

HIGH-FREQUENCY ACOUSTICS OF MARINE VEGETATION – ROLE OF FREQUENCIES AND IMAGING ANGLES

Philippe Blondel^a, Aleksandra Kruss^b, Jaroslaw Tęgowski^c, Jennifer L. Wladichuk^d

^aUniversity of Bath; Bath, United Kingdom

^bISMAR; Venice, Italy

^cUniversity of Gdansk; Gdansk, Poland

^dJASCO Applied Sciences & University of Victoria; Victoria BC, Canada

Philippe Blondel, Department of Physics, University of Bath; Bath BA2 7AY, UK;

P.Blondel@bath.ac.uk

Abstract: *Marine vegetation is extremely varied and an essential component of shallow-water habitats. This paper will present two independent strands of work, using a variety of high-frequency acoustic sources to image macrophytes for different purposes. The first series of studies focuses on gas-filled kelp *Nereocystis luetkeana*, a seaweed ranging along the west coast of North America from California to Alaska, and is an important component of its diverse coastal ecosystems. As part of an investigation into grey whale habitats, we have measured propagation and attenuation through kelp beds of different densities, using broadband (1-20 kHz) white noise (Wladichuk, 2010, and other works). These field measurements in British Columbia (Canada) were compared with Monte Carlo simulations of sound propagation through kelp beds of increasing densities. The second series of measurements (started in Kruss et al., 2007 and continued through to Kruss et al., 2017) looked at gas-free macrophytes in shallow polar habitats; namely *Saccharina latissima* (L.) and *Laminaria digitata* (Huds.) in Svalbard fjords. These were mapped with traditional single-beam echo-sounders (such as the Biosonics DTX, 420 kHz) and with multibeam echo-sounders (such as the Imagenex 837 Delta-T, 260 kHz), investigating the ranges of angles at which macrophytes could be reliably mapped and what signal processing approaches were the most adapted. These two types of work are combined to show how they can be interpreted in the light of the seminal work done by Jean-Pierre Hermand on seagrass acoustics, for example Hermand et al. (2000) and Hermand (2004), and how his scientific legacy influences future efforts in acoustic mapping of marine vegetation.*

Keywords: *seagrass acoustics, *Nereocystis luetkeana*, *Laminaria digitata*, *Saccharina latissima*, acoustic propagation, single-beam echo-sounder (SBES), multibeam echo-sounder (MBES), acoustic emissions, Arctic fjords, temperate marine habitats*

1. RATIONALE

Macrophytes comprise all aquatic plants large enough to see with the naked eye, for example seaweed, algae and kelp. They rely on photosynthesis and can therefore be found at shallow depths all around the world, including coastal waters, estuaries, lakes and rivers. They are an important component of marine habitats, as they support biodiversity (including fish), stabilise bottom sediments and maintain coastal water quality and clarity. Some algae are also extensively used in the chemical, pharmaceutical and food industry. Kelps (*Laminariales*, *Phaeophyceae*) are the largest marine crop, with over 4 million tonnes harvested annually [1]. As a source of ecosystem services and natural capital, macrophytes are valued at \$19k ha⁻¹ yr⁻¹ [2], accounting for at least 11.4% of the worldwide value of all ecosystems. These environments are directly threatened by coastal development, growing human populations and climate change [3-5]. These variations are strongly affecting local food webs and ecosystems [6]. For example, eutrophication is the result of nutrient run-off (usually related to intensive agriculture) and can increase macrophyte concentration and biomass until marine life disappears. In waterways, it can make navigation difficult or more costly. Siltation (increased concentrations of very fine, loose sediment) is closely related to deforestation and soil erosion, and will instead decrease macrophyte concentration [6]. Destructive fishing practices (e.g. trawling) will physically affect the seabed and macrophyte-based habitats [7]. Fish stocks will be directly influenced by these processes. Macrophyte concentrations also act as physical security, buffering shores from waves and extreme weather [6,8]. This is best achieved with acoustic tools, analysing propagation through large bodies of macrophytes, interpreting echoes from the seabed and from any overlying vegetation [7,9].

2. SOUND GENERATION AND ACOUSTIC PROPAGATION IN KELP BEDS

The first study presented in this article formed part of a larger research effort, aimed at understanding the underwater soundscapes of British Columbia. This area corresponds to the summer feeding grounds of grey whales migrating along the western North American and Mexican shores, and an open research question was how they can use the different sources of noise as aids to navigation ([10,11]. Whale behaviours were compared with environmental and acoustic conditions along a 40-km stretch of coast, with open water, rocky and sandy shores and beaches. Kelp beds are important to grey whales, as they contain large quantities of mysid shrimps, their main food in the study area.

These kelp beds mainly consist of bull kelp, *Nereocystis luetkeana*. Individual kelp can grow to 36 m long, with a holdfast (foot) of approximately 40 cm and a single stipe (Fig. 1) Each stipe is topped with a mostly CO-filled pneumatocyst, from which sprout the numerous blades. In sufficiently shallow areas, the top of the stipe can lay at the sea surface at low tides (Fig. 1c). Kelp beds are often dense enough to form what are called “kelp forests” (Fig. 1d). Bull kelp is common along the Pacific Coast of North America, from Southern California to the Aleutian Islands and Alaska, and can form large “forests” (Fig. 1d).

Because of their rich biodiversity [12], in particular very high numbers of mysid shrimps, kelp beds might contribute acoustically to the soundscapes. Movements of the stipes with tides and currents, and their effects on waves at the surface, might also have an effect. This was tested by measuring broadband noise spectra with SQ26-07 hydrophones (Cetacean Research Technology) and digital recorders (sampling at 99.6 kHz and 44.1 kHz), using silent platforms (kayaks). Average frequency spectral levels were taken in kelp beds (of varying densities) and in open shallow water nearby, in similar oceanographic conditions (a few hours apart at most). Typical spectra (Fig.2, top) show that, in the absence of dominant sound

sources in the vicinity (e.g. surf noise), sound levels in kelp increase across all frequencies > 250 Hz, with a maximum of 2.9 dB above open-water background at 3.1 kHz. Repeat measurements over different kelp beds showed water depth only affected frequencies > 7 kHz. These contributions to the soundscape are rather small, of the order of a few dB; however due to the mid-frequency composition, have the ability to propagate well. Since grey whale vocalizations are also in the mid-frequency range (0.09-2 kHz) [22, 23], their auditory sensitivity is likely acute at these frequencies. Therefore, it is plausible that grey whales could use these acoustic “hotspots” produced by the kelp beds and their inhabitants for finding their food but a small increase in the ambient noise could mask this.

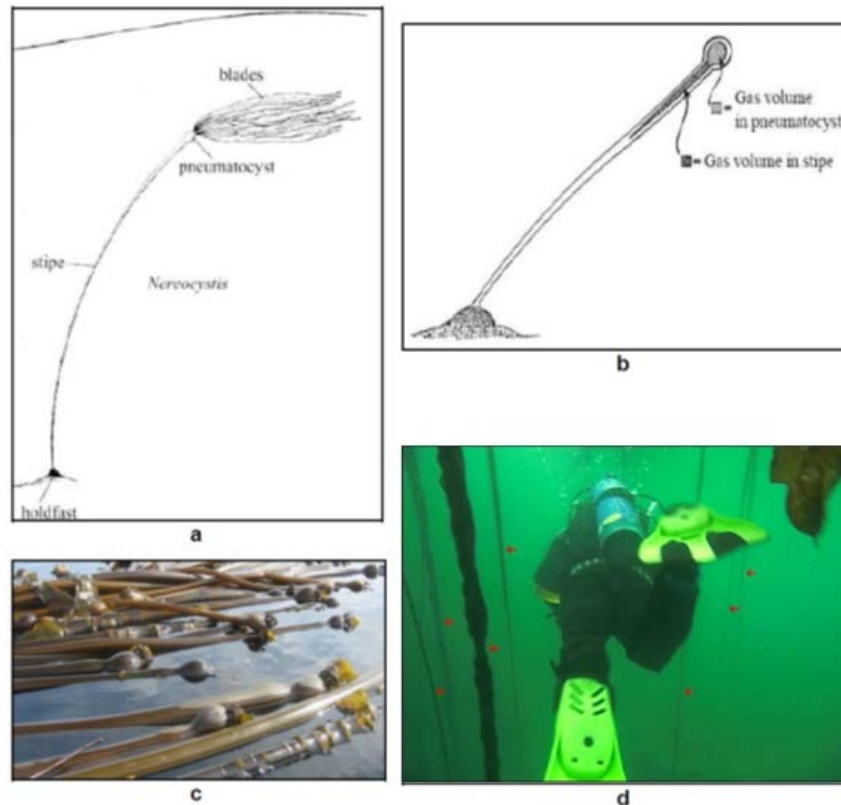


Fig.1: (a) general geometry of bull kelp; (b) distribution of gas in stipes; (c) and (d) field photographs of bull kelp at the sea surface and within a kelp bed. From [10].

As an example, Fig. 2 (inset) shows the relative variations measured as a ship passed behind the kelp bed. There is a 7-dB drop as the ship moves to the other side of the kelp bed and a further drop of 2.5 dB as it gets shielded by the denser part of the kelp bed. More systematic measurements were made, transmitting broadband noise (0.1 – 20 kHz) across kelp beds of different densities, at water depths of ca. 12 m, Fig.2 (bottom) shows the noise measured 1 m from the source, and averages over similar ranges through open water and kelp. The presence of kelp beds significantly reduces sound at nearly all frequencies (0-19 kHz), with higher transmission losses around 1.1, 2.3, 5.3 and 7.7 kHz [10,11]. Corrected for other effects (e.g. attenuation, spreading), broadband transmission losses were measured to vary between 0.4 and 1.2 dB/m, depending on kelp density (0.1 to 0.8 stipes/m² in the study area).

Kelp densities will vary with areas and they will show strong seasonal differences, increasing to up to 3.5 stipes/m² [12]. The individual arrangements of stipes will also affect sound propagation through kelp beds. We used Monte Carlo simulations of sound attenuation through different densities (0.1 – 10 stipes/m²), for frequencies of 0.01 to 20 kHz (at 10 Hz steps), over a 10 × 10-m grid (with a cell resolution of 1 cm). Individual stipes were modelled as cylinders, with sizes and physical properties based on previous field measurements [10], with kelp tissue (sound speed 604 m/s, attenuation coefficient 10⁻⁵ dB/m, density 1,077

kg/m³) surrounding a CO-O₂ gas mixture (sound speed 354 m/s, attenuations coefficient 52 – 1045 dB/m, density 1.145 kg/m³). These simulations confirmed field measurements and extended them to higher kelp densities, with a positive linear increase with plant density. The actual slopes vary with gas content in the stipes, ranging from 0.34 to 4.84 dB m.

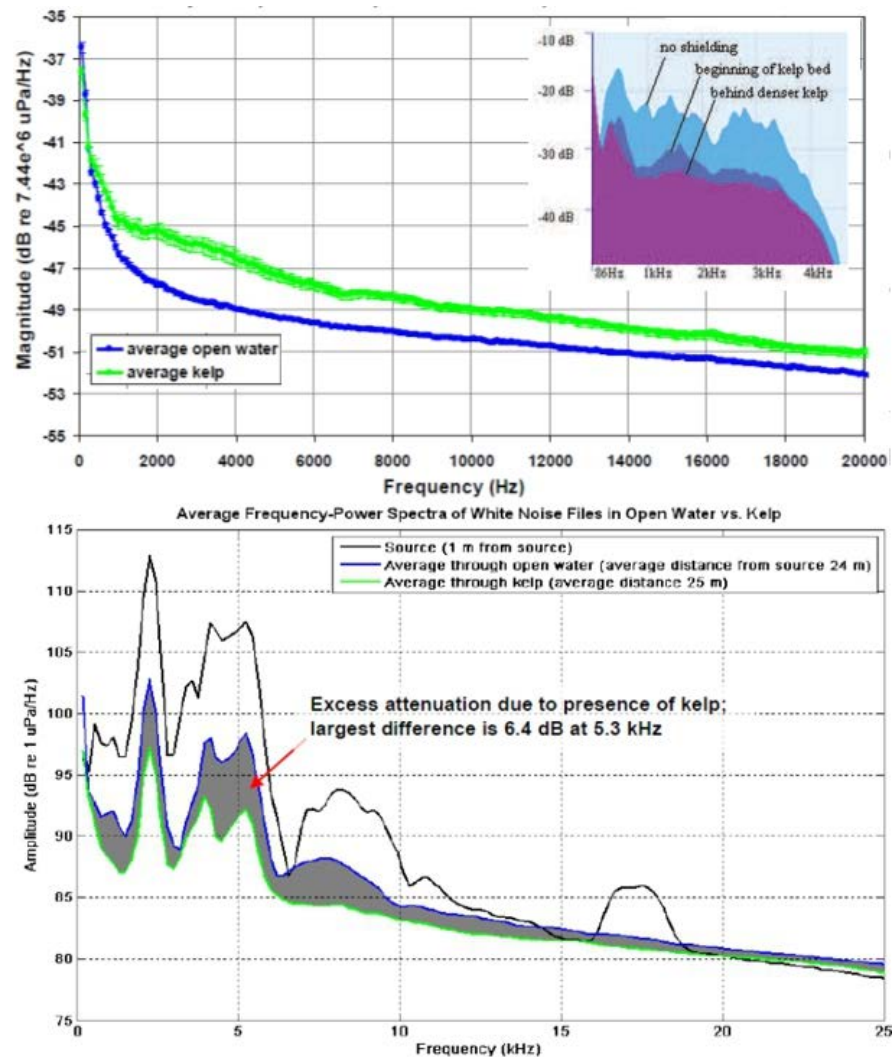


Fig.2: (top) broadband ambient noise measured in a typical kelp bed, and in open waters of similar depths and proximity to shore [10]; (inset) attenuation of ship noise through a kelp bed [13]; (bottom) systematic broadband attenuation through a typical kelp bed [10].

3. MULTI-ANGLE IMAGING OF MACROPHYTES

Climate change is at its most visible in the Arctic, and the results presented in this section form part of a larger research project, understanding how fjord habitats and ecosystems change with global warming. Macrophytes are important indicators of habitat health and glacier melting, and direct sampling [14,15] provides the most information, but it relies on previous knowledge of where the macrophytes are. Their large-scale extent is usually assessed from satellite or aerial imagery, if the water is clear enough, or using acoustics tools such as sidescan sonar [7,9]. These tools are good to map the areal extent of marine vegetation but cannot provide information on volumes or biomass. This is traditionally achieved using Single-Beam Echo-Sounders (SBES) [16], detecting both the seabed and the heights of the marine vegetation (or the top of the canopy if dense enough). Multi-Beam Echo-Sounders (MBES) extend this approach cross-track, and have proved very useful for

other studies [17], but their potential for marine vegetation had not been systematically compared until recently.

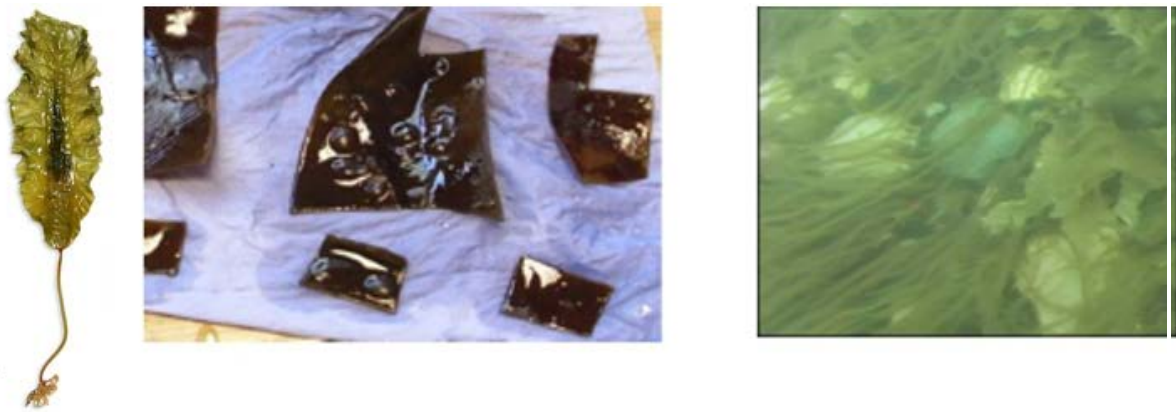


Fig.3: (left) full view of *Saccharina latissima*; (middle) samples measured in the laboratory; (right) shallow macrophytes in Svalbard. From [18].

Laminaria saccharina (Linnaeus) Lamouroux are very common macrophytes in Arctic fjords, at depths shallower than 20 m. They are also common in other parts of the world (www.habitas.org.uk/marinelife/species.asp?item=ZR6360), including temperate Europe, North America and other polar regions. *Laminaria* have thallus up to 4 m long, and they are attached to rocks by strong stipes (Fig.3). The blades are about 15 cm wide, “flat but wrinkly with wavy margins”. Conversely, *Laminaria digitata* is a seaweed common on North Atlantic shores, and it can grow up to 2-3 m (www.seaweed.ie/descriptions/Laminaria_digitata.php). Its stipe is flexible and oval in cross-section, up to 2.5 cm in diameter. The blade is laminate, large (up to 2.5 m) and palm-shaped. The large sizes of the macrophytes mean they can be mapped with different types of sonars (e.g. [16]) but the very thin blades, with little to no gas content, mean their acoustic response is likely to vary significantly with imaging angles.

MBES provide acoustic profiles with narrow beams, at angles from vertical to highly oblique. They cover more ground than SBES along-track, and less across-track (Fig. 4), with similar measurements of vegetation heights (Fig. 5). Depending on the MBES used, up to 30% of measurements in the centre beams can be affected by noise or lost, but this is corrected by averaging over several pings, taking advantage of the higher imaging rate. Our analyses show that MBES beams at angles $> 55.5^\circ$ from the vertical are noisy enough to be safely rejected before further analyses. Angles of 50.5° – 55.5° fared little better, with faint seabed traces and no indication of the presence (or not) of macrophytes. Between 15.5° – 30.5° , acoustic returns from macrophytes also seem to disappear. Theoretical simulations [18] showed this was mostly explained by the physical characteristics of the macrophytes present in the Arctic, thin and with no gas content and therefore very close acoustically to the surrounding seawater. On a positive note, though, angles less than 15.5° from the vertical, and between 30.5° and 50.5° , were extremely helpful in identifying macrophytes, their partial extent and their respective heights above the seabed. The Arctic results were corroborated with measurements in controlled conditions, using freshly collected samples of similar macrophytes and also looking at the role of gas vesicles in the acoustic returns [18]. The Arctic measurements (2007), the laboratory tank measurements (2011-2012) and the open-water measurements (2011) all used the same sonar, and found the same results. Another MBES, working at a higher frequency (i.e. higher resolution), confirmed the conclusions from the tank experiments, with slightly different angular ranges for the “dark zone” at which acoustic returns from macrophytes disappear.

In conclusion, the angles at which macrophytes can be detected with MBES extends further away ($\pm 15^\circ$) from the vertical than would be possible with SBES, and encompasses a further range of angles (30° – 50° from the vertical, on either side of the MBES), but there is a

“dark zone” between these angles, explained by the acoustic characteristics of the macrophytes, and data beyond 50° angles is not useful at all. Anecdotal evidence from other teams indicates this is a common observation.

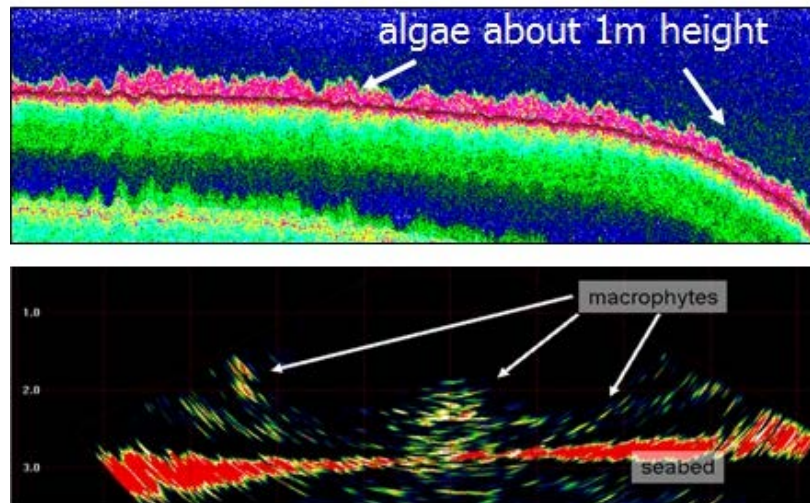


Fig.4: Typical views of along-track SBES measurements of macrophytes (top) and across-track MBES measurements over a wide range of angles (bottom). From [18].

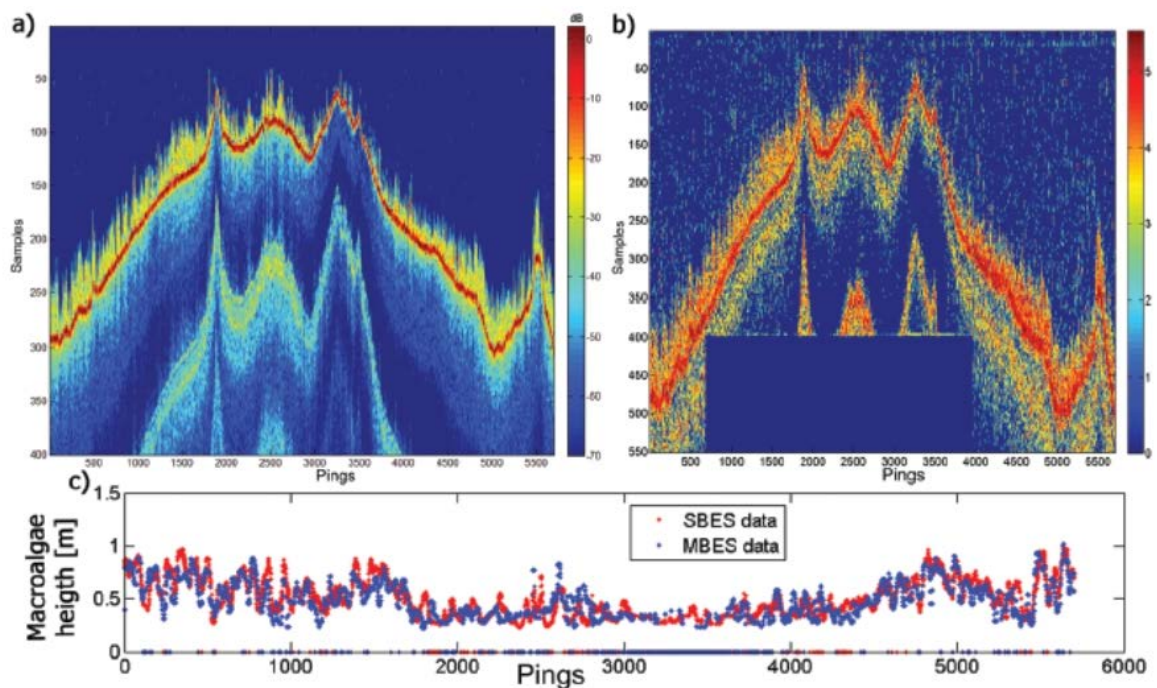


Fig.5: SBES (a) and central-beam MBES (b) measurements, with derived heights (c) [19].

4. CONCLUSIONS

Measurements and simulations of kelp beds (*Nereocystis luetkeana*) in British Columbia showed they were associated with acoustic emissions, relatively low above the open-water background (ca. 3 dB) but within the estimated hearing range of grey whales.. Sound attenuation (ca. 6 dB) strongly depends on kelp bed density and is frequency-dependent. The overarching study [10] concluded grey whales can use the different attenuation of natural sounds (surf noise, winds, waves) through kelp beds as an aid to underwater navigation. Any

temporal variability due to the presence of kelp is masked by these natural processes, in particular weather-related sounds.

Measurements and simulations of gas-free macrophytes (*Laminaria digitata* and *Saccharina latissima*), in Arctic fjords and in controlled experiments in laboratory and open water, showed how adequate processing of SBES and MBES measurements can provide useful measurements of vegetation heights, biovolumes and (for MBES) areal extents [19]. Cross-validation of SBES and MBES measurements show the latter are comparable within $\pm 15^\circ$ and $\pm (30^\circ - 50^\circ)$ from the vertical, with a “dark zone” between these angles, explained by the acoustic characteristics of the macrophytes, and data beyond 50° angles is not useful at all.

These field observations inscribe themselves within the scientific legacy of Jean-Pierre Hermand and his famous experiments on seagrass acoustics (e.g. [20,21]), which inspired many researchers. Broadband propagation (0.2 – 16 kHz) through meadows of *Posidonia oceanica* and individual plants showed frequency variations related to the physical make-up of each plant and gas circulation (in microbubbles and in plants) associated to photosynthesis. The modelling of multipath propagation over different ranges (50 – 1,500 m) also showed the importance of intermediate grazing angles [21]. As work on acoustic scattering by different types of marine vegetation progresses, it will be very important to see how these elements contribute to multi-path scattering, and for example assess whether the “dark zones” of MBES imaging can be filled up with multi-aspect sonars). Jean-Pierre’s work will continue to inspire scientists in the field, and in the laboratory, for many years to come.

5. ACKNOWLEDGEMENTS

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