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Sonar for environmental monitoring of marine renewable energy technologies

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Abstract

Human exploration of the world oceans is ever increasing as conventional industries grow and new industries emerge. A new emerging and fast-growing industry is the marine renewable energy. The last decades have been characterized by an accentuated development rate of technologies that can convert the energy contained in stream flows, waves, wind and tides. This growth benefits from the fact that society has become notably aware of the well-being of the environment we all live in. This brings a human desire to implement technologies which cope better with the natural environment. Yet, this environmental awareness may also pose difficulties in approving new renewable energy projects such as offshore wind, wave and tidal energy farms. Lessons that have been learned is that lack of consistent environmental data can become an impasse when consenting permits for testing and deployments marine renewable energy technologies. An example is the European Union in which a majority of the member states requires rigorous environmental monitoring programs to be in place when marine renewable energy technologies are commissioned and decommissioned. To satisfy such high demands and to simultaneously boost the marine renewable sector, long-term environmental monitoring framework that gathers multi-variable data are needed to keep providing data to technology developers, operators as well as to the general public. Technologies based on active acoustics might be the most advanced tools to monitor the subsea environment around marine manmade structures especially in murky and deep waters where divining and conventional technologies are both costly and risky.

The main objective of this PhD project is to develop and test active acoustic monitoring system for offshore renewable energy farms. This was done by integrating a multitude of appropriate monitoring sonar, hydrophones and cameras systems to be developed with standards suitable for subsea environmental monitoring. A first task was to identify, then secondly, acquire and test sonar systems. A platform was designed and built, a data acquisition device control systems were developed, and finally, additional instruments such as video cameras and sonars were added. Then a systems integration was followed by calibration of devices. The sonar systems were used for quantitative measurements of the occurrence of e.g. schools of fish near marine renewable energy converters. The sonar systems were also used for seabed inspections, depth measurements and cavitating flow observations.

So far, the combination of multibeam and dual-beam sonar systems produced good results of target detection, bottom inspection, depth measurements and

biomass estimation. The multibeam sonar system was capable of resolving isolated targets located near high acoustic retroreflective objects. Panoramic acoustic images of wave and instream energy converters were acquired using a multibeam sonar operating at frequencies near 1 GHz. The Dual-beam and split-beam sonar systems produced data referent to acoustic background intensity of targets that helps classifying targets according to its size, composition and 3-Dimensional location within the water column. During the next phase of this project, the platform will be deployed for longer periods in order to gather consistent acoustic and optical backscattering data of e.g. marine animal occurrence within marine renewable energy farms.

"Every morning, in Africa a Gazelle wakes up. It knows it must run faster than the fastest Lion, else will be a meet.
Every morning, a Lion wakes up. It knows that must outrun the slowest gazelle or will starve to an end.
It does not matter if You are a Lion or a Gazelle. When the sun comes up, you had better be running"

-- An African Proverb --

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Parwal, A., Remouit, F., Hong, Y., Francisco, F., Castellucci, V., Hai, L., Ulvgård, L., Li, W., Lejerskog, E., Baudoin, A., Nasir, M., Chatzigiannakou, M., Haikonen, K., Ekström, R., Boström, C., Göteman, M., Waters, R., Svensson, O., Sundberg, J., Rahm, M., Strömstedt, E., Engström, J., Savin, J., Leijon, M. (2015). Wave Energy Research at Uppsala University and The Lysekil Research Site, Sweden: A Status Update. Proceedings of the 11th European Wave and Tidal Energy Conference (EWTEC), Nantes, France, 6-11th Sept 2015.

II Francisco, F., Sundberg, J. (2015). Sonar for Environmental Monitoring. Initial Setup of an Active Acoustic Platform. The Twenty-fifth (2015) International Ocean and Polar Engineering Conference Kona, Big Island, Hawaii, USA, June 21-26, 2015. Kona, Big Island, Hawaii, USA, June 21-26, 2015.

III Francisco, F., Sundberg, J. (2015). Sonar for Environmental Monitoring: Understanding the Functionality of Active Acoustics as a Method for Monitoring Marine Renewable Energy Devices. Proceedings of the 11th European Wave and Tidal Energy Conference (EWTEC), Nantes, France, 6-11th Sept 2015.

IV Francisco, F., Sundberg, J. Sonar for environmental monitoring: Construction of a multifunctional active acoustic platform applied for marine renewables. (Submitted paper)

V Francisco, F., Carpman, N., Dolguntseva, I., Sundberg, J. Observation of cavitation-induced flow using multibeam and dual-beam sonar systems: A comparison of wake strength caused by propeller vs waterjet thrusted vessels. In a marine renewable energy perspective (Part-a). (Manuscript)

VI Francisco, F., Sundberg, J., Ekergård, B., Leijon, M. An estimation of wave energy flux and variability in the Ada Foa region: Towards commissioning of the first commercial wave power farm in Africa – Ghana. (Submitted paper)

Contents

Abbreviations and nomenclature

ADCP	Acoustic Doppler Current Profiler
DAQ	Data Acquisition and processing
DBS	Dual-beam Sonar
DEFRA	Environment, Food and Rural Affairs
ECMWF	European Centre for Medium-Range Weather Forecasts
EMEC	European Marine Energy Centre LTD
FLOWBEC-4D	FLOw, Water column and Benthic ECology 4-D
FORCE	Fundy Ocean Research Centre for Energy
FOV	Field of View
GSM	Global System for Mobile Communication
MBS	Multibeam Sonar
OWC	Oscillating Water Column
PV-SP	Photovoltaic Solar Panel
RADAR	RAdio Detection And Ranging
SBS	Split-beam Sonar
SONAR	Sound Navigation And Raging
SWAN	Simulating Waves Nearshore
TEC	Tidal Energy Converter
TVG	Time varied gain
UU	Uppsala University
VC	Video Camera
WEC	Wave Energy Converter

Symbol	**Unit**	**Entity**
ρ	Kgm^{-3}	Density
t	s	Time
x	m	Horizontal displacement
λ	m	Wave length
f	Hz	Linear frequency
ϕ	ms^{-1}	Phase speed
C	ms^{-1}	Speed of sound
Z	m	Depth
I	dB re 1 μPa	Intensity of Sound
k		Absorption coefficient
R	m	Radius of a sphere
TL	dB re 1 μPa	Transmission Loss
A	m	Amplitude of the sound wave
T	°C	Temperature
DI		Directive index
SL		Target source level
N		Noise
NL		Ambient Noise
TS		Target strength
v	ms^{-1}	Radial velocity
θ	π rad	polar angle
F_e	kW/m	Wave energy flux
H_{m0}	m	Significant wave height
T_{m0}	s	Wave mean period
Dir	° in geo-reference	Wave mean direction

1 Introduction

Energy conversion is vital for human development and maintaining acceptable societally standards. In this modern era, the demand for electricity is increasing. For example for the period between 1970s until now, the electricity consumption raised roughly from 9 to 14 MWh/capita in a well-developed country such as Sweden; From 0.1 to 0.45 MWh/capita in developing countries such as Mozambique, and from 0.1 to 4 MWh/capita in fast-emerging economies such as China [1]. This rise in consumption drastically increases the electricity generation in order of thousands of TWh, which exerts more pressure on the energy sources. The world's energy needs is largely met by fossil fuels which are finite, toxic and contribute to the greenhouse effect and changes in the Earth's climate. However, energy conversion systems based on fossil fuels are in matured stages and are cost efficient which makes them the most dependable source for electricity conversion. But to secure a global sustainable development on energy conversion systems based on today's fossil fuels, and other conventional sources such as nuclear and hydropower have to give more room to new and less mature technologies such as conversion systems based on renewable energy sources. Recent data [2] shows that the share of renewable energy sources in electricity production remains roughly the same in well developed countries and in fast growing economies, but it increases substantially in developing countries.

Although the modern society continues to increase electricity generation and consumption, substantial gains are also being taken in terms of energy efficiency. Moreover, human society has notably become aware of the well-being of environment that we live in. With that comes the human desire to implement technologies which are sustainable to the natural environment. However, this environmental awareness also poses difficulties to approve new renewable energy projects, being the offshore wave and tidal energy farms the most scrutinized.

By date, several ideas have been put in practice in order to harvest the energy contained in wind, waves, tides, and in stream flows. Although offshore-wind power is at an advanced stage of development, and already in a commercial phase, wave power has an enormous potential in terms of energy density and global availability. Tidal power also have high energy density but this resource is only available in regional to local scales comparing to offshore-wind and wave power [3]. In the last 20 years, great effort has been set into developing and commercializing wave and tidal power. Several concepts for wave power have been tested but few have succeeded to a pre-commercial phase. Examples of success are the Seabased Wave Power Technology, the Carnegie Wave Energy, among few others. The relative slow success rate on commercializing wave and tidal power, compared to offshore-wind, may mostly be related to the natural environment in which the technology operates, higher technology-development costs and reliability of materials. Thus, tremendous effort are being put by technology developers, researchers, environmentalists and police makers in order to accelerate the maturity of marine renewable energy sector.

From developing to the commercial stage, environmental monitoring is essential to a successful implementation of marine renewable energy technologies (MRETs). Lessons from the past has taught us that the lack of high-quality environmental data can become an obstruction when consenting permits for testing and deployments MRETs. For example within the European Union, the majority of the member states requires a rigorous environmental monitoring program to be in place when marine renewable energy technologies are commissioned and decommissioned. Thus, long-term environmental monitoring framework that gathers multi-variable data are needed to keep feeding data to technology developers, operators as well as to the general public. Modern environmental monitoring techniques have to evolve from the conventional ones which are limited by whether conditions, safety issues, and survivability. Until today, high operational costs and low reliability has contributed to uncertainty and lack of environmental data of the marine environment. The overall commissioning costs of MRETs projects can be brought down by adopting modern environmental monitoring frameworks. This is the vision shared by the present PhD project.

1.1 Environmental issues related to marine renewables

Any kind of human activity in the marine environment may cause disturbances to nature. With the ever increasing human activities and occupation of the oceans new technologies, such as offshore renewables introduce new stressors to the marine environment beyond our common knowledge. More information related to marine environment is being acquired from offshore wind power (e.g. [4]), as this subsector grows steadily fast. However, much less is known about other technologies such as wave and tidal-current power and their possible impacts on the marine environment.

Impacts of offshore marine renewable energy devices can be divided into phases such as the installation, operation and decommission of single devices or farms. Each phase has its characteristics impacts according to the type of energy converter, size of the project and local environmental conditions [4-5]. In general, the common impacts associated to an installation phase are: alteration of bottom habitats caused by foundations and submarine cables, suspension of sediments, loss of vegetation, disturbance on reef-forming benthos and macroalgae [6, 7, 8]. The water quality can be negatively affected by dispersion of fine-grained sediments resultant from drilling, dredging and cable trenching [6]. Underwater noise from deployment machinery also causes a great impact to the marine environment during installation phase, for example: pile driving can produce high amplitude impulsive sounds, in order of 240 dB re 1 μPa at 1 m from the source which is almost the double over the ambient noise [9, 10].

During the operation phase, several environmental interactions can occur. Probable effects include alteration of local and regional hydrodynamics, under water and aerial noise emissions, electromagnetic emission from submarine power-cables, collision between devices and marine organism, colonization and reef effect, leakage of fluids and contaminants, cumulative effects (combined effects of past, current and future human activities) among other unknowns [5-7].

The effects that may occur during decommissioning of marine renewable energy converters are likely similar to the installation phase. However, the marine environment may undergo greater impact caused by the removal of such devices. For example, after 15 or more years of colonization, marine organisms co-habituating within offshore renewable energy farms may lose their habitats, that may trigger other chains of environmental effects [7-12].

Cumulative and unidentified effects may be the largest uncertainties affecting a successful implementation of MRETs, especially with reference to wave and tidal power. The marine ecosystem is too complex and dynamic, prediction and forecasting of human-driven ecosystem changes and other environmental variations can occur at different space-time scales [7-12]. Continuous environmental monitoring practice is one of the manners to learn and improve offshore operations as well as the renewable energy converters and farms. There are several known techniques and technologies designed to monitor environmental variables and parameters focused on traditional activities such as marine transportation, oil and gas prospection, military, safety and rescue, marine-biology and oceanographic research, among others. However, marine renewable energy conversion is a new activity which needs new techniques and technologies for environmental monitoring. For example, sonar systems equipped with high resolution transducers with feature-extraction and target detection capabilities, are one of the technologies that can be used to monitor marine renewable energy farms, especially in murky and deep water conditions.

2 Scope of this research and specific objectives of this thesis

Marine renewable energy technologies may cause damages to the marine environment. Therefore, there is a need of better understanding on how these new technologies interact with nature. By date, several studies have utilized predictive models of collision risk between marine animals and MRETs, mainly tidal turbines [3, 13]. The common finding is that marine animals may change their behavior in response to the presence of such devices. However, many questions are still to be answered in respect to how MRETs can be further improved in order to cause even less negative effects to natural environment.

Technologies based on active acoustics have the potential to be one of the most advanced tools to monitor the subsea environment around marine renewable energy farms especially in murky and deep waters where divining and conventional technologies are costly [14, 16]. Thus, with the perspective to minimize the risks associated with subsea operations, this research project aims the following: (a) Develop an active acoustic monitoring system for offshore renewable energy farms (Fig. 1). By proposing standardized hardware and data acquisition and analysis tool for a continuous environmental monitoring and reporting. (b) Integrate commercial hardware brands of sonar and hydrophones to be developed with standards suitable for subsea environmental monitoring.

The following methodology is adopted (1) use sonar systems for quantitative measurements of the occurrence of larger marine animals and schools of fish within and around the farms; (2) integrate the sonar system with array of hydrophones used to measure underwater noise; (3) benchmarking studies, construction of control systems, data loggers, energy backup systems and robust sealing systems, followed by validation in real sea conditions.

Additional to the use of sonar for marine biological studies, this technology is also used for seabed inspections and depth measurements, which was the case of the two surveys in Ghana prior to the deployment of WECs (Paper-VI). Active acoustics is also used for measure turbulence within a water column as well as to inspect under water structures such as WECs, TECs, vessels, different types of foundations etc., (Papers - II - IV).

This thesis is part of the marine renewable energy projects undertaken by the Div. of Electricity, Dept. of Engineering Sciences – Uppsala University (UU). It complements other environmental studies carried out within this research group which used other environmental studies such as: study of underwater radiated noise characteristics and possible environmental effects of point absorbers wave energy converters (conducted by [10]); study of colonization patterns and habitat dynamics related to operation of the Lysekil Wave Power Research Site (conducted by [8]); study of buoy and generator interactions of the Lysekil Wave Power Project (conducted by [16]). It also contributes to the operation, installation and maintenance of the wave energy conversion systems, an area that so far have been done by sub contracted divers.

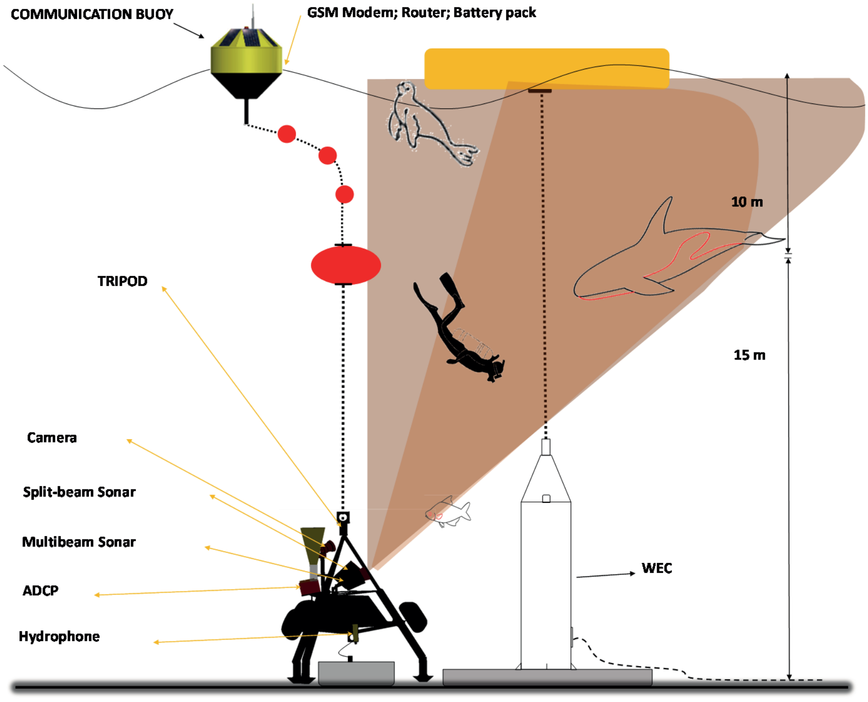

Figure 1. An example of an environmental monitoring platform applied for marine renewable energy technologies. It comprises a tripod anchored to the seabed near an MRET, and a communication buoy. The DBS may be pointing upward and tilted enough so that the acoustic beam covers MRETs. The MBS will be near horizontally aligned but tilted upward enough to cover wider area targeting as many ORETs as possible. However, other configurations are applicable. [14, 15]

3 Theory

The research work narrated in the present thesis is specially focused on sonar systems. Sonar operate by the mean of underwater radiated active acoustic energy. This chapter outlines the general theory of active acoustics and sonar systems.

3.1 Sonar systems

The term SONAR stands for Sound Navigation And Raging. Technically a sonar is an echo-ranging technology that uses sound energy to locate and survey objects within a water column. A target can be living organisms, biomass, sediments, vessels etc., [17]. The sonar technology was also used in air before the use of RADAR (RAdio Detection And Ranging) and is still being used today for robotic navigation and atmospheric studies. Sonar can be used in several frequencies, depending on the objective of the survey. They can be used to perform civil or military tasks. Military sonar uses almost the whole sound diapason while the civil sonar uses mostly medium and higher frequencies [18]. The very low acoustic frequencies used by sonar are classified as infrasonic, and the extremely higher acoustic frequencies are classified as ultrasonic.

Sonar systems are also divided in passive or active types. The passive sonar basically listen for incoming sounds emitted from any specific object or background. Active sonar emits pulses of sound and listens for echoes. A typical sonar systems comprises a transducer, a set of electronics that control the excitation of the transducer, and a display unit (Fig 1). A transducer convert acoustic energy through controlled conditions into electric signals. The display unit deliver an echogram for an echo-sounder, or an acoustic image for a multibeam or side-scan sonar. A typical echogram consists of a series of echo records in which each record represents the real time receiver output signal, visually encoded by intensity or color [14]. An acoustic image consists of several echo records resulting from multiple beams that are spatially distinct, and the echo magnitude on each beam is generally encoded by intensity or color as in an echogram [19].

3.2 Underwater sound propagation

To better understand the sonar technology, it is important to first understand the sound-carrying medium, water, and the physical processes behind the sound propagation. Thus, the efficiency and classification of sonar systems depends on variables such as the geophysical environment, the receiving and transmitting equipment and the background noise.

The basic principle of sound propagation is fairly simple. Sound is a propagation of a mechanical disturbance in a medium, a wave [17]. This wave is associated with fluctuations on pressure and density brought by particle motions, and is related to medium distortion. For a small amplitude mechanical waves, including sound, the equation of motion, continuity and state may be combined into one partial differential equation known as the wave equation (Equation 1), as follow:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \qquad \text{Eq. 1}$$

Equation 1 has a solution in the form of:

$$p(x,t) = p_0 \sin(\frac{2\pi}{\lambda} - 2\pi f t + \phi) \qquad \text{Eq. 2}$$

Where $p = p(x_1, x_2, x_3, t)$ is the excess of pressure, $c = c(x_1, x_2, x_3)$ is the speed of sound, p_0 is the amplitude of the pressure disturbance, λ is the wavelength, f is the frequency, and ϕ is the phase speed.

The speed of sound in oceans is a function of temperature, salinity and pressure [20, 21]). The following empirical formula (Equation 3) gives the speed of sound in ms^{-1}:

$$\begin{aligned} c = 1448.96 + 4.591\, t - 0.05304\, t^2 + 0.0002374 t^3 \\ + 0.0160\, Z \\ + (1.340 - 0{,}01025)(S - 35) + 1.675 \\ \times 10^{-7} + Z - 7.139 \times 10^{-13} t\, Z^3 \end{aligned} \qquad \text{Eq. 3}$$

Here *c* is the speed of sound in [ms^{-1}], *t* is the water temperature in [Celsius], *S* is the salinity, and *Z* is the depth in [m]. This equation has an accuracy of about 0.1 ms^{-1} [20, 21].

The speed of sound *c* in water is in the interval between 1450 ms^{-1} and 1550 ms^{-1} [20]. Using the formula on the Equation 3, it is possible to calculate the sensitivity of *c* to changes of temperature, salinity and depth within values typical to the ocean, and the results are: 40 ms^{-1} per 10°C of temperature, 1.5 ms^{-1} per 1 increase in salinity, and 16 ms^{-1} per 1000 m increase in depth [20]. The conclusion is that the primary causes of variability of the speed of sound in seawater are temperature and depth. Thus, as the variation of salinity is small, it does not have considerable influence in the speed of sound.

3.2.1 Intensity of Sound

Sound propagation is associated with an acoustic energy which is composed by part kinetic and part potential energy. The kinetic part corresponds to the particle motion, and the potential part corresponds to the work done by elastic pressure forces. The intensity of the sound propagation, or acoustic intensity is the energy flux mean value per unit of surface and time [22]. For a plane wave, the acoustic power is given in Watts per square meter, by the Equation 4:

$$I = \frac{p_0^2}{2\rho c} = \frac{p_{rms}^2}{\rho c} \quad \text{Eq. 4}$$

3.2.2 Acoustic Absorption

The main cause of acoustic absorption in water is viscosity, ionic relaxation of baric acid and magnesium sulfate [23] and loses at the fluid boundaries, surface (bubbles and ice) and bottom (sediments).

The acoustic absorption per unit distance *x* depends on the intensity *I* of the sound, as described on the Equation 5:

$$dI = -\mathrm{k} I_0 \, dx \quad \text{Eq. 5}$$

Where I_0 is the intensity before absorption and *k* is the absorption coefficient which depends on the frequency of the sound. The solution of the Equation 6 is in the following form:

$$I = I_0 \exp(-kx) \quad \text{Eq. 6}$$

Values of *k* in decibels (dB) per kilometer are: 0.08 dB/km at 1000 Hz, 50 dB/km at 100.000 Hz [20]. A decibel is obtained as $dB = 10\log(I/I_0)$, where I_0 and *I* are the original acoustic power and acoustic power after absorption respectively. Low frequencies are much less attenuated than higher frequencies. For example, a signal of 1000 Hz travelling 1 km is attenuated by 1.8%, meaning that $I = 0.982I_0$, while at the same range, a 100.000 Hz is attenuated to $I = 10^{-5}I_0$.

3.2.3 Reflection and scattering of sound

Apart from isolated targets, the water surface and the sea bottom are both reflecting and scattering boundaries: *Surface* – for many reasons, the sea-air boundary layer is a perfect reflector, the impedance (the product of density and phase speed) contrast is very pronounced so that very little energy can cross this boundary. Sound waves reflected from the sea surface suffer a 180° phase change. In high frequencies, normally above 1 kHz, or when the sea is rough, part of the incident sound waves are scattered instead of reflected. In this case, the coefficient of reflection has a magnitude less than one. Close to the normal incidence, the coefficient of reflection is given by the Equation 7 following:

$$R = -e^{-2k^2h^2sin^2A} \qquad \text{Eq. 7}$$

Where A is the amplitude of the sound wave, and h is the root mean square of water wave height [24].

In addition to the frequency of the sound, waves and roughness of the sea surface, factors such as wind generated bubbles, living organisms, biomass and fish close to the surface, interfere on the reflection and scattering of the sound waves [25]. Bubbles are known to absorb and scatter part of the incident and scattered sound [26].

Seabed – the contrast of acoustic impedance between water and the sea bottom is much less that at the surface, although the process is more complex due to the dependence on types of bottom materials (such as clay, mud, rock, etc.), and depth of the layers. The *Biot* and *Buckingham* theory explain in details the propagation of sound in the bottom layers [27].

At a target – reflection of sound at a given target whose dimensions are larger than the incident sound wavelength, depends on its size and shape relative to that of the surrounding water. Simple equations can describe the reflection strength of various simple shapes of targets as a function of the incidence angle of the sound. The complex shapes can be approximated by combining the simple shapes [28].

3.2.4 Geometric spreading loss

When a front of acoustic wave propagates in a homogeneous medium, the amplitude of the wave decay with increase of the distance from the source, resulting that energy content at far offset is smaller than at near offset. The two main types of geometric spreading are the spherical and cylindrical. In both cases, losses due to spreading are expressed in *x* dB per doubling of distance from the source. The geometrical loss of an acoustic signal emitted by a sonar is independent of frequency and affects most of all scenarios of sound probation [28]. Under water, the acoustic wave expands as a spherical wave. The decrease in acoustic intensity between target (1) and target (2) is inversely proportional the radio of the sphere i.e.:

$$\frac{I_2}{I_1} = \left(\frac{R_1}{R_2}\right)^2 \qquad \text{Eq. 8}$$

Where R_i are the distances between the source and the targets.

For one way propagation, i.e. for a passive sonar (ex: hydrophone), the acoustic intensity decreases with range in inverse proportion to the surface of the sphere, i.e. $I \sim 1/R^2$. In a situation of a two way propagation, i.e. for an active sonar, the acoustic wave expands as a spherical wave to the reflector, the reflected filed expands as a spherical wave back to the receiver, then the two way loss becomes $I \sim 1/R^4$.

3.2.5 Transmission Loss

Transmission Loss (*TL*) is the parameter that compares the strength of intensity of the signal at a specific range from the source to the source intensity at reference unit distance ($R_{1m} = 1\ m$). Transmission loss can be expressed in dB (Equation 9). However, spherical spreading loss is mostly expressed as $TL = 20\log R$, with no reference in unit distance [28]. The transmission loss is in most cases the result of geometrical spread plus absorption. It means that each frequency will have a certain maximum range. Thus in the conception of a sonar systems, the frequency is a critical design parameter. For a passive sonar, the transmission loss is given by the Equation 11. For an active sonar, the transmission loss is given by undergoing loss on both outgoing and returning paths (Equation 10):

$$TL = 20\log\left(\frac{R}{R_{1m}}\right) \qquad \text{Eq. 9}$$

$$2TL = 40logR + 2kR \qquad \text{Eq. 10}$$

Where k is the absorption coefficient which is better explained by the *Model of Francois-Garrison*, and depends on the contribution of boric acid ($B(OH)_3$), magnesium sulphate ($Mg(SO)_4$) and pure water [28]. In a simplified form this coefficient can be written as a function of temperature:

$$k = (0.17 \times 10^{-3} f^{-})/(T + 18) \qquad \text{Eq. 11}$$

Where *T* is the temperature of the water and *f* is the frequency.

3.3 Sonar equations

As mentioned above, passive sonar systems depends on receiving a signal that is radiated by a source. The irradiated sound can be generated by a variety of targets such as propellers, hull flow, operating machinery, marine animals, waves, coastal processes, etc. The passive sonar equation must satisfy S - $N \geq DT$. This means that when a target radiates a signal of SL (Target Source Level), the sound intensity is reduced while in course to the receiver as result of a Transmission Loss (TL). The process of discriminating the noise (*N*) is referred as spatial processing gain, and is designated as the Receiving Directivity Index (DI). The DI provides the reduction in noise level obtained by the directional of the transducer array. Taking into account the self and ambient noise (NL), the passive sonar equation is givens as:

$$SL - TL - NL + DI \geq DT \qquad \text{Eq. 12}$$

An active sonar uses an acoustic transmitter and receiver (hydrophone). It generates a pulse (ping) which is transmitted towards a target and afterwards, the pulse or signal is reflected by the target and a receiver listens and records the reflected pulse (echo). When the transmitter and receiver are in the same place, it is designed as a monostatic operation. When the two are separated it is designated as a bistatic operation. Moreover, when more transmitters or/and receivers are used spatially separated, it is designed as a multistatic operation. As mentioned before, sonar system measures the distance to the target by measuring the round trip time of the pulse. But, to measure the bearing, the sonar may use several hydrophones to measure the relative time to each other in a process designated by beamforming. A beam-former may be used to concentrate the acoustic power into a beam, which may be swept to cover the desired search angles. In general, the transducer can be optimized to achieve maximum performance over the widest bandwidth, so that the efficiency of the overall system is optimized. As it is for the passive sonar, the active sonar also needs to satisfy the condition that the signal minus the noise must be equal or greater than the detection threshold. However, for an active sonar system, the equation depends upon the characteristics of the noise present at the receiver when the returning signal is detected. Thus, the ambient noise can be described as either isotropic or as a reverberation. Isotropic noise occurs when much noise power arrives one direction as for any other direction, and the reverberation noise occurs when the noise returns primarily from the same direction as the sonar signal path. The basic active sonar equation used when the sonar is operating in a noise-limited scenario (Equation 13).

$$SL - 2TL + TS - NL + DI \geq DT \qquad \text{Eq. 13}$$

Table 1 contains acoustic and sonar parameters that govern the underwater acoustics. These parameters are defined according to the equipment specifications, characteristic of the medium (water), and characteristics of a target [22-24, 29]. All parameters are levelled in decibels relative to the standard reference intensity of a 1 μPa of plane wave. A diagram illustrating an active acoustic system is given on Fig. 2.

Table 1. Summary of acoustic and sonar parameters. [22-24, 29]

Source Parameters	Symbol	Definition
Source Level	SL	10log10*(source intensity / reference intensity)
Source Directivity Index	Dis	10log10*(intensity of a directional source in the source-to-target direction / intensity of an Omni- directional source of equal power)
Medium Parameters		
Transmission Loss	TL	10log10*(signal intensity @ source / signal intensity @ target or receiver)
Noise Level	NL	10log10*(noise intensity / reference intensity)
Target Parameters		
Target Strength	TS	10log10*(echo intensity / incident intensity)
Receiver Parameters		
Received Level	RL	10log10*(received intensity / reference intensity)
Receiver Directivity Index	DIr	10log10*(intensity measured by an Omni-directional receiver / intensity of a directional receiver in the same isotropic sound field)
Detection Threshold (signal-to-noise ratio)	DT	10log10*(signal intensity / noise intensity) @ threshold

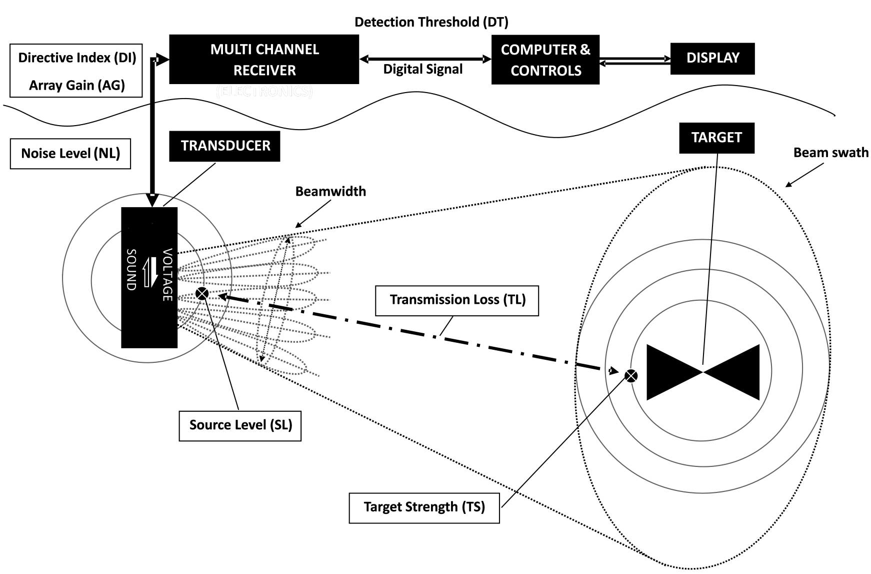

Figure 2. Working principle of an active sonar system.

3.4 Calibration of sonar systems

A precise correlation between pressure and voltage is very important in scientific applications of sonar. It means that a precise calibration must be established. For assessments of biological resources by backscattering, the correlation between pressure and voltage is normally established by standard-target method [30]. A set of sonar parameters such as transmitting signal type, amplitude, period, spectrum, and receiver characteristics the echo is correlated to the standard target. Measures of the echo such as intensity, amplitude, or energy content are correlated to the cross section of the backscattering of the standard target. If the backscattering cross section of the target is already known, by a primary calibration, a secondary calibration is required for secondary standards. By knowing the correlation between the backscattering and a standard target, similar processed echo signals from other targets may be expressed in physical scattering units.

4 Types of sonar systems used in this project

Among several existing sonar systems, this project opted to use multibeam sonar (MBS), dual beam sonar (DBS), and split beam (SBS) systems. This choice was made after carefully evaluating 19 different sonar systems among ca. 200 identified models of sonar/echo sounders.

4.1 The Multibeam sonar system (MBS)

In a MBS, acoustic energy is irradiated and received in multiple angles across-track swath, typically in a fan shape [31]. Transmitting and receiving elements (transducer and hydrophone respectively) are arranged in a 2-dimensiconal array. Generally each element transmits pulses individually in a crescent order, and the echo is received simultaneously by all receivers, however, each signal (echo) is processed separately enabling a number of echo-beams to be formed by combining the outputs of the several arrays of transducing elements with different phasing functions. This setup effectively steers the beam in several directions at the same time. Furthermore, these elements are arranged in a spiral configurations so that the beam pattern fill the field of view (FOV). Higher resolutions are even higher when the beams are aligned side by side in the same plane [32]. The number of beams can reach up to 1500 unities in angular sectors up to 180° of FOV. Modern MBS systems can operate in frequencies up to 3 MHz obtaining range resolution up to 1 cm and beam spacing of about 0.2°. The use of several narrow beams with a minimized transmit pulse (beam spacing) maximizes the effective sampling volume covered in the entire swath in a single ping (ping rates can reach 25 Hz).

The setbacks of multibeam imaging sonar systems are mainly the range which is limited to less than 100 m to no more than 10 m when the operating frequency is in order of MHz. Noise is another disadvantage of MBS systems. Background noise generated by seabed echoes affects the signal, mainly when the target is located at longer distance than the bottom depth [33]. Bubbles within the swath causes intense noise, mainly in sonar systems operating with very high frequencies. Data processing of a MBS sonar is complex and time consuming. Constant correction on pitch and roll are required, plus MBS systems which generates large volume of data. MBS systems are very useful for bathymetry data gathering, seabed mapping, fishery, underwater navigation, inspection of underwater structures, underwater surveillance etc.

4.2 The Dual beam sonar system (DBS)

In DSBs, the transducer is composed by two arrays of single frequencies elements, a narrow and a wide beam receiver. This configuration allows all the transducer elements to act equally in transmission producing a single narrower beam. However, the echo is received simultaneously by the two arrays of narrow and wide beams. The resulting effect is a coaxial beam pattern featuring a core beam within a relatively broad beam. The beam pattern can be pre-determinate by comparing the two output signals if a single target is detected [34]. This procedure allows the direct measurement of backscattering cross section by removing the beam pattern. DBS systems only make use of acoustic intensity

or amplitude, taking no account to the phase of the signal. Thus, among the three parameters of the spherical coordinate system (r, θ, φ), it can only determine two (r, θ) [34, 35].
Dual beam sonar systems operates with frequencies up to 1 MHz, with a beam width up to 60°. Apart from scientific use, this type of sonar are normally used on recreational sports fishing and navigation, where accurate signal processing protocols are not required. Therefore, DBS systems are easy to operate and are offered in affordable low prices.

4.3 The Split beam sonar system (SBS)

The transducer in a SBS is divided into four quadrants which transmit acoustic waves simultaneously, but receive the echoes independently, forming four beams arranged perpendicularly two by two. SBS system uses both amplitude and phase of the acoustic signal to determine the accurate target position in a $r, \theta, \emptyset$ spherical coordinates taking advantage of the interferometer technique that uses phase differences between adjacent quadrants [36]. This type of sonar can operate in frequencies up to 1 MHz. In coastal areas, the sonar ping rate can be set very high to provide multiple reflections from a single target and to facilitate tracking. Each target detection is passed to a fish-tracking-routine that combines successive pings in the same or adjoining range cells into a track of the fish path through the beam of the sonar [37, 38]. SBS systems are superior comparing to DBS systems mainly due to superior SGN (signal to noise ratio) figures and accurate target location. However, target identification and spatial resolution can be limited. SBS are normally the standard technology in industrial and scientific fisheries surveys [34].

5 The monitoring platform

The platform includes a set of sonar systems as sampling methods. In addition, it could include video camera and hydrophone arrays among other instruments. The main features of this platform are versatility and autonomy that allows it to be easily packed and transported to any surveying site of interest. This section describes how the multifunctional monitoring platform (Fig.1) is being built.

Acoustic instruments, as for marine remote sensing applied for hydrokinetic sites, are already being used by few entities within the marine renewable energy sector. For example [38, 39] used sonar systems to monitor fish and mammal interactions with tidal turbines and wave energy converters; [38] used multi-beam sonar systems to map seabed within hydrokinetic sites; The FORCE project in the Bay of Fundy is a good example which highlight the relevance of using active acoustic for environmental assessment surveys and continuous monitoring of hydrokinetic sites. In the FORCE project, the test site was monitored using multi-beam sonar (MBS), side scan sonar, and deep-towed seismic systems, among other acoustic water column and seabed profilers [40]. The European Marine Energy Centre LTD (EMEC) has recently deployed its own integrated monitoring platform which in many ways is similar to our proposed platform, but differs in a few crucial points such as size, wired communication among other features [41]. Apart from these two projects, there is another platform, the NERC/Defra collaboration

FLOw, Water column and Benthic ECology 4-D (FLOWBEC-4D), which is an upward looking sonar platform designed to monitor marine animals within a designated water column. It is self-contained, portable but with a very limited survey span.

5.1 The Mechanical design

The platform is divided into a submerged and a surface unity. The submerged unity includes a tripod and the surface unity includes a communication buoy. The tripod is anchored on the seabed and the communication buoy on the surface are linked by a mooring wire. The entire system in the platform is designed to be autonomous as well as remotely controlled. The platform also includes a portable mount system mostly used for surface surveys and calibration tests. The designing process of the tripod was a challenging part of this project. It evolved from an ideal, sophisticated concept shown in Fig. 3a to a more practical and realistic concept (Fig. 3b) which was easier to build, more robust and faster to assemble.

5.1.1 Tripod

The tripod is made of aluminum, it measures 1.7 m high, 1.8 m wide, and a maximum gross weight of 250 kg (Fig. 3b). The tripod comprised 1 MBS, 1 DBS, and presently 1 SBS, 2 video cameras, 1 on-board computer and a battery pack. Later the platform could integrate a hydrophone array, an ultra-high sensitive camera, an acoustic ADCP, among other instruments, depending on desired need.

The MBS is used to acquire acoustic images at near-field range up to 100 m. It operates with a frequency of 0.9 GHz, refresh rate of approximately 25 Hz. It has a total of 768 beams separated by 0.18° making a field of view: 130° H / 20° V, with a range resolution of 25 mm. The SBS and DBS are utilized to detect and track targets at longer range and provide a tri-dimensional information of the target position. The DBS has 2 beams operating at frequencies of 0.05/0.2 GHz, with a conic FOV of 29°/12° respectively. The SBS has a wide band operating frequency of 0.2 GHz, with 4 beams of 12° FOV.

The on-board computer controls all the devices, stores data and runs the sampling routines. The battery pack is made by a set of 130 Ah 12V deep cycle unities delivering a total of 6.2 kWh. It can uninterruptedly supply power for the entire system for long deployment periods, which can be extended if a well-balanced power-efficient-plan is put in place. In near future, this battery pack will be charged by a set of solar panels placed on the communication buoy.

In Table 2 are the technician specifications of a set of optical cameras in use in this platform. These cameras are initially designed for surveillance purposes. However, due to its favorable performance, they were modified to operate in underwater environments.

Table 2. Technical specifications of the main instruments in use on the UU monitoring platform.

Component	Specification
PC	Clock: 1.0 GHz RAM: 4GB DDR3 HDD: 2TB (storage memory) VGA: FULL HD 3D Input Voltage: 12 VDC
MBS	Frequency: 0.9 MHz (operational) Number of Beams: 768 fps:20Hz (sample frequency) FOV: 130x20 (field of view) Angular resolution: 0.18° Range resolution: 2.54 cm Maximum range: 100 m Input Voltage: 12-48 VDC Power consumption: 13 W
DBS	Frequency: 50/200 KHz (operational) Number of Beams: 2 FOV: 29/12 Maximum range: 762 m Input Voltage: 10-19 VDC
SBS	Frequency: 200 KHz (operational) Number of Beams: 4 FOV: wide-12 Maximum range: 550 m Input Voltage: 12-48 VDC
VC 1	FOV: Hemispherical (180°) Sensitivity: 0,05 lux Max. image resolution: 2048 x 1536 (3MP) Max frame rate: (M-JPEVGA: 22 fps Video stream: (MxPEG) 30 fps
VC 2	Lense: 2.8-8 mm / F1.2 FOV: 92°-32° Sensitivity: 0.04 lux Max. image resolution: 2592x1944 (5 MP) Max frame rate (M-JPEG): 30 fps Video stream (MxPEG): H.264

5.1.2 Portable mount system

This unity consists of a pole mount with an adjustable length of 1-5 m (Fig. 3c). The pole mount weights approximately 3 kg and is made of polyvinyl chloride reinforced with an aluminum stripe, attached to a thin baseplate. This system can be easily deployed from the surface (refer to Fig. 5, Paper IV).

5.1.3 Communication buoy

The buoy with measures of approximately 1 m of diameter, 1.7 m of height and weight of approximately 500 kg (the top structure in Fig. 3d). It will contain a set of solar panels, a modem, a router and a battery pack. This unity will establish the remote connection between the tripod and the users. Data stored on the computer located on the tripod, is transmitted to the buoy by a wire, and then uploaded to users via wireless connection. Solar panels attached to the communication buoy will charge the batteries located inside the buoy.

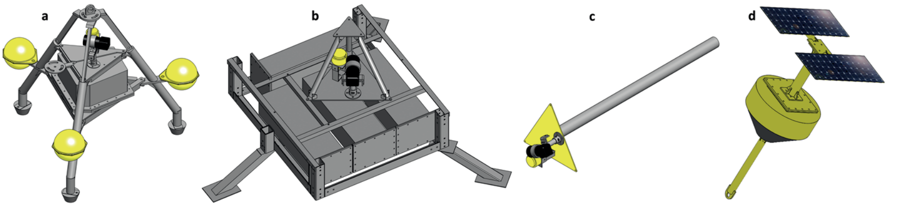

Figure 3. Computer rendering of the UU environmental monitoring platform. (a) The original design of the submerged unit comprising a sophisticated structure; (b) A redesigned concept of the submerged unit, aimed to save construction time and costs. This concept was converted into reality, and is shown in Fig. 5. (c) A portable pole mount; (d) A communication buoy.

Below (Fig. 4) are images taken during construction and deployment of the UU platform. Several real-sea-conditions tests have been conducted to tune the equipment and improve deployment procedures.

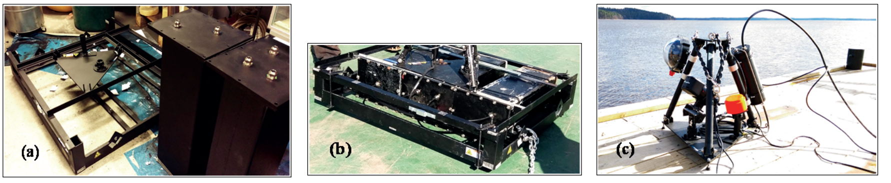

Figure 4. Constraction and deployment of the UU monitoring platform. (a) construction of the submerged unit comprasing a chassis, tripod and preassure-sealed compartments that supports batteries and controll-electronics. (b) already assembled bottom-part of a submerged unit that contains the control-electronics and a battery bank. (c) already assembled top-part of a submerged unit.

5.2 System-integration plan

The platform can be electrically divided into three sections: sensors, power supply and communication unity (Fig. 5). Each sensor is connected to a computer through a switch and/or controller. The controller works as a power trigger which tells when each sensor should turn on/off. The power supply section consists of a battery bank, inverters, and chargers. If a permanent power cable is present, the inverters will turn AC to DC power and feed the entire system. The communication section located on the buoy includes a router, wideband GSM antenna, batteries, photovoltaic solar panels (PV-SP), and a multipurpose plug. The battery bank - II supplies power to the router and antenna, and recharge the batteries located in the submerged unity. The PV-SP recharge the Battery Bank - II. The multipurpose plug contains power and data connectors that are meant to stablish a direct wire-link between the submerged unity and a user when maintenance is needed.

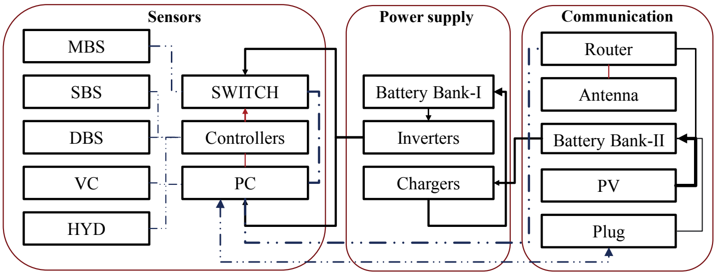

Figure 5. This diagram shows how the different sensors are linked to the power supply and communication systems. The dashed line represents the data link, the full line represents the power supply.

5.4 Deployment setup

The platform is made versatile allowing it to be easily deployed in several configurations as shown in Fig. 5, Paper IV. For surface surveys the platform can be deployed using a pole mount that can be attached to a vessel or fixed structure (configuration-A or configuration-B). For submerged surveys, the platform uses a tripod that can be either deployed temporary using an umbilical cord from a vessel or fixed structure (configuration-C or configuration-D) or it can be deployed to run autonomously for a longer period (configuration-E), which is the main idea of this project. More details on deployment techniques can be found in Paper IV.

5.3 A method for WEC detection and seabed inspection using pole mount system

Surface surveys were conducted using deployment configurations-A and B (Fig 5, Paper IV). The configuration-A employed vessels of the type recreational craft. Here, the outline-survey technique was the most used, spited in two stages (Fig. 6, Paper IV). In the first stage, the vessel quickly covered the overall site on widely spaced transects (scouting transects) to detect and locate targets. The vessel traveled at a steady speed ($\overleftarrow{V}_{vessel}$) of 9 kmh^{-1}. In the second stage, the vessel returned to each target locations, and performed an intensive and detailed survey at steady speeds of approximately 6 kmh^{-1}. The MBS and DBS systems were deployed in different drafts (*Ds*) that varied from *Ds* = 0.1 m to *Ds* = 4.0 m (Fig. 6, Paper IV). The MBS was deployed in three adjustable pitch angles (α_{MBS}) in respect to the water level (WL), these were $\alpha_{MBS} = 0°$, $\alpha_{MBS} = 45°$ and $\alpha_{MBS} = 90°$ respectively. The DBS (and SBS) transducer was always deployed with constant pitch angle of $\alpha_{DBS} = 90°$.

For bottom depth measurements, the algorithm shown in Equation 14 was used, assuming that the pitch and roll errors are small or self-corrected by the sonar's computer. The module of real depth (*Z*) can then be calculated taking in account the heavy, tide and draft of transducer as:

$$\boldsymbol{Z = z_{eco} \pm z_{heave} - z_{tide} + z_{draft}} \qquad \text{Eq. 14}$$

Where: z_{eco} is the depth value measured by the DBS, $z_{heave} = 2 \cdot std(z_{eco})$ is the wave height derivate by altimetry data measured by a GPS, and z_{tde} is the tide height at in synchrony with the *insitu* measurements and z_{draft} is the Sonar transducer draft.

5.4 A data acquisition and analysis tool

Construction of software that automatically control underwater measurement devices, remains a challenge. In this particular case, a simple-flowing protocol is needed to control, treat and analyze data form each measurement device. Each device samples in bursts of approximately 90-300 s, with intervals of 1800-7200 s. Data from each instrument is treated by its own algorithm and routine. Following, Fig. 6 shows an example describing how the MBS data is acquired, processed and analyzed.

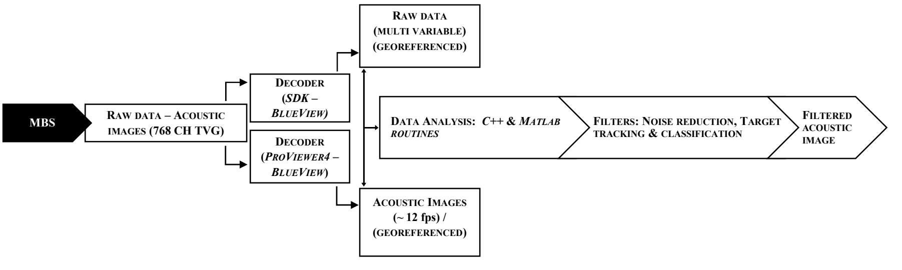

Figure 6. Overview of the data acquisition and processing (DAQ) architecture for detecting, tracking and classifying underwater targets of interest. The data is acquired by the sonar transducers, then pre-processed by sonar software. Algorithms (in developing phase) decode and further filter the acoustic signal. The MBS signal is quickly processed by the SDK/ProViwer software running on C++ programming environment. The acoustic images are then analyzed and filtered using the same software previously mentioned, and using other image analyzing tools such as Matlab - Image processing Toolbox.

6 Performance of the platform and possible use

Laboratory and field tests are being conducted as the platform is being developed. The nature of these tests involve system checks, familiarizations, calibrations and real measurements. This chapter describes how these tests were conducted and their results.

6.1 An actual status of research and dissemination of the Lysekil wave power project (PAPER I)

The Div. Electricity of UU, has been conducting research on electric conversion systems and technologies that can harvest wind, waves and hydrokinetic energy to convert it into useful electricity, electricity distribution and systems for energy storage. The Lysekil wave power research site has been operating since 2004, so far there were deployed ca. 12 WECs, 2 submarine substations, submarine power and communications cables, and ca. 30 dummy WECs for environmental studies among other measurement devices. In Paper I is a summary of research activities conducted within the wave power group in the period between 2013 and 2015. However, a summary of other research activities prior to 2015 can be found in [42, 43, 44].

By 2015, several experiments were conducted, from performance curves of direct-driven linear generators, control systems, measurements systems, communication, grid connection, planning a modelling of farms, underwater connections, survivability and reliability, to environmental monitoring studies. An example of a UU WEC performance curve is given in Fig. 22, Paper I, where experimental data was plotted against simulated data resultant from the delivered output voltage when a WEC was connected to a resistive load.

6.2 Initial test of MBS system (PAPERS II & III)

Several acoustic images were acquired in the first set of test using MBS system. These initial tests were conducted using the pole mount (Configurations A and B, Fig. 5. Paper IV), with the sonar head oriented under 0°, 45° and 90° pitch angles. For example Fig. 7 shows a dummy fish measuring 1.10 m. Here, the MBS acoustic images tool measured 1.11 m while the exact length measured using a tape measure is 1.10 m (Refer to Paper III). This test was conducted for calibration and familiarization of the MBS system as stand-alone unity.

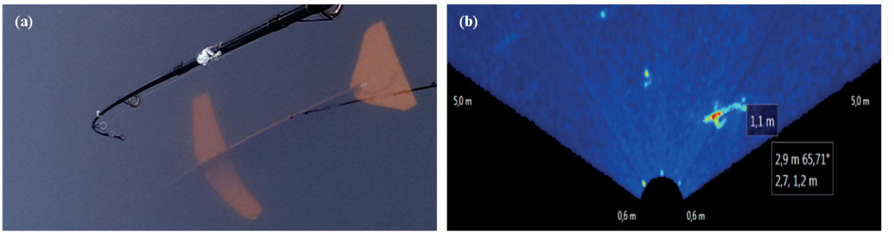

Figure 7. Cross comparison of target dimensions. (a) Optical image of a dummy fish of a dummy fish; (b) MBS acoustic image (generated by SDK 3.6 software) of the same dummy fish. (Refer to Paper-III)

6.3 Biomass estimation using DBS systems (PAPER III)

Before the purchase of the SBS unity, the DBS served as a consistent instrument to acquire amplitude echograms during all field tests. During initial phases, biomass was estimated using MBS, DBS systems and test fishing nets. These surveys served as mean to evaluate the sonar system capabilities of tracking fish according to its size and shape. Five nets were deployed longitudinally in parallel to the flow of the river Fyrisån, Flottsundborn, and river Dalälven by the Söderfors turbine location. As a sampling method, the test fishing nets were directly insonifyied (beamed) while they were loaded with fish. As a result, Fig. 8 show an amplitude echogram of fish trapped in the deployed test fishing nets. (Refer to Paper- III). So far, more calibration is needed to validate the SBS field data.

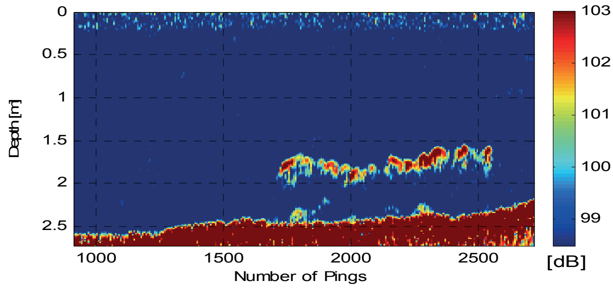

Figure 8. Fish trapped in a test fishing net. Each arc on this echogram represents a fish trapped on a net. This survey was conducted using deployment configuration-A with the vessel traveling at steady speed of 5.5 km/h. (Refer to Paper-III)

6.4 WEC detection using MBS (PAPERS II - IV)

The MBS performed well on detecting the UU WECs as well as the Söderfors Turbine. These power unities were surveyed in several occasions under different environmental conditions. For example, the object shown on Fig. 9a is a UU WEC sampled during fall 2014 using deployment configuration-A with the sonar head oriented with pitch angle of 45° and at a distance of approximately 18 m from the top of the WEC. Notable features found are that the seabed and the WEC's base plate foundation are the most reflective targets, while the cylindrical body of the WEC is less acoustic retroreflective. Likewise, Fig. 9b shows echo-image of the CP power unity acquired using the deployment configuration-B. The sonar head was attached to bridge pillar at pitch angel of 45 ° at a distance of 5 m form the top of the turbine. Using this deployment configuration resulted in echo-images in which the rocky riverbed acoustic retro-reflectivity surpasses by a large magnitude the turbine's echo.

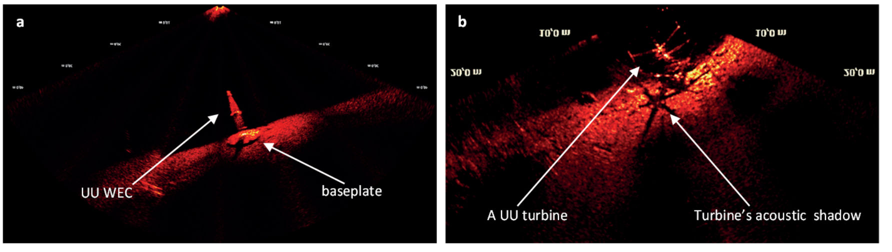

Figure 9. Acoustic image captured using a MBS system. (a) The environment surrounding a UU WEC deployed at depth of 25 m. The seabed and the WEC gravity foundation are the most reflective targets. The dark region represents the range limit of acoustic beams. (b) A Söderfors turbine. Given the narrow structure of the blades, most of the acoustic energy is scattered by the rocky seabed with a much higher acoustic reflectivity compared to the turbine structure. However, it is much easier to the human eye to see the turbine when the images are presented in multi-frame as a movie. (Refer to Paper – IV)

6.5 Structures and bottom inspection using MBS and DBS (PAPERS III & IV)

The DBS coupled with the MBS produced good bottom inspection results. Several surveys were conducted to measure depth and access the seabed conditions prior to deployment of WECs as well as pathway inspections for large deployment vessels that needed to dock in narrow and shallow harbors. An example of results from a seabed inspection is given in Fig. 10 referring to data gathered at the dock area of a wave power factory (Seabased Industry AB) in Lysekil. For this case, the test survey results can be presented in a form of bathymetric contours (Fig. 9c, Paper IV) derivate from eight transects depth measurements done in which one of them is shown in Fig. 10a. The bottom depth measured 5 m by the west side of the dock and decreases to less than 3 m towards the far (east) side of the dock where a barrier of rocks is located. The seabed in this pool is mainly flat with a south-north (transversal) inclination of approximately 2.3° and a longitudinal inclination of approximately 2° from the east edge to west aperture. The sonar system could detect few large stones and small wrecks of about 0.4 to 2.3 m^2 (Fig. 10b). The seabed appears to be made by thin layer of soft substrate which would be lying under a hard bottom layer which is the general characteristics of the seabed on that region. The MBS performed well on inspecting submerged structures such as bridge pillars, hull of vessels and the energy converters.

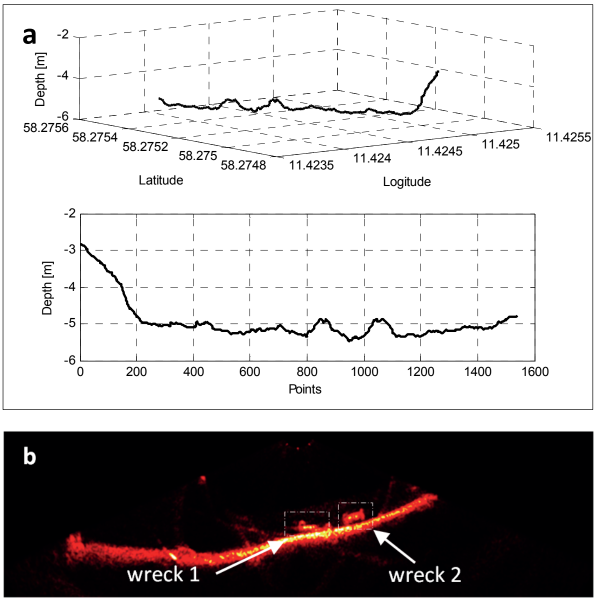

Figure 10. Seabed inspection of the area by the dock of Seabased Industry AB in Lysekil. (a) Measured Depth [m] displayed in form of spatial contours. (b) Overview of the seabed through an imaging MBS system, here wrecks were detected lying on the bottom. Wreck 1 measured approximately 0.7 x 0.6 m, wreck 2 - 0.8 x 0.5 m, and wreck 3 – 1.5 x 1.5 m, the dock wall is made of steel with in a c-shape.

6.6 Wake measurements using MBS and DBS systems (PAPER V)

There is a possibility of using areas with high energy potential and located in heavy boat traffic to deploy instream energy converters. This study was conducted to access the depth range of cavitating flow that is produced by transiting boats in narrow channels. The study regions was the vicinity of Finnham Island – Stockholm archipelago. The objective of the survey was to measure the depth of the cavitating flow produced by boat with propellers and waterjet thrusters that frequently transit that area, and investigate if the turbulence caused by the wake would be deep enough to disturb the water column unearth the surface. The hypothesis is that strong and deep cavitating flows (turbulence or wake) can disturb the optimal operation of an inflow energy converter, therefore causing damages to its rotors or hydrofoils. The results from observations and measurements (Fig. 11) showed that a boat with propeller thruster has a wide and intense cavitating flow that reached 12 m of depth, and lasted approximately 90 s. On the other hand, a boat with waterjet thruster produced a narrower and less intense cavitating flow with the same duration as the propeller and reaching depths of approximately 10 m. The average bottom depth of this particular site varied from 12 to 33 m. From this study, it was concluded that boats with propellers produce stronger cavitating flows compared to boats with waterjet thrusters, at least when referring to mid-size passenger ferry of a carrying capacity of about 350 people.

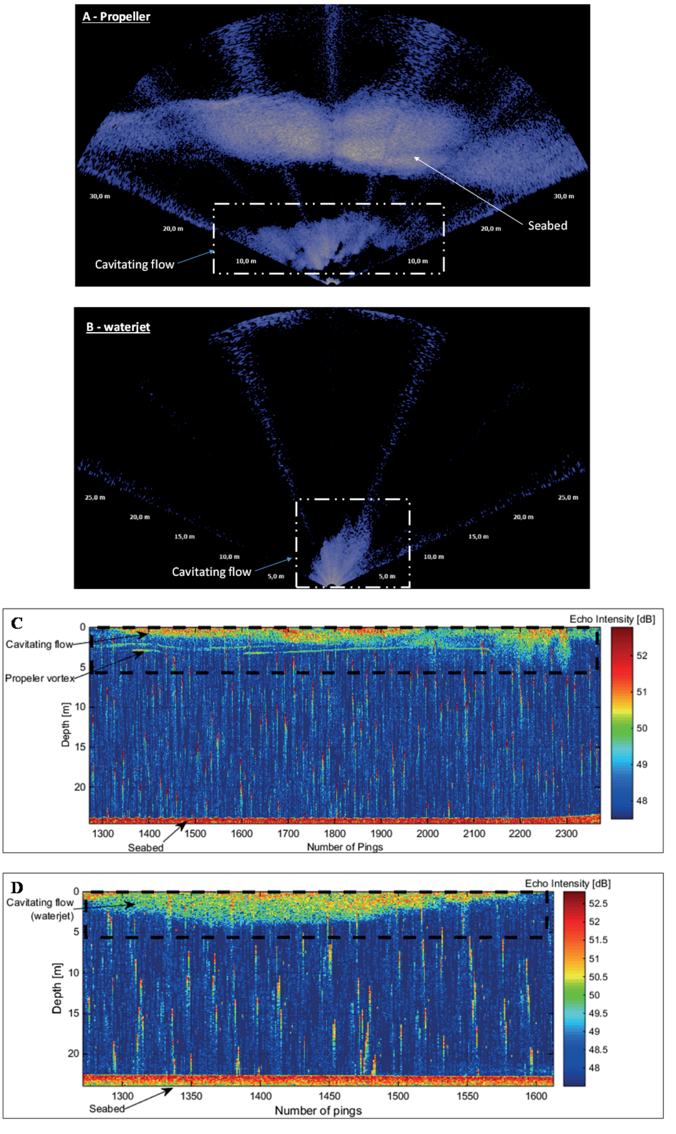

Figure 11. Observation of cavitating flow produced through a MBS and DBS system: (A) and (B) acoustic image of a boat with propeller and a boat with a waterjet respectively. Both flows reached depths close to 10 m and lasted about 90 s however, the propeller produced a more intense and larger cloud of bubbles comparing to the waterjet thruster. The propeller boat produced a tubular flow-shape and the waterjet produced a radial flow-shape. (C) and (D) - Filtered echograms obtained using DBS data referent to the cavitating flow left by a boat with propeller thruster (C) and by the boat with waterjet thruster (D). The flow shown in this filtered echograms is seen as reaching depths close to 6 m however, from non-flirted echograms, it is observed that the flow reached approximately 8 m for the propeller case. (Refer to Paper-V)

6.7 Echo intensity analysis (Paper IV)

The task of identifying and classifying targets can be improved by undertaking an unsupervised classification of the acoustic backscattering intensity values. This is done by analyzing echograms, histograms and clusters of the same sample. This information can tell how detected targets of interest, background noise, benthic zone, and water surface contributes to the entire echo intensity detected by the sonar. For example Fig. 16 shows echo intensity referent to targets around an UU WEC. Four clusters were identified (Fig. 12), the first cluster refers to echoes from an UU WEC (red dots), the second cluster represents the seabed, the third cluster represents the background noise and the surface turbulence, and the fourth cluster contains the most frequent echoes of the entire volume backscattering. From this graph (Fig. 11b, Paper IV) the most frequent values of echo intensity are between -98 dB and -102 dB, the water surface and riverbed reflected echoes above -100 dB of intensity, suspended targets and noise had values between -65 dB and -96 dB.

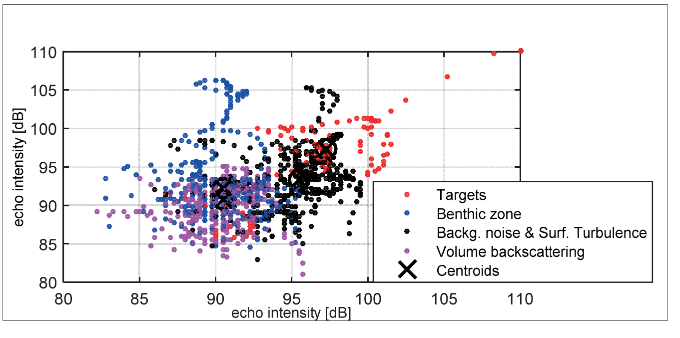

Figure 12. Post-analysis of echo intensity data referent to the echogram of a UU WEC. (A) Distribution of the total volume backscattering, mode of echo intensity that represents background noise, maximum that represents target, and minimum of echo intensity that represents both target and noise. (B) k-means clustering that identified four groups of targets namely: red dots – UU WEC, blue dots – seabed, black dots – background noise and surface turbulence, cyan dots – entire volume backscattering of targets with low echo intensity. (Refer to Paper-IV)

6.8 Wave climate analysis for the region of Ada – Ghana: A coupling of wave hindcast data with DBS/MBS bathymetric data. (PAPER VI)

With the aim of commissioning a wave power farm in Ghana, which would be the first commercial wave power farm in Africa, surveys were conducted to assess the local wave climate (wave energy flux (F_e)) and seabed characteristics. Parameters such as significant wave height (H_{m0}), wave mean period (T_{m0}), wave mean direction (*Dir*) were estimated using ERA Interim data set provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) Data Server. Data of parameters such as local bathymetry and seabed characteristics were acquired *insitu* using MBS, DBS systems and video camera. The wave data covered a period between 1979 and 2014, with a spatial resolution of 0.125° x 0.125° interval of latitude and longitude respectively, and a temporal resolution of 6 h (analyses at 0000, 0600, 1200 and 1800 UTC each day) at zero-step. Sonar surveys were conducted in two campaigns, one in fall 2014 and other in winter 2016. Insitu bathymetry data was used to feed a wave model (Simulating WAves Nearshore - SWAN), and SwanOne, providing estimation of wave propagation and transformation from the offshore to onshore. Absolute wave energy flux ($F_{e(stp)}$) was used to represent the sum of F_e estimated using H_{m0} and T_{m0} and a wave setup caused by the local bottom profile.

Estimation of nearshore density distribution of F_e (Fig. 13a), resulted in approximately 75 % of waves have F_e in the interval between 5 and 10 kW, 20 % have F_e of approximately 3 kW/m and less than 3% have F_e in the interval between 12 and 20 kW/m. The dominant mean direction of propagation is from the southwest. The Ada region has the following sea states (Fig. 13b): Slight-moderate from southwest (47 % of occurrence) with H_{m0}, T_{m0} and F_e of 0.5–1.5 m, 6–16 s and 5-12 kW/m respectively; Moderate and more westerly with (37% of occurrence) with 1.5 – 2.7 m, 6–14 s and 10–17 kW/m of H_{m0}, T_{m0} and F_e respectively; Smooth and more southerly (11% of occurrence) with H_{m0}, T_{m0} and F_e of 0.5 m, 10–12 s and 4 kW/m respectively. The least frequent sea state, with approximately 5 % of occurrence, is rough and more south easterly with H_{m0}, T_{m0} and F_e of 2.5 – 3.8 m, 10 s and 20 –25 kW/m of respectively.

The calculations of nearshore wave propagation resulted in H_{m0} values that decrease toward shore at a smooth rate smaller than 0.1 m per 1000 m of transversal distance to shore (Fig. 14). Sonar data of depth profile, suggest the existence of sand banks oriented longitudinally in relation to the coastline. The average bottom inclination was in the order of 10° within the 5800 m transversal transect starting from the shore. Here, the wave propagation and dissipation follows the bottom profile. The wave setup is small and vary seasonally, but it is enough to contribute to the absolute wave height and energy flux. In January at 30 m water depth the value of H_{m0}, F_e and $F_{e(stp)}$ are approximately 1 m, 3 kW/m and 8.7 kW/m respectively. For the same month, at 10 m depth, the values are 0.9 m, 2.5 kW/m and 6.8 kW/m for H_{m0} F_e and $F_{e(stp)}$, respectively. For July, at 30 m depth the values are 1.2 m, 4.5 kW/m and 16 kW/m for H_{m0}, F_e and $F_{e(stp)}$ respectively. Around 10 m depth, the values of H_{m0}, F_e and $F_{e(stp)}$ are 1.1 m, 4 kW/m and 11 kW/m respectively. This study concluded that the wave climate in West Africa and at the AOWE farm site is mild. Estimation based on hindcast data reveal that the most frequent sea state is slight-moderate from southwest with a range F_e of 5-12 kW/m. The magnitude of the wave field is high in July and lower between December and February. The wave setup can be small but, it has an impact on the absolute wave height and energy flux.

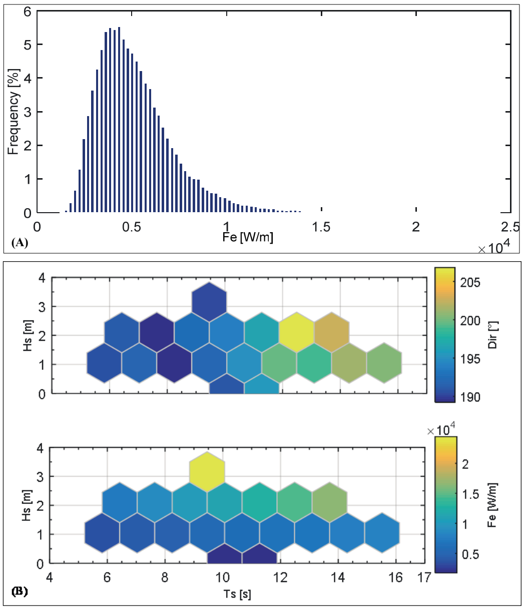

Figure 13. (A) Probability distribution of nearshore wave energy flux, for the Ada Offshore Wave Energy farm region. The frequency of occurrence is given in percentage. (B) Scatter diagrams showing the occurring sea states.

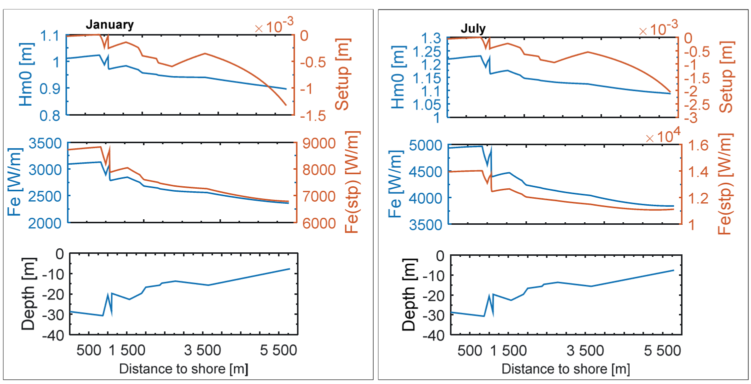

Figure 14. Profile of the nearshore wave propagation at the Ada Offshore Wave Energy farm region. The profiles are similar in January and July, which represents the low and high season respectively. However, the magnitude of H_{m0} and F_e increases in the order of 0.1 m and 0.5 kW/m nearshore and less than 0.1 kW/m in the surf zone respectively. The wave setup has smaller magnitude in January compared to July.

7 Conclusion

The first conclusion reached from this work is that building a monitoring platform based on sonar systems and made to operate underwater is a massive challenge. However, data such as acoustic images, ecograms acoustic backscattering altimetry produced by this type of platform are highly relevant for the operation and development within the marine renewable energy sector.

Specifically, this work concludes that the selected MBS system operating at frequency of 0.9 MHz with over 700 beams could detect targets as small as 30 mm. This MBS system was also capable of resolving isolated targets located near high reflective objects such as sea/riverbed, metal and concrete structures, etc. The MBS acquires better images when deployed on steady platforms, and when the water column is well mixed. The combination of a MBS and DBS system produced both qualitative and quantitative sampling data of biomass. Water column stratification and air bubbles are great sources of noise that drastically affects the MBS and DBS data. The MBS pitch angle also influences the quality of an acoustic image, low pitch angles are ideal for targets located close to the sonar and higher pitch angles are ideal for targets located far from the sonar head as well as for deployments in fast flowing water. The MBS system performed well on detecting WECs, TECs, and other types of underwater structures located within 70 m from the head of sonar.

The combination of MBS and DBS systems produced high quality bottom depth inspection data that can be used to access local bathymetry and bottom composition, as a pilot task prior to deployments of MRETs. This set of instruments also proved to be useful to measure cavitation flows produced by vessels.

When comparing target detection capabilities between MBS and VC systems, the conclusion is that VC performed well in clear water conditions but just for the surface water layer. However, a MBS system was able to detect targets at both clear and murky water conditions.

This licentiate thesis also includes a wave climate analysis for the region of Ada in Ghana. This conclusion is that the wave climate is mild in Ada as well as the entire West Africa region. The most frequent sea state is slight-moderate from southwest with range Fe of 5-12 kW/m. The magnitude of the wave field is high in July and lower between December and February. The wave setup can be small but, it has an impact on the absolute wave height and energy flux.

In short, this thesis concludes that the built environmental monitoring platform based on sonar systems can be used for inspections of underwater structures (MRETs, vessels, etc.). It can provide reliable data of biomass, bathymetry, cavitating flows and turbulent flows, underwater navigation and surveillance, search and rescue among others applications.

8 Future work

Environmental monitoring tools will continue to be very important in almost every industrial sector. Building such tools and platforms can be challenging when the objective is to survey the hydrosphere. So far this project have designed and built a platform that comprises sonar systems, video cameras that are integrated into a submerging chassis. However, making this environmental monitoring platform fully operational, several steps have to be taken such as:

- Recalibrate and integrate the SBS systems.
- Improve the electrical installation in order to make it even easier to interconnect the devices that will lead to quicker deployments.
- Improve the deployment procedure, by redesigning chassis.
- Complete the data acquisition software for the sonar systems, as well as build an all-in-all software able to access and treat data of both sonar and video cameras using graphic user interfaces.
- Deploy the platform in several other sites for various sampling periods.

9 Summary of papers

The chapter presents short summaries of each paper in this liciate Thesis.

PAPER I

Uppsala University Research, Lysekil Research Site, Sweden: A Status Update

This paper summarizes the research work on wave power that the Uppsala University has done in the period between 2013 and 2015. Experimental results such as grid connections, modelling of wave power farms, power production from the generators connected to different buoys and environmental studies are presented in this paper.

The author contribution to this paper was the writing of *Section H* that regards environmental studies, and language check.

Published in *Proceedings of the 11th European Wave and Tidal Energy Conference, EWTEC15, Nantes, France, pages 09A2-3-1–8, September 2015*.

Reviewed conference paper.

PAPER II

Sonar for Environmental Monitoring. Initial Setup of an Active Acoustic Platform

This paper refers to technical aspects regarding the hardware and software design of an environmental monitoring platform based on active acoustics.

The author did most of the work in this paper and presented it orally at the ISOPE 2015 Conference.

Presented at the 25th International Ocean and Polar Engineering Conference Kona, Big Island, Hawaii, USA, June 21-26, 2015. ISOPE-2015 Kona.

Reviewed conference paper.

PAPER III

Sonar for Environmental Monitoring: Understanding the Functionality of Active Acoustics as a Method for Monitoring Marine Renewable Energy Devices.

This paper provides the calibration results from tests conducted using multibeam and dual-beam sonar systems. The objective was to learn how to interpret acoustic images of WECs and TECs, as well as to learn the limitations of sonar systems sampling in different aquatic environment taking turbidity, water velocity, and stratification, among other factors into account.

The author did most of the work and presented the content in a poster at the EWTEC 2015 Conference.

Published in *Proceedings of the 11th European Wave and Tidal Energy Conference, EWTEC15, Nantes, France, pages 09A2-3-1–8, September 2015*.

Reviewed conference paper.

PAPER IV

Sonar for Environmental Monitoring: Construction and Deployment of a Multifunctional Active Acoustic Platform Applied for Marine Renewables

This paper describes with details how an environmental monitoring platform based on sonar systems was build, how it is been developed and deployed. The paper also presents results from initial deployments

that were performed using a downward sampling (the platform in the surface sampling the water column bellow it).
The author did most of the work in this paper.
Submitted paper.

PAPER V

Observation of Cavitation-Induced Flow Using Multibeam and Dual-Beam Sonar Systems: A Comparison of Wake Strength Caused by Propeller vs Waterjet Thrusted Vessels. In a Marine Renewable Energy Perspective (Part-a)

With the prospectus to deploy energy converters in areas with heavy boat traffic, we investigated the depth range of cavitating flow produced by transiting ferry boats in narrow channels. This work demonstrated that the monitoring platform in development by the present project, can be used to observe and measure cavitating flows.
The author did most of the work in this paper.
Manuscript.

PAPER-VI

An Estimation of Wave Energy Flux and Variability in the Ada Foa Region: Towards Commissioning of the First Commercial Wave Power Farm in Africa – Ghana.

This paper investigated the wave climate in terms of wave energy flux, significant wave height, wave mean period, and wave mean direction for the region of Ada in Ghana. This work proceeded the deployment of a pilot wave power farm in Ghana.
The author contributed with the most of the writing (literature), gathering and analysis of data.
Submitted paper.

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Svensk sammanfattning

Människans utforskning av världshaven ökar samtidigt som konventionella vattenberoende industrier växer och nya industrier uppstår. En ny snabbväxande bransch är marin förnybar energi. De senaste decennierna har präglats av en accentuerad utveckling av teknik som kan omvandla energi som finns i vattenströmmar, vågor, vind och tidvatten. Denna tillväxt gynnas av det faktum att samhället har blivit märkbart medveten om den sårbara miljö vi alla lever i. Med detta följer en mänsklig önskan av att utveckla teknik som bättre anpassas till den naturliga miljön. Denna miljömedvetenhet kan även medföra svårigheter i att få acceptans för förnybara energiprojekt, som havsbaserad vind-, våg- och tidvattensenergi. En lärdom har varit att brist på konsekvent miljödata kan vara ett hinder när tillstånd söks för testning och uppbyggnad av marin förnybar energiteknik. En majoritet av medlemsstaterna i Europeiska unionen kräver noggranna miljöövervakningsprogram när marin förnybar energiteknik utplaceras och avvecklas. För att uppfylla de höga krav som ställs och samtidigt hjälpa fram den marina förnybara sektorn behövs långsiktig miljöövervakning som samlar in en mängd information för att ge data till teknikutvecklare, operatörer samt till allmänheten. Teknik som bygger på aktiv akustik är kanske det mest avancerade verktyg som finns tillgängligt för att övervaka undervattensmiljön runt marina strukturer, speciellt i grumliga och djupa vatten där dykning och annan konventionell teknik är kostsam och riskabel.

Det huvudsakliga syftet med detta doktorandprojekt är att utveckla och testa ett aktivt akustiskt övervakningssystem för havsbaserad förnybar energi. Detta görs genom att integrera en mångfald av ekolod, hydrofoner och kameror lämpliga som övervakningssystem och som är ändamålsenliga i marina mil-

jöer. Som första uppgift identifierades, sedan införskaffades och testades ekolod. Vidare har en plattform med datalogger och ett kontrollsystem utvecklats. Slutligen byggdes instrument på plattformen, som videokameror och ekolod, och systemintegration följdes av en kalibrering av enheterna. Sonarsystemet användes för kvantitativa mätningar av förekomsten av t.ex. fiskstim nära marina förnybara energiomvandlare. Sonarsystemen användes även för havsbottensinspektioner, djupmätningar och observationer av vattenflöden.
Hittills har kombinationen av multibeam och dual-beam ekolod system producerat goda resultat som måldetektering, botteninspektion, havsdjupsmätningar och uppskattning av biomassa. Systemet med multibeamekolod har varit kapabelt till upplösningar som hjälpt identifiera isolerade mål belägna nära objekt med hög akustisk reflektion. Akustiska panoramabilder av våg- och strömkraftverk kunde fås genom att använda en multibeamekolod vid frekvenser nära 1 GHz. Dual-beam och split-beamekoloden producerade data, i relation till den akustiska bakgrundsintensiteten av föremål som hjälper till att klassificera mål i enlighet med dess storlek, sammansättning och 3-dimensionella läge inom vattenmassan. Under projektets fortsättning kommer plattformen att sjösättas under längre perioder för att bl.a. samla akustisk och optisk backscatterdata av marina djurs förekomst inom marina energiparker.

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