WP4: Research to innovate and improve infrastructures, technologies and techniques

D4.09: Remote underwater motion measurement

Authors:

Sylvain Bourdier  
Florent Thiebaut  
Jean-Marc Rousset  
Jérémy Ohana  
Marc Le Boulluec  
Gregory Germain  
Lars Johanning  
Gilbert Damy  
Alan Tassain  
Francisco Castillon  

ECN  
UCC-HMRC  
ECN  
IFREMER  
IFREMER  
IFREMER  
UNEXE  
IFREMER  
IFREMER  
UNI-STRATH

Status: Final  
Revision: Marinet D4.09  
Date: 04-Sep-2015
ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for Emerging Energy Technologies) is an EC-funded consortium of 29 partners bringing together a network of 42 specialist marine renewable energy testing facilities. MARINET offers periods of free access to these facilities at no cost to research groups and companies. The network also conducts coordinated research to improve testing capabilities, implements common testing standards and provides training and networking opportunities in order to enhance expertise in the industry. The aim of the MARINET initiative is to accelerate the development of marine renewable energy technology.

Companies and research groups who are interested in availing of access to test facilities free of charge can avail of a range of infrastructures to test devices at any scale in areas such as wave energy, tidal energy and offshore-wind energy or to conduct specific tests on cross-cutting areas such as power take-off systems, grid integration, moorings and environmental data. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users.

MARINET consists of five main areas of focus or ‘Work Packages’: Management & Administration, Standardisation & Best Practice, Transnational Access & Networking, Research and Training & Dissemination. The initiative runs for four years until 2015.

Partners

Ireland
University College Cork, HMRC (UCC_HMRC)
Sustainable Energy Authority of Ireland (SEAL_OEDU)

Netherlands
Stichting Tidal Testing Centre (TTC)
Stichting Energieonderzoek Centrum Nederland (ECNeth)

Denmark
Aalborg Universitet (AAU)
DanmarksTekniskeUniversitet (RISOE)

France
Ecole Centrale de Nantes (ECN)
InstitutFrancais de Recherche Pour l’Exploitation de la Mer (IFREMER)

United Kingdom
National Renewable Energy Centre Ltd. (NAREC)
The University of Exeter (UNEXE)
European Marine Energy Centre Ltd. (EMEC)
University of Strathclyde (UNI_STRATH)
The University of Edinburgh (UEDIN)
Queen’s University Belfast (QUB)
Plymouth University(PU)

Spain
Ente Vasco de la Energia (EVE)
Tecnalia Research & Innovation Foundation (TECNALIA)

Belgium
1-Tech (1_TECH)

Germany
Fraunhofer-GesellschaftZurFoerderung Der AngewandtenForschungE.V (Fh_IWES)
Gottfried Wilhelm Leibniz Universität Hannover (LUH)
Universitaet Stuttgart (USTUTT)

Portugal
Wave Energy Centre – Centro de Energia das Ondas (WavEC)

Italy
Universitàdegli Studi di Firenze (UNIFI-CRIACIV)
Universitàdegli Studi di Firenze (UNIFI-PIN)
UniversitàdegliStudidellaTuscia (UNI_TUS)
ConsiglioNazionale delleRicerche (CNR-INSEAN)

Brazil
Instituto de Pesquisas Tecnológicas do Estado de São Paulo S.A. (IPT)

Norway
Sintef Energi AS (SINTEF)
NorgesTeknis-NaturvitenskapeligeUniversitet (NTNU)

About MARINET
Remote underwater motion measurement

Marinet D4.09, 04-Sep-2015
Page 3 of 46

ACKNOWLEDGEMENT

The work described in this publication has received funding from the European Union Seventh Framework Programme (FP7) through the Infrastructures initiative under grant agreement no. 262552, MARINET.

LEGAL DISCLAIMER

The views expressed, and responsibility for the content of this publication, lie solely with the authors. The European Commission is not liable for any use that may be made of the information contained herein. This work may rely on data from sources external to the MARINET project Consortium. Members of the Consortium do not accept liability for loss or damage suffered by any third party as a result of errors or inaccuracies in such data. The information in this document is provided “as is” and no guarantee or warranty is given that the information is fit for any particular purpose. The user thereof uses the information at its sole risk and neither the European Commission nor any member of the MARINET Consortium is liable for any use that may be made of the information.
EXECUTIVE SUMMARY

In the marine energy research and development space, a large number of projects require underwater motion measurement during experiment trials. Motion measurement of the model or some of its components, which can be under the free surface, is vital to the analysis of the full scale device response and power extraction. Some motion measurement system are physically attached to the model but non-contact systems are sometimes the only solution or required to avoid interference with the motion of the model. A number of commercial solutions exist and the optimal technology depends on the characteristics of the motion and the test location in hydrodynamic facilities or offshore. In this document, the state of the art technologies available for remote, non-contact, underwater motion measurement is described.

Non-contact optical motion tracking systems are commonly used in hydrodynamic facilities to carry out remote motion measurement of a body underwater because good visibility conditions can be obtained with low water turbidity. These systems, measuring with great accuracy the six degree-of-freedom (6 DOF) motions of one or several bodies, were used in a large number of tests carried out by Marinet partners.

At sea, optical devices cannot be used in most cases due to the low visibility conditions, and the larger distances involved. Therefore, acoustic systems become more attractive, despite the lower flexibility and accuracy. Acoustic positioning techniques were first developed for the marine industry such as ship, marine survey, oil, military applications and more, in order to pinpoint assets above and under water.

This document aims at reviewing the technical solutions, available or under development, for remote underwater motion measurement, in controlled ocean test facilities and in real conditions offshore. It provides a technical understanding of the systems, their limitations and field of applications. It also includes feedback from experience gained by Marinet partners.
# 1 INTRODUCTION

Remote underwater motion measurement

# 2 UNDERWATER OPTICAL MOTION MEASUREMENT

## 2.1 PRINCIPLES OF UNDERWATER MOTION MEASUREMENTS BY OPTICAL DEVICES

### 2.1.1 Underwater lighting

### 2.1.2 Reflective objects

### 2.1.3 Markers

### 2.1.4 Cameras

### 2.1.5 Image processing

### 2.1.6 Examples of remote underwater measurement devices

## 2.2 OPTICAL MOTION MEASUREMENT SYSTEMS

### 2.2.1 Krypton underwater by MARIN

### 2.2.2 Dynoscope by Sirehna

### 2.2.3 Qualisys motion capture system

### 2.2.4 LA Vision Particle Image Velocimeter

## 2.3 EXAMPLES OF UNDERWATER OPTICAL MEASUREMENT IN MRE TESTING

### 2.3.1 Steel catenary riser in IFREMER deep seawater wave tank

### 2.3.2 Marine riser at the University of Strathclyde

### 2.3.3 Wave energy converter S3 at ECN

### 2.3.4 Sustainable Marine Energy PLAT-O tidal device tests at IFREMER in 2013

### 2.3.5 TFI tests at ECN

### 2.3.6 SWMTF tests at IFREMER deep water tank

# 3 ACOUSTIC POSITIONING

## 3.1 UNDERWATER SOUND PROPAGATION

## 3.2 MEASUREMENT PRINCIPLE

## 3.3 ACOUSTIC POSITION MEASUREMENT SYSTEMS

### 3.3.1 Long Baseline (LBL) systems

### 3.3.2 Multi User LBL (MULBL) systems

### 3.3.3 Short baseline (SBL) systems

### 3.3.4 Ultra Short Baseline (USBL) systems

### 3.3.5 GPS intelligent Buoys (GIB)

### 3.3.6 Passive sonar reflectors

### 3.3.7 Acoustic imaging

# 4 INERTIAL SENSORS

## 4.1 TECHNOLOGY

## 4.2 APPLICATIONS

## 4.3 EXAMPLE: SOUTH WESTERN MOORING TEST FACILITY (SWMTF)

# 5 CONCLUSIONS

# 6 WORKS CITED
# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUV:</td>
<td>Autonomous Underwater Vehicle</td>
</tr>
<tr>
<td>CCD:</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CDOM:</td>
<td>Coloured Dissolved Organic Matters</td>
</tr>
<tr>
<td>CMOS:</td>
<td>Complementary Metal–Oxide–Semiconductor</td>
</tr>
<tr>
<td>2D:</td>
<td>Two Dimensions (plane)</td>
</tr>
<tr>
<td>3D:</td>
<td>Three Dimensions (volume)</td>
</tr>
<tr>
<td>6D:</td>
<td>Six dimensions (volumes and orientation)</td>
</tr>
<tr>
<td>DGPS:</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DLT:</td>
<td>Direct and Linear Transformation</td>
</tr>
<tr>
<td>DOF:</td>
<td>Degree-Of-Freedom</td>
</tr>
<tr>
<td>DVL:</td>
<td>Doppler Velocity Log</td>
</tr>
<tr>
<td>EM:</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>FOV:</td>
<td>Field Of View</td>
</tr>
<tr>
<td>GPS:</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IMU:</td>
<td>Inertial Motion Unit</td>
</tr>
<tr>
<td>INS:</td>
<td>Inertial Navigation System</td>
</tr>
<tr>
<td>LBL:</td>
<td>Long Baseline</td>
</tr>
<tr>
<td>MEMS:</td>
<td>Micro-machined Electro-Mechanical Systems</td>
</tr>
<tr>
<td>MRE:</td>
<td>Marine Renewable Energy</td>
</tr>
<tr>
<td>MULBL:</td>
<td>Multi User LBL</td>
</tr>
<tr>
<td>ROV:</td>
<td>Remotely Operated Vehicle</td>
</tr>
<tr>
<td>SBL:</td>
<td>Short Baseline</td>
</tr>
<tr>
<td>SPM:</td>
<td>Suspended Particulate Matters</td>
</tr>
<tr>
<td>SWMTF:</td>
<td>South West Mooring Test Facilities</td>
</tr>
<tr>
<td>USBL:</td>
<td>Ultra Short Baseline</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

Entertainment companies as well as an increasing number of industrials have enabled large audiences to experience spatial (3-D) and immersive views of the environment. Techniques are now mature enough to bring the concept of Augmented Reality into every-day life. Smartphones, Unmanned Autonomous flying Vehicles are equipped with state-of-the-art electronic components able to give to the user their position according to the ground and their instantaneous attitude in the air. The gaming industry has developed some low-cost camera-based devices able to process the images and to recognise the motions of the subject (human being or object) almost in real-time. However most of these technologies are not at a scientific grade in term of repeatability, resolution, sampling frequency and data output. Most of them are developed for aerial conditions, without perturbing factors such as wind, rain, etc.

On the other hand, technology for underwater remote motion measurement in industrial or scientific activities are commercially available and are in continuous development due to higher technical requirements. In the offshore industry, underwater remote motion measurement is carried out for survey, installation, inspection, repair and maintenance of subjects such as:

- Marine Biology and fish studies: in-situ behaviour and movements of species, etc.
- Hydrodynamics and physics, including Marine Renewable Energy (MRE) devices: motions of platforms, lines and cables behaviours, etc.
- Robotics and Autonomous Underwater Vehicles (including MRE operation and maintenance): validation of control and guidance strategies, etc.

These operations are or will be carried out by the Marine Renewable Energy (MRE) industry and research groups during phases of installation, operation, maintenance, etc. and existing instrumentation for remote underwater motion measurement can be used.

The development path of MRE devices also includes experimental test campaigns of scaled models in hydrodynamic facilities (wave tanks, towing tanks or recirculating water channels). Motion measurement of the scaled model or some of its components, which can be under the free surface, is vital to the analysis of the full scale device response and power extraction. For such tests, measurement systems often need to be non-intrusive and therefore not affecting the motion and loads on the body.

Non-contact optical motion tracking systems are commonly used in hydrodynamic facilities to carry out remote motion measurement of a body underwater because good visibility conditions can be obtained with low water turbidity. Amongst the Marinet partners, ECN, IFREMER and FloWaveTT have been identified, at the time of writing, as facilities having an underwater optical measurement system. These systems, measuring with great accuracy the six degree-of-freedom (6 DOF) motions of one or several bodies, were used in a large number of tests carried out by Marinet partners.

At sea, optical devices cannot be used in most of the cases due to the low visibility conditions, and the larger distances involved. Therefore, acoustic systems become more attractive, despite the lower flexibility and accuracy. Acoustic positioning techniques were first developed for the marine industry such as ship, marine survey, oil, military applications and more, in order to pinpoint assets above and under water. Most acoustic techniques do result in three-dimensional coordinates of a body, but do not allow, on their own, 6 DOF motion tracking. Only recent developments in acoustic methods allow 6 DOF motion tracking of underwater bodies. Acoustic imaging techniques also improved recently and can now be used for motion tracking of objects in turbid waters.

This document aims at reviewing the technical solutions, available or under development, for remote underwater motion measurement, in controlled ocean test facilities and in real conditions offshore. It provides a technical understanding of the systems, their limitations and field of applications. It also includes feedback from experience gained by Marinet partners.
2 UNDERWATER OPTICAL MOTION MEASUREMENT

Optical measurement derived from stereovision is a common technique to measure position and motion of objects. A number of cameras are used, two at least, and setup to monitor the same object with different viewing angles. Each camera records two dimensional views of a scene and specific points are identified on each image. The three dimensional coordinates of each point can then be calculated by triangulation of the data from each camera. The 6 degree-of-freedom (DOF) motions of a rigid body can also be obtained by measuring the motion of at least three points linked to the body. There is a number of commercial systems developed for optical motion measurement in the air but only a few have underwater capabilities and will be described in the section. The most relevant requirements for underwater systems are listed below:

- the equipment has to be waterproof.
- the equipment has to be small to limit hydrodynamic effects.
- the supporting frames has to be sturdy to withstand hydrodynamic forces due to waves or currents.
- a specific Electromagnetic (EM) wavelength has to be chosen depending on the medium. Some EM frequencies are quickly absorbed in water.
- the equipment may have to be partly autonomously powered.

Several techniques can give remote measurements through glass windows of tanks as found in cavitation tunnel or circulating water channel experiments. This techniques can be considered as aerial ones as the measuring device is not submerged but only looking to underwater subjects. They are considered to be out of the scope of the document.

2.1 PRINCIPLES OF UNDERWATER MOTION MEASUREMENTS BY OPTICAL DEVICES

An underwater optical measurement system uses an optical camera system and measures the position of a subject (animal or object) according to its position in the camera field of view. It is at least composed of one camera for two dimensional applications and two cameras in stereovision for three dimensional applications, each camera generating a picture of the subject. A specific image processing method is then required to extract the needed information and obtain position data. Most configurations also involve a specific lighting equipment to improve the image quality and focus on specific reflective materials.

2.1.1 Underwater lighting

Reliable motion measurement relies on the quality of the image recorded on each camera which depends on the characteristics of the camera but also on sufficient light reaching the camera sensor. While light can propagate over long distances in the air, light propagation in water is limited. This is mostly governed by three physical limiting factors, absorption, scattering and attenuation. Ambient light coming from above the free surface is often insufficient and partly reflected on the water surface. Therefore, this section only considers lighting equipment located under the free surface for the purpose of the measurement.

2.1.1.1 Light absorption

Light absorption in water can significantly impact the light propagation. The absorption coefficient varies with the water quality (dissolved chemicals or particles in suspension) and the light Electro-Magnetic (EM) wavelength. The Figure 1, from (Bogdan Wozniak 2007), shows an example of averaged empirical absorption spectra of light in pure liquid water, for a wide spectral range (a) and focusing on the visible range (b). It highlights the lowest absorption coefficient values in the visible light range of EM wavelengths and therefore underwater optical measurement systems are tuned to be in specific ranges of visible frequencies with low absorption.
The coefficients of absorption presented in Figure 1 do not take into account absorption from dissolved gases, atoms, salts and other inorganic substances which can be found in sea-waters but also in fresh waters. Visible EM frequencies are also absorbed (or sometimes emitted) by organic molecules and organic matters. It is therefore necessary to take into account Dissolved Organic Matters (DOM, typical dimension < 10^{-6} m), Suspended Organic Matters (SOM) and Particulate Organic Matters (POM) with dimensions over 10^{-6} m.

Always present in the sea water, these organic matters are also frequently met in fresh water tanks when the chemical and mechanical filtering processes are not efficient enough, leading to the presence of phytoplankton and algae. Their presence mainly affects the Infra-Red (IR) and yellow frequencies which are absorbed in large proportions.

Beside organic matters, water contains inorganic suspended matters of various sizes for which absorption coefficient is low around the IR wavelength but very high at visible ranges. Once again, the fresh tank water may be highly affected by the Suspended Particulate Matters (SPM, including organic and inorganic matters) when the treatments are not efficient.

The Figure 2, from (Miller R.L. 2007), shows the absorption differences between pure water, and water containing phytoplankton and Coloured Dissolved Organic Matters (CDOM). It should be mentioned that the comparison is
based on very small dimensions and low concentration, i.e. CDOM are not distinguished by an observer eye: the water seems to be almost as clear as tap water.

Finally the light absorption in the water is a critical parameter as it can change drastically according to the density of DOM and SPM. This phenomenon is often under-estimated in laboratory experiments, especially in large tanks where the filtration process may not be efficient enough.

On a practical side, to ensure the best underwater measuring conditions with respect to the water content, precautions must be taken in relation with:

- risks on large models tested in the field before basin tests. Organic matters may be shipped with the model from natural waters (sea, lake or estuarine water) to a laboratory tank. In this situation, organic developments may occur, often reinforced by the slightly higher temperature in the lab. It is therefore important to clean the model before installation in the tank.
- risks of corroded elements staying for a long time in the tank, these parts from models and / or experimental frames can generate inorganic matters in the tank. Frequent cleaning and replacements have to be organised and care should be taken about electrolysis between different usual metals (Carbone steel, aluminium, stainless steel, coper, etc.). Small electrical leaks should also be avoided (through instrumentation for example).
- difficulties to foresee the real depth of view from the camera to the object. The maximum distance has then to be checked on an empirical manner and the lighting conditions are to be tuned accordingly.

2.1.1.2 Light scattering

When the particle size is large compared to the EM wave length (diameter between $10^{-6}$ m and $10^{-5}$ m), the light is interacting with the matter and partially deflected. This phenomenon is generating a scattering effect which is described by (Mie 1908) scattering theory. The graphs in Figure 3 show a normalised scattered intensity of glass particles for 3 different particle diameters in water and for a wave length of 532 nm (green). Incoming light from the left is not blocked but spread in many directions.
Figure 3: Normalised scattered intensity of glass particles in water with diameters of 1, 10 and 30 micrometres from top to bottom (Raffel M. 1998)

The light scattering depends on:
- the ratio between the refractive index of the particles and the surrounding medium;
- the particles sizes and shapes;
- the light polarisation;
- the observation angle.

Even with a minimum particle concentration, the emitted light can be scattered in all the water volume. In small particle concentrations, a large proportion of the light is not affected and can reach the subject with high intensity (here for 180° on the curves) but the scattering effect increases the global illumination of the water. On a photographic point of view, the light received at the camera sensor contains higher intensity at the object location and lower intensity on the back-ground (assumed to be a noise) and the higher the scattering the lower the signal to noise ratio. An observer would see, in high scattering conditions, an image similar to one of a car headlight in the fog. Increasing the light intensity does not improve the image quality nor the maximum illuminated reachable distance. Therefore the water quality needs to be at the best level to avoid large scattering effects.

The length the light travels between the source and the camera sensor also needs to be optimised to ensure a better image. The Figure 4 illustrates these effects in a brief summary from different lighting setups.
2.1.1.3 Light attenuation

Light attenuation in pure water (absorption of some EM frequencies by H₂O molecules) is generally lower than absorption and scattering. Global attenuation is mainly driven by both absorption and scattering effects but the absorption may not be caused only by particles or chemicals. Some experimental results in pure water are shown Figure 5 where it can be observed that cyan (green/blue) light seems to be the best compromise with lowest attenuation in water. Using these frequencies would therefore give the ability to observe objects placed further away.

![Figure 4: A tentative classification of different underwater imaging setups (Jaffe J.S. 2001)](image)

![Figure 5: Experimental attenuation coefficients of pure water (modified, from (Ivanoff 1975))]
2.1.2 Reflective objects

The capacity of a subject to be seen in water does not only depend on the intensity of light reaching its surface. It also depends on its capacity to reflect light back towards the observer (camera sensors). The light reflection properties of a material can be characterised by its refraction (the way the light is traveling through the material) and reflection (the way the light is bouncing off the material surface) properties. These two principles are described by linear and non-linear optics which are out of the document scope. Interested readers can get in-depth information in (Träger 2012).

The subject monitored need to have high reflection properties from part or all of its surface. Light reflections on the subject surface should also be known and of simple geometry in order to keep the image processing as easy and accurate as possible. The subject do not have to be reflective as a whole but only specific parts of its surface, the rest of the surface in the cameras fields of view having a lower reflection coefficient. If reflective materials are used on another part of the subject or experimental equipment they must be covered with masking techniques or the camera system must be able to filter the information in order to avoid confusion with designated parts of the subject.

The reflective material for underwater measurement may be different than those usually used for aerial measurements. As an example, many reflective tapes are made of very small glass spheres glued on an adhesive strip. Working well on visible and near IR lights in the air, their reflective properties are cancelled once underwater as their reflective index is similar to the water index, the lights are not reflected but passing through the spheres. It can be also mentioned that raw aluminium tapes or frames are not suitable reflective materials when placed underwater.

Usual efficient underwater reflective devices can be found in equipment developed for safety at sea (SOLAS, International Convention for the Safety of Life at Sea). The reflective SOLAS tapes are easy to find by ship chandlers and inexpensive but should be chosen carefully as there are differences in term of reflection coefficient between each model. Figure 6 presents an empirical comparison between 4 different reflective tapes mounted on an underwater matt support. The pictures are extracted from an internal project performed at Ecole Centrale Nantes in 2010. The lighting and imaging conditions are different in the 4 pictures:

- a) picture from a regular digital camera at daylight and automatic exposure, located 1m from the frame;
- b) similar conditions as “a” but with the camera flash light;
- c) picture from a camera located 3m from the frame;
- d) picture from the underwater motion tracking at an approximate distance of 10m.

This simple comparison shows the behaviour of the reflective material with the incident light and the water quality varies widely and therefore needs to be assessed in-situ. In Figure 6, picture “b” the four tapes have a similar reflection (1m from the camera) but in picture “d” (10m from the camera) only two of them reflect sufficient light to the camera for an accurate measurements.
2.1.3 Markers

On a subject, markers are the reflective objects used to describe the movement of the subject. For underwater applications it can be made of dedicated markers or viewable items on the subject itself. Dedicated markers are manually placed on the subject at the most appropriate locations. Viewable items already on the subject can be edges and remarkable points, contrasted elements, etc. with reflective surfaces. This is a marker less method and frequently performed in field studies when the subject cannot be prepared for the experiment (fishes, large offshore equipment etc.).

When light propagation is an issue, emitters such as LEDs can be mounted on the subject reducing the travel distance of the light. The light is emitted from the subject and directly captured by the camera with only one-way path from the subject to the camera. Hence, light absorption and attenuation is noticeably reduced. The Figure 7 shows an example of an underwater LED used for motion tracking. The LED is encapsulated in a small resin box and powered with 2 thin wires. The emitted light in water is seen by the camera as a 20mm reflective strip approximately.

This solution is recommended for some applications where light propagation is an issue. However, it is not recommended otherwise as it requires cables to the subject or batteries to power the electronic component which can remain a disadvantage in some experiments, when cable stiffness or weight is non negligible and can affect a body motion for example.

Figure 6: Empirical comparison between different reflective tapes under various lighting conditions (courtesy of ECN)

Figure 7: View of an underwater LED for motion tracking (courtesy of ECN)
2.1.4 Cameras

2.1.4.1 Sensors
During a few decades, digital cameras were based on CCD (Charge-Coupled Device) sensors, providing direct digital pictures without the drawbacks of argentic films. Many types of cameras, including underwater ones, were developed for professional and leisure purposes. However, high-quality sensors, with high sensitivity or large resolution, were quite expensive.

Since 2000, the CMOS (Complementary Metal–Oxide–Semiconductor) sensors which are purely integrated circuitries provide new opportunities to improve the vision systems. As such they are designed and supported by the large and strong industry of electronic components, leading to reductions in manufacturing costs. Almost all recent cameras, except low quality cameras, now use CMOS sensors providing high resolution, sensitivity and speed using small dimension sensors.

In order to perform quick analysis and mask unwanted subjects, scientific grade of this type of sensor also allows an easy definition of the region of interest in the image. The quality of a sensor (and its cost) is however estimated with its number of ‘dead’ pixels. The highest rank is supposed to only be affected by a maximum of 1 or 2 dead pixels in a 1024x2048 (2Mb) sensor. On the other hand, a common sensor found in webcams or equivalent cameras may have tens of black pixels.

2.1.4.2 Optical corrections
The camera sensor is generally coupled with an optical device, most often a photographic lens, which may be made of 1 to 10 lenses mounted in a frame. The manufacturing processes can induce some minor optical aberrations especially around the limits of the image, far from the lens centre. Other distortions are occurring in the image in relation with the focal length. It can be easily illustrated using a square grid for subject as shown in Figure 8. Hence, the first step in the experimental setup for optical motion measurement is to correct and remove the distortion effects affecting the quality of the picture collected.

![Figure 8](image.png)

**Figure 8:** Effect of distortion: the regular grid of (b) in the object plane is either distorted in the image plane to a pincushion shape (a) or a barrel shape (c).

Dedicated algorithms are used on the digital image in order to correct the image distortion, the simple ones being based on a linear theory. Such a process can as well be performed to remove unwanted perspective effects. The Figure 9 shows a correction to get a plane image from a fish-eye picture on which it would not be possible to perform a direct and accurate image analysis.
The process is performed once when the camera is installed in place for the experiment and is leading to a set of calibration coefficients from linear (or quadratic) equations. In order to speed up the calculation during the experiment, these coefficients and equations are applied to the image often in real time at the level of the camera. They are called intelligent cameras as their embedded electronics is able to perform simple image processing and to deliver corrected image to a computer or the user. In a commercial software this method is usually called linearization.

It should be mentioned that the linearization coefficients are referring to a specific setup, i.e. a package with a camera (with its sensor size and type) and a lens. If the lens or its focal length is changed (with multifocal lens), the linearization processed is to be performed again. In the case of underwater measurements, the linearization process has to be performed in water as the different media (air, water and glass) increases the optical distortions.

2.1.4.3 Stereo-photogrammetry and calibration

The stereo-photogrammetry method was developed to measure subject position in a volume (3D). It requires the use of at least two cameras placed at different locations and looking towards the same subject. With a similar principle than human eyes, the two cameras provide two images of the same subject seen from a different point of view. An image processing algorithm, comparing the two images, can then calculate the depth of the field of view and the volume of the subject. Some specific developments are done to get this volume with a single camera (Mathieu 2005) and (Park J-Y 2009) but they seem to be limited to a relatively small field of view and / or virtual reality purposes.

Therefore, a setup is based on several cameras (at least 2, hundreds at the maximum) oriented towards a subject. The fields of view can be described according to the Figure 10, Figure 11 and Figure 12 from (Gruen A 2001). The 2 lines from the image plans to the object point are called epipolar lines.
Figure 10: Principle of stereo-vision including epipolar geometry

Figure 11: Geometric description of a 2 cameras setup.
A Direct and Linear Transformation (DLT) is a geometric relationship between the coordinates of 2 images from the definition of Figure 12:

\[
x + \Delta x = \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1}
\]

\[
y + \Delta y = \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1}
\]

The calibration for a given camera setup can be defined with these 11 coefficients but other methods can use only 7 coefficients to reduce the processing time. Schematically, algorithms based on DLT method allow to connect 2D coordinates of a point in simultaneous images to the 3D coordinates of this point on the object. The point displacement can be estimated from position changes between each successive sample images. The stereo-vision calibration is the critical part of the experiment as the coefficients are used to go from 2D to 3D and vice-versa. The application of the coefficients can be performed in real time on usual computers.

In practice, calibration of a camera setup can be performed by empirical methods using a physical frame of known geometry providing at the end the set of DLT coefficients for each camera. One common calibration techniques is based on the use of a triad with subjects fixed at known absolute coordinates and a wand with two subjects at a known distance and moved in the camera space. The other common method uses a 2-D plane fixed at known absolute coordinates and a graduated rod placed at various locations with known relative distances. Calibration equipment used for these methods are shown in Figure 13. The work presented in (Silvatti A P 2011) analyses these two methods for an underwater setup and provide comparative results summarised in Table 1.
Table 1: underwater calibration setup comparison

<table>
<thead>
<tr>
<th>Type of calibration</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triad + wand Calibration</td>
<td>• Equalization of the reconstruction error across the calibration volume</td>
<td>• The wand must be moved opportunistically to cover all the calibration volume</td>
</tr>
<tr>
<td></td>
<td>• Only one point to track</td>
<td>• Accuracy strictly depending on the construction of the triad</td>
</tr>
<tr>
<td></td>
<td>• Calibration structures are light and easy to setup</td>
<td>• High sensitivity of wand marker tracking to water quality</td>
</tr>
<tr>
<td></td>
<td>• High portability</td>
<td>• Assumes the vertical axis based on the swim pool floor</td>
</tr>
<tr>
<td>Graduated rod + 2D Plate</td>
<td>• Each camera can be calibrated separately</td>
<td>• Unbalanced camera network</td>
</tr>
<tr>
<td>Calibration</td>
<td>• Better corner visibility</td>
<td>• High number of corners to track</td>
</tr>
<tr>
<td></td>
<td>• More accurate distortion correction</td>
<td>• Chessboard are cumbersome</td>
</tr>
<tr>
<td></td>
<td>• Lower sensitivity of corner detection to water</td>
<td>• Accuracy strictly depending on the construction of the chessboard</td>
</tr>
<tr>
<td></td>
<td>• Allows to correct the vertical axis based on the water plane</td>
<td></td>
</tr>
</tbody>
</table>

2.1.4.4 Underwater cameras

The underwater cameras may be found in very diverse configurations. They are fitted inside waterproof housings and cables are used for camera control, power source and transferring images to the computer. Recent progresses in leisure cameras are leading to the use of common devices which have constantly and rapidly improving capacities in term of resolution, sensitivity and sampling frequencies. However, they are usually fitted with low quality optics and their use in scientific experiments is not straightforward. The work presented in (Bernardina G R D 2014) provides a comparison between ‘sport action’ cameras and Qualisys cameras, an underwater motion dedicated system. They conclude that these cameras may provide quality with position uncertainty ranging between 1 and 2 mm which is suitable for many biomechanical experiments. The synchronisation of the affordable cost cameras remains a critical point when the motions are large in speed and excursions.

2.1.5 Image processing

A dedicated image post processing software must be used in order to calculate the subject position information from raw camera images using the techniques described in section 2.1.4. It should be designed to perform the following calculations at each time step in real time or post processing:

- Raw image analysis, in order to locate the markers in each 2D image. Markers used in underwater measurements to describe a subject can be made of dedicated active or passive markers or viewable items on the subject itself. These need to be pre-programmed in the software and identified in each image analysed.

- Use the stereo-vision methods with images from all cameras installed and the camera setup characteristics (obtained from the calibration process) to calculate the 3D position of each subject and generate position time series.

- Additional processing can include the calculation of 6D subject position using the 3D position from a minimum of three points with a specific pattern and known relative position in relation with a rigid subject.

During calibration, most commercial software are also able to assist the user in the calibration process. They automatically process the data from known markers positions and calculating all calibration coefficients.
2.1.6 Examples of remote underwater measurement devices

The following references are given as a brief overview of experiments performed with commercial or ‘tailor-made’ devices. The list is of course not exhaustive.

- Wu (Wu J 2005) describes an ‘in-house’ system designed to measure motions of an underwater towed system up to 5m/s. Two underwater CCD cameras were mounted on a towing platform (Figure 14) and the model 6 DOF motions were analysed with dedicated programs with respect to actuators control.

![Figure 14: Cameras setup from (Wu J 2005)](image)

- Chu et al. (Chu P C 2005) describe an experiment that consists in dropping three cylinders of various lengths into a pool where the trajectories were filmed from two angles. Two CCD analogue cameras fitted in waterproof enclosures were located mid-depth in a pool and the processing was performed off-line, from digitised images, with Matlab routines. Trajectories of the cylinders were then analysed according to the matrix of displacement and location of the centre of gravity.

![Figure 15: Falling cylinder test described in (Chu P C 2005)](image)

2.2 Optical motion measurement systems

This section gives an overview of the technology and information on the operating principle of known underwater motion measurement systems based on the experience from Marinet partners.
2.2.1 Krypton underwater by MARIN

In 2004 Marin initiated modifications on its aerial motion measurement system, Krypton (now Nikon) Rodymm K600-DMM (Marin 2009), in order to use it underwater. This optical system was commonly used for the motion measurement of floating structures. The K600 uses three linear cameras fixed on one rigid frame inside a housing, to measure with great accuracy the positions of targets (METRIS 2015).

![Picture of the underwater modified K600 system at MARIN. The sturdy waterproof housing for the three cameras can be seen in the left picture. Red LEDs being followed by the system can be seen in the right picture. From (Marin 2009).](image)

The changes made to the aerial system are reported in (Marin 2009). Modifications performed on the aerial system included these three major changes:

- The EM wavelength of the light used was changed from infrared to ultra-bright red
- A single waterproof housing was used for the three cameras
- An underwater stiff support structure. The stiffness of the support was important in order to avoid movement induced by hydrodynamic loadings.

The system was able to measure the 3 DOF motions of up to 30 individual LEDs, or 6 DOF motions of up to 3 rigid bodies. It could measure in a 3x3 m area, at a distance of up to 6 m from the cameras, with a resolution of 0.2 mm and a specified measurement uncertainty of 0.3 mm.

This underwater motion measurement system was used for the study of turret systems that can be disconnected in survival conditions, hybrid riser towers and other subsea systems in current and waves. This system is however not in use anymore at Marin.

2.2.2 Dynascope by Sirehna

At Ifremer, a stereoscopic underwater video camera system called Dynascope and developed by Sirehna was used in the Nineties. The system was based on a system of acquisition of analogue images developed by SECAD. The position and orientation of the cameras could be adjusted to optimise the position and geometry of the measurement volume, in which target positions were measured. The setup with two independent cameras provides a higher flexibility to adjust the measurement volume but the setup must be calibrated each time one camera is moved in order to know the relative position between cameras and provide their position and orientation in the absolute basin referential.

It was used for example to study the displacement of Steel Catenary Risers (SCR) in the Touch-Down Zone (TDZ) induced by top motion (Le Cunff, Biolley and Damy 2005). For this study, two model pipes were tested, corresponding to oil-filled and gas-filled risers. The motions of the risers in the TDZ were recorded by two different optical systems, as shown in Figure 21. One 2D-tracking system was recording the motion of six to seven points of the riser (marked with white bands glued to the riser) continuously in contact with the seabed, and the Dynascope system using two cameras for recording the 3D-motion of about eight targets above the touch-down point.
The authors mention that the absolute precision of motion measurement was of about 1 cm, while the relative precision was of about 1mm.

Since 2007, the system developed by Qualisuys is used at Ifremer. It was chosen for its ability to include many cameras, including underwater cameras.

### 2.2.3 Qualisys motion capture system

Qualisys motion capture system is a commercial system developed for the motion capture of rigid or deformable objects and is by far the most common in the Marinet community. It is based on stereo vision principle and can operate in air, underwater and combined volumes. Description of the system used in air for MRE testing was also provided in (Ohana and Bourdier 2014). Hardware and software are continuously developed by Qualisys and details on the latest equipment available can be seen on the Qualisys website.

#### 2.2.3.1 Operating principle

Qualisys operating principle is based on stereo-vision principle and is composed of:

- A set of infrared or visible light cameras. The number can vary from a minimum of two until a large number in order to improve the measurement quality, extend the size of the measurement volume or avoid shadows when a camera view is obstructed.
- A set of markers reflecting or emitting light. Any number of markers can be used depending on the application.
- A computer and QTM software connected to the camera array via an Ethernet cable. The software is developed to assist in the hardware set-up and processing of the raw data received from all the cameras to standard motion time series.

**Markers:**

Markers can be either passive or active. Passive markers are reflective surfaces placed on a body. When used with passive markers, the cameras emit pulses of light which reflect off the marker(s), and the cameras capture the part of the reflected light going back onto them. Active markers contain LEDs that emit the light which is captured by the cameras. Sequence-coded pulses of light can be used to distinguish several markers.
Passive markers are easier to use as they only need to be attached onto a body, for example with double-sided tape. Using active markers requires a power source and pulse control system on the subject, which can result in longer installation time and interaction between the power cable and subject motion. However, active markers provide a better measurement quality, especially in large distances underwater when light propagation is restricted.

**Motion measurement principle:**
During acquisition, each camera collects images and creates a two dimension (2D) image recording light intensity in its 2D plane. The 2D position of each marker, of known shape and higher light intensity in the image, can be obtained from each camera. The combination of the 2D marker positions from each camera can then be combined to calculate the 3D coordinates of each marker in the global referential. The 3D coordinates of a minimum of three markers placed on a rigid body can be used to calculate its position and orientation (6 DOF motion) at each time steps.

For use in the air or underwater, the operating principle presented above is valid but the two volumes (air and water) cannot be monitored by the same cameras due to light reflection and refraction at the water surface in both directions.

**Underwater system characteristics:**
The main system differences, between above and underwater, are the wavelength of the light used and the waterproof housing enclosing the underwater cameras. Each underwater camera is pressure tested to 40m and is corrosion protected for use in salt water tanks or chlorinated swimming pools. Weight and volume is balanced to give the camera neutral buoyancy for easy handling in water (Qualisys website 2015).

As illustrated by Figure 18, light absorption in water is minimum for wavelengths of about 500 nm. For this reason, the underwater Qualisys system uses light at 505 nm, corresponding to a cyan colour. Oqus underwater cameras, shown in Figure 19, are equipped with a special strobe with high power directive cyan LEDs.

![Figure 18: Light absorption coefficient of liquid water as a function of the wavelength.](image)
Longer exposure times are needed to get enough light in water and therefore the maximum LEDs flash is extended from 10% of the sampling period (for aerial cameras) to close to 100%. This has a direct impact on the use of the underwater Oqus cameras: their powerful LEDs can be used only in water as they would get warm very quickly without water cooling. Because water absorbs more light than air, the measurement distance depends on the exposure time. An Oqus Underwater camera is typically able to measure markers up to a distance of 15-20 meters depending on the water quality and the type of marker used.

The Field Of View (FOV) is also modified due to the water refraction properties ($n=1.33$). Underwater Oqus cameras are equipped with lenses providing a 48º FOV in air, which reduces to about 38º FOV in water (Berlander, M. 2009).

### 2.2.3.2 Installation in marine laboratories

Before using the Qualisys system, all cameras are mounted on fixed and rigid structures, pointing towards the volume where the targets may evolve. The entire volume should be seen by at least two cameras and they must be placed on a rigid structure since any movement of one of the cameras can reduce the measurement accuracy or make this camera out of range. Each time the camera setup is modified or one camera moves, the setup must be calibrated as described in section 2.2.3.3.

Installation practices vary, mostly depending on the tank configuration. Qualisys offers sturdy tripods with suction cups to properly fasten their feet to the tank floor. They require a clean and flat ground and have been used, for example, in a swimming pool to measure swimmer motions (Olstad, et al. 2014). For MRE tests, a more robust solution is usually required as wave or current loading acting on such tripods could induce vibrations of the cameras, which would immediately corrupt the recorded motions.

Some wave basins have dimensions adapted so that a system of underwater cameras can be installed permanently, on its sides for example, to measure the motions of scale models in different experimental tests. In this case, installation of the cameras is done once, and calibration of the system has to be made only to ensure calibration quality over time. In a large scale wave basin, the experimental set-up can differ for each test campaign. The geometry of the scale models, their size, number, constraints (and therefore excursions) as well as their arrangement in the wave basin vary, making unlikely the use of the same camera arrangement in the tank. Hence, spatial arrangement of the cameras has to be changed for every new experimental campaign.

As most MRE devices are moored or fixed to the ground, the motion of the moving parts on the models are restricted to a volume that can be estimated before the tests (through quick numerical simulations, and/or
Remote underwater motion measurement

Therefore the volume where motion capture is required is known and cameras can be adjusted on a frame outside the test location.

Common practices amongst Marinet partners:
- At ECN, the set of underwater cameras is generally setup for each project. It is first installed on a very rigid frame above water, in order to adjust the relative orientations of the cameras and obtain the expected field of view. The frame, with the cameras, is then craned in the tank and firmly fixed to the tank floor. Such procedure reduces the installation time, especially the time to be spent by a diver manually adjusting the orientation of each camera underwater. The frame never moved and motion measurement remains accurate even in the presence of large waves.
- In FloWaveTT, the underwater motion cameras can be fixed on the raisable floor when this latter is above water, and lowered down with the basin floor.
- In the recirculating water channel in IFREMER, cameras are fixed to the frame of the tank by a diver or from an aerial frame partly submerged. They are usually placed downstream the object(s) to be followed in order to reduce hydrodynamic interference.
- The system can also be fixed on a towing carriage, for tests in a towing tank. In the Kelvin hydrodynamic laboratory at the University of Strathclyde, cameras were installed on partly submerged vertical rigid beams mounted on the aerial towing carriage.

2.2.3.3 Calibration in marine laboratories

Once all the cameras are placed in their final locations, calibration needs to be done in order for the QTM software to know each camera position relative to the global referential. The calibration procedure is entirely programmed in the QTM software. The procedure requires an L-shaped reference structure with four markers and a calibration wand which are used as follows:
- The L-shaped structure is placed in a fixed position at the centre of the expected Qualisys referential. It carries four (passive) markers with known relative positions and is used by QTM to define the origin and orientation of the global referential system. Hence, the structure has to be installed either horizontally or vertically, with great accuracy, inside the measurement volume. In the case of a dual volume including one aerial volume and one underwater, a single frame with two L-shaped structure can be used. This allows, knowing the relative position of each markers on the frame, KTM to link both volumes and create a unique referential. The Figure 20 illustrates a dual calibration structure including an L-shaped frame placed in the air and one placed underwater. The same device with only one L shaped structure is used for single volumes either in air or in water.

![Figure 20: Illustration of a dual calibration frame for above and underwater dual volume](image)

- The calibration wand, composed of a holding stick and two markers, is moved in the entire volume covered by the cameras (above and/or underwater). Underwater, it is usually moved by a diver or held on a long stick moved manually from above the surface. The distance between the two markers is accurately know and entered in the software.

The system calibration needs to be done each time a new camera set-up is used or when one camera has moved from its original position. The calibration technique is similar for either under or above water but one system cannot
be used for both locations because it involves two sets of independent cameras. However, the two volumes can be linked together and the QTM software is able to acquire motion in the two volumes simultaneously and combine them into one.

At ECN, once the system is calibrated, a procedure is used to ensure that the global coordinate system is correctly oriented. Two plumb lines, each going through the centre of two circular markers, are installed, in the measurement volume, in a plane parallel to one of the planes of the global coordinate system (the plumb lines are placed far apart to minimise alignment errors). The measured positions of the four markers inform on the accuracy of the global coordinate system orientation. If the global coordinate system is not perfectly aligned, it can be rotated in the QTM software after calibration until alignment of the global coordinate system is satisfactory.

### 2.2.3.4 Measurement accuracy

Accuracy of the measurement in the range of 1mm with the Qualisys system can be achieved but depends on the camera characteristics and the camera array setup. In the 2D plane of a camera, the accuracy depends on the distance, angle of view of the camera and its resolution. For a given angle of view, the greater the distance between a camera and a marker, the larger field of view and the lower accuracy. Therefore, the camera setup, camera position, resolution and the number of cameras used dictate the system accuracy. In recent years, thanks to a continuous increase in camera resolution, the Qualisys system improves quickly. The highest resolution improved from 1.3MP (megapixels) to 12MP between 2008 with the QOUS3+ and 2015 with the QOUS7+. Characteristics of the cameras available in year 2015 are shown in Table 2. In this table, the “normal mode” with recording rates above 180 frame per second (fps) is suitable for most of the MRE testing.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Normal mode (full FOV)</th>
<th>High-speed mode (full FOV)</th>
<th>Max fps$^1$ (reduced FOV)</th>
<th>High-speed video</th>
<th>Outdoor$^2$</th>
<th>Motorised lens control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oqus 1</td>
<td>0.3 MP</td>
<td>250 fps</td>
<td>n/a</td>
<td>1 000 fps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oqus 3+</td>
<td>1.3 MP</td>
<td>500 fps</td>
<td>0.3 MP</td>
<td>1 750 fps</td>
<td>10 000 fps</td>
<td></td>
</tr>
<tr>
<td>Oqus 5+</td>
<td>4 MP</td>
<td>180 fps</td>
<td>1 MP</td>
<td>360 fps</td>
<td>10 000 fps</td>
<td></td>
</tr>
<tr>
<td>Oqus 7+</td>
<td>12 MP</td>
<td>300 fps</td>
<td>3 MP</td>
<td>1 100 fps</td>
<td>10 000 fps</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Qualisys video camera specifications (information from Qualisys website: [http://www.qualisys.com/products/hardware/oqus/](http://www.qualisys.com/products/hardware/oqus/))

It can also be noted that a range of lenses is available for the cameras, resulting in angle-of-view in air between 14 and 70 degrees. Introducing wide-angle lenses and higher camera resolution is a significant improvement as the number of cameras needed to cover a wide volume can be reduced.

### 2.2.3.5 Integration with other acquisition systems

The Qualisys data software operates independently from conventional analogue sensor signals and is not usually connected to the same acquisition system as other sensors in use. This means the position time series recorded will be stored in a separate data file.

Within most of the projects involving underwater motion measurement, other parameters (such as force, pressures, water levels, etc.) need to be recorded and synchronised with the position data. Two technique can be used to synchronise the two sets of data:

- **Trigger signal:** this is the most common practice, using a digital trigger signal. The acquisition system sends a pulse when starting the acquisition. Qualisys software can be setup to start when receiving the pulse from an external acquisition system.
- **Real time streaming:** Qualisys developed toolboxes allowing real time data streaming to other applications such as Matlab, Labview, Simulink, etc. Therefore all the recorded data can be stored on a single file. This can also be used with Labview for example, in a feedback loop for real time control. However, it does not allow data post processing if errors are encountered or data is corrupted.
2.2.3.6 Equipment available amongst Marinet partners

Amongst Marinet partners the Qualisys motion measurement is the only system used for general MRE testing in test facilities. While most of the partners own an aerial system, only four partners own the hardware required for underwater motion measurement. Partners and their system characteristics are listed below:

- **ECN**: six Oqus underwater cameras and an aerial system.
- **FloWaveTT**: eight OQUS7 above water covering an area of about 12 to 20m above the water surface. Four OQUSS+ underwater fixed on the raisable floor.
- **IFREMER**: three Oqus 3+ underwater cameras and aerial system available. This is used either in the deep seawater wave tank at IFREMER in Brest or the wave-current circulation tank at IFREMER in Boulogne sur Mer. Cameras are installed on the basin floor or held below the surface with a frame fixed on an aerial structure.
- **Plymouth**: both aerial and underwater cameras are available.
- **University of Strathclyde** does not own underwater cameras, however, a course and demonstration tests was carried out in the Kelvin hydrodynamic laboratory. This setup included three underwater cameras (2 x Oqus 310+, 1 x Oqus 510) and six aerial cameras. The demonstration test is described in more details in section 2.3.2.

2.2.4 LA Vision Particle Image Velocimeter

LA Vision Particle Image Velocimeter is developed for the measurement of particles motion giving a representation of the water velocity in the entire field of view. The system detects the position of particles in suspension in water and calculates their motion using high sampling rates. They are generally used to measure the water velocity around an object underwater in a small area, typically under 0.5m length. It is composed of one laser and two cameras underwater measuring in stereovision the motion of particles in suspensions.

This system cannot be used for the motion measurement of a floating body, given the restricted measurement volume dimensions. It can however be used for the measurement of small and constrained movements on a fixed object underwater such as a PTO system or material deformation. The principle of operation is similar to other stereo vision systems described in this document. For the measurement of objects, the laser is not required and markers can be placed on the moving parts.

There is no application know amongst Marinet partners. However UCC, Plymouth University and Edinburgh University own this equipment and could use it for future trials when applicable.

2.3 EXAMPLES OF UNDERWATER OPTICAL MEASUREMENT IN MRE TESTING

Underwater optical motion measurement systems were used in a large number of tests in the field of offshore technologies, including MRE. This section highlights examples carried out by Marinet partners.

2.3.1 Steel catenary riser in IFREMER deep seawater wave tank

The Dynascope system was used to study the displacement of Steel Catenary Risers in the Touch-Down Zone (TDZ) induced by top motion (Le Cunff, Biolley and Damy 2005). For this study, two model pipes were tested, corresponding to oil-filled and gas-filled risers. The motions of the risers in the TDZ were recorded by two different optical systems, as shown in Figure 21. One 2D-tracking system, with one camera, was recording the motion of six to seven points on the riser (marked with white bands glued to the riser) continuously in contact with the seabed, and the Dynascope system using two cameras for recording the 3D-motion of about eight targets above the touch-down point. The absolute motion measurement precision was about 1 cm, while the relative precision was about 1mm.
2.3.2 Marine riser at the University of Strathclyde

Tests of a marine riser were carried out at the University of Strathclyde in 2014 in the Kelvin Hydrodynamics laboratory. During experimental work, presented in (Castillon, Barltrop and Day 2014), a vertical beam partially submerged in a flow of water was tested. The cantilever beam motions, induced by vortex shedding, were measured by a Qualisys motion tracking system including five aerial and three underwater cameras. Markers on the cantilever beam were made using reflective tape.

Figure 22: Overlay view obtained with QTM software. From (Castillon, Barltrop and Day 2014).

The overlay view obtained with QTM and reproduced here in Figure 22 shows the riser in the centre of the towing tank, with the markers identified by QTM as blue dots. An underwater camera can be seen on the right side of the picture.
2.3.3 Wave energy converter S3 at ECN

The wave energy converter S3 developed by SBM was tested at ECN in 2013 (Babarit, et al. 2013). Structural deformations of the 10m-long flexible tube were measured with the Electro-Active Polymers (EAP) on its surface, while its motion was recorded by the underwater Qualisys system.

![Image of S3 being tested at ECN](image)

*Figure 23: Picture of the S3 being tested at ECN. The Qualisys markers reflecting the cyan light used by Qualisys underwater system can clearly be seen. Picture from (Babarit, et al. 2013).*

The underwater markers attached to the bottom of the tube can clearly be seen in the picture reproduced here in Figure 23. During these tests, the three Oqus cameras used were placed about 10 m away from the device.

2.3.4 Sustainable Marine Energy PLAT-O tidal device tests at IFREMER in 2013

A 12\textsuperscript{th} scale model of Sustainable Marine Energy (SME)’s PLAT-O tidal device was tested in the recirculating water channel in IFREMER, Boulogne-Sur-Mer, under wave and current conditions (SME 2013). The device’s motions were tracked using three underwater Oqus cameras, with two placed close to the tank floor and one placed close to the surface, downstream of the device. In Figure 24, the underwater cameras can be seen on the left picture. Qualisys markers are indicated by the letter d on the right picture. The picture colour is characteristic of the cyan blue used by the underwater motion tracking system.

![Image of SME's PLAT-O device](image)

*Figure 24: Pictures of SME’s PLAT-O device being tested at the recirculating water channel in IFREMER. From (SME 2013).*

2.3.5 TFI tests at ECN

The Underwater Qualisys system was used for mooring lines testing at ECN. Access to ECN wave tank, granted by Marinet to the company Technology From Ideas (TFI), aimed at testing combined elastomeric and thermoplastic mooring elements. As mentioned in the access report (TFI 2013), and shown in the Figure 25, Qualisys markers were placed on the mooring components in order to follow their relative movements.
The tests carried out concluded that the TFI tethers did manage to reduce the peak mooring loads by 60 to 70% depending on the sea state, and the standard deviation in loads by up to 50%.

### 2.3.6 SWMTF tests at IFREMER deep water tank

In 2014, IFREMER carried out tests on the dynamic behaviour of mooring lines in the Brest deep-water wave tank. The model chosen for the tests was a fifth scale model of the “South West Mooring Test Facilities” (SWMTF) buoy developed within the MERIFIC project (Marine Energy in Far Peripheral and Island Communities). These tests aimed at better understanding the mooring lines effects on the behaviour of the buoy. A better estimate of the damping of the low frequency motions was expected. The originality of the set-up lied in the use of a hexapod (6 DOF motion generation system) upside down over the tank. This was used to control the buoy motions while measuring the mooring line forces and mooring line motions using the Qualisys underwater system.
The mooring lines, made of textile lines and chains, were equipped with reflective tape, as shown in Figure 28 and Figure 29.

![Figure 28: reflective tape positioned on the mooring lines](image)

![Figure 29: reflective tape on the chain.](image)

Three Oqus 3+ underwater cameras were used to track the mooring lines motion. As shown in Figure 30, a bridge across the tank width was used as support structure to hold the three cameras at 50 cm under the water surface.

![Figure 30: Model and underwater Oqus cameras setup in Ifremer’s wave tank.](image)

This setup enabled an easy adjustment of the cameras fields of view from the surface. Also, the absence of large waves allowed camera proximity to the free surface. Large waves could induce camera motions and measurement distortions. The working volume was approximately a cube of 5m x 5m x 5m. The calibration was carried out using the calibration frame fixed on a mechanical structure, hung from the carriage, behind the lines and aligned with the tank axis.

The Automatic Identification of Markers (AIM) mode was used in order to ease the data processing of the numerous recorded trajectories. This mode is programmed in the QTM software to recognise each markers placed on a flexible structure when the distance between each successive marker remains constant. In this case the mooring line is not elastic and the AIM mode can be used.
More underwater cameras would be a real advantage to improve the motion tracking quality and enlarge the working volume (limited to a volume of 5*5*5m in this setup). The data set is not complete so far, some further investigation should be carried out in the future.
3 ACOUSTIC POSITIONING

The low visibility conditions under the surface do not allow light propagation over long distances, and the fact that radio waves penetrate only a few wavelengths in water render impossible radar detection. Acoustic waves do however propagate in water and are not influenced by the water turbidity or small particles in suspension. Hence, they are so far the most effective information carrier for underwater remote transmission over large distances. For this reason, acoustic systems for localization and positioning were developed and are now commonly used in the offshore environment.

Many acoustic position measurement systems exist or are under development. They range from the measurement of a single point position to multiple points and full 3D imaging. They are able to measure the position at each time step and create position and motion time series. These systems are widely used in offshore engineering and they are found or can be used in applications in the field of MRE.

3.1 UNDERWATER SOUND PROPAGATION

Sound propagates further than any other known communication techniques underwater. Sound also propagates further and faster in water than in air. This makes acoustic systems a suitable technique for underwater communication and position measurement over much larger distances than optical solutions. In deep offshore locations an acoustic signal can travel tens of kilometres if the emitted power is sufficient. Research on underwater acoustics started in the nineteenth century and is now in an advanced stage.

The intensity of the sound, as it propagates through water, reduces for two main reasons, absorption and spreading. The sound is in most cases emitted in all directions and propagates in a sphere shape surface. Therefore, the further from the point of emission, the larger the surface of the sphere. The sound decreases in inverse proportion to the sphere surface.

The magnitude of the absorption coefficient in seawater is a function of three components: the absorption of sound by pure water, by boric acid, and by the magnesium sulphates. The thermal energy transfer associated with chemical relaxation processes drives the absorption of sound by seawater salts. In specific wavelengths, pressure variations frequencies cause dissociation of the magnesium and boron salts. For frequencies >10 kHz and <100 kHz, most of the absorption is due to magnesium sulphates. Below 10 kHz the boric acid term is important and above 1000 kHz absorption by pure water is significant. The Figure 32 (Lurton 2010) provides the sound propagation absorption in sea water. The top left graph gives the contribution of the three components, pure water, magnesium sulphates (MgSO4) and boric acid (B(OH)3) for the average sea water conditions at the water surface (Temperature of 15 °C, salinity of 35 p.s.u.). The other graphs show the influence of salinity (top right), temperature (bottom left) and water depth (bottom right).
Additional conditions can affect the sound propagation:

- The water surface: on a smooth water surface, a large part of the sound is reflected and on a rough surface, reflected sound is widely spread in direction.
- The sea floor: on the sea floor, absorption, reflection and directional spreading can happen depending on the floor characteristics and the acoustic signal frequency. High frequency signals mostly reflect on the sea bed and low frequency signals mostly penetrate the sea bed.
- Non-linear propagation: over long distances and variable depth, large variations in water characteristics and sound speed can induce a channelling effect where sound doesn’t propagate in straight lines.
- Water current creates a linear displacement of the acoustic signal.
- Background noise from the sea, from reflection on the sea bed or sea surface and from the survey vessel can also affect the measurement accuracy.

The sound speed must be accurately assessed as it varies underwater depending on the water conditions. The three main factors influencing the sound speed in water are the temperature, salinity and hydrostatic pressure. Generally, an increase in temperature and salinity will increase the speed of sound in water. This ranges from about 1450 to 1570 m/s and can be calculated using known formulas that take into account at least these three parameters.

### 3.2 Measurement Principle

Most acoustic position measurement systems measure the distance between the target (objects with position to be measured) and each acoustic transponders placed at a known location. The 3D position of a target is known by triangulation of its distance from at least three transponders. The relative distances are estimated from the measured time-of-flight and known speed of sound. They use a specific acoustic communication protocol between transponders and target(s) in one or both directions. The travel time and speed of sound are used to estimate the distance and acoustic signal frequencies are used to communicate useful information such as transponder identity.

Most common underwater acoustic waves used have frequencies between 10 Hz and 1 MHz, because sound waves with frequencies greater than 1 MHz are quickly absorbed, and those with frequencies lower than 10 Hz penetrate into the seabed.

### 3.3 Acoustic Position Measurement Systems

Underwater acoustic position measurement systems can be classified into three broad classes: Long baseline, Short baseline and ultra-short baseline. They are classified in this list by the distance between transponders in the array and the way they are positioned.

#### 3.3.1 Long Baseline (LBL) systems

Long Baseline (LBL) systems are characterised by a network of sea-floor mounted baseline transponders, as shown in Figure 33. LBL systems get their name from the fact that the distances between the transponders are of the same order of magnitude as the distance between the interrogator and the transponders.
The interrogator, attached to the system to be monitored, first emits an acoustic signal, which is received by the baseline transponders. Those latter reply to it, with a specific frequency for each transponder, and their replies are received back by the interrogator. The time of flight of the feedback signals are measured, which result in the estimation of the distances between the interrogator and each baseline transponder. This is then used to compute by triangulation the 3D position of the interrogator. The resulting position, obtained in a referential linked to the transponders, can be directly converted into geo-referenced position if the transponders positions are known.

![Figure 34: Picture of transponders deployed on flotation collars (left) and on seabed tripods (right). From (http://www.sonardyne.com).](http://www.sonardyne.com)

Transponders are installed on the sea bed with gravity base such as tripods or a combination of anchor and floating collars as shown in Figure 34. They are lowered from the vessel to the seabed with low positioning accuracy and then calibrated in position. The transponder position calibration can be done by referencing the transponders to either an absolute position such as Global Positioning System (GPS) or a relative coordinate reference frame. The absolute positioning with GPS can be done by sailing a vessel around the unit and record simultaneously acoustic ranges from each transponder to vessel, and the vessel GPS position. Relative positions can be measured through baseline calibration, measuring the acoustic time of flight and calculate the distances between each transponder.

LBL systems offer the highest accuracy potential and large distances and depth ranges. Accuracy in the range a few decimetres can be achieved with distances from 50 to 2000m and operation depth of 7000m. They are generally used on underwater work sites where large structures are installed and accuracy is expected to be high, such as oil platforms. LBL systems become less attractive for projects with lower risks and budgets as they are costly and may be complex to deploy on the sea bed.

This technology was not used by Marinet partners, however a number of LBL systems are commercially available.

### 3.3.2 Multi User LBL (MULBL) systems

Multi User LBL systems are setup as LBL systems and use the standard LBL transponders but the acoustic communication protocol between each element is specifically designed for the positioning of multiple targets simultaneously and with a unique transponders array. The main hardware difference is in the target acoustic interface being an acoustic receiver only.

In MULBL systems, transponders are placed on the sea bed and calibrated in position, such as LBL systems. One transponder is acting as a master and emits a first signal at the start of each sampling period. When other “slave” transponders receive the signal, they synchronise their clock and emit a signal to the targets at a predefined time after the start of the sampling period. The time lag between the first “master” signal and the synchronised signal must be higher than the acoustic time of flight from the master transponder to the furthest slave transponder.
The position is therefore determined on the targets from the time shift between each signal received from all transponders.

This technique offers high accuracy and update rates of about 2 seconds. It is suitable for multiple targets on multiple structures or can be used for multiple targets on one large structure which can be processed to provide the 6D position of the structure.

### 3.3.3 Short baseline (SBL) systems

Short Baseline (SBL) systems are characterised by a network of transponders mounted under a platform or a large boat, as shown in Figure 35, with spacing of typically tens of meters. This solution removes the need for seabed-mounted equipment. SBL systems get their name from the fact that the distances between the transponders are limited to the size of the floating structure under which they are attached. Minimum vessel dimensions are required depending on the distance to the target.

![Illustration of a short baseline system. From (http://en.wikipedia.org/wiki/Short_baseline_acoustic_positioning_system).](image)

The interrogator, attached to the system to be monitored, first emits an acoustic signal, which is received by the baseline transponders. Those latter reply to it, with a different frequency, and their replies are received back by the interrogator. The time of flight of the signals is used to estimate the distances between the interrogator and the baseline transponders, which are then used to compute by triangulation the position of the interrogator. The resulting position, obtained in a referential linked to the transponders, can be directly converted into geo-referenced position if the transponders geo-locations are known.

The accuracy of SBL systems depends on the spacing between transponders and the distance to the target object. The position accuracy using vessel-mounted instrumentation is also heavily dependent on the knowledge of the vessel position, and therefore on the quality of its on-board instrumentation.

This technology was not used by Marinet partners, however a number of LBL systems are commercially available.

### 3.3.4 Ultra Short Baseline (USBL) systems

Ultra Short Baseline (USBL) systems are characterised by an array of transponders placed on a single head with dimensions that can be less than one meter. This results in a much more compact system as illustrated by the picture of Teledyne’s Benthos DAT probe shown in Figure 36 and can be mounted on vessels of any size.
Unlike LBL and SBL systems, which determine position by measuring multiple distances, USBL systems measure the target distance from the transducer pole by using signal flight time, and the target direction (angular position) by measuring the phase shifts between the reply signals recorded by the individual transducers. Three or more sound transducers are required to measure the angular position of the target and the six degree vessel position must be accurately known.

USBL are generally fixed onto a pole aside a vessel, offering an easier deployment than SBL systems. Operating ranges of greater than 6,000 metres are achievable, with the capability to follow multiple targets. USBL systems present good long term accuracy but can be affected by the background noise and environmental conditions (aeration, noise, thruster wash).

Other USBL configurations exist, for example USBL systems can be used in the so-called inverted configuration (IUSBL mode). In this configuration, the transceiver (with interrogation transponders array) is fixed on-board the target object, and a transponder is fixed onto the vessel or any known location. In this configuration, accuracy and repeatability of the acoustic signals are improved, as the transceiver is located in a low noise and dynamically stable environment. Such IUSBLs are often implemented for automatic docking capabilities of an Autonomous Underwater Vehicle (AUV).

Research and development is ongoing, with recent developments such as:

- A method for USBL navigation of an AUV including measurements from on-board Doppler Velocity Log (DVL) and an attitude and Heading Reference System (AHRS), as well as Differential Global Positioning System (DGPS) position from the USBL (Ridao, et al. 2011). In this case, the USBL transponder is fixed onto the AUV, and the transceiver fixed onto a vessel.
- Implementation of a system using a combination of USBL transducers on an AUV and an array of LBL transponders (Batista, Silvestre and Oliveira 2012). As shown in Figure 37, the considered AUV is equipped with five USBL probes and evolves in a zone marked with a LBL acoustic positioning system. The authors present a novel Attitude and Heading Reference System for underwater vehicles, based on the LBL and USBL combination, in addition to rate gyro measurements, avoiding the use of magnetometers that can yield inaccurate or wrong results when operating near structures with a strong magnetic signature.
One Marinet partner, WavEC, is using a Tritec USBL system to track the coordinates of an Remotely Operated Vehicle (ROV) and the path covered during operation. During post processing, the ROV position data is compared with the vessel position recorded with a GPS and absolute position of the ROV can be calculated. The ROV is mainly used for recording videos for the survey of existing structure at sea.

### 3.3.5 GPS intelligent Buoys (GIB)

The GPS Intelligent Buoy (GIB) is a position tracking system characterised by an array of transponders mounted on a network of surface buoys with a large spacing between each transponder (similar to LBL systems). It was developed by ACSA, a company specialised in undersea robotics and underwater positioning systems. During each cycle, the transmitter placed on the target emits two signals, one synchronous with the GPS reference time and one after a time lag proportional to the depth of the target (the depth of the target is derived from an additional sensor mounted on the target). Each transponder on the surface buoys record the time of arrival of the two signals and calculate the time of flight and depth of the target. The position of the acoustic source is then derived by triangulation knowing the GPS position of each buoy and the relative distance of the object to each buoy.

![GIB Concept](http://www.acsa-alcen.com/how-does-system-work)

**Figure 38: GIB equipment set-up. From ACSA website (http://www.acsa-alcen.com/how-does-system-work)**

The main advantages of GIB systems are:
- fast installation on board non dedicated ships
- no offshore calibration required
- real-time measurement capability

Their main drawbacks are:
- lower accuracy, around one metre in the three directions
- require multiple buoy and mooring lines installation in the water
- Sampling rate in the order of one sample per second
- High power consumption
GIB systems were not used by Marinet partners. However they are used within numerous Navies and commercial organisations in Oceanographic applications, ROVs or divers guidance, survey applications, submarine tracking, in a wide range of environments such as harbours, shallow to deep water, open waters.

### 3.3.6 Passive sonar reflectors

Passive sonar reflectors are objects designed to reflect acoustic waves back towards the sources that emitted them. Traditional passive sonar reflectors are of the corner type, shown in Figure 39 (a). They are made with three perpendicular planes intersecting. The incoming waves are reflected three times on the reflector, on each of its faces, resulting in a direction reversal.

![Figure 39: (a): Picture of a corner reflector from West Marine; (b): Picture of a SonarBells on a bridge. Image copyright © Mercator Media 2015](image)

Spherical targets have also been a popular reflector geometry for decades. Several solutions have been attempted to increase its target strength (a measurement of the reflector’s properties to reflect back acoustic signals). The SonarBells device, commercialised by SALT, a spin-off of the UK Ministry of Defence shown in Figure 39 (b), is an omnidirectional high target strength passive sonar reflector available in sizes from 50 mm to 275 mm in diameter that can be matched to a broad range of sonar operating frequencies (Islas-Cital, et al. 2013). The two materials of its shell and core create a constructive interference which delivers a return signal significantly above what might be expected from a hard reflecting sphere.

SonarBells are easily put down in depths of water up to 300m to mark assets that need to be monitored, repaired or recovered. Although the units are currently certified to 100m, they have recently been tested down to 4,100m.

### 3.3.7 Acoustic imaging

For almost forty years, there have been numerous attempts to design an acoustic camera. In the journal article (Jonsson, et al. 2009) is mentioned that one of the first successful was the EWATS system created by EMI in the seventies. It had two hundred lines of resolution and a maximum of ten meter range. Today, several commercial products exist. The system DIDSON developed by Soundmetrics (http://www.soundmetrics.com) is widely employed. The Echoscope, developed by CodaOctopus, combines measurements from 16000 acoustic beams to obtain 3D images at rates of up to 12 frames per second. It can combine the measurements made over a volume to obtain a full 3D image of the objects or sea bed, as the one shown in Figure 40.
Measurements, or at least good estimates, of the motions of the observed bodies can be obtained with such 3D video imaging technique. This 3D sonar was used for example at the SEM-REV test site to observe the power cable connecting the offshore site to onshore electrical grid.

Multibeam sonar profilers, as those developed by Teledyne, are also used in the offshore industry. More details on imaging sonar technique can be found in (Murino and Trucco 2000).

4 INERTIAL SENSORS

4.1 TECHNOLOGY

Motion Measurement systems using inertial sensors calculate the position of a target based on an initially known position and integration of measured motions after the last calibration. Hence, their calculation method is based on a different approach in comparison with acoustic or optical systems and they can operate stand alone, no external element with known position is needed (transponders, cameras, etc.). They generally combine measurements of linear accelerations and angular velocities from at least three orthogonal accelerometers and three orthogonal rate-gyrosopes. The system integrates its measured velocities and accelerations in the six degrees and therefore provides its position relative to the position it was setup and calibrated. They can be very accurate in the short term but drifts building up from the integration of measured motions can be an issue for long term applications.

Recent inertial navigation systems integrate three gyroscopes, three accelerometers and three magnetometers. They can obtain high accuracy of the order of some tenths of degrees in rotation. The magnetometers are less accurate than gyroscopes (Woodman 2007) and can be affected by local disturbances in the earth’s magnetic field caused by nearby magnetic objects. However they can be used to reduce the long term drift in an Inertial Navigation System (INS). An INS can also fuse the inertial data they measure with data from different sources including Global Navigation Satellite System, odometer, DGPS, Doppler Velocity Logger (DVL), or acoustic positioning systems.

The sensors are Micro-machined Electro-Mechanical Systems (MEMS) devices. They are very small and many sensors can be integrated in a single device, Figure 41 shows as an example the INS developed by the company SBG depicted.
Figure 41: Picture of the Inertial Navigation System Ellipse-E developed by SBG. Picture from SBG website.

Advantages:
- These systems do not rely on any external infrastructure such as transponders with known location.
- They provide high accuracy in the short-term and high acquisition rates.
- They can be lightweight and low energy consumption.
- Low price.

Drawbacks:
- The six degree position is obtained from the integration of measured parameters which introduces a long term drift. This can be corrected by fusing data from other sensors with the data from the Inertial Motion Unit (IMU).

4.2 APPLICATIONS

A large number of manufacturers provide commercial and robust INS (SPATIAL, SBG systems, Vectornav, Xsens, etc...) for a wide range of applications such as aircrafts, missiles, but also weather buoys, submarines or AUVs. They could be used on MRE test sites to help during the descent of heavy machinery on the seabed, like a connection hub, which needs to stay horizontal.

Experimental tests of MRE devices included one or more IMU units measuring body motions and communicating data wirelessly to external systems. For example, the floating wind turbine model tested at ECN by the INNWIND consortium during a free-of-charge access period granted by Marinet did include such instrumentation (INNWIND 2014). Inside the floating platform, an IMU was installed to measure its motions. It was connected to an on-board acquisition board which sent wirelessly the IMU data to the control computer on the side of the tank. The system electrical power was provided by a battery pack.

4.3 EXAMPLE: SOUTH WESTERN MOORING TEST FACILITY (SWMTF)

The South Western Mooring Test Facility (SWMTF), part of the MARINET network, is a mooring load and response test facility using inertial sensors and designed to conduct long term sea trials of mooring components. The research equipment is mounted on a buoy that can be moored in Falmouth Bay off Cornwall, UK, see Figure 42. It is fully equipped with load cells, motion sensors and other instrumentation to test a variety of catenary and taut mooring arrangements offshore. It can transmit data to shore in real time and allows comprehensive evaluation of mooring systems under real sea conditions. The sensors available are listed below:

- Six-axis inertial sensing system, 'MotionPack'
- Tri-axis Load Cell (3 off)
- In-line Load Cell (3 off)
- Vishay CEA-06-26OUR-350 strain rosettes
- Tilt-compensated flux-gate compass
Inertial sensor:
It is composed of a Systron-Donner Motionpak multi-axis inertial sensing system and is installed in the Electronics Module to provide high precision measurement of acceleration and rate of rotation about three axes. The Motionpak contains three axes gyroscope and accelerometer with characteristics shown in Table 3.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Acceleration (g)</th>
<th>Rotational speed (degree/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>V/g</td>
</tr>
<tr>
<td>X</td>
<td>+/-2</td>
<td>3.75</td>
</tr>
<tr>
<td>Y</td>
<td>+/-2</td>
<td>3.75</td>
</tr>
<tr>
<td>Z</td>
<td>+/-3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 3: Measurement ranges and sensitivities of the Motionpak sensor

The unit is mounted on the vertical centreline of the electronics module such that its base plane is 177 mm above the lower outside face of the electronics module. The Z axis is aligned with the axial centreline of the electronics module, positive downwards.

Note: when interpreting the accelerometer outputs gravitational force must be deducted before calculating accelerations. Thus when the Module is vertical and stationary the Z output will read an acceleration of 1 g upwards, while X and Y accelerations are zero.

Compass:
The electronics module contains a flux gate compass mounted towards the top of the enclosure to provide a measurement of heading. The heading reading is compensated for tilt in pitch and roll angles. The compass heading output is substantially affected by objects (primarily stainless steel and plastic) in its vicinity. It is recommended that the compass be ‘swung’ when installed in the buoy. The voltage output spans 0 to +5V over the range 0 to 360 degrees magnetic, corresponding to a sensitivity of 72 degrees per volt.

Additional equipment and description on this facility are provided in the publication written by (Johanning 2008) and more recently by (Harnois 2012). Results from this facility have also been used by (Thies PR 2014) for mooring line fatigue evaluation. In particular, a study focused on wave conditions which induce responses that lead to mooring fatigue loads. The results of this study indicate a concentration of fatigue mooring loads for specific Hspeak/Tppeak values inside the measured wave joint probability distribution. This has its importance in the design of a mooring system for floating MRE devices as it affects the accumulated fatigue damage, and should consequently be included in future mooring standards for MRE’s.
5 CONCLUSIONS

In the development of marine renewable energy technology, underwater motion measurement is required for research activities at all scales. The systems for remote underwater motion measurement presented in this document highlight that solutions are commercially available for most of the applications in MRE development activities. Solutions commonly used can be classified in three categories having different principles of operation, using either optical, acoustic or inertial devices. Their characteristics and limitations make each of these solutions more suitable for specific applications. While optical systems are the most suitable in hydrodynamic test facilities indoor, acoustic and inertial systems are more common in offshore applications. Although they are available, all these systems are still under development in order to increase their accuracy or operation range and reduce costs or installation requirements.

For applications in indoor facilities, optical methods derived from stereo vision are the most commonly used. Their accuracy can be very high and they are commercially available. Several underwater systems exist but the Qualisys system is one of the most common in experimental hydrodynamic facilities in Europe. It is also the only one used amongst Marinet partners. This is due to the versatility of the system which can be used above and underwater and with a large number of cameras to increase the size of the measured volume or its accuracy. It is suitable for accurate motion measurement of several rigid or deformable bodies. The system, applicable in air or water, can also be setup as a twin system to monitor motion above and below water simultaneously. This offers great possibilities for non-intrusive remote motion measurement of floating, submerged or semi-submerged wave energy converters. It is also developed with an advanced software making its setup, operation and data collection simple. It has been used in the past years to investigate many different systems, including riser dynamics, power take off motion, deformable wave energy converters, mooring lines and mooring line components. The main limitation for available underwater optical motion systems is the hardware cost which is often too high for small scale facilities.

Acoustic positioning systems are a solution for applications where optical systems cannot be used. The setup and principle of operation can be considered similar to optical systems but they are suitable for measurement in much larger distances (tens of meters with optical and kilometres with acoustic systems) and are not significantly affected by the water quality. However, they have a lower accuracy and most of the systems can only measure one single target which does not allow for 6D coordinates measurement. They are used extensively in the offshore industry and have been used in some MRE development activities. Many types of technologies are developed and use different system architectures and acoustic communication protocols, each with their advantages and drawbacks. They are all composed of one or more acoustic emission devices and one or more receiver placed at specific locations. Most of the systems use the time of flight of the sound to estimate distances between the target and a number of devices at known positions. The target position is calculated by triangulation of distances obtained. More advanced systems can measure multiple targets or recreate a full object image. The offshore industry frequently uses acoustic positioning systems in underwater works such as inspection, maintenance of offshore structures, cable laying, ROV interventions and more. During future development activities of marine renewable energy technologies, some of these operations will be commonly carried out and similar techniques and equipment can be used.

Inertial sensors are a very different approach to the motion measurement as they measure the position and motion of a rigid body in relation to an initial know position where the sensor was setup. It integrates its measured velocities and accelerations, and therefore its position relative to its starting point. These sensors can be found nowadays very accurate, affordable and lightweight. However a drift in the position estimate is expected for long term application. Therefore, in a complete motion tracking system, they are usually used with other sensors, such as acoustic sensors, Doppler Velocity Logs, or GPS. These sensors have a lower accuracy but absolute reference which is able to correct the long term position drift.

These three solutions are considered as remote motion measurement systems. The measurement does not require any connection between the target body and a sensor or external body. However, target subjects in offshore applications are commonly used with a cable connection for data and power transmission. For a complete remote system, in most cases, the measured target needs to be equipped with an on-board battery and, when the position calculation is made on the target, an acoustic modem can be used if real time motion data is required.
6 WORKS CITED


Berlander, M. 2009. “Qualisys Oqus underwater system.”


Castillon, F., N. Barlitrop, and S. Day. 2014. “VIV and fatigue damage design guides during the tow operation for installation of free standing risers.”


INNWIND. 2014. “Floating Wind Turbine Model Test.”


Mie, Gustav. 1908. *Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen*.


Remote underwater motion measurement


TFI. 2013. *Tank testing of combined elastomeric and Thermoplastic tethers on a Wavebob WEC scale prototype device*. Infrastructure access report, Marinet.

TFI. 2013. “Tank testing of combined elastomeric and Thermoplastlc tethers on a Wavebob WEC scale prototype device.”


