpolated every metre (in order to achieve a regular grid and therefore the same number of video points around each SIS point) and averaged 5 m around each SIS data point. Averaging video parameters around SIS points reduces uncertainty due to variations in the height of the camera above the bed and the lateral difference between the location where the camera and SIS were recording the seabed, which could not be corrected. This averaging exercise was done in order to obtain coincident points from the SIS and video data and therefore be able to compare the 2 datasets; in the future however, it is not necessary if the aim of the survey is to assess seagrass presence and density without comparing datasets.

3. Results

3.1. Comparison of instruments

A total of 1007 sweeps, each composed of 75 beams, was recorded during the 3 h of the camera survey. In each sweep, the seabed was clearly recognisable by its strong backscatter (Fig. 3a). Where seagrass was present, a strong backscatter was observed above the bottom, which was weaker than the bottom return but stronger than ambient noise. Seagrass could be detected over the whole length of the sweep (Fig. 3b) or only parts of it where the seagrass bed was patchy (Fig. 3c).

The correspondence was good between Zostera Density (ZosD) calculated from the video data and patchiness (P) computed from the SIS data (Fig. 4a, \( R^2 = 0.61, n = 1007, p < 0.001 \)). The correlation was not as strong between Seagrass Index and ZosD (Fig. 4b, \( R^2 = 0.44, n = 1007, p < 0.001 \)). In order to compare the 2 datasets SI and P were scaled to the video data values. Most of the points with an SI inferior to 85 or P inferior to 0.05 had low ZosD values (on average 0.4 and 0.3 respectively), indicating that no seagrass or only a few shoots were observed on the video for such points and these can be assigned a value of 0. Points with SI greater than 180 or P greater than 0.85 had high ZosD values (on average 3.4 and 3.1 respectively) indicating that the seagrass canopy was seen on the video and that these points could be attributed a value of 4. Based on the above, SI and P were scaled as followed:

\[
SI_b = \frac{(SI - 85)}{(180 - 85)} \times 4
\]

\[
P_b = \frac{(P - 0.05)}{(0.85 - 0.05)} \times 4
\]

In doing so, SI_b and P_b have the same range as ZosD, and the values of SI_b and P_b of a given point can be interpreted following the description of ZosD as summarised in Table 1, i.e. SI_b or P_b of 0 shows an area with no or very little seagrass, whereas SI_b or P_b greater than 3 can be classified as a dense canopy (see Fig. 2). The correlation coefficients between SIS data (\( P_b \) and SI_b) and video data (ZosD) remained the same after scaling (Fig. 4c and d).
Along the survey lines, there was general agreement between the video and SIS evaluations of seagrass density; $P_s$, $S_I$, and $ZosD$ showed the same trends and intensity ranges (Fig. 5a and b). Only at some locations, e.g. around 4500 m along the line, $P_s$ predicted a canopy less dense than $ZosD$. $S_I$ showed similar trends to $ZosD$ and $P_s$ but had more along-line scatter. Seagrass canopy height ($CH$) was found to be between 0.1 and 0.2 m (Fig. 5c). The video system could not produce quantitative data for canopy height and so assessment of accuracy was not possible for this parameter. However, canopy height, which is dependant on current speed and seagrass density (Gambi et al., 1990), was observed during dives and found to be between 0.15 and 0.3 m. It thus appears that $CH$ calculated from the SIS data was a good approximation of the measured height of the canopy.

The algae abundance parameter ($AlgI$) did not correlate with seagrass density evaluated from the SIS data, $P_s$ or $S_I$ ($R^2 = 0.03$ and $p < 0.001$ for both parameters). Furthermore, when $AlgI$ was greater than 1.5 and $ZosD$ was 0, i.e. significant quantities of algae seen on the video but no seagrass, both the scaled patchiness ($P_s$) and Seagrass Index ($S_I$) had values below 0.5, i.e. no seagrass or only few shoots were present (Fig. 5d). This suggested that $S_I$ and $P_s$ were not influenced by algae presence.

**Fig. 3.** Examples of SIS sweeps over a. bare seabed; b. continuous seagrass canopy; c. patchy seagrass. Distance along the x-axis refers to the horizontal distance along the sweep. The strongest backscatter denotes the seabed. A backscatter higher than ambient noise above the bed indicates the presence of seagrass. The seabed is seen to be undulating due to boat movements with waves. The horizontal distance covered by the sweep is a function of seabed depth, hence the difference in the extent of seabed (in red) and water column (in blue) seen on each sweep (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 4.** The relationship between seagrass coverage estimated from the video ($ZosD$) and from the SIS data: a. $P$ ($R^2 = 0.61$); b. $S_I$ ($R^2 = 0.44$); c. $P$ scaled with equation (2) ($R^2 = 0.61$); d. $S_I$ scaled with equation (1) ($R^2 = 0.44$). On all graphs the regression line associated with $R^2$ is shown; each graph contains 1007 points and $p$-values were always $<0.001$. 

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Seabed backscatter did not show the same along-line variations as bottom type assessed from the video, BoTyp (Fig. 5e and f). Furthermore, backscatter on the seabed exhibited strong point to point variations. Acoustic attenuance is affected, amongst others, by sound travel distance, turbidity in the water column and presence of submerged vegetation (Katsnelson and Petnikov, 2001). Results indicated that backscatter on the seabed was weakly correlated with depth during the survey ($R^2 = 0.3$) and that it was not correlated with average water column backscatter ($R^2 = 0.06$) or Zostera Density ($R^2 = 0.01$). A relationship was sought between bottom type and bed backscatter in areas with no or little seagrass ($ZosD < 1$) by averaging the bed backscatter for each bottom type (Fig. 6). The average backscatter on the seabed was found to be the lowest on sandy bottom (179), intermediate on mixed sand and gravel (190) and highest on areas of gravel (198). However, the standard deviations of each distribution (20, 21 and 23 respectively), were higher than the difference in average values therefore reflecting the high variability of the backscatter on the seabed. As the scatter in the bed backscatter data was very high, this parameter could not be used to determine bottom type, even in areas with little or no seagrass.

3.2. Description of the survey area and seagrass distribution

The combination of direct measurements by beach and diver surveys and remote sensing with SIS and video systems produced a valuable dataset with which to map the survey area. The video and SIS systems offered the opportunity to rapidly classify a large portion of seabed whereas direct measurements, although time-consuming, provided shoot densities and leaf length measurements unavailable with remotely acquired data. The maximum average shoot density encountered was 150 shoots m$^{-2}$. However, individual shoot densities in a quadrat were often higher, reaching a maximum of 500 shoots m$^{-2}$. Seagrass was rarely encountered as a dense continuous meadow and more frequently as small (decimetres) patches with locally high densities. Maximum leaf length varied from 20 to 90 cm with an average of 33 cm (average standard deviation 18 cm).

The only seagrass species recognised on the video was Zostera marina. Densities varied from very sparse (a few shoots seen during the 2–3 s assessed) to a dense meadow (only a dense Z. marina canopy seen on the image). Frequently, algae (Enteromorpha spp, Ulva lactuca, Halurus flosculosus, and Ceramium spp.) and epiphytes
were also seen. The sediment varied from fine sand to mixed sand/ gravel and gravelly beds. Shells were often seen on the bottom although never formed an extensive mat. At some locations, small sand ripples were observed. These were aligned with the camera track, hence parallel to the shore. Ripple dimensions could not be precisely assessed due to the lack of a scale on the video image and the varying depth of the camera sledge above the bed. It was estimated that they had a wavelength of 5–10 cm and a height of about 1 cm.

Quantitative maps of the different parameters calculated using SIS and video data were produced from the GIS raster. The survey area was thereafter classified according to bottom type (BoTyp = 0.5, 1 < BoTyp < 1.5, 1.6 < BoTyp < 2.5 or BoTyp > 2.6), seagrass coverage (ZosD/Si/Li/Ps < 0.5, 0.6 < ZosD/Si/Li/Ps < 1.5, 1.6 < ZosD/Si/Li/Ps < 2.5 or ZosD/Si/Li/Ps > 2.6) and algae abundance (AlgI < 1.4 or AlgI > 1.5). Eight regions with distinct characteristics were recognised from this classification (Table 2 and Fig. 7). Around 4 ha of the survey area (Zone 1) were categorised as dense seagrass meadow with an average ZosD of 3.1 and Ps of 2.4. This zone also comprised the locations with the highest densities counted from the beach and diving surveys ranging from 110 to 145 shoots m–2. The average canopy height was 12 cm and the maximum leaf lengths from beach and diving surveys were between 40 and 80 cm. The difference between maximum leaf length and canopy height might be explained by the bending of the canopy (Fonseca et al., 1982) and variations in leaf length within the canopy, as during the surveys, only the maximum length was recorded. The edges of the seagrass meadow (Zone 2) were much patchier than Zone 1, with an average ZosD of 2.1 and Ps of 1.7. Beach and intertidal surveys showed densities in this zone between 80 and 110 shoots m–2 with a strong standard deviation over the quadrats measured at the same location (around 60 shoots m–2) also suggesting patchy beds. Around the patchy seagrass was an area of sparse seagrass (Zone 3) with an average ZosD of 1.2 and Ps of 0.9. The two direct measurements performed in this area recorded a shoot density of about 50 shoots m–2. An area with mixed sand and gravel (average BoTyp 1.7) without seagrass (average ZosD and Ps of 0.1) was found in the southern region of the survey area (Zone 4). In the middle of the mixed sand and gravel area was found an area characterised by abundant algae (Zone 5, average AlgI of 1.5) and no seagrass (average ZosD and Ps of 0.0) on a sandy bottom with some gravel (average BoTyp of 1.3). In the middle of a sandy intertidal flat was found an area with small sand ripples (average BoTyp of 0.5) and very few seagrass plants (Zone 6). Small portions of the survey area (11%) were characterised by bare sand (Zone 7, average BoTyp of 1.0). The most southerly part of the survey was characterised by bare gravel (Zone 8, average BoTyp of 2.7). No seagrass and very few algae were found in this area.

The classification of the survey area showed that the gravel zone was free of seagrass. Amongst the survey points recognised as seagrass (ZosD or Ps > 1), 98% had a BoTyp smaller than 1.5 indicating that Zostera marina in Calshot was found only on sand and was absent from gravel zones. Furthermore, Z. marina was found to prefer depths of between −1 and −0.5 m CD (80% of the distribution, Fig. 8) and was seldom found at depths below −1.5 m CD (3% of the distribution). Around 10% of the points recognised as Z. marina were situated between −0.5 and −0.93 mCD, which was the upper limit of the survey due to boat limitations. However, beach surveys and aerial photos indicated that Z. marina plants can be found on Calshot beach up to +1.5 m CD. In total, 35% of the points recognised as Z. marina were found within the lowest intertidal zone.

4. Discussion

The results indicate that it is possible to use SIS data to predict seagrass abundance and canopy height through Ps, Si and CH and that these parameters were not affected by the presence of algae. The SIS has therefore proved a reliable tool to detect seagrass, giving estimates of canopy height and density as well as measures of bathymetry. The video system provided continuous visual observation of the seabed and therefore was used to identify seagrass and algae species and abundance and to assess bottom type. Agreement between the 2 instruments was very good; seagrass density evaluated from the video was better correlated with the parameter initially calculated to measure patchiness Ps than to the one specifically used for seagrass detection Si (R2 of 0.61 and 0.44

### Table 2

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<th>2</th>
<th>3</th>
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<td>Sparse seagrass</td>
<td>Sand/gravel</td>
<td>Algae</td>
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<td>0.01 ± 0.01</td>
<td>0.01 ± 0.01</td>
<td>0.01 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.05 ± 0.05</td>
</tr>
<tr>
<td>AlgI</td>
<td>0.3 ± 0.2</td>
<td>0.5 ± 0.2</td>
<td>0.5 ± 0.3</td>
<td>0.9 ± 0.3</td>
<td>1.5 ± 0.2</td>
<td>0.1 ± 0.1</td>
<td>0.3 ± 0.3</td>
<td>0.3 ± 0.3</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td>BoTyp</td>
<td>1.0 ± 0.0</td>
<td>1.0 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>1.7 ± 0.4</td>
<td>1.3 ± 0.2</td>
<td>0.5 ± 0.0</td>
<td>1.0 ± 0.1</td>
<td>2.7 ± 0.2</td>
<td>1.2 ± 0.6</td>
</tr>
<tr>
<td>Back</td>
<td>192 ± 7</td>
<td>186 ± 7</td>
<td>181 ± 8</td>
<td>189 ± 12</td>
<td>191 ± 15</td>
<td>183 ± 9</td>
<td>180 ± 11</td>
<td>197 ± 15</td>
<td>186 ± 11</td>
</tr>
</tbody>
</table>
Fig. 7. a. Location of the survey lines and the 8 zones defined in the text; b. interpolated bathymetry and scaled Seagrass Index (SI) along the survey lines; c. interpolated Zostera Density (ZosD) raster and algae abundance (AlgI) values along the lines; d. interpolated Bottom type (BoTyp) raster and scaled patchiness ($P_s$) values along the lines. Refer to Table 1 for definitions of the parameter values. Aerial photos (2001, ortho-rectified) are courtesy of the Channel Coastal Observatory (www.channelcoast.org).
The patchiness in the sweep and hence covers 0.3–0.8 m of the seabed. In the present study, the bed was always found to consist of point seagrass (ZosD) or as a function of depth, as indicated by the relatively low shoot densities encountered in Calshot. However, if the maximum backscatter is found on the seagrass canopy, bathymetry, SI, CH, and P will be incorrectly calculated. This might happen in the case of high shoot densities, e.g. Zostera marina bed described by Cabello-Pasini et al. (2003) with densities of 1400 shoots m⁻²; other seagrass species might also create a stronger backscatter than those observed in our study and therefore the maximum backscatter might be found within the seagrass canopy rather than on the seabed. As this is the first time the SIS has been used to survey a seagrass canopy, it is not possible to determine the influence of seagrass species on backscatter at present, but care will have to be taken in further studies to ensure consistency of bed depth along a sweep.

The processing methodology used to calculate SI, P and CH from the SIS data was found empirically by trial and error. The threshold values and heights of averaging worked for the survey presented here, however, they will probably need to be changed for other surveys, depending on environmental conditions and seagrass species surveyed. For example, the height where the backscatter is averaged to calculate SI might have to be different in the case of a smaller seagrass species. Moreover, threshold values might need to be adjusted due to water turbidity.

Overall, seagrass densities calculated from the video (ZosD) and the SIS (P) had similar intensities. At some locations however, P had smaller values than ZosD. This discrepancy could have been caused by errors in estimating seagrass density either from the video or from the SIS data. Video interpretation is a time-consuming activity and clearly subject to interpreter bias (Crawford et al., 2001). Density evaluation could have been wrongly evaluated due to poor visibility (high turbidity in the water column) or variations in the height of the sledge above the bed revealing more or less of the seagrass bed and therefore affecting observer classification. The SIS acoustically detected the changes in seagrass densities. As the SIS does not incorporate a TVG, water depth variations during the survey might have had an influence on the backscatter intensity from the seagrass and led to inaccurate estimations of seagrass density. A weak correlation (R² = 0.35) was found between water depth during the survey and P greater than 1, i.e. points with a seagrass canopy. However, correcting for this relationship did not reduce the discrepancy sometimes observed between video and SIS data.

The abundance of benthic invertebrates is generally higher in a Zostera marina bed than in adjacent bare sand (Boström and Bonsdorff, 1997; Hirst and Attrill, 2008). Shelled benthic fauna has a higher density than the surrounding water and therefore produces a strong backscatter echo (Sauriau et al., 1998). Variations in backscatter intensity within a seagrass canopy could hence be related to invertebrate density. Epiphyte loading has potentially an influence on backscatter intensity in a seagrass bed. This effect has not been studied and has yet to be tested. Although shelled fauna may play a role in seagrass detection, the plants are thought to be acoustically identified mainly by their air-filled tissues (Sculthorpe, 1967) which produce a density contrast with seawater and create a strong acoustic echo (Sabol et al., 2002; Warren and Peterson, 2007). Variations in gas production may therefore also account for some of the differences encountered between video and SIS estimations of seagrass density. This effect also needs to be studied in more details.

Parameters calculated from acoustic data (SI and P) were related to seagrass densities and were not affected by the presence of algae. Algae lack vascular tissues and most of the species noted during the survey were very thin foliaceous or filamentous, thus
unlikely to produce as strong an acoustic return as the seagrass. Besides, SI was calculated by averaging the backscatter 10–15 cm above the bed, which was found to be the height of the highest backscatter on the seagrass. Most algae have smaller dimensions and should not produce a strong echo at this height. Algae might present a problem in mapping and identifying smaller seagrasses (e.g. Zostera noltii) which have the same dimensions as most algae observed in this area.

The survey presented here aimed to test the instruments' capabilities and assess the extent of the seagrass bed in Calshot. The spacing between survey lines was large (50–100 m) and therefore, parameter values were highly interpolated between the lines, especially compared to the interpolation between 2 consecutive points (separated by 4–10 m). This can result in incorrect spatial distribution of the parameters between the survey lines. In future surveys aimed at mapping seagrass beds, line spacing should be smaller (less than 50 m) in order to reduce errors which might arise from highly interpolated data. Despite the uncertainties due to the large interpolation applied, the dataset produced by the beach, diver and boat surveys was used to describe the Zostera marina bed in Calshot as some characteristics were little or not affected by interpolation.

The seagrass bed was characterised by small patches of seagrass in the lower intertidal area and a small area with a higher density canopy around the −1 m depth line. Seagrass densities (150 shoots m⁻²) were low compared to those reported in some locations e.g. 1400 shoots m⁻² in Baja California, Mexico (Cabello-Pasini et al., 2003) or in New Jersey, USA (Bologna, 2006) but related well to densities described in other locations e.g. 100 shoots m⁻² in Woods Hole, USA (Worcester, 1993) or between 60 and 500 shoots m⁻² in the Baltic Sea (Bostrom and Bonsdorff, 1997). Few Zostera beds have been described in the south coast of England. Tubbs and Tubbs (1983) summarised the spatial distribution of Zostera in the Solent. They described sublittoral beds of Zostera marina in the Solent occurring on relatively exposed shores on firm sand from about 1 m below to 1 m above CD; the beds are thus mostly permanently submerged, though the upper margins may be exposed at extreme low-water spring tides. Flowering stem densities varied from 25 to 75 shoots m⁻² and leaf length reached 30 cm. More recently, Hirst and Attrill (2008) described a Z. marina bed in Devon, on the south coast of England, which is exposed at extremely low water. The seagrass coverage was sparse in the intertidal zone, ranging from a few shoots to patches up to 1.6 m across, and more continuous into the subtidal zone. The Zostera bed mapped in Calshot, where the patchy, low density seagrass bed was exposed during extreme low water and a more continuous bed was found in the subtidal down to −1.5 m CD, therefore is in line with descriptions by previous authors in the same area (Tubbs and Tubbs, 1983; Hirst and Attrill, 2008). However, the only seagrass recognised in Calshot was Z. marina, unlike in Langstone Harbour where Zostera noltii and Z. marina occurred in homogeneously mixed patches (den Hartog, 1994).

5. Conclusion

The use of both a video camera sledge and a high-resolution profiling sonar during the survey allowed the evaluation of the SIS for seagrass detection and a preliminary mapping of the seagrass bed in Calshot. The advantages of the camera system were direct observations of the seabed, the possibility of flora identification and bottom type classification. However, data processing was time-consuming and subject to observer error. The SIS has proved to be a useful tool for seagrass surveying. An algorithm was developed and tested to analyse the data. The Seagrass Index (SI) was calculated as the average backscatter 10–15 cm above the bottom of 5 beams averaged in the middle of a sweep and the patchiness (P) as the percentage of beams in a sweep where the average backscatter 10–15 cm above the bottom were higher than a threshold value. It was possible to estimate seagrass abundance using SI and P. Furthermore, the SIS was used to estimate canopy height and accurately measure depth. On the other hand, the backscatter on the bottom showed too much scatter to be used for bottom type determination. The system needs to be tested with different seagrass species in order to assess the influence of seagrass morphology on SIS backscatter.

The combination of the two systems provided a valuable dataset with which to study a seagrass bed in Calshot, which was completed by direct measurements during beach and diver surveys. The survey area has been classified according to seagrass density, algae abundance and bottom type. Eight regions were distinguished, comprising areas of bare gravel, bare sand, rippled sand, mixed sand and gravel, sparse seagrass, patchy seagrass and dense seagrass meadow. Seagrass was found only on sandy bottom and at depth above −1.5 m CD. Around 35% of the seagrass was distributed in the lower intertidal zone where it formed small patches. 4 ha of the survey area were classified as dense meadow with average densities of 150 shoots m⁻² and reaching local maxima of 500 shoots m⁻².

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Appendix 3: Spectra (normalised power) estimated from seabed and canopy elevations using method 1.
Appendix 4: Profiles recorded in the straight recirculating flumes at a free-stream velocity of 10 cm s\(^{-1}\)

Run 1
Runs 3 (black) and 5 (blue)
 Runs 7 (black) and 9 (blue)