Search, identification and collection of marine litter with autonomous robots

SeaClear

https://seaclear-project.eu

D3.1

Sensors selection report

WP3 – Robotic hardware developments

Grant Agreement no. 871295

Lead beneficiary: Subsea Tech

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Deliverable description	This report describes the results of the sensors trials to be mounted on the observation ROV, for litter detection and classification. The trials were carried out by Subsea Tech in Marseilles harbor. The report also explains the final selection made, based on sensors' performance, data quality and format, ease of integration and cost.

1 R = Document, report, DEM = demonstrator, DEC = Websites, patents filing, etc. OTHER: Software, technical diagram, etc. ETHICS = Ethics

2 PU=Public, CO=Confidential, only for members of the consortium (including the Commission Services), CI=Classified, as referred to in Commission Decision 2001/844/EC.

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Definitions

- **Beneficiary:** A legal entity that is signatory of the EC Grant Agreement no. 871295.
- **Consortium:** The SeaClear Consortium, comprising the below-mentioned list of beneficiaries.
- **Consortium Agreement:** Agreement concluded amongst SeaClear Beneficiaries for the implementation of the Grant Agreement.
- **Grant Agreement:** The agreement signed between the beneficiaries and the EC for the undertaking of the SeaClear project (Grant Agreement no. 871295).

Beneficiaries of the SeaClear Consortium are referred to herein according to the following codes:

- **TU Delft:** Delft University of Technology.
- **DUNEA:** Regional Development Agency Dubrovnik-Neretva County - DUNEA.
- **Fraunhofer:** Fraunhofer Center for Maritime Logistics.
- **HPA:** Hamburg Port Authority.
- **Subsea Tech:** Subsea Tech SAS.
- **UTC:** Technical University of Cluj-Napoca.
- **TUM:** Technical University of Munich.
- **UNIDU:** University of Dubrovnik.

Abbreviations

- **ASV**: Autonomous Surface Vehicle
- **GPS:** Global Positioning System
- **HD:** High Definition
- **INS:** Inertial Navigation System
- **SVP:** Sound Velocity Profiler
- **ROV:** Remotely Operated Vehicle
- **RTK:** Real Time Kinematic (enhanced GPS positioning)
- **UAV**: Unmanned Aerial Vehicle
- **USV:** Unmanned Surface Vehicle
- **UTOFIA:** Underwater Time Of Flight Image Acquisition
- **UV:** Ultra Violet

Executive summary

In order to optimize marine litter detection and classification, a set of various underwater sensors have been tested in real conditions (Marseilles harbour) to determine the most suitable ones for integration on the observation ROV. Different types of sensors have been tested, both visual and acoustic, including conventional video with standard and UV lights, a time of flight camera (Utofia), and a multibeam imaging sonar (Blueprint Oculus 750d).

This report gives the results of the different trials followed by a comparative analysis recommending the sensors giving the best performance for the purpose. The analysis is based on data quality, format exploitability, immunity to environment parameters such as water turbidity, ease of integration including weight and dimensions, and cost. While the former parameters define the detection and classification capabilities, cost is a major factor for the scalability of the system and the envisioned business case.

The recommended sensors are the conventional full HD video camera with high power LED lights and the dual frequency multibeam imaging sonar Oculus 750d. The first one will be used mainly in clear water to low turbidity waters (e.g. Dubrovnik sites) and the sonar will be essential in low visibility environments (Hamburg harbour).

Besides, upon recommendation from partner HPA (Hamburg Port Authority), an investigation has been made to identify adequate magnetic sensors to be able to detect and map buried metallic objects using remotely controlled metal detectors as opposed to divers hand held devices. The report gives the outlines of this investigation.

1. Introduction

1. SeaClear at a glance

The main goal of the proposed Search, Identification and Collection of Marine Litter with Autonomous Robots - SeaClear - project is to develop a collaborative, heterogeneous multi-robot solution engaged in collecting marine waste. The proposed solution will be the first that uses autonomous underwater robots for cost-effective marine litter collection. This goal will be reached by bringing together state-of-the-art technologies from the fields of deep learning, sensing, manipulation, aerial and marine technologies and by building a stable and reliable system capable of tackling a highly disputed social, economic and environmental issues, namely ocean pollution.

The SeaClear system will deploy a state-of-the-art ASV, capable of launching simultaneously 2 ROVs and serving as a landing platform for an UAV. The UAV and one ROV will be responsible for mapping the litter on the seabed, while the second ROV will collect the waste and transfer it to a collection basket, which in turns, is launched from the ASV and lowered to the seabed. Besides an initial bathymetry survey, the ASV will serve as a bridge of communication for the shore centre, where the entire operation is overseen and commanded. Clients can demand the service provided by the SeaClear system and follow-up the progress by simply accessing the web interface from their internet browser.

2. Deliverables objectives

The main objective of the deliverable is to report on the tests of the various sensors carried out since June 2020 to select a suitable suite to be integrated on the observation ROV for litter detection and classification in the SeaClear project.

The report presents the different tests and their results together with a comparative analysis on performances to make recommendation on the best suited sensors for this application.

2. Trials set-up and location

Most of the trials have been performed in Marseilles harbour, in front of Subsea Tech facilities using the inspection class ROV Tortuga, which is the designated collection ROV (see Figure 2). Some preliminary tests have been carried out in the Subsea Tech test tank. The bathymetry sonar has been deployed on the small Subsea Tech USV Cat-Surveyor (see Figure 32).

The location of Subsea Tech facilities immediately next to the seaside, within the harbour, allows deploying the ROV directly from our offices. Besides, the presence of numerous litter in this area, due to the public access to the water front, makes it a natural test site for litter detection.

Figure 1: Subsea Tech facilities on the seaside within Marseilles harbour

Figure 2: Subsea Tech inspection class ROV Tortuga

The inspection class ROV Tortuga is one of the standard underwater vehicles designed and manufactured by Subsea Tech. It was used for performing the tests as its important payload (12 kg) and its power allow integrating heavy sensors such as the time of flight camera Utofia or simultaneous sensors such as video and 2D sonar.

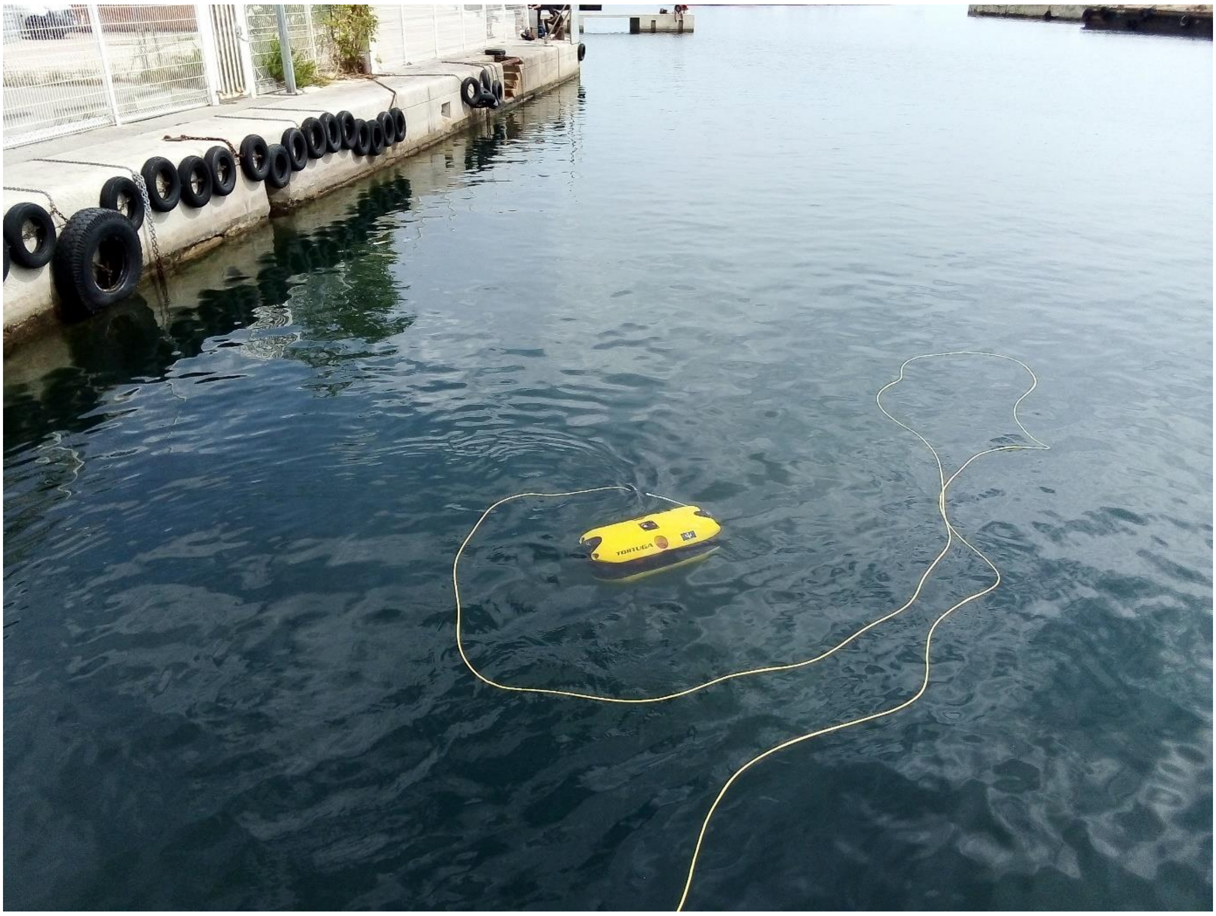


Figure 3: Tortuga ROV navigating in front of Subsea Tech wharf

In order to make preliminary tests before deploying the ROV and the sensors in a natural environment, Subsea Tech also uses a test tank, located in its facilities and which can be filled up with fresh or sea water as desired. Besides, the tank allows adjusting accurately the water turbidity by adding a given amount of silt, which can then be removed by the filtering system.

The tank has been used for the following sensors: UV light and Utofia camera.

The others sensors have been deployed directly with the Tortuga ROV except for the bathymetry sonar which was operated from the Cat-Surveyor USV.

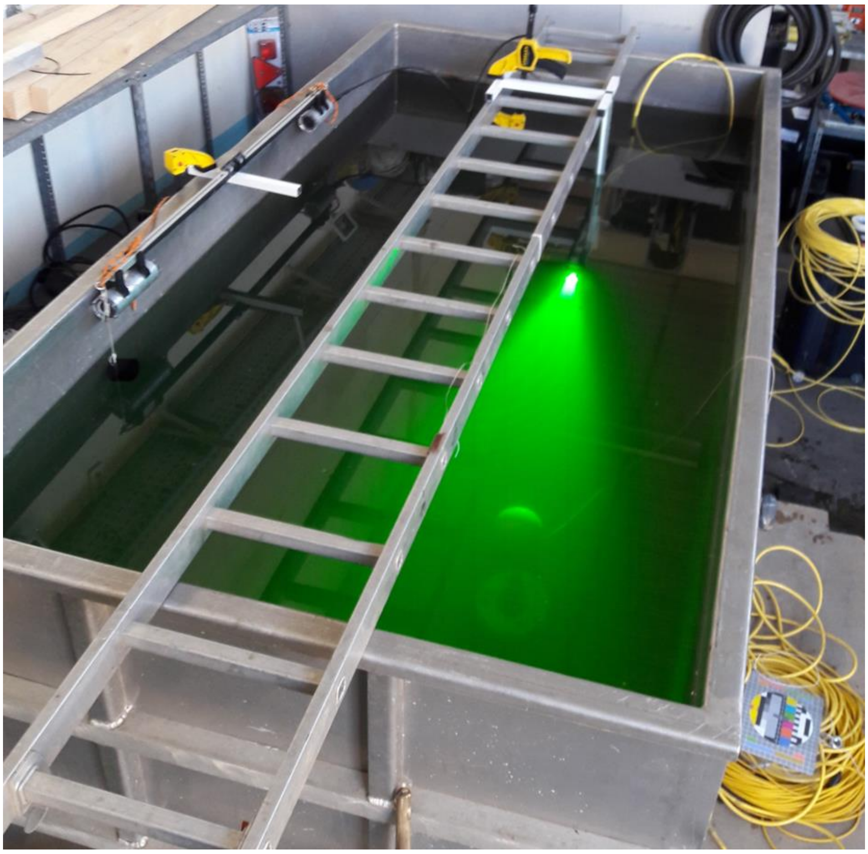


Figure 4: Subsea Tech test tank With Utofia time of flight camera under testing

2.1. Conventional video

The most common vision sensor on underwater vehicles is the conventional video camera. The former popular PAL or NTSC analog cameras have now been mostly replaced by full HD digital cameras with a clear improvement on resolution but no real gain in image quality when water becomes turbid.

4K cameras are also available but their resolution underwater is only enjoyable in ultra-clear waters. On the other hand, the large amount of data generated by 4K format requires a very high-speed communication and significant storage space which can be a drawback for integration on compact systems.

A lot of ROV operators are still using old fashioned low resolution but high sensitivity black and white cameras because they are better adapted to turbid environments (less light needed = less refraction on particles). It is not uncommon to see both high resolution color cameras and high sensitivity black and white cameras on the same ROV.

As a compromise, we have selected a high sensitivity (0.05 lux) full HD color camera which requires powerful but still reasonable LEDs lights (2 X 10 000 lumen) for optimal imaging in low light conditions.

Camera specifications:

Brand	SONY
Model	SIP-E510AS
Camera type	IP camera module H.265 5.0 Mp
Image sensor	1/2.7" 5.0 Mp OV OS05A10 CMOS
DSP	Hisilicon 3516A
Efficient pixels	2592x1944
Scan System	Progressive
Electronic shutter speed	Auto (1/25 ~ 1/10000s)
Min. Lighting - Colour	0.05Lux/F1.2
S/N ratio	≥ 50dB(AGC off)
Day/Night	Auto(ICR)/colour/B/W
WDR	Digital WDR >80db
White Balance	Auto
Control Gain	Auto
Noise reduction	3D-DNR
Lens FOV	Focal length 2.8 mm – Angle 115° (in air)
Aperture	F2.0

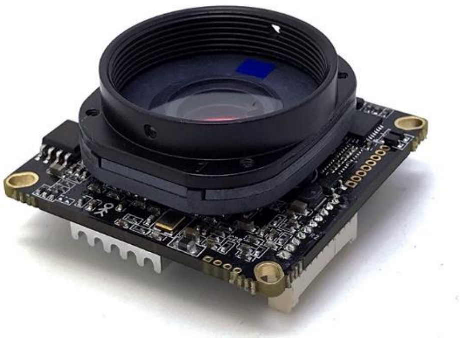


Figure 5: Tortuga full HD SONY camera

The SONY camera is mounted inside a waterproof casing on a Subsea Tech designed pan& tilt unit with an optical quality PMMA dome. One 10 00 00 lumen LED is installed on each side of the camera.

Figure 6: SONY camera mounted on Tortuga ROV with two 10 000 lumen LED lights

The standard Tortuga ROV is equipped with two of these cameras, one at the front, and the other at the back so integration work was not necessary. Similarly, both front and rear sides of the ROV carry two 10 000 lumen led lights, with the intensity adjustable from the pilot console. This last feature is important because light adjustment is necessary depending on parameters such as ambient light (solar light in shallow water) and turbidity. When solar light is available, there is no need for artificial light.

One of the problems with underwater video is the absorption of certain wavelengths depending on the depth and quality of the water. The blurred appearance of images acquired in turbid waters is mainly due to the phenomenon of scattering of incident light by the presence of particles, obscuring the scene similar to the fog in the atmosphere. Under such condition, images suffer from low contrast and low illumination, altered colour balance, and reduced viewing distance.

On underwater colour images, we notice a significant absorption of the red wavelength as soon as the depth reaches between 2 and 10 meters. Wavelengths having the best penetration capability are the green and the blue as showed in the diagram below. This explains why underwater images are mostly bluish, even after only a few meters depth.

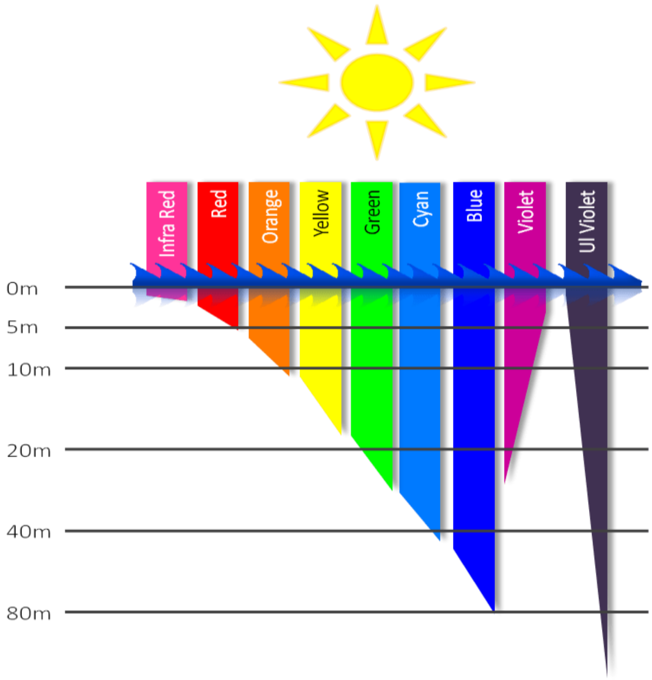


Figure 7: Typical absorption of colors underwater

This phenomenon appears clearly in the histograms of each red, green and blue component of an image taken a few meters below surface.

The colour distribution curves do not cover all possible intensities, and the maximum amplitude of the red component, and also of the green component to a lesser extent, is significantly reduced compared to that of the blue component.

A simple and automatic improvement over this problem of histogram distribution would be to apply a histogram equalization operation. In fact, by refocusing and "spreading" the distribution of the histograms between them, followed by an equalization of the amplitudes of each component, a significant improvement in the general quality of the image is obtained, particularly specifically for a human eye (sensitivity range colour).

However, this improvement based on a high-pass filter quickly shows its limits compared to groups of images with medium or high turbidity. The noise becomes too high, the colour distribution is distorted, and a tendency to strengthen and spread out "burnt" areas has been observed.

Sophisticated real time video enhancement systems such as LYYN systems (www.lyyn.com) offer interesting improvements in medium turbidity waters but only when such turbidity is uniform and created by very fine particles. This statement is issued from our 10 years' experience using LYYN systems (Subsea Tech is LYYN distributor for France since 2010) and we would not recommend the use of such a system for this application especially since the images will be processed for automatic detection and classification.

Following images have been taken in front of Subsea Tech facilities in July and November 2020. Note: the image quality is lower than the original video image because these are snapshot taken from the video stream. Main litter items are car tires, plastic bottles, plastic bags, aluminium cans, and metallic scrap

Figure 8: Car tire, partially covered with seaweed.

Figure 9: Plastic bottle, plastic glass and broken concrete pipe

Figure 10: 2 pieces of steel pipe, 1 m long – 500 mm diameter, left by Subsea Tech 5 years ago for ROV pilot training purposes.

Figure 11: Pipe extremity with small car tire in frontPipe extremity with small car tire in front

Figure 12: Unidentified piece of scrap

Figure 13: Plastic bottle and 2 plastic bags

Figure 14: Old aluminium can

Figure 15: Recent aluminium can, next to an old tire

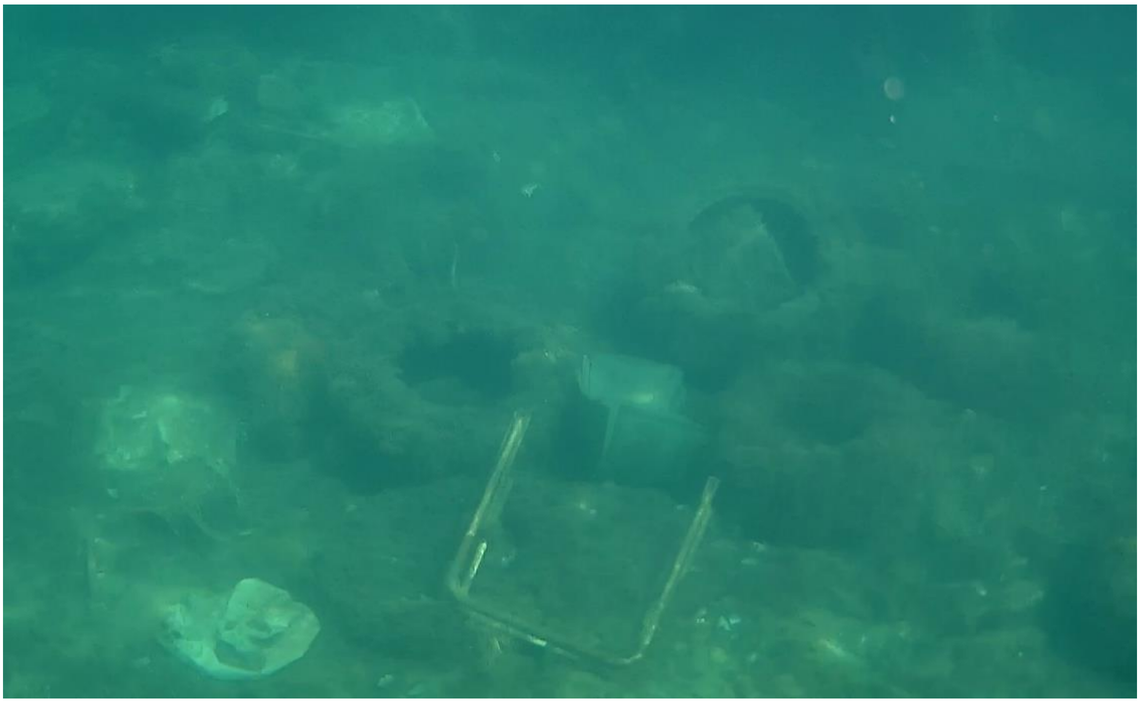


Figure 16: Bunch of tires with plastic bag and chair frame

Figure 17: Loss of targets when trying to see too far ahead

Figure 18: Pieces of rope

Figure 19: Piece of rope next to an old car tire heavily covered with seaweed.

Figure 20: Old motorbike frame

For both campaigns, weather was mostly sunny. Due to the limited water depth, 2.5 to 3 m, sun rays are sometime visible on the sea bottom (e.g.: Figure 10, Figure 14 and Figure 16). This could be a drawback and a challenge for image processing.

It can be easily noted that all images are mostly in green and blue colours not only because of light absorption (water depth is only about 2.5 m) but because most of the litter has been in the water for some time (typically more than one year) and is well covered with seaweed. “Recent” objects like plastic bags or aluminium cans are much more visible than large object like car tires thanks to their contrasting colour. On the other hand, targets like car tires are more easily classified thanks to their specific shape, even in low quality images.

Colour analysis and shape recognition are therefore potentially two complementary ways of detecting and classifying targets.

Complex targets like the motorbike frame or the unidentified scrap could be challenging tasks for automatic recognition, even with deep learning techniques.

As we will see later, HD video is clearly the most efficient sensor for litter detection and classification, at least for the human eye, but this efficiency is very quickly hindered by the level of turbidity.

2.2. Conventional video with UV lights

To enhance the capability of the system to detect and classify more easily the various targets, Subsea Tech proposed to use Ultra Violet (UV) lighting in replacement to standard white lights.

UV lights are well known by marine scientists to be efficient in discriminating live animals form each other and from non-living pieces of scene, as illustrated in the two images below:

Figure 21: Examples of underwater images with UV lights

UV lights for ROV are not readily available and delivery schedule was not compatible with project timing. It was therefore decided to build a homemade UV light from an off the shelf UV LED encapsulated in a waterproof enclosure

The selected UV LED is a Starboard LST1-01G011-UV02-00 LED with a 385 nm wave length.

Preliminary tests were made in the fresh water test tank with varying light conditions from full sunny to dark night.

Results were pretty disappointing, especially in ambient light conditions, the UV rays being hardly visible with human eye or video camera. This was later confirmed by scientists from IFREMER (French Marine Research Institute) using that technology that full darkness was required to obtain good results.

We therefore concluded that this solution was not compatible with the normal operating conditions of the SeaClear system where we will be most of the time in shallow water with an important ambient solar light. The UV light would also not be compatible with standard white light used for conventional video, ruling out the possibility of using both systems in parallel.

2.3. Time of flight Camera – UTOFIA

From 2015 to 2018, Subsea Tech participated in a H2020 project led by Norwegian SINTEF called UTOFIA, which stands for **U**nderwater **T**ime **O**f **F**light **I**mage **A**cquisition.

UTOFIA offers a compact and cost-effective underwater imaging system for turbid environments. Using range-gated imaging (Figure 22), the system extends the imaging range by factor 2 to 3 over conventional video systems. At the same time, the system has the potential to provide video-rate 3D information. This fills the current gap between short-range, high-resolution conventional video and long-range low-resolution sonar systems.

UTOFIA offers a new modus operandi for the main targeted domains of application: marine life monitoring, fisheries stock assessment, aquaculture monitoring, and seabed mapping.

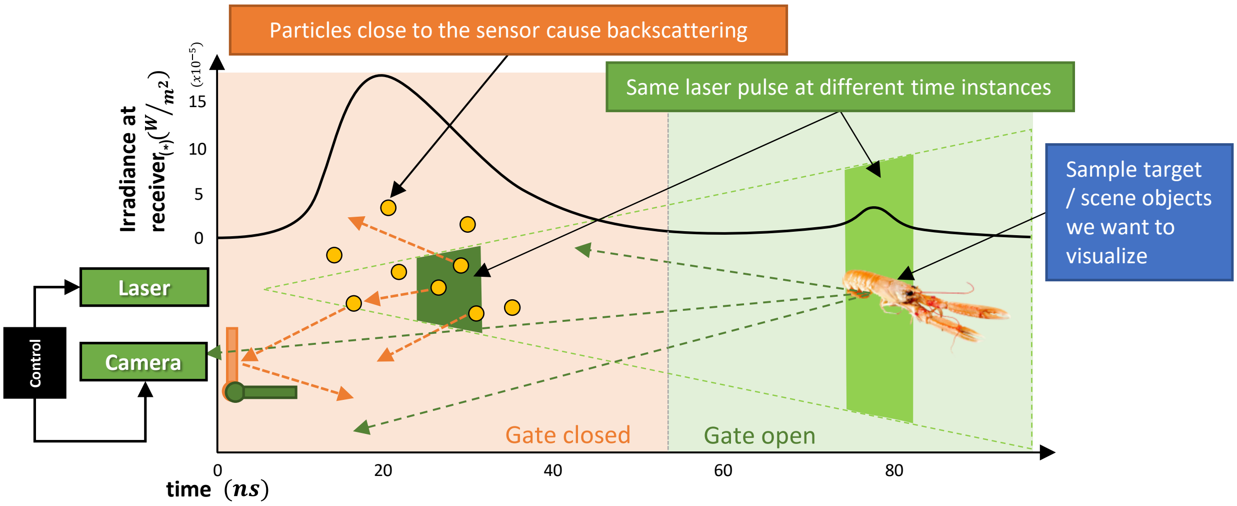
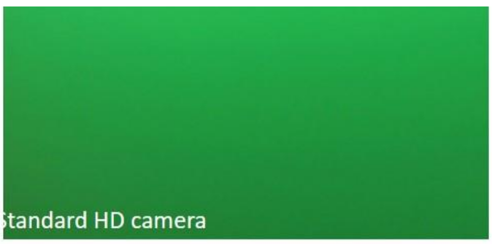
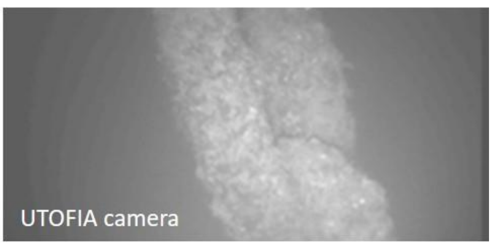


Figure 22: UTOFIA Camera - Range-gating reduces the effect of backscattering.

In this figure an underwater object at a distance of approx. 9m is imaged. The graph shows the reflected signal from a laser pulse as a function of time. The first peak of the curve corresponds to backscattering from particles in the water. The second, attenuated peak corresponds to the reflection from the object of interest (e.g., a lobster). The camera shutter is kept closed for approximately 50ns before it opens. Since the image is created from an integration of all light received, when the first 50 ns is gated out, most of the backscattering contribution to the fundamental noise is removed.





The technical specifications of the UTOFIA camera are the following:

Table 1: Utofia camera specifications

Main features	
Depth rating	300 m standard (1 000 m optional)
Dimensions	Length 434 mm, Diameter 155 mm
Weight	In air: < 10 kg / In water: < 2 kg (to be confirmed upon final design)
Power and communication	
Voltage	36-48 V DC. Other voltages on demand
Power	300 W Max
Data	Ethernet Gb (actual 500 Mb/s)
Connector	Impulse MCBH-16 (16 pins, wet-mateable)
Umbilical	Hybrid GigE, power and signal. Standard cable whip: 1.2 m, cable extension up to 70 m.
Imaging	
Laser	3 mJ at 1 kHz, active Q-switch. Eye safety: 3R class
Camera	Monochromatic, 7, 14 or 34 μm sensor
Camera lens	17.5 mm focal length, f/# 0.95 + sunlight filter
Field of View	50° diagonal
Temperature control	Internal temperature control with active cooling system
Housing materials	
Front/rear flanges	Aluminum
Body	POM (Acetal)
Windows	PMMA
Packaging and documentation	
Transport	All in one transport case (Peli type) with wheels and handle, total weight < 20kg (camera, surface console and whip cable)
Maintenance	No specific maintenance needed
Documentation	Operator manual in paper and electronic version
Warranty	1 year parts and labor excluding transport cost

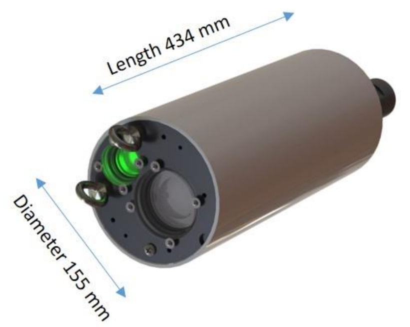


Figure 23: Utofia camera

UTOFIA camera has been initially designed to operate in a static position and to visualize moving targets such as fishes in the water column. For the SeaClear application, it would work the other way round, the camera being onboard the ROV and looking at static objects on the seafloor. The difficulty in that configuration is to discriminate the non-moving objects from the surrounding seafloor, including in turbid waters.

In order to optimize the camera parameters before going at sea, preliminary tests have been conducted in the test tank. For this purpose, two targets have been used: an orange float (20 cm diameter) to simulate objects in the water column and a white plastic box.

To better evaluate the performance, a Subsea Tech conventional camera is used in parallel to the Utofia camera. The tests are done with varying conditions in terms of turbidity, external light (luminance) and target distance. The conventional camera is fixed to the top of the UTOFIA camera and looks in the same direction, with the same tilt and at the same distance from the different targets (white box and orange float) in the test pool as the UTOFIA camera.

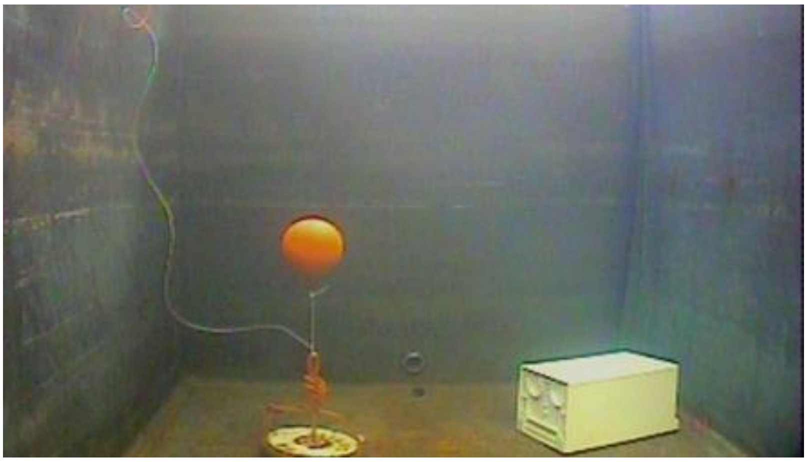


Figure 24: The two targets used for the Utofia tests: orange float and white plastic box

The turbidity is adjusted by the addition of silt in the tank.

Turbidity control

Before each test, the water turbidity is controlled using a laser transmitter-receiver tool giving directly the attenuation length. The attenuation length (or absorption length) is defined as the distance where the beam flux has dropped to 1/e of its incident flux (i.e. 37% of the flux remaining).

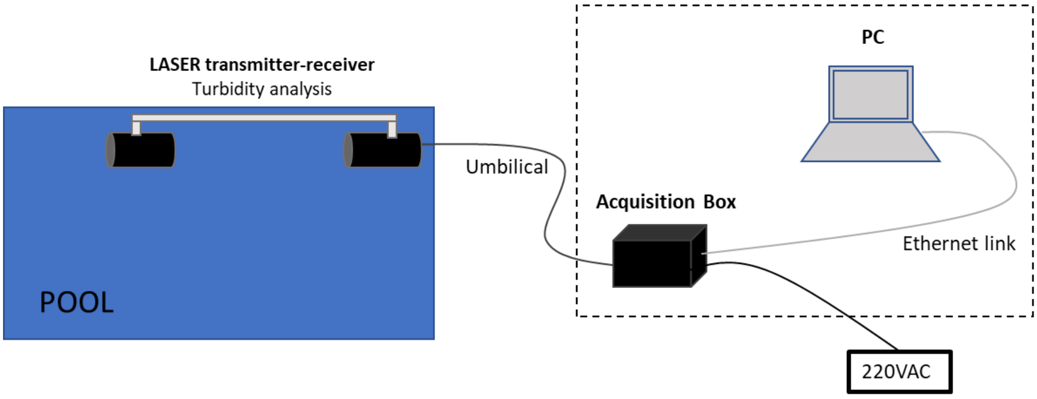


Figure 25: System set-up for turbidity control

UTOFIA Camera acquisitions

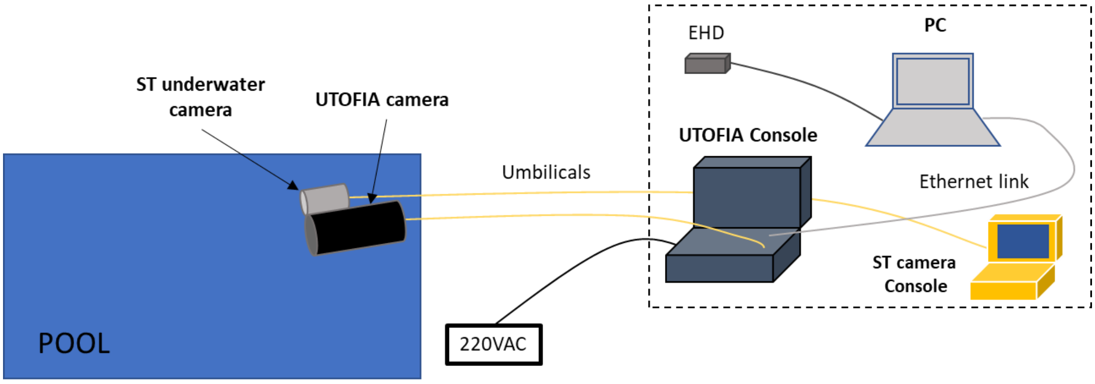


Figure 26: System set-up for images acquisition

It takes about 5 minutes for the LASER to heat up. It lights up once the optimum temperature is reached and the camera automatically displays an image on the screen.

- **Pool dimensions**

The dimensions of the test pool are: 2800*1400*1300 mm

- **Turbidity**

We used 3 different levels of turbidity with attenuation lengths of 3.3 m, 1.2 m and 0.8 m. The tables below give the values of illumination versus time of the day, inside the workshop. The values extended from 65 to 1400 lux

- **Luminance**

During the tests, the ambient luminance (luminous flux per unit area measured in lux) is made variable by opening/closing the workshop main door (sunny outside). For reference luminance with on a sunny day is between 10 000 to 25 000 lux while house lighting gives values of around 100 to 300 lux.

Tests 1 to 15 (Water Attenuation: 3.3 m):

10:00	10:10	10:20	10:30	10:40	10:50
800	866	933	1000	1066	1133
11:00	11:10	11:20	11:30	11:40	11:50
1200	1266	1333	1400	1333	1266
12:00	12:10	12:20	12:30	12:40	12:50
1200	1133	1066	1000	933	866

Tests 16 to 30 (Water Attenuation: 1.2 m):

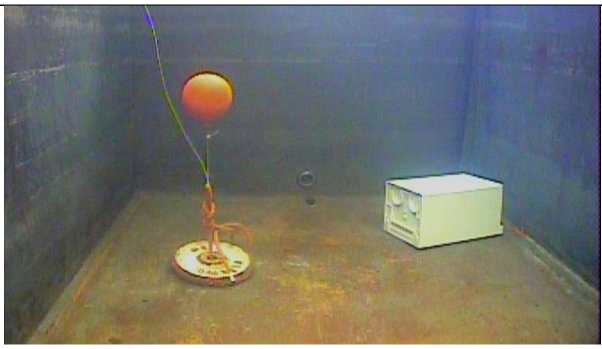
Tests 16 à 23	12h	12h10	12h20	12h30	
	630	620	610	600	
Tests 24 à 30	9H50	10h	10h10	10h20	10h30
	710	675	640	605	570

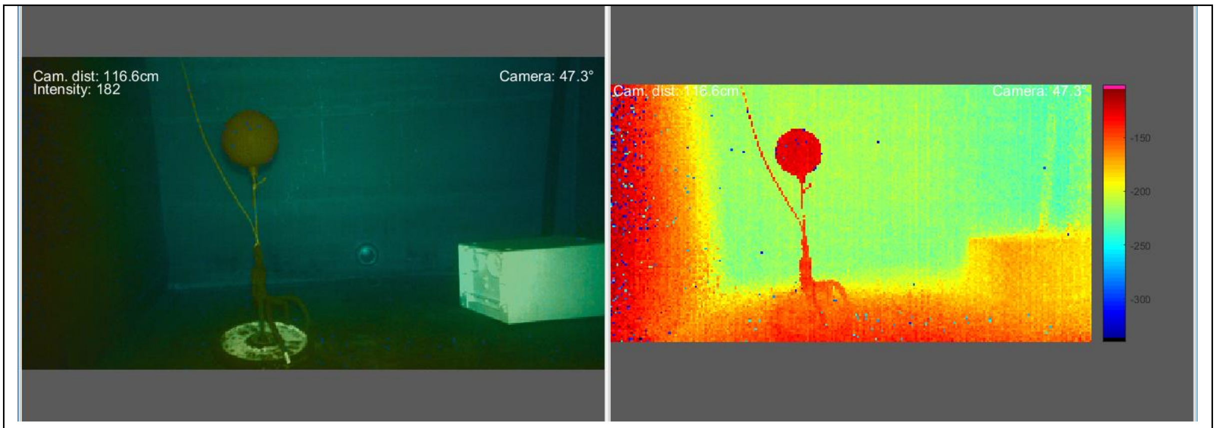
Tests 31 to 45 (Water Attenuation: 0.8 m):

Tests 31 à 38	15h00	15h30	16h	16h30	17h00
	800	580	350	230	65
Tests 39 à 45	16h40	16h50	17h	17h10	17h20
	210	190	160	130	90

The results are summarized below with some examples of images among the 45 acquisitions. For each test result, the top right image is the image taken with the conventional video, the bottom left is the UTOFIA 2D black and white image (with false colour giving the pixel distance to the camera, red: near, blue: far)) and the bottom right is the 3D view of the scene.

Table 2: Test with Utofia camera in clear water

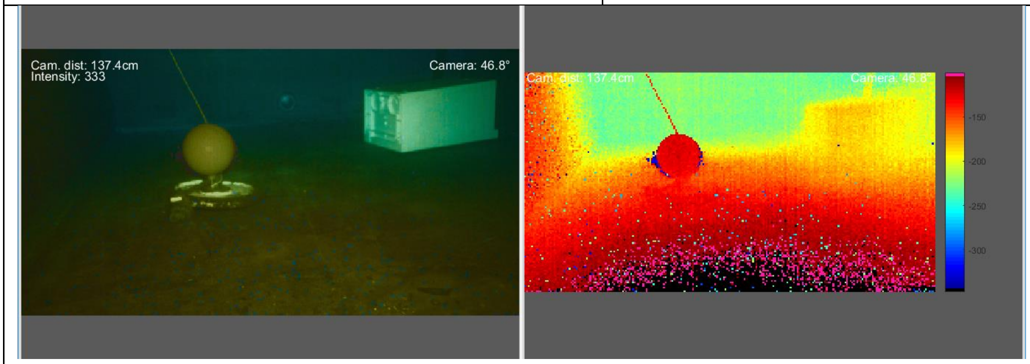
Test 7 Time : 10 :56 Luminance (lux) : 1170 Water attenuation (m) : 3.3 Tilt camera (°) : -10 Distance camera-target (m) :1.3	



For clear water (attenuation length 3.3 m), both the conventional camera and the Utofia camera give good quality images but it can already be seen that the floating target is much more visible than the bottom one which contours disappear in the surrounding bottom.

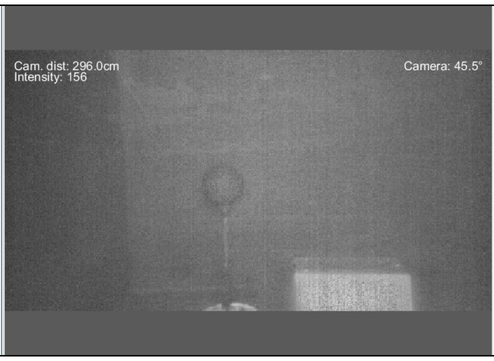
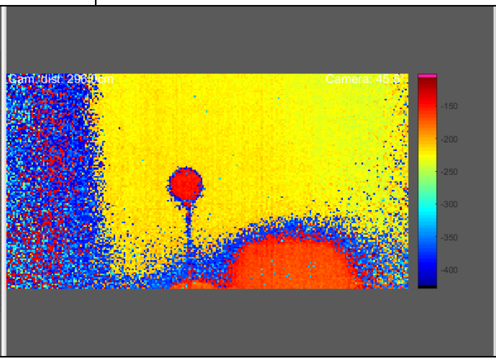
Table 3: Test with Utofia camera in clear water and floating target on bottom level

Test 11 Time : 12 :01 Luminance (lux) : 1190 Water attenuation (m) : 3.3 Tilt camera (°) : -20 Distance camera-target (m) :1.15	



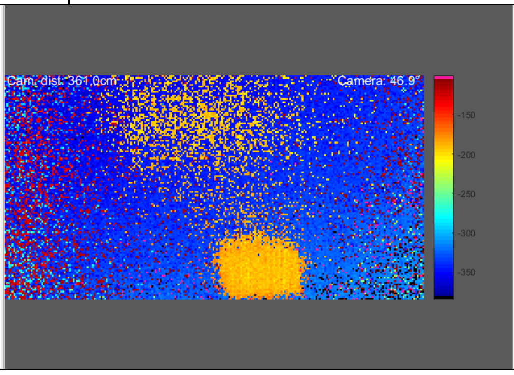
With the floating target taken down to the bottom level to simulate seabed litter and the camera orientated downwards, both targets are much less visible in the 3D view, and a lot noise appears.

Table 4: Test with Utofia camera in water with increased turbidity

Test 18 Time : 12 :17 Luminance (lux) : 613 Water attenuation (m) : 1.2 Tilt camera (°) : -10 Distance camera-target (m) :1.5	
	

When increasing the turbidity (attenuation 1.2 m), the targets contours get blurred and the white box is no more identifiable.

Table 5: Test with Utofia camera in water with increased turbidity

Test 35 Time : 15 :15 Luminance (lux) : 680 Water attenuation (m) : 0.8 Tilt camera (°) : -10 Distance camera-target (m) :1.9	
	

With even higher turbidity (0.8 m attenuation length), the targets are no more visible with the conventional video while the white box is still well present on the 2D and 3D Utofia views but the lack of resolution of the image make the identification almost impossible.

The equipment was then taken to the quayside to test it in a natural environment. The conventional camera is fastened on top of the Utofia camera (see picture below) and suspended along the quay with a 20° angle downwards to the sea bottom.

Figure 27: Utofia and conventional cameras hung alongside the quay

Figure 28: Images taken with the conventional camera, without and with Utofia laser switched on

The water quality is good and they are various small litter items on the sea bottom (plastics, ceramic tiles, steel scrap).

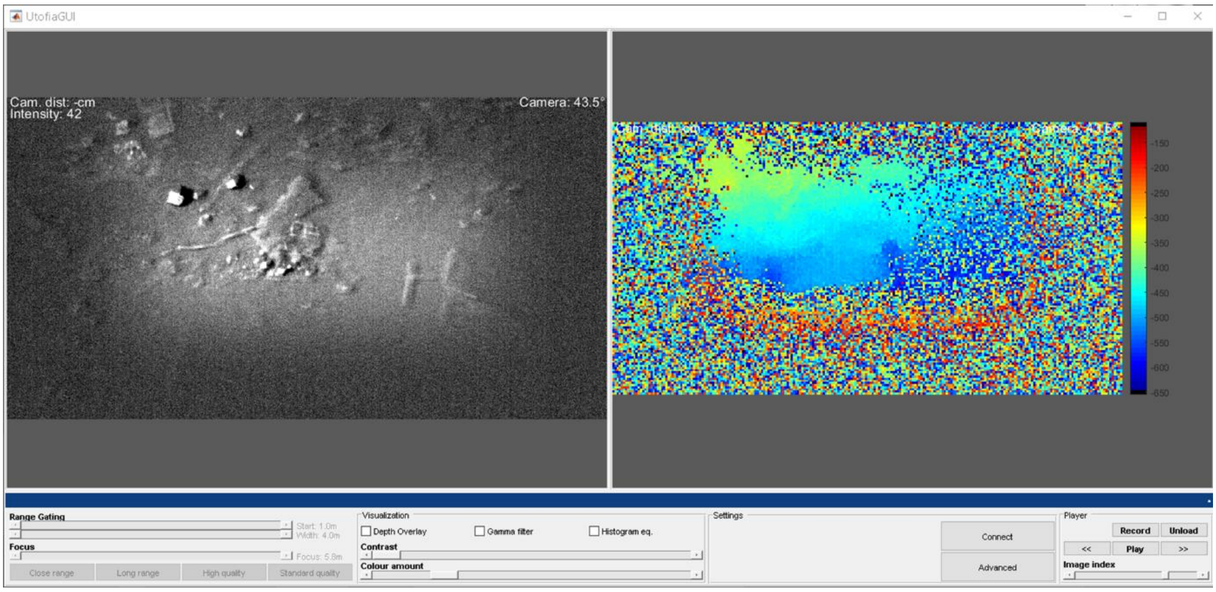


Figure 29: Utofia images in natural environment

Looking at the Utofia images, it is almost impossible to correlate objects in the scene with the conventional camera image. The 3D image is not exploitable at all due to the surrounding noise.

Conclusion: although the Utofia camera is an interesting and innovative concept for underwater 3D imaging in turbid waters, giving good results in the water column with low to medium turbidity, it does not bring a significant improvement to images quality compared to conventional video, and its performance in turbid waters is not as good as imaging sonars (see chapter 2.5) especially in terms of range and with high levels of turbidity. Besides, its relatively high price (50 k€) and non-competing weight and volume compared to other sensors, it is probably not retained as a potential sensor for the SeaClear application. See Chapter 3 for details.

2.4. Multispectral camera

Multispectral and hyperspectral cameras are largely deployed in many out of water applications and industries. Quality inspection of food and beverage products, pharmaceutical products inspection and sorting, colors inspection, process monitoring, agriculture imaging, and more recently plankton satellite imaging and coral reef aerial imaging are just few of examples of how non-visible imaging components are used into machine vision systems.

On the other hand, their use underwater is still very limited as applications cases are very few, underwater systems are not available off the shelf, and performance is not as good as above water one due to environmental constraints (light attenuation and turbidity particularly).

It was however our objective to assess ourselves the pertinence of using such a sensor to detect marine litter. Due to COVID travels bans, it was not possible to go and visit manufacturers or to attend trials and the only French manufacturer identified has been little responsive and rather negative about the potential capacity of its systems to efficiently detect and classify underwater objects.

We will have access to a multispectral camera manufactured by a Greek company (QCell, Chania – Crete) during the second quarter of 2021 and we will carry out tests at our facilities but we are already sceptical about the potential added value of such technology, supported by the fact that there is no known usage underwater as of today.

2.5. Multibeam imaging sonar

Multibeam imaging sonars, also called “acoustic cameras” are high resolution sonars capable of creating instant images, unlike scanning or side scan sonars, thanks to their multibeam arrangement generating a full scene image instantaneously.

There are four main manufacturers of such systems worldwide: Sound Metrics (USA), Tritech (UK), Teledyne Blueview (USA) and Blueprint Subsea (UK).

The Sound Metrics ARIS sonar is undoubtedly giving the best resolution with almost video like images, but its narrow field of view (40°) does not make it a good candidate for search type operation, reducing the swath and multiplying the number of transects to cover a given zone. Besides it is also a much more expensive (80 k€ +) and a bulkier product than its competitors’ ones.

Teledyne Blueview have a wide range of 2D imaging sonars with frequencies from 450 to 2 250 kHz, field of view of 130° and prices from 25 to 40 k€. Having started their products commercialisation more than 15 years ago, they are probably the market leader today.

Tritech Gemini sonars offer a cheaper alternative with prices starting as low as 7 k€ for their small narrow angle version, but the image quality is well below the others.

Finally Blueprint Oculus sonars offer a good compromise between cost effectiveness and quality with a good range of frequencies (from 370 to 2100 kHz), dual frequency heads, 120° field of view and prices starting at 15 k€.

We have therefore decided to select the dual frequency Oculus 750D imaging sonars for the trials, which specifications are presented below:

Mechanical

Dimensions	125mm Long × 122mm Wide × 62mm High
Construction	Anodised Aluminium
Weight	980g (air), 360g (water)
Depth Rating	300m
Temperature Range	-5°C to +35°C (operating) -20°C to +50°C (storage)

Electrical

Connector	Impulse IE55 Series, 6-way
Communications	4-wire 100-BaseT Ethernet, 2-wire DSL extender module (Trigger in/out and RS232 aux options ♦)
Supply Voltage	18V to 32V isolated DC (12V non-isolated option ♦)
Power Consumption	10W to 35W (model and range dependent ★)
Integrated Sensors	Water pressure and temperature (for Velocity-of-Sound calculation)

Performance	**M750d** *BP01032*
Operating Frequency	750kHz / 1.2MHz
Range (max)	120m / 40m
Range (min)	0.1m
Range Resolution★	4mm / 2.5mm
Update Rate (max)★	40Hz
Horizontal Aperture	130° / 70°
Vertical Aperture	20° / 12°
Number of Beams (max)	512
Angular Resolution	1° / 0.6°
Beam Separation	0.25° / 0.16°

★ indicates parameter is depen

Figure 30: Blueprint Oculus 750d sonar mounted on Tortuga ROV

As explained in the Blueprint Oculus sonar manual, the imaging sonar can be thought of like a hand-held torch with an illuminating beam that is wide horizontally and narrow vertically – continuing this analogy, the sonar images shown on the operator's display can then be thought of as a "top-down" view of the area being illuminated.

The Oculus beam pattern is described in the figure below:

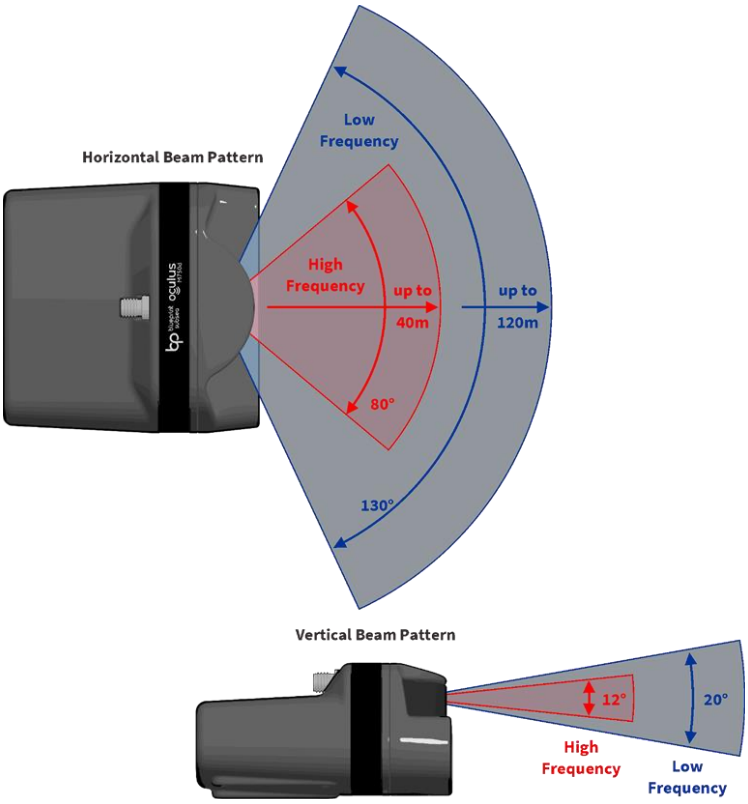


Figure 31: Oculus sonar beam pattern

The targets outside these patterns will not be visible.

Besides, as illustrated below, the sonar cannot determine the echoes incoming <u>vertical arrival angle</u>, so if two targets are in front of the sonar at the same range vertically above each other the sonar will show both these as a single result made up from a combination of their echoes.

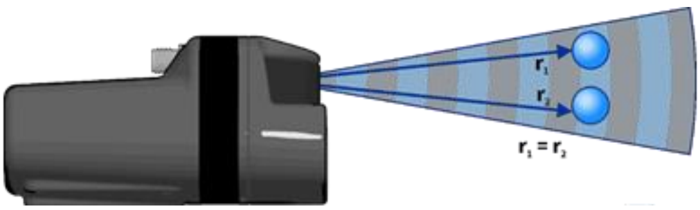


Figure 32: The 2D imaging sonar cannot discriminate targets in the vertical plan

The orientation of the sonar relative to the seabed is very important to optimize the imaging area.

As illustrated in the figure below, if the sonar is close to the seabed and angled downward then only a small strip in front of it will be shown. By gaining altitude from the seabed the operator can illuminate a wider swathe that will make better use of the display.

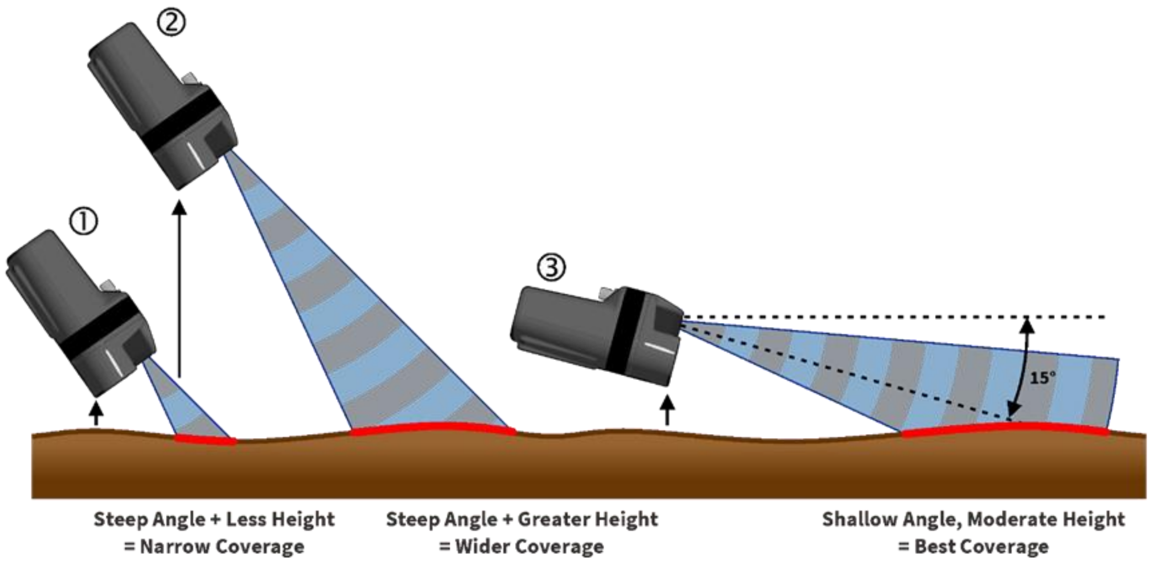


Figure 33: Impact of sonar height and angle on coverage

For situations requiring the sonar to be searching the seabed in front of it, the best use of the display comes from balancing the altitude above the seabed with the sonar down angle such that the largest amount of the seabed is illuminated.

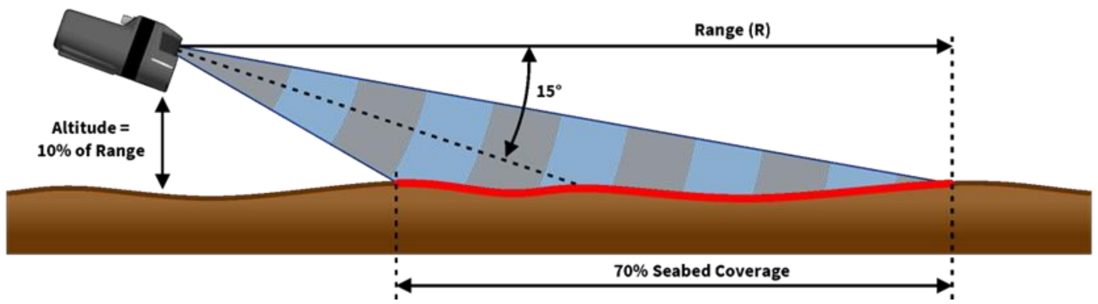


Figure 34: Optimal sonar height and angle

The similarities between a sonar and torch continue as the 'illumination' from the sonar can be used to generate acoustic shadows, and these can be of great assistance to the operator in determining the height, shape and orientation of targets in front of the sonar.

As previously mentioned, the display can be thought of as a top-down (or satellite) view of what lies in front of the Oculus:

If the sonar is close to the seabed and at a shallow angle, the acoustic shadows cast by targets will be long (similar to an aerial photograph taken in the evening when the sun is low in the sky).

However, if the sonar is high above the seabed and point steeply downwards then acoustic shadows will be short (like an aerial photograph then at midday when the sun is high in the sky). In this case targets are generally harder to see, and make estimates of their height and geometry.

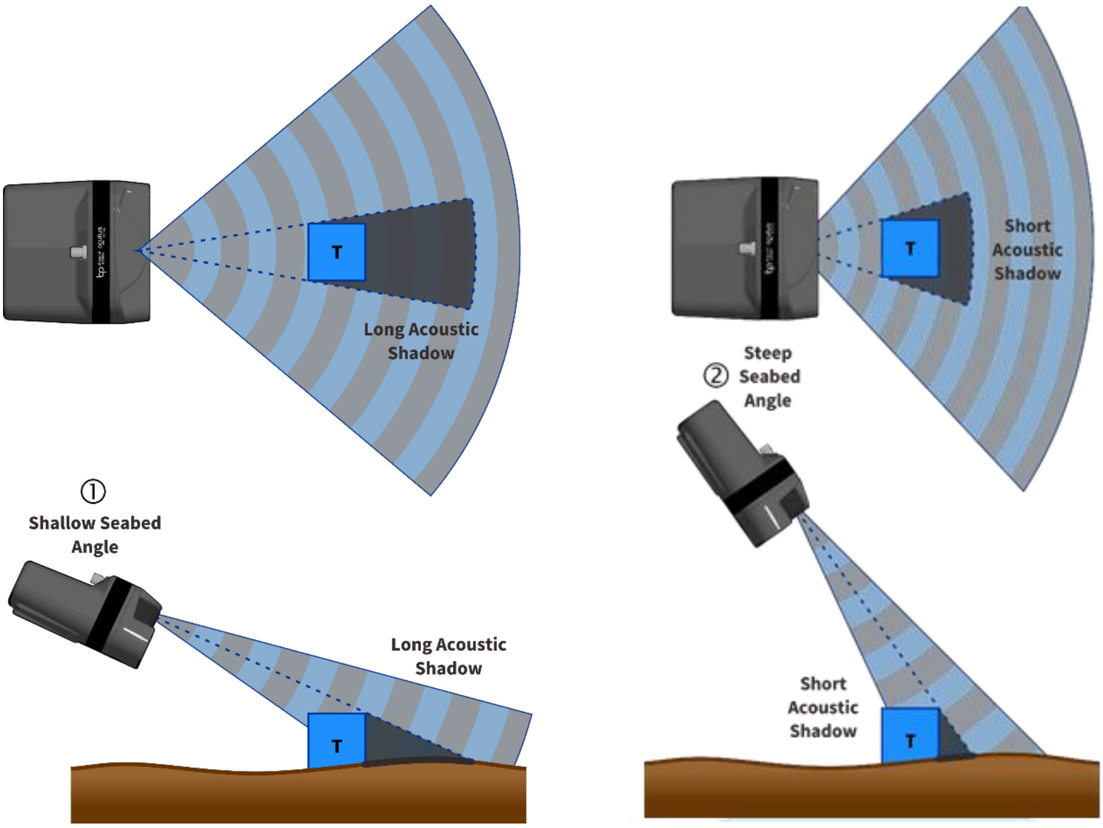


Figure 35: Impact of sonar height on acoustic shadow

Depending on how close the sonar is to a target can also make a significant difference to the image.

Due to the way sounds waves spread out from the transmitter, shadows cast by targets that are far away will be narrow behind them, but the shadow width will increase as the sonar is moved closer to them (see figure below). In these situations, the operator should be aware that these shadows may then hide other targets as there is no sound present to illuminate them.

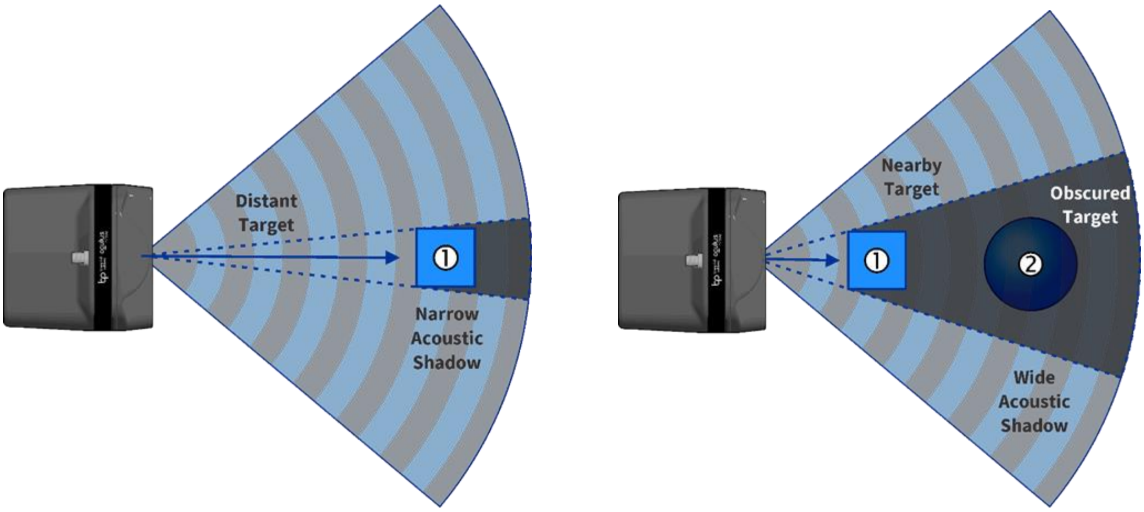


Figure 36: Impact of distance to target on shadow size

Where the operator's visibility is becoming restricted due to shadowing from close-by targets, they should aim to increase the sonar altitude above the seabed (and the targets causing the shadows) and is possible angle the sonar downwards to compensate.

The image below shows an example of shadows from 3 targets being cast.

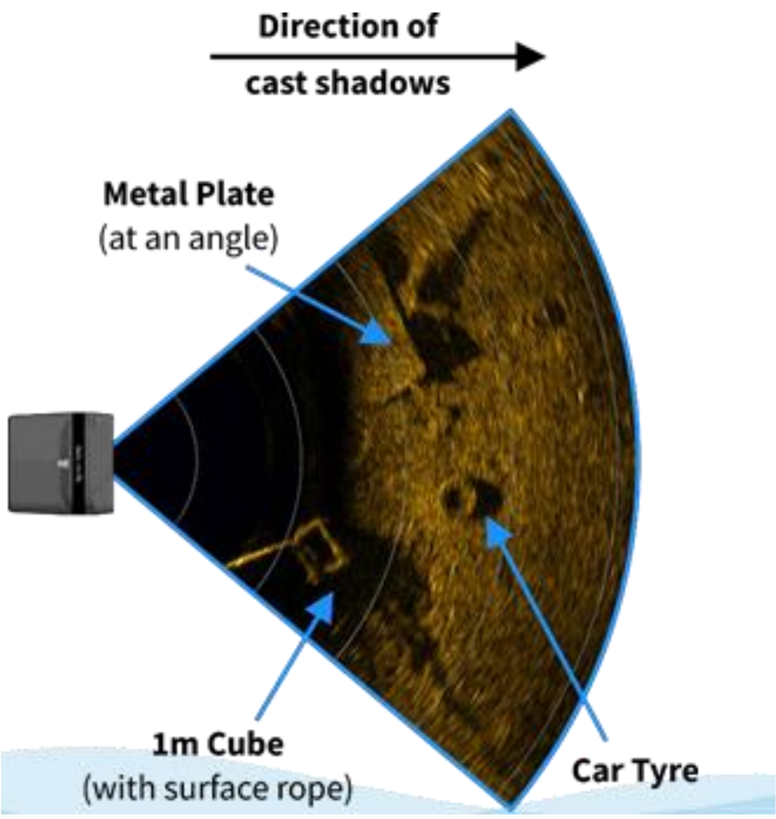


Figure 37: Example of target sonar casts

The sonar is positioned at the left of the image, and because the targets are raised above the seabed, their bright echoes are seen first and shadows are cast away from it. The length of the shadow gives an indication of the car tire height, while the metal plate is probably angled upwards as the shadow size increases along its edge.

Using the "10% rule" discussed on page 37 (Figure 34) will allow the sonar to produce good shadows behind possible targets, which may be used for estimating their height and orientation, or the terrain in front of them.

Although it has been mentioned that the sonar display can be thought of as a top-down image of the area in front of them, there are some limitations to this analogy. As the image is illuminated from the side by the sonar, only the edges or faces of targets closest to the sonar will be illuminated.

If a target face is at an angle, then some of the incoming sound waves will be reflected towards the sonar while others will be scattered away in different directions and the overall brightness of the target will be reduced. The figure below illustrates this, highlighting in red the areas on three simple targets that will appear brightest on the display, and how these appear from real-world targets:

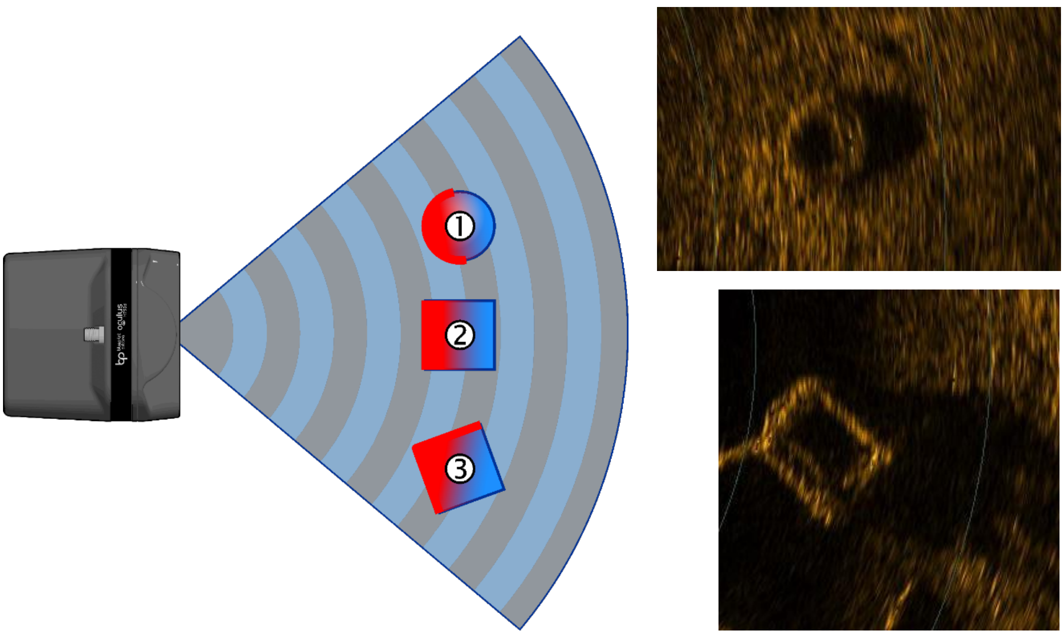


Figure 38: Understanding the bright and dark pixels on sonar image

Sonar imaging trials have been conducted at the same place as the previous video shootings, i.e. in front of Subsea Tech facilities. Here below are some sample images extracted for the sonar files showing different types of targets on the seabed:

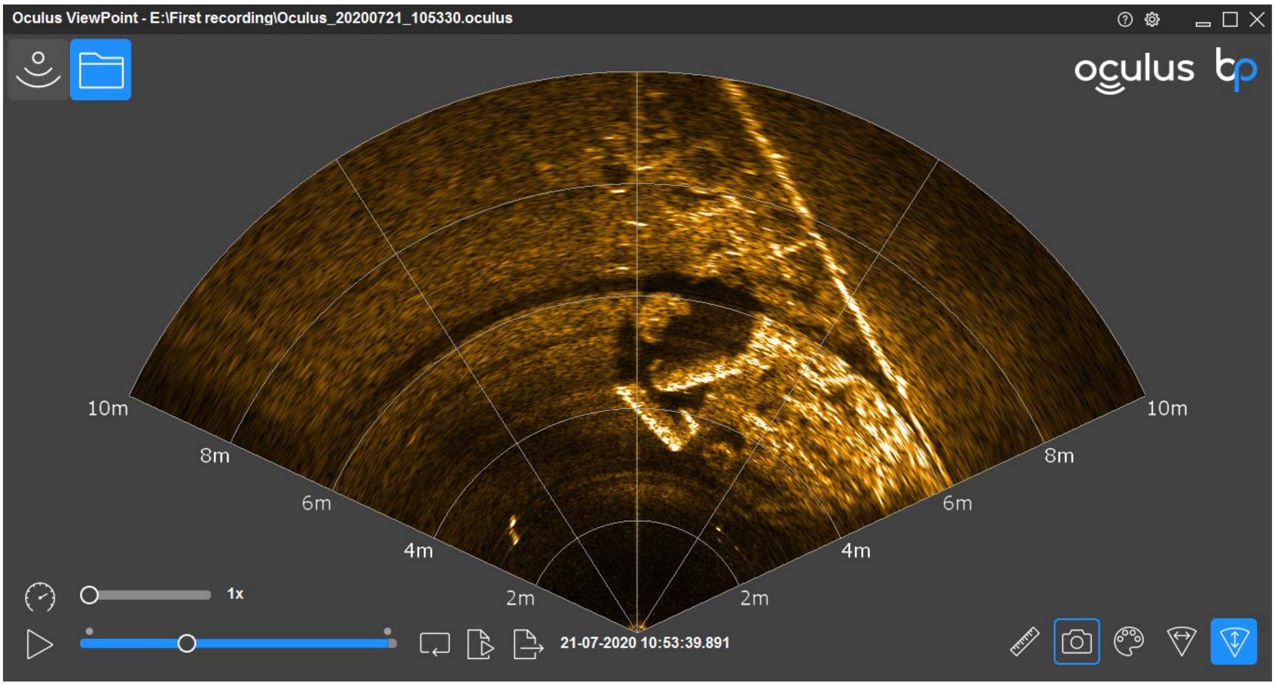


Figure 39: Sonar image with the two pipes and large + small tires

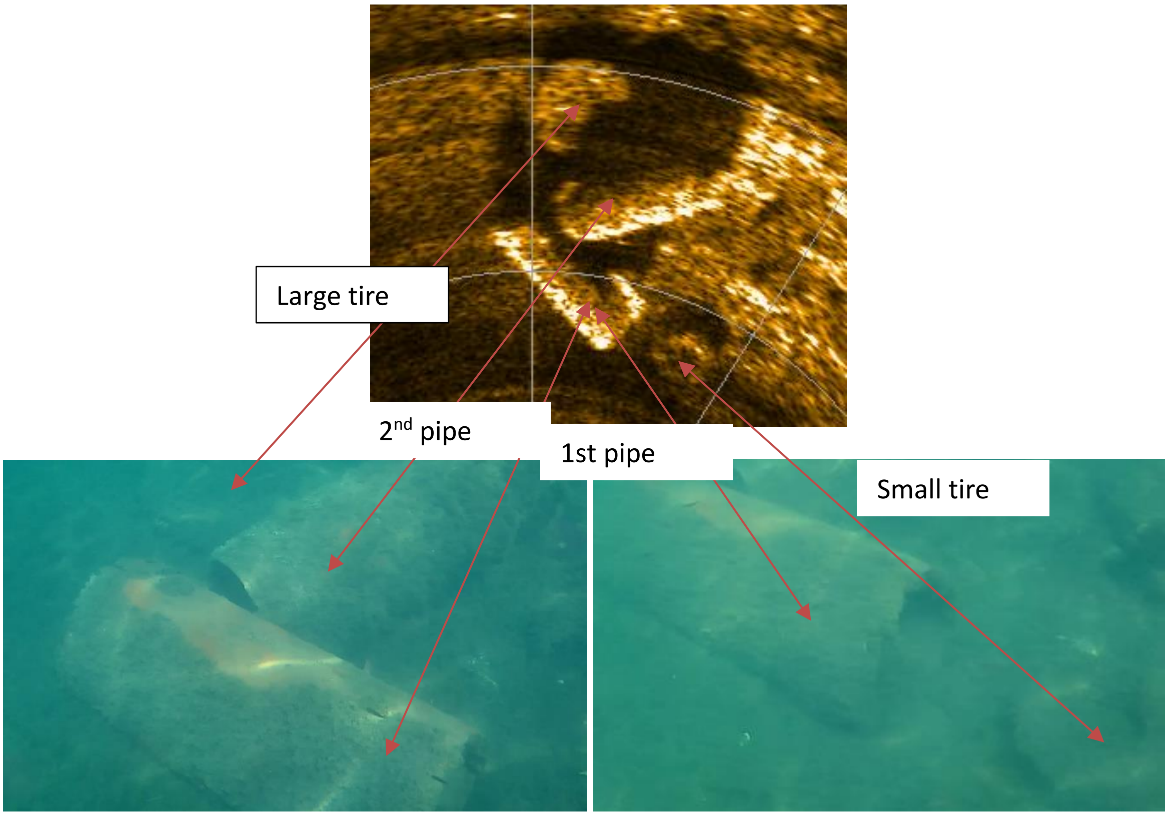


Figure 40: Correlation between video and sonar image

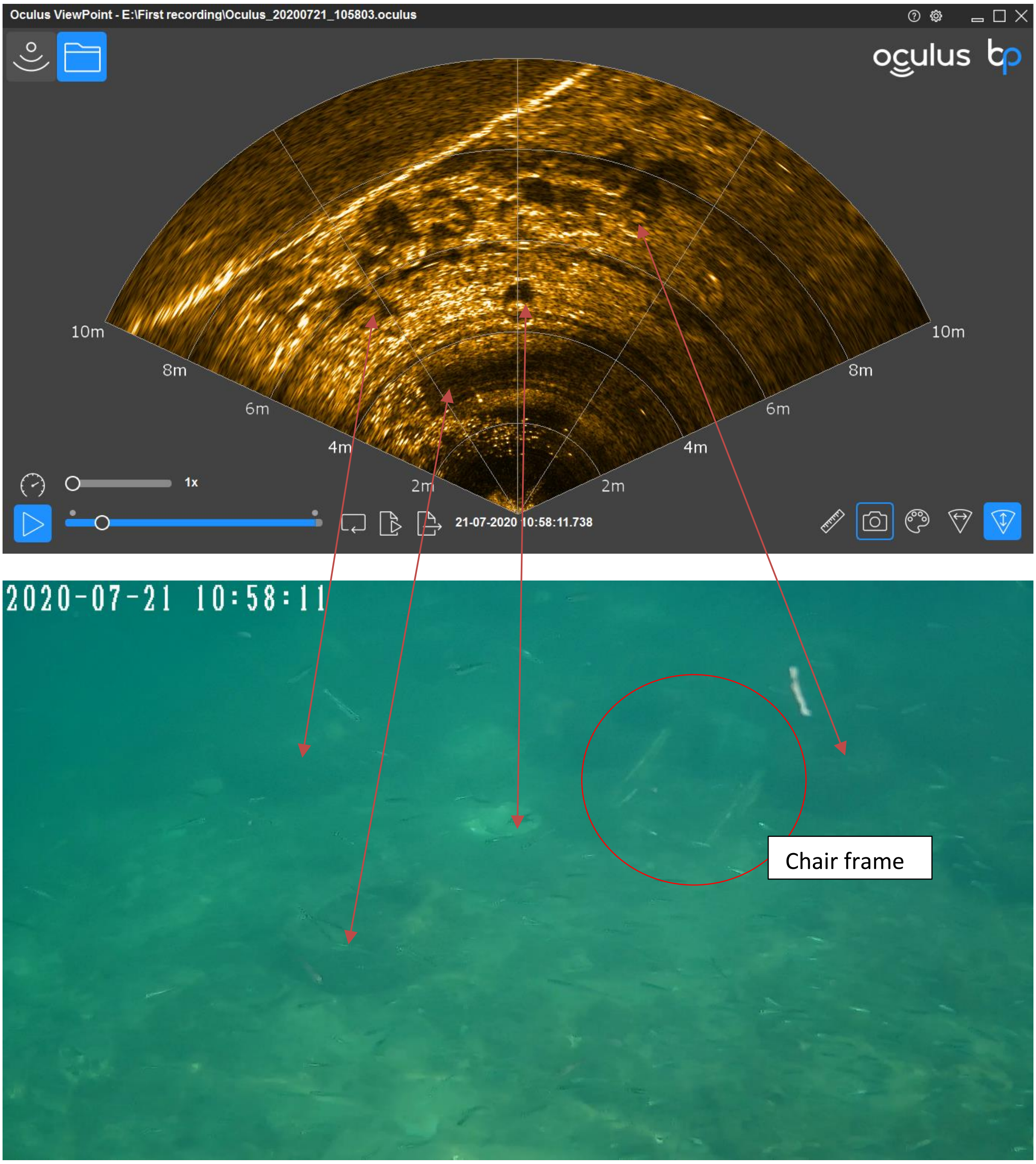


Figure 41: bunch of tires – sonar + video images

If we look at the two images above, one taken with the sonar and the other one with the video at exactly the same time (10:58:11), we can see that the tires are much more visible and at longer range on the sonar image than on the video. On the other hand, we can see the chair frame on the video but not on the sonar. It can be also noted that the small fish school is visible on both the sonar and the video images.

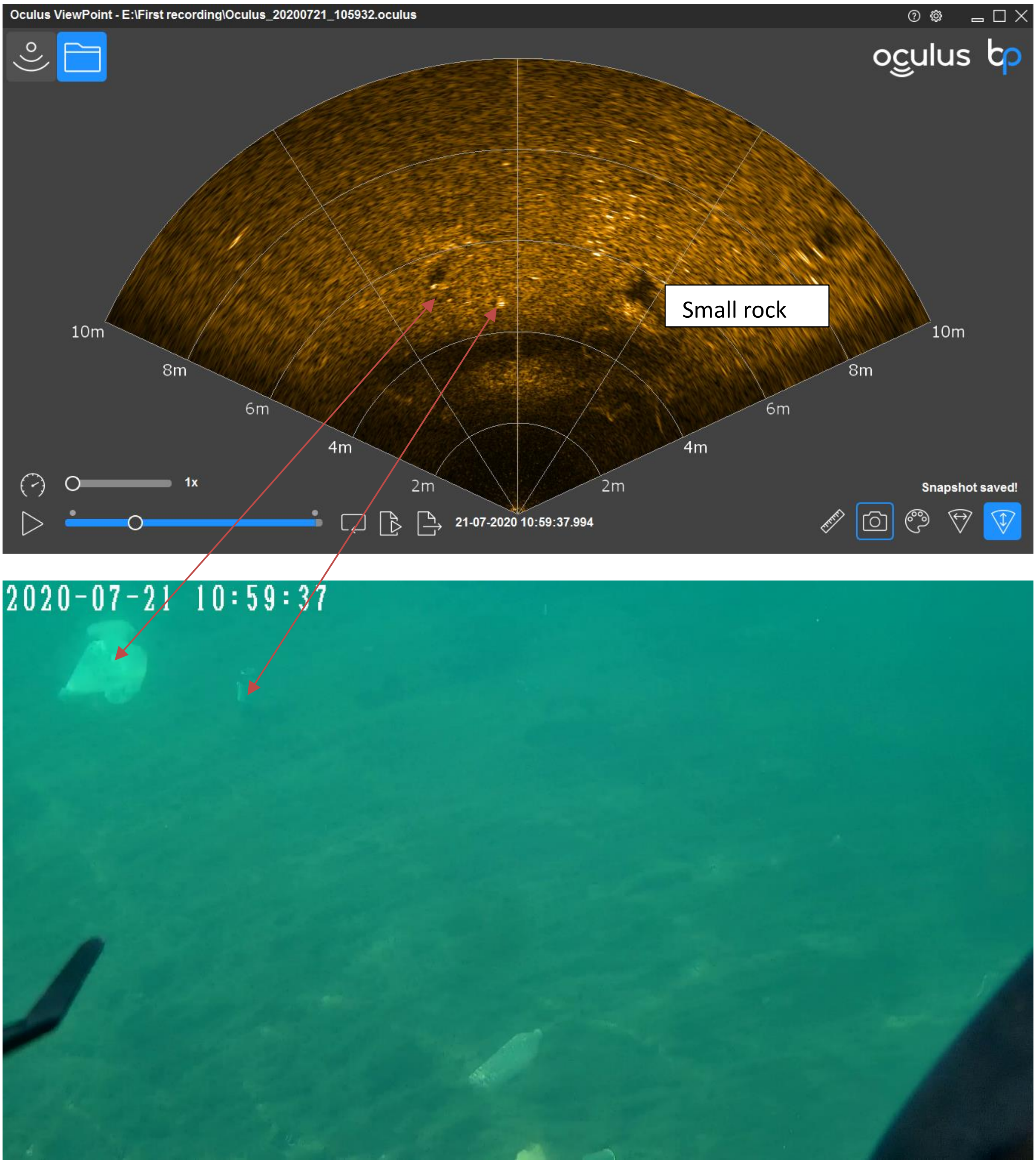


Figure 42: Sonar and video images of plastic bottles and bag

In these two images, sonar and video, the plastic bottle at the bottom of the screen is not visible on the sonar because it is too close to the ROV. The second bottle is visible on both but impossible to classify on the sonar image. Idem for the plastic bag. The small rock at the right of the second bottle is not yet visible on the video.

Conclusion: the imaging sonar proves to be a very useful complementary tool to the video even in low turbidity waters. If turbidity is high, it becomes unavoidable. The sonar allows to “see” farther than video but only large size objects such as tires and rocks. Acoustic signature of plastic bottles for example is weak and probably too difficult to process.

A way to improve acoustic imagery could be to use a higher frequency Oculus sonar (e.g. the 2.1 MHz version or the new 3 MHz coming to market early next year) and to fly the ROV closer to the seabed (about 1.5 m altitude in our images) to reduce the “blind” zone in front of the sonar

2.6. Metal detector

Although not initially planned in the project, and after discussion with Hamburg Port Authority partner, it was decided to look into the possibility of integrating a metal detection capability to the ROV specifically for harbour environments where buried metallic objects such as anchors, chains, cables and the like are a hazard for dredging operations.

Most of the underwater metal detectors are handheld systems like the one shown on the picture below:

Figure 43: Handheld underwater metal detector

These metal detectors have a very narrow swath, roughly equivalent to their physical width and require the diver to swing it right and left to cover a reasonable area while progressing along a line.

There also exist more industrial systems such as the SEARACK frame from SENSYS (Germany), holding FGM3DUW magnetic sensors. The system is scalable and can be adapted to the size of the supporting ROV but the smaller unit is already 1 m large and not really compatible with SeaClear observation ROV size. The picture below shows the system with a 3 m rack on a large size ROV.

Figure 44: 3 m large SENSYS SEARACK metal detector on large size ROV

To match SeaClear observation ROV capabilities and project budget, it was decided to modify an existing diver detector to integrate it onto the observation ROV during Hamburg trials. The acoustic signal which normally goes to the diver headphones will be changed to an electrical signal taken back to the surface PC via the ROV telemetry. It will allow then to map metallic objects.

2.7. Multibeam bathymetry sonar

Multibeam bathymetry sonars are typically used for generating 3D models of seabed and surrounding infrastructures. The basic technology (2D multibeam) is the same as for the imaging sonars but the beams are orientated vertically downwards and their horizontal pattern angle is much narrower.

The bathymetry sonar is moved along the area to be surveyed coupled to a high precision GPS with RTK correction and a survey grade INS (Inertial Navigation System). This means that most of the time, the bathymetry sonar has to be operated form a surface vessel to have the GPS communication.

In our case the bathymetry sonar will be operated from the SeaCat USV.

Considering the fact that we will be using this sonar essentially in shallow waters (less than 100 m), we have selected a high resolution wide beam sonar which is the WBMS from Norbit.

It is equipped with a Novatel Inertial Motion Unit, a dual antenna RTK GPS system and an integrated AML Sound Velocity Profiler for calibration purpose.

The data acquisition is done using the QINSY hydrographic software running under Windows operating system.

Technical specifications of the NORBIT WBMS sonar system:

NORBIT WBMS Sonar		
Swath Coverage	7°min, 179° max, 140° optimal	
Range resolution	<10mm	
Number of beams	256	
Operating frequency	360-440kHz	
Range	0,2 m – 200m	
Resolution	0,9° across track x 1,9° along track @ 400kHz	
Power	20-28Vdc / 36W	
Dimensions	236x154x200 / 4,5kg in air & 3kg in water	
Inertial Motion Unit and GPS positionning		
Attitude	MEMS sensor NovAtel STIM300 with underwater housing	
GNSS	Dual Antenna RTK GPS	
Accuracy	Position 0,01m Pitch/Roll 0,02° Heading 0,07°	
Power	9-36Vdc / 13W	
Sound Velocity		
Surface	Sonar integrated AML Xchange SV probe	
Profile	AML Base-X Sound Velocity Probe Sensors AML P-Xchange & SV-Xchange	
Software		
QINSy	Professionnal hydrographic data acquisition, navigation and processing software package	

Figure 45: NORBIT WBMS sonar and Cat-Surveyor USV

Here below is a 3D acquisition made in front of Subsea Tech facilities, using the Norbit sonar mounted on Subsea Tech USV Cat-Surveyor.

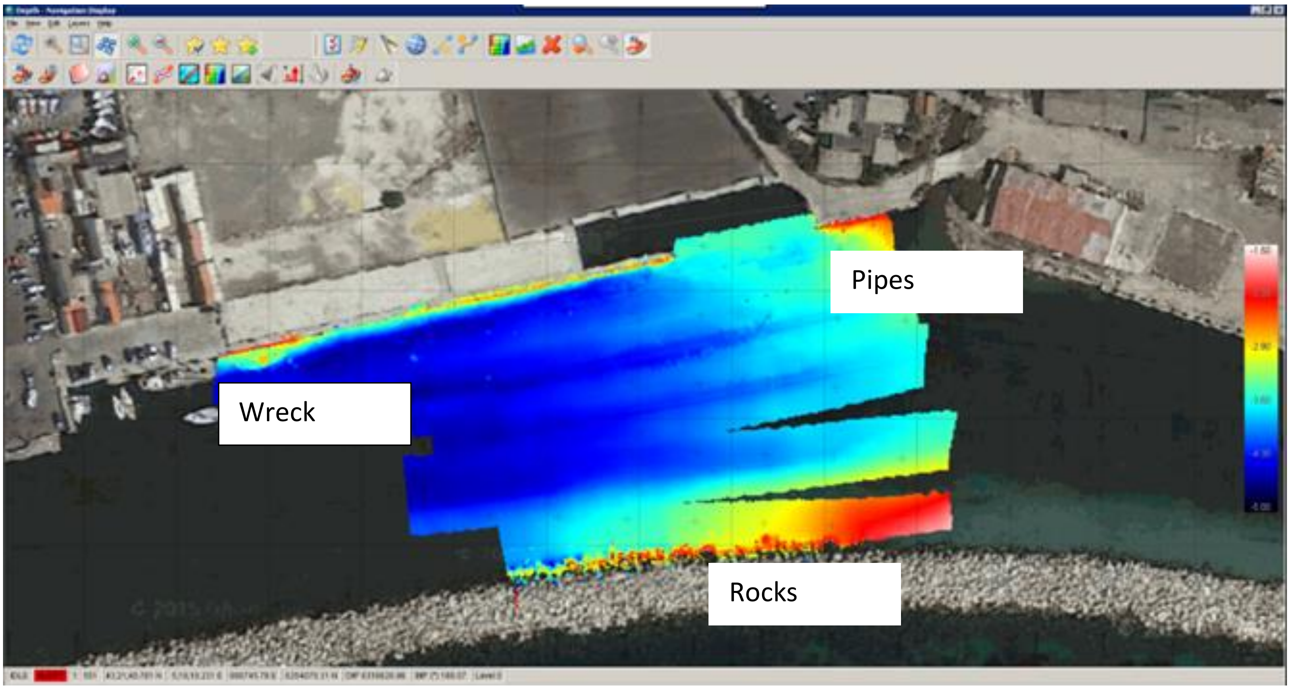


Figure 46: Bathymetry map in front of Subsea Tech facilities

To understand the resolution obtained with such sonar, we can zoom in some areas where we have singular objects like a ship wreck on the left, pipes in front of Subsea Tech quay and rocks from the breakwater (see images below).

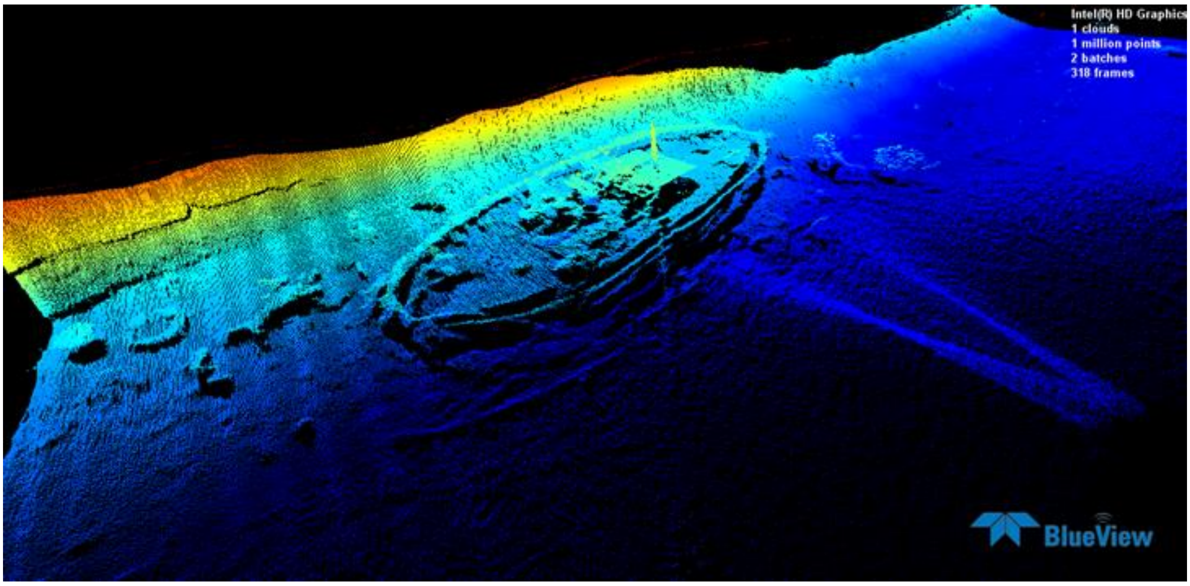


Figure 47: Small ship wreck

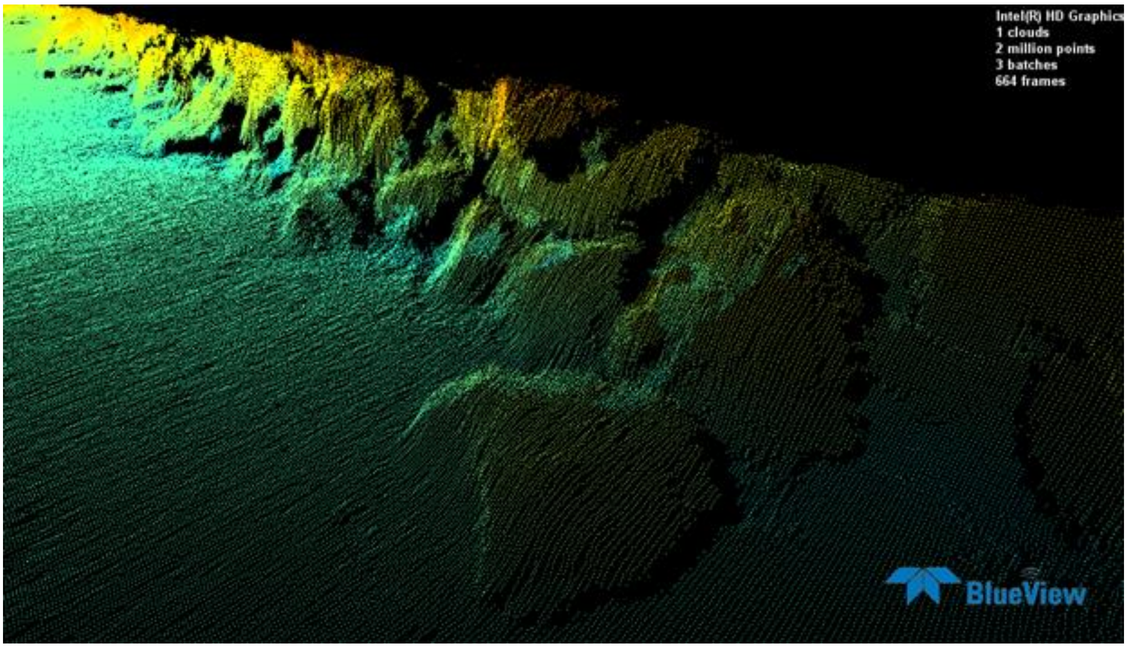


Figure 48: Rocks from the breakwater

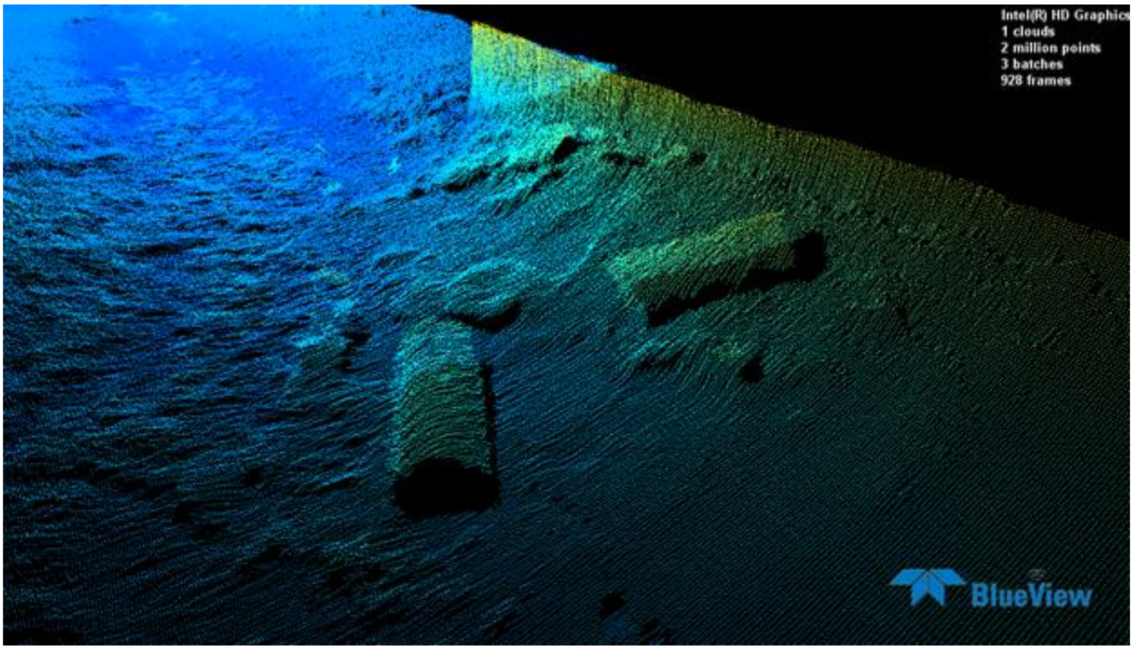


Figure 49: Pipes and tires in front of Subsea Tech quay

The bathymetry sonar will therefore allow not only create a terrain model of the whole area before the actual cleaning operation starts, but also detecting and localizing main litter objects with typical size over 20 to 30 cm.

3. Comparative analysis and recommendations

In order to compare the various sensors with respect to their potential use in SeaClear projects, we have defined several criteria which are noted 1 to 5 (1: poor, 2: fair, 3: good, 4: very good, 5: excellent).
These criteria are:

1. Image quality (in the sense that it can help to identify and classify marine litter like good resolution)
2. Immunity to water turbidity
3. Immunity to solar light
4. Ease of integration on small vehicle (maximum power, weight and dimensions)
5. Cost

The results are presented in the table below:

Sensor	Image quality	Immunity to turbidity	Immunity to solar light	Ease of integration	Cost	Overall note
Conventional video	5	1	5	5	5	38
UV light	3	1	2	5	5	26
Multispectral camera	3	1	2	5	4	25
Time of flight camera	2	2	3	3	3	24
2D imaging sonar	3	5	5	5	3	42
Bathymetry sonar	2	5	5	2	1	34

The last column is an overall note considering all the criteria but with different weighing as some of them are more important than the others. The first 3, i.e. image quality, immunity to turbidity and solar light are weighed with a coefficient 3 while the last two, ease of integration and cost, have a coefficient 1.

It appears that the conventional video and the 2D imaging sonar have the highest ranking, reinforced by the fact that they are well complementary while the bathymetry sonar, although handicapped by its size and cost, is still a good candidate for integration on the surface vehicle.
Suitability of the two sensors for the machine learning-based detection and classification tasks has been shown in Fulton et al. 2019[3] for camera-based and Valdenegro-Toro 2016[4] for sonar-based

[3] M. Fulton, J. Hong, M. J. Islam and J. Sattar, "Robotic Detection of Marine Litter Using Deep Visual Detection Models," *2019 International Conference on Robotics and Automation (ICRA)*, Montreal, QC, Canada, 2019, pp. 5752-5758, doi: 10.1109/ICRA.2019.8793975.

[4] M. Valdenegro-Toro, "Submerged marine debris detection with autonomous underwater vehicles," *2016 International Conference on Robotics and Automation for Humanitarian Applications (RAHA)*, Kollam, 2016, pp. 1-7, doi: 10.1109/RAHA.2016.7931907.

classification. Preliminary results with image-based classification of underwater debris by partner UNIDU also highlight the feasibility of using conventional cameras as a primary sensor.

The other sensors, as anticipated during the tests, have less added value, and besides their requirement for specific light conditions make them difficult to combine with standard video and/or solar light. As can be seen from the test images of the UV-lights and UTOFIA camera, the signal-to-noise ratio for the conditions under which the system will operate is deemed unsuitable for robust feature detection and is therefore highly unlikely to improve detection and classification results. It remains to be seen if the multi-spectral camera can add additional classification features for the machine learning algorithms to make them more robust, especially in terms of IR emission from animals and spectroscopic characteristics of different materials.

4. Conclusions

In the light of the above tests results and comparative analysis, it is recommended to retain the conventional video with white LED lights and the 2D imaging sonar for the observation ROV, and the bathymetry sonar for pre-survey campaign from the USV.

The complementarity of the video and the sonar sensors, high resolution for the first one and immunity to turbidity for the second, should give a good combination for coping with different environmental conditions, from clear waters to highly turbid ones.

As for the magnetic detector, a modification of an existing hand held system will be carried out and integrated on the observation ROV.