Autosub5: Preparing for Science

Alberto Consensi, Matthew Kingsland, Nick Linton, Leon Bowring, Daniel T. Roper
Richard Austin-Berry, Stewart Fairbairn, Alexis Johnson, Richard Morrison, Konrad Ciaramella, Daniel Matterson
Miles Pebody, Val Williams, Francesco Fanelli, Davide Fenucci, Achille Martin, Eoin Ó hÓbáin
Shivan Ramdhanie, Rashiid Sherif, Ashley Morris and Alexander B. Phillips
Marine Autonomous Robotic Systems, National Oceanography Centre, UK
a.consensi@noc.ac.uk

***Abstract*—Autonomous Underwater Vehicles (AUVs) are proving to be a key component in the global observing system, with their ability to provide unique data sets particularly at abyssal depths or under ice. Autosub5 is the latest in a line of large work class AUVs developed by the National Oceanography Centre specifically tailored for oceanographic science applications. This paper describes the work currently being undertaken to transition the vehicle from an engineering prototype through to a science ready platform. The 18 months process saw the AUV assembled in early 2021 and then undertake a series of trials and incremental payload integrations through to a science rehearsal trial planned for summer 2022.**

***Index Terms*—AUV, Trials, Payload Integration**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) offer the potential to monitor the global oceans at much higher temporal and/or spatial resolutions than is possible using conventional ship-based methods. From a scientific perspective AUVs are providing unprecedented understanding of the seafloor [1] as well as providing access to otherwise inaccessible areas such as under ice [2].

The Autosub programme has been developing AUVs for science applications since the 1980s [3]. Key achievements include: Autosub3 successfully exploring under the Pine Island Glacier in 2009 [4] and 2014 providing unprecedented multi-beam imagery of the underside of the ice [5], [6], Autosub6000 [7] locating the then deepest known hydrothermal vent at nearly 5000m in the Mid-Cayman Rise [8] and Autousb Long Range [9] conducting multi-day operations: in the Southern Ocean [10]–[12], under the Ronne-Filchner Ice Shelf [13] and under the Dotson Ice Shelf.

This paper describes the preparation required to commission Autosub5 a new work class AUV developed for oceanographic science. Autosub5 is being developed to replace the high power under ice survey capability of Autosub3 [4] and deep water science capability of Autosub6000 [7] for which the vehicle is being equipped with a range of acoustic and optical sensors. During the design phase of the project, the vehicle was known alternatively as Autosub2KUI [14] and Autosub6000 MK2 reflecting the two major use cases. The vehicle will complement the ongoing low power, long range capabilities of Autosub Long Range. The remainder of this paper is structured as follows: Section II provides an overview of the AUV, Section III describes some of the preparatory simulation and hardware testing as well as in-water trials conducted in Loch Ness. Section IV provides a foward look to upcoming deep water trials and first science, finally Section V presents conclusions and future work.

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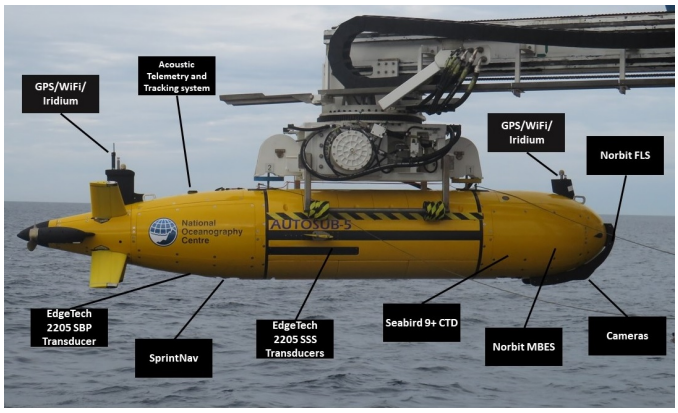

Fig. 1. Autosub5 in Loch Ness

II. VEHICLE OVERVIEW

Autosub5 is a 5.8m long high-power, short-range, flight-style AUV, designed for blue water and under ice operations. To meet these use cases the AUV has explicitly designed to simplify the integration of a wide range of sensors and deliver a semi-redundant system. The vehicle design consists of three sections: the free flooded nose, the central section and the free flooded tail. The flooded nose houses the forward control tube, Seabird 9+ CTD, Norbit WBMS-bathy MBES, Norbit Obstacle Avoidance Sonar (OAS) and a large modular space for additional mission specific sensors. The central section houses syntactic foam encasing pressure tolerant lithium polymer battery packs. Transducers for an Edgetech 2205 Side Scan Sonar (SSS) and Sub Bottom Profiler (SBP) are placed in this section. The free flooded tail houses the power tube, the second control tube, Sonardyne Sprint Nav 700 combining 600 KHz DVL and INS system, Sonardyne AvTrack acoustic

modem, actuators and control planes in a cross configuration and twin thrusters for forwards propulsion.

A. On-board Control Software

Frontseat control of the AUV is undertaken utilising NOC's muli-platform On-board Control Software (OCS) [15], a unified multi-platform software architecture developed to run across all the Autosub vehicles. The OCS architecture is based on the Robot Operating System (ROS) [16]. Both of the OCS computers on Autosub5 run Ubuntu 18.04 Bionic Beaver and ROS Melodic. The recent release of the OCS contains a high number new packages and paradigms. These include:

- updated control (GNC) implementation, which supports varying configurations of thrusters and control planes, including the 'X-form' arrangement utilised in Autosub5,
- updates to the navigation system to incorporate USBL position updates. This feature is important for operating the AUV in the scenario where the vehicle is launched from a ship in open ocean and it needs to navigate for a couple of hours without having bottom lock to reach the seabed for a camera or SSS survey. This acoustic aiding significantly reduces the navigation error improving the survey accuracy.
- additions to the mission executive to support under ice behaviours for all Autosubs,
- continued development of a new Obstacle Avoidance System (OAS) [17]. For camera surveys the vehicle is required to fly at only a couple of meters of altitude from the seabed. The altitude control based on the range provided from the DVL with bottom lock is not sufficient to guarantee that the sub will operate safely. For this reason is critical to develop the capability of having the OAS reacting also on the data provided by the Norbit FLS. The new version of the OAS will fuse multiple ranges provided by different sources to provide a reactive strategy that will allow the sub to avoid a potential obstacle safely.
- the Device Base Package (DBP), explicitly designed to simplify the process of integrating new devices into the system, minimizing the software development time typically needed for these tasks,
- a trigger manager which schedules acoustic and sonar systems to prevent interference.

B. Payload integration

The Autosub AUVs have always been designed to be modular to enable the rapid integration of the new and novel payloads requested by the science users to help address their data gathering needs. One of the key aspects of the latest version of the OCS is the ability to easily integrate a new device or a new sensor into to the system. As mentioned in the previous section, the DBP plays an important role in this providing a base layer for each of the three layers of a standard OCS device ROS node. A generic device node in fact consists of three layers: the driver layer, the algorithmic layer and the ROS layer.

1) The driver layer handles the interface with the physical device including the communication protocol implementation.
2) The algorithmic layer is where the logic of the node is handled and this includes any high-level processing of the data provided by the device.
3) The ROS layer is the one interfacing the device node with the rest of the OCS ecosystem using ROS tools.

For each of these layers the corresponding DBP base layer provides a set of common features that can be imported and used into the device node simply inheriting from the abstract class defined in the base layer. Part of these tools are embedded in the base layers itself and they are not accessible from the device layers. Other tools have a standard implementation in the DBP base layer that can be overwritten by the device layer. For the driver layer the DBP provides a set of tools handling the communications with the device, the raw data logging and in built communication line monitoring. The DBP algorithmic layer contains the definition of a state machine handling the logic for a generic device in the OCS. Each device node inheriting from this object can apply additional functionalities maintaining the same core capability.

The DBP ROS layer provides a dedicated interface with the Power Manager (PM) node. The PM node is responsible to handle the power lines for all the devices in the vehicle. The DBP makes a generic device node to register to the PM and handles the on/off sequences. Since the DBP-PM paradigm is the same for all the devices, the number of device nodes does not need to be known a-priori and each device can register itself at runtime. This built-in DBP-PM paradigm reduces dramatically the software integration time for a new device.

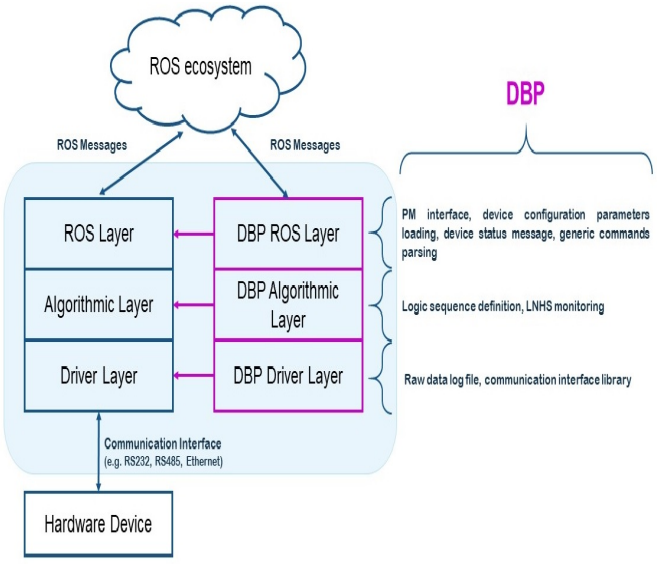

Fig. 2. OCS Device Node DBP architecture

In addition to the standard payloads listed above the following additional payloads have been requested for upcoming deployments scheduled for 2022/3:

- **Robotic Cartridge Sampling Instrument (RoCSI) Water Sampler**: RoCSI [18] is a robotic device, developed by NOC, for collecting RNA samples in commercial Sterivex filter units by pumping a known volume of sea-water through them, followed by a small amount of preservative. A small amount of metadata is stored both in the sampler and (experimentally) in RFID tags on the cartridges themselves. A single sample will take about 1 to 1.5 hours depending principally on the volume requested but also on the amount of clogging of the filter.
- **Applied Physics Systems Fluxgate Magnetometer**. A high-speed 3-axis fluxgate magnetometer employing 24-bit analog-to-digital converters.The 1540 system employs three ring core fluxgate sensors together with analog processing electronics to produce analog output voltages proportional to the measured magnetic field along three orthogonal axes.
- **Autosub AESA Cameras**: which consists of a camera logger, two gigabit Ethernet machine vision cameras and two custom flash modules. Each flash is slaved to a specific camera through the logger tube. For a full photographic mission 200,000 5MP 16bit RAW colour images are collected which equates roughly to 1 Terabyte, [19].
- **Wet Labs BBRTD ECO**: single-angle sensor for determination of bio-optical and physical parameters within natural waters, in particular determination of optical backscatter.

C. Acoustic Devices Triggering

Operating multiple acoustic devices at the same time on the vehicle is not a trivial task and the acoustic frequency spectrum needs to be considered for each device. In its standard configuration the spectrum consists in: Norbit **FLS** nominal frequency spectrum: 400-700 KHz (0-80 KHz), Norbit **MBES** nominal frequency spectrum: 200-700 KHz (0-80 KHz), Edgetch 2205 **SSS+SBP** SBP nominal frequency spectrum: 2-16 KHz. SSS Dual Frequency: 90-111 KHz and 360-440 KHz. Sonardyne Syrinx Down **ADCP** nominal frequency spectrum: 475-725 KHz, Sonardyne AvTrak **MF Beacon** nominal frequency spectrum: 19-34 KHz.

Considering the global acoustic frequency spectrum, it can be observed that most of the devices are separated in frequency. However a couple of points cannot be ignored. The reported frequency are the nominal transmission and reception ones. In addition to this, out of band noise needs to be considered. Additionally it is important to notice that older devices using analogue technology do not interfere as much as modern digital devices. For these reasons a centralized triggering system is required. Each device can trigger at a specific frequency and the length of the transmission time, the duty, can also vary from a device to another one. The idea is to trigger consecutively all the acoustic devices and then have a listening period until the next trigger period is fired. In order to handle this mechanism a bespoke OCS Node, the Trigger Manager, has been designed. Based on the desired configuration, the node defines a set of parameters for each device and transmits them to the electronics handling the trigger lines. Two of these parameters are the trigger period and the duty as mentioned above. The third one is the offset. This parameter defines the amount of time elapsed between the beginning of the general trigger period and the moment at which a specific device is triggered. This implementation guarantees that the final behaviour respects the desired sequence and avoids clashes between devices triggering at different frequencies.

D. Piloting Toolchain

The Oceanids C2 project [20] is a web based piloting management system and it supports Autosub5. It can be used to operate the sub over the horizon via Iridium. For ship based applications a stand alone version of the C2 has been developed and is called ”C2 in a box” (C2iab). The C2iab is a self-contained system that does not need a connection to the internet and provides the capability to operate the sub via Wi-Fi and/or via Acoustics. Both the C2 and the C2iab have been updated to support the new maneuvers defined in the OCS GNC maintaining a very similar user interface with respect to the previous version. The same interface is adopted by C2 and C2iab to make easier for the user the piloting experience. The C2iab system also provides the capability to integrate the visualisation interface with the one of the ship operating nearby. This gives the team the possibility to correlate the AUV position with respect to the ship one on a single console reducing the time needed to plan the ship positioning strategy.

III. Trials and Testing

A. Simulation and Hardware in the Loop Testing

The OCS simulator is a multi-platform, ROS based software, developed in the last two years, combining multiple environmental tools including the Unmanned Underwater vehicle (UUV) simulator, ROS Rviz and Gazebo. Based on a dynamic model of the vehicle it can provide a real-time simulation of a generic mission. It is a crucial tool for testing and debugging high-level functionalities of the software like the Helm [21] logic and the GNC control chain. All the new maneuvers developed in OCS V3 have been extensively tested in this way as well as the control allocation component. The tool also provides the possibility to run end-to-end tests including the C2 and the hardware. A specific extension of the simulator is able to support Hardware In the Loop (HIL) features. The simulator can support multiple virtual environments including our usual Loch Ness testing area and open ocean locations as well as under ice scenarios. Additional environments can be configured if required. Using this tool it has been possible to de-risk dramatically the trials in Loch Ness as well as operational deployments and maximise the efficiency of the time spent in the water.

B. Loch Ness Trials May 2021

The AUV was tested in the water for the first time in May 2021 for a period of two weeks. This can been considered the flight dynamic trial where the main focus was to commission

the vehicle and its main dynamic control. The first week was spent testing all the basic functionalities of the vehicle including the new navigation system, the actuators cross-form, the double thruster propulsion system and the payload integration. This time was used to gain confidence with the AUV and with the piloting tools. The AUV was equipped with one power tube and one control tube containing the OCS computer. In particular the electronics has been demonstrated to be highly reliable. For this reason it has been possible to maximise the amount of time spent in the water. The AUV ran an initial set of missions on the surface. A simple single track mission, A to B 500 meters long, has been used to test the capability of the AUV to navigate using the track following algorithm maintaining a constant heading. The complexity has been increased with reciprocal missions composed by two tracks, typically A to B and back again to A. These missions aimed to test and tune the heading control, to evaluate the turning radius of the AUV and to evaluate the roll during the turns. These missions have been also useful for tuning the GNC chain, for testing the new maneuvers composing a generic mission and for verifying the ballasting of the sub. During the second week of the trials the AUV ran a set of dived missions. These missions were used to evaluate the hydrostatic stiffness of the AUV and the depth control performance. Particular attention was dedicated to the configuration of the run-up dive; this is the maneuver the AUV uses to gain speed before attempting to dive. The navigation system has been also tested with and without DVL bottom lock. More complex maneuvers have been also tested including lawnmowers with active roll control. The actuators cross form configuration in fact allows the AUV to actively control the roll. During this trial the AUV proved to be extremely reliable from a mechanic and an electronics point of view and the general performance went beyond expectations.

C. Loch Ness Trials November 2021

The second trial took place in Loch Ness in November 2021 for a period of three weeks. From an electronics point of view the main difference with respect to the previous trial was the addition of the second control tube. However this was not the main focus of this trial. The aim of this trial was to commission all the acoustic devices and demonstrating the capability of delivering science data. The first device to be tested was the EdgeTech 2205. A series of lawnmower missions have been ran for testing the SSS and and the SBP. The lawnmower was performed at $15m$ altitude for the high frequency mode and at $50m$ for the low frequency mode, see Figure 3. The same missions have been used for testing the SBP. An example of the data, elaborated in post processing, are shown in the picture.

A second series of missions have been executed to test the Norbit MBES Bathy. A similar lawnmower shape, but with different line spacing, have been configured specifically, see Figure 4. The data provided by the device have been analysed in post-processing and noise filters have been applied, see Figure 5. Most of the trials has been spent gaining experience in operating the acoustic devices, post-processing the data and tuning the vehicle dynamic behaviour.

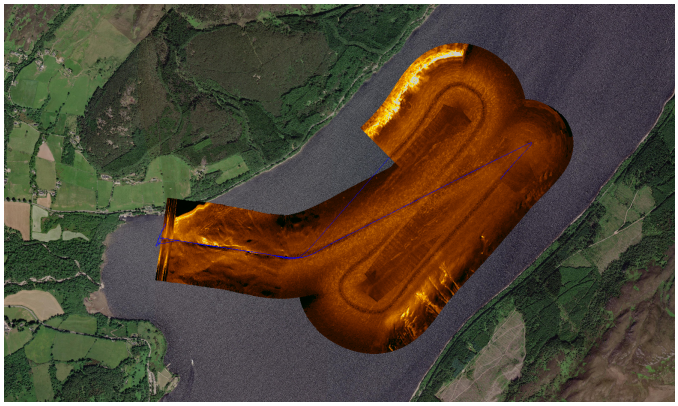

Fig. 3. Side Scan Sonar data

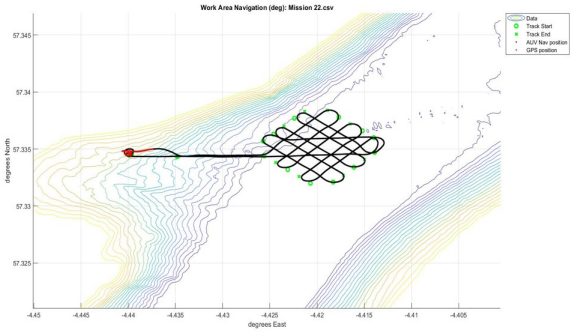

Fig. 4. Example of lawnmower mission

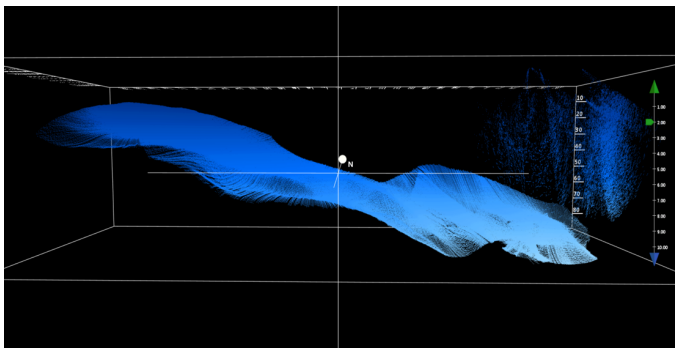

Fig. 5. Multibeam data

D. Loch Ness Trials May 2022

In April 2022 the vehicle went back in Loch Ness for a period of two weeks for a trial that aimed to:

- train the NOCs AUV Operations team to operate the vehicle,

- commission the newly integrated camera system and demonstrate the AUV undertaking low altitude flight,
- commission the latest OCS and C2iab features.

During this trial the AUV undertook 40 missions tailored to test the capabilities of the system. Mission 37 had the AUV dive from inside Urquhart Bay and transit out to deep water in the centre of the loch where it conducted a short high frequency side scan mission (2 x 1km legs with 150m line spacing) at 15m altitude with the MBES (700kHz) on, we then dropped down to 7.5m altitude and repeated the lines and then dropped down to a nominal altitude of 3.5m for a camera survey, see Figure 6. The terrain was mostly flat but does have some small circa 1.5m high features but the altitude following did fairly well, see Figure 7. The team is still working on the analysis of the sidescan and MBES data but it is looking promising. Initial inspection of the camera images suggests the installation is functioning but the turbidity in the Loch prevented aquisition of good images, this was expected. To support the development of the OAS system we also acquired a useful set set of data the fowards looking sonar system. This data set will be used for improving the collision avoidance package. Mission 40 had the AUV flying close to the side of the Loch at 75m altitude to test how the 400kHz multibeam behaves at high swath angles, in preparation for DY152/JC237 activities in Whittard Canyon, see Figure 8. Throughout this mission the AUV was tracked from a workboat with a USBL so we had live status updates from the AUV and we were updating the AUV's onboard navigation systems with the USBL positions.

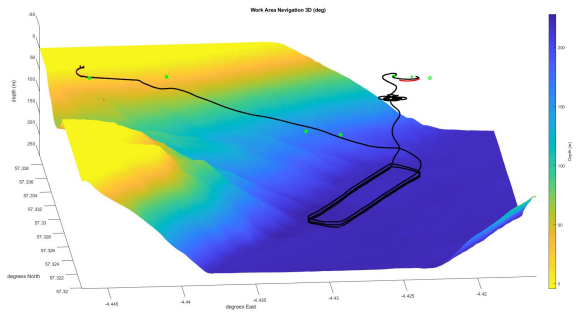

Fig. 6. Mission 37 trajectory

IV. Ship based Expeditions in 2022: DY152 and JC237

The plan for the summer 2022 is intense with two science expeditions scheduled for Autosub5. The first cruise will be DY152 onboard of the Royal Research Ship (RRS) Discovery, one of the two oceanographic vessel operated by the National Oceanography Centre. The main working area will allow the team to operate the vehicle on and off the continental shelf with a particular interest in the High Fras and Whittard Canyon areas, see Figure 9. DY152 will be a science rehearsal and the main objective for the team will be to commission at sea

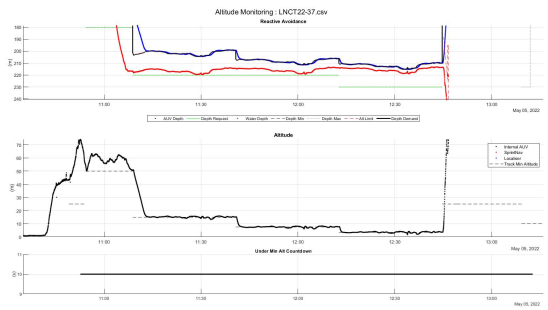

Fig. 7. Mission 37 altitude

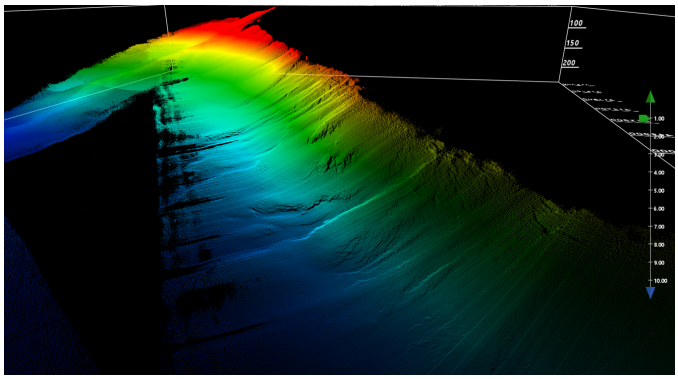

Fig. 8. M40 Multibeam data of the loch wall

Autosub5 for science gathering activities, the new OCS release and the new capabilities tested in Loch Ness in May 2022. The deployments plan will include camera surveys at 3 meters altitude, SSS/SBP surveys and MBES surveys. The following cruise will be JC237, onboard on the RSS James Cook, the second research vessel operated by the NOC. This cruise will represent the first science mission for Autosub5. The vehicle will deliver oceanographic data to be used by the scientists for understanding the changing Atlantic Ocean and in particular the Whittard Canyon activity: sediment transport, internal tides and the flora and the fauna populating the area.

V. Conclusions

The Autosub family of AUVs have been supporting oceanographic research in the deep ocean and under ice for 25 years. Autosub5 is the latest and most technologically advanced AUV the NOC has developed. Having undergone a year long period of trials and commissioning, Autosub5 is now ready to undertake science deployments. The modular nature of the hardware and software enables the platform to be adapted depending on the science application and in her first year of science will see her undertake, benthic surveys in UK Marine Protected Areas, searching for hydrothermal vent sites in the Pacific and monitoring the impact of experimental deep sea mining activities in the Clarion-Clipperton Zone.

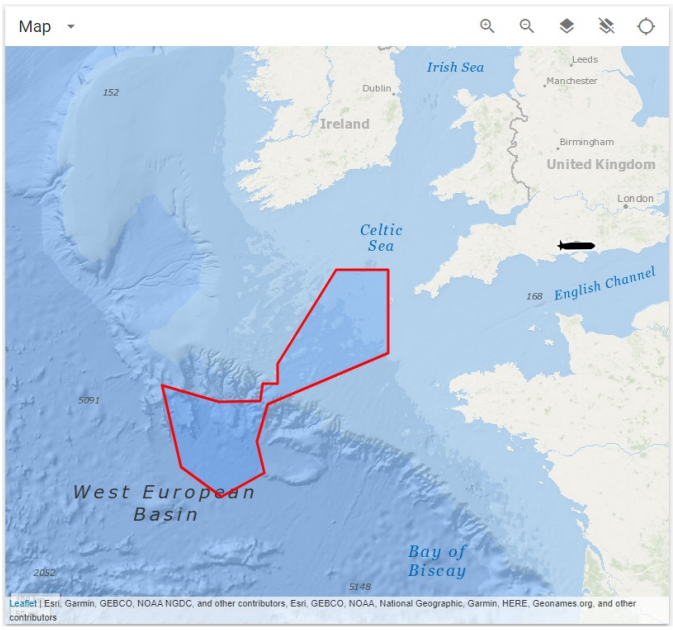

Fig. 9. DY152 working area

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