URready4OS

PROJECT WHITE PAPER

EXPANDED UNDERWATER ROBOTICS READY FOR OIL SPILL

VERSION 2 | JANUARY 2019
http://www.upct.es/urready4os

European Commission

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Introduction

The Directorate-General Humanitarian Aid and Civil Protection – ECHO of the European Commission co-funded the "Underwater Robotics Ready for Oil Spill – Urready4OS" and "Expanded Underwater Robotics Ready for Oil Spill – e-Urready4OS" projects by its Civil Protection Financial Instrument in the 2013 and 2016 Calls for proposals - preparedness and prevention projects- respectively. This document can be downloaded from the project's web site http://www.upct.es/urready4os where additional information is available.

The purpose of this white paper is to show some technical characteristics of the developed system to track and monitor underwater oil in water plumes. Intended to be a live document, it will evolve with future developments and expansion with new robotics assets.

The general aim of the project is to join forces to make available to European Civil Protection a fleet of autonomous underwater vehicles (AUVs), unmanned aerial vehicles (UAVs) and unmanned surface vehicles (USVs) with operational capability to intervene against oil spills in European Seas using new cooperative multivehicle robotic technologies. Surface oil is not the only effect of an oil spills. Underwater oil plumes can come from bottom leaks and from surface patches forming subsurface plumes, as the 2010 Deepwater Horizon incident brought into the public eye. This approach allowed to use relatively low-cost standard sonar and oil-in water sensors, with novel advanced algorithms to design a fleet of vehicles to get the most out these devices. The distributed intelligence of these devices across the spill will then be able to build up a highly accurate and dynamic image of the spill. Ultimately, this cooperating multivehicle robotic technology allows a cheap, flexible, expandable, precise and rapid decision support system for Civil Protection decision makers by optimizing the response time before the oil reach the coast.

Two training exercises where performed during the URready4OS project in order to prove the concept. The first in Split, Croatia, to test the communications and set up of the fleet. The second in waters off Cartagena, Spain, on board of the Spanish Maritime Safety Agency (SASEMAR) “Clara Campoamor”.

The challenge of the new e-URready4OS project was to provide a larger number of trained teams as to be better prepared to deal with an emergency. Underwater robotics is widely used in the military and scientific domains, but not yet by Maritime Safety Agencies (MSAs). Our proposed strategy to accelerate the use of robotics against oil spills is twofold. On one hand, we have expanded the number of different countries trained teams with available vehicles from universities and research centers to increase the capabilities to handle an emergency elsewhere in European Seas. Secondly, we are transferring the know-how of these institutions to MSAs performing training exercises on board of their rescue vessels and giving courses to their technical personnel in charge of this technology.

During the e-URready4OS project two more experiments where performed. The first was held in Cartagena, Spain, on board of the same Spanish Maritime Safety Agency (SASEMAR) “Clara Campoamor”, increasing the training fleet of autonomous vehicles. The second in waters off Cork, Ireland, on board of the offshore patrol vessel of The Irish Naval Service “LÉ Róisín”, coordinated by the Irish Coast Guard.

Chapter one of this document is focused on knowing what oil spill tools are available today. The goal of this chapter is to provide the reader with a state of art of the Oil Spill tools to focus on the Oil Spill underwater robotic technologies. Advantages of using this emergent technology is enhanced by pointing out the utility of underwater technologies in a subsurface oil spill by finding the gaps in the existing tools.

The second chapter describe the system, the diverse kinds of vehicles covering the underwater, surface and air segments. Detailed information on the vehicles and contact links are also accessible through our web site. Also, in this chapter the communications between agents – operator and robots between them – are described, the communication pathways and the protocols. In third place the software involved are described. The MEDSLIK II trajectory and forecast model was chosen for this project and a brief description is provided. The Command and Control console NEPTUS, which can plan and execute mission for any kind of vehicles, was also implemented in the project. Adaptation for new vehicles like IVER or SPARUS, or fate and forecast models, like MEDSLIK or GNOME, are now integrated in the platform that will be expanded in the future.

Finally, the third chapter describes briefly the training exercises performed in which all vehicles were working collaboratively to detect and monitor an underwater plume made of Rhodamine WT.

Teams from four European countries participated in the first edition of the project: Technical University of Cartagena (UPCT), Spain; The Underwater Systems and Technology Laboratory (LSTS) from University of Porto, Portugal; The Laboratory for Underwater Systems and Technologies (LABUST) from University of Zagreb, Croatia; and The Oceanographic Centre at the University of Cyprus. Also SASEMAR participated in the project. New teams joined for the second edition: Irish Coast Guard (IRCG), SASEMAR, The Scottish Association for Marine Science (SAMS) from United Kingdom. The Tallinn University of Technology (TUT) from Estonia. The Norges Teknisk-Naturvitenskatelige Universitet (NTNU) from Norway. University of Girona (UG) and University of the Balearic Islands (UIB) from Spain.

CHAPTER 1

Review of Available Tools for Oil Spill Response

1. Review of Available Tools for Oil Spill Response

1.1. General overview

In order to understand the tools available for responding to oil spills in natural bodies of water like seas, lakes, and rivers, one must first define such a spill. These are defined here as unwanted release of a hydrocarbon compound or mixture of hydrocarbon compounds from a closed vessel. A number of characteristics help define the spill such as:

- Type(s) of hydrocarbon. This can be considered as crude (as it has been extracted from its source) or refined (fuels and fuel oils as produced in refineries from crude). A classification system for the density of crude and refined oil has been developed by the American Petroleum Institute (API).
- Rate and duration or volume of release. How many liters per second are leaving the container, and for how many seconds. Naturally, if this is not known, the product of the two, total volume released is also useful.
- Position of release. Its geographic coordinates and vertical position in the body of water (either a point or a distribution of points)
- Environmental Conditions of release (sea state, winds, currents, sea surface temperature, stratification)

The physical and chemical properties of the oil, together with the environmental conditions determine its behavior in the water. Properties such as the melting, boiling and flash point (the lowest temperature at which the fractions of oil will ignite, when exposed to an ignition source) determine the state of the oil. Other properties, such as the pour point (the lower temperature at which the oil will flow and below which it acts as a semisolid substance), the specific gravity (the density of the oil normally determines the buoyancy of spilled oil in the seawater) and surface tension, control the rate of spreading. Whereas viscosity, stickiness and solubility influence the interaction with sediments, beaches and biota.

The oil (crude or refined) spilled on the sea is subjected to a series of diverse processes that distribute the oil in the environment (as stated above) and simultaneously cause changes in the physical properties and chemical composition. The weathering process, as is it called, is summarized in Figure 1. A concise summary of the properties of oil and the weathering process are provided by Technical Report 2 of ITOPF [1].

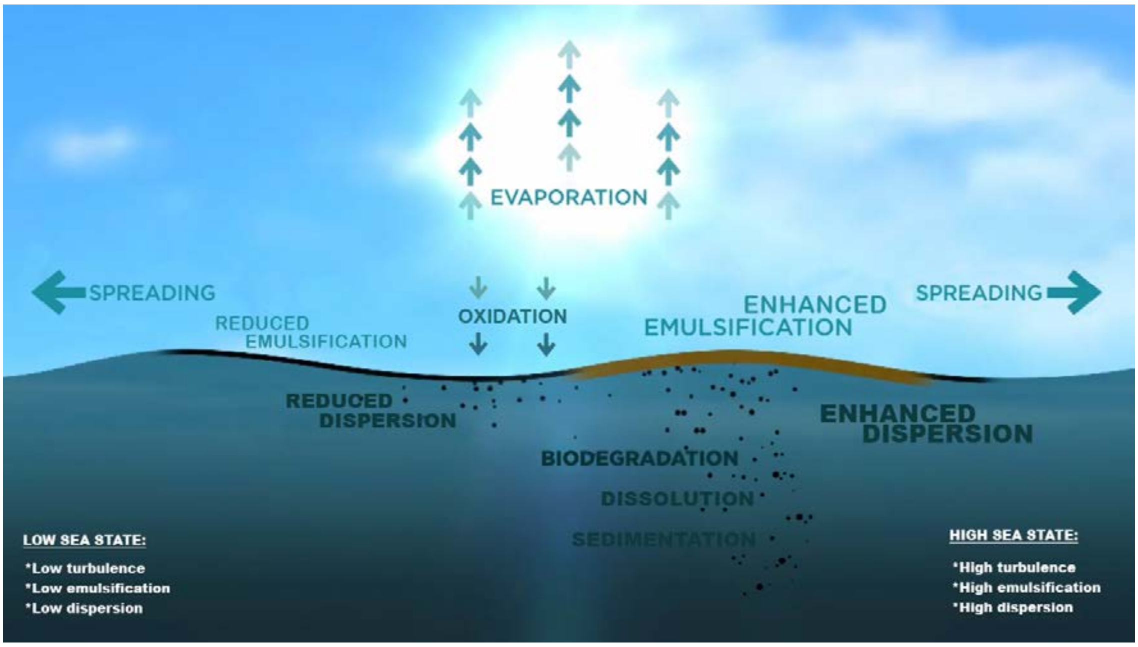


Figure 1. Weathering oil process (redrawn from [2] and ITOPF).

Evaporation is a significant component of the fate of an oil spill, depending on the type of oil (vapor pressure of the components), wind speed, and surface temperature. In some cases, up to half of the spill can evaporate in one day. Other surface processes include spreading and advection, and oxidation. Only about 1% of the spilled oil may be dissolved, dispersed or suspended within seawater. The emulsion of water and oil can form with medium to high winds, especially for certain types of less viscous oils, and are very persistent over time because other weathering processes are inhibited. Dispersed oils spread laterally until eventually breaking into droplets. For droplets smaller than about 70 microns, turbulence in the water prevents substantial upward drift [1]. Larger drops can return to the surface and form very thin films and/or more droplets. The dissolved hydrocarbons are predominately aromatic in nature, whereas the dispersed ones are probably deficient in aromatics. Dissolved components of the oil would probably act by diffusing into the vital fluids and organs of marine organisms, thus giving toxic effect. Although this amount of oil is almost negligible in the mass balance, it is probably the pathway of highest persistence and danger to living organisms. Other processes include collisions of oil droplets with sediments, resulting in settling on the seabed. An example of guidelines on oil characterization to inform spill response decisions with further readings on this issue is provided by IPIECA [3].

With this information in mind, it is possible to imagine how the spill can be discovered (section 1.1.1), and how its fate can be predicted (section 1.1.2). A large body of knowledge exists in this field, which is impossible to be summarized in one report. However, a summary of the most relevant international efforts will be summarized here (section 1.1.3). In the second part of this chapter, we review the state of the art for underwater oil spill detection (section 1.2.1). This will include the application of fate prediction models that have been or could be used for underwater application and the use of underwater vehicles (section 1.2.2).

While the first part of the report will generally be familiar to many readers, since most previous work has dealt primarily with surface oil slick detection and modelling, the second part of this chapter will be of special interest because underwater detection and modelling are much more difficult and uncommon. Naturally, oils are usually less dense than water so eventually find their way to the surface. They are often spilled at or near the surface anyway, so up to now, the focus on surface work has been justified. It is also true that oil spills are more easily visualized and tracked at the surface, allowing relatively easy sampling and study. However, with the increase in deepwater and ultra-deepwater offshore activity, it is important to increase awareness of the tools available for sub-surface releases of hydrocarbons, as the tragic Deepwater Horizon accident in the Gulf of Mexico in 2010 illustrated.

1.1.1. Remote detection systems

The science of oil spill remote sensing on the surface of the water is well developed. A range of airborne and spaceborne sensors are currently available. Most successful applications of remote sensing technology require the combination of several sensors and data sets to satisfactorily address the unique situation at hand [4]. The major types of platforms used include satellite systems, aircraft systems, unmanned aerial vehicles, tethered balloon systems, and surface vessels. Surveillance capabilities of satellite sensors and platforms for oil spill response are assessed in several technical documents (e.g. [5] and [6]), while capabilities and gaps associated with surveillance monitoring from aircrafts are identified in OGP/IPIECA [7].

An excellent review of current methods is given by Fingas and Brown [8]. The principles of detection are summarized from that paper as follows: optical, laser, and microwave with a large number of variations of the latter in particular. Visible detection is good for surveying regions of known spills, although quantitative results are difficult because in the visible range of wavelengths, oil and water show very small difference in absorption or emission, only in reflectivity (sheen). One way to address this is through hyperspectral imaging, in which hundreds of images at different wavelengths are collected simultaneously, but analysis is difficult and time consuming. Airborne/satellite optical multi-spectral sensors have had good success in mapping the location of oil floating on water [5]. For example, Clark et al. [9] use both the shape of near-infrared (NIR) absorption features and the variations in the spectral continuum due to organic compounds found in oil, to identify different oil chemistries, including its weathering state and thickness. Surface layers of oil can be detected and quantified with thermal infrared (IR) images, although they cannot detect emulsions or subsurface oil. Ultraviolet (UV) detectors can map sheens of oil for very thin layers ($1x10^{-7}$ m). Laser fluorosensors can be carried by aircraft or drones, and emit UV light, while detecting returns in a range of longer wavelengths, over a ‘gated’ time interval. With different gates, it is even possible to detect oil emission from 1-2 m below the sea surface. They are able to discriminate between oil and other matter that may appear similar using other techniques.

Satellite remote sensing is now an accepted and integral component of effective oil spill response [5]. The most accurate way for the detection and monitoring of oil spills as well as of illegal discharges from ships is the use of Synthetic Aperture Radar images (SAR) images or Side-Looking Airborne Radar (SLAR) in the case of aircraft, due to their exceedingly high spatial resolution under all-weather and all-day conditions [10, 11 and references therein]. SAR requires the active emission of microwaves by the instrument, followed by detection of the return. They rely on the oil (or other substance or phenomena) to make the sea surface more smooth and therefore have a lower return of signal (a dark region). This of course means the chance of false positives is high when there are biogenic or current upwelling regions. This also means that the method will not work when the sea is already very smooth (low winds) or when it is very rough and waves obscure part the sea surface from the radar (high winds). In practice, this is a range from 1.5-10 m/s [8]. Satellite images can improve the possibilities for the detection of oil spills as they cover large areas and offer an economical and easier way of continuous coast areas patrolling [12]. Several spaceborne SAR systems have been used for oil spill monitoring using sensors that are characterized by their frequency band. Image resolution is usually reduced in order to have increased swath coverage. The main methods used for oil spill detection with single-polarised SAR images are the adaptive threshold method, the bimodal histogram method, and neural network method [11].

Commercial products and services based on SAR are now commonly available. For example, the European Maritime Safety Agency offers service to national or European public authorities through its CleanSeaNet product [13], but also companies in the private sector [14, 15] offer oil spill monitoring in near real time.

Other sensors are also used given that the SAR ones are not free of limitations, which calls for a multi-platform SAR slick detection effort, as well as for the additional use of satellites with optical sensors [16, 17]. Optical sensors are characterized by daily global coverage and wider swaths and can complement and optimize SAR detection, especially with the recent technological advances, e.g. Moderate Resolution Imaging Spectroradiometer (MODIS). Nevertheless, studies concerning oil spill detection by exploiting its optical properties in MODIS data are still few [17,18]. Two problems with using optical satellites are the need for cloudless conditions and problems with sun glint [8].

1.1.2. Numerical Modelling

Oil-spill modelling has advanced recently due to the need to mitigate possible impacts of oil spill on vulnerable and sensitive coastal areas [19]. Fate and transport of spilled oil in the sea is a complex process governed by spreading, evaporation, emulsification, dispersion, advection, photo-oxidation, biodegradation, dissolution, encapsulation and sedimentation, which take place simultaneously after an oil spill [20]. Hence, the fate of marine oil-spills depends upon many factors, such as the initial physical and chemical characteristics of the oil as well as its quantity, the meteorological and sea conditions, its initial position and the neighboring coastline [1].

MEDSLIK II is a commonly used oil-spill model in the Mediterranean Sea and was used in the first part of this project. This is a freely available community model, which takes into account the effects of the meteorological and marine conditions at the air-sea interface, the chemical characteristics of the oil, its initial volume and release rates, and, finally, the marine currents at different space scales and timescales, in order to predict the evolution and movement of oil-spills in the sea [21, 22].

Globally, there are many other models used. For example, the freely-available General NOAA Operational Modeling Environment (GNOME) oil spill trajectory model used by the National Oceanic and Atmospheric Administration's (NOAA) [23]. It can use local conditions (tides, currents) to predict trajectories and weathering effects. During the second part of this project, GNOME was used instead of MEDSLIK II. It was realized from the exercises during the first part of the project that MEDSLIK II was not able to pinpoint the model source nor bin average the concentration of oil parcels on a fine enough grid (only 0.1 arcmin). It was also found that the output was not available on a fine enough time scale (only 1 hour). The relative advantage of MEDSLIK II is that it allows for vertical structure on the plume, but the vertical resolution is limited to only 4 layers, and not seen as important in this environmental situation.

GNOME, however, addressed the above issues in its freely-available form providing data output in an internationally-accepted standard by default (KML). It should also be noted that GNOME can also be used with netCDF input files for ocean currents, either from regional modeling systems, or from their own servers for several free sources. The same is true for coastline, tides, and winds. A short GNOME start-up guide has been developed and placed in this document.

Within the GNOME suit, some models simulate only the weathering (like ADIOS: Automated Data Inquiry for Oil Spills from NOAA) or advection/diffusion such as the Community Climate System Model (CCSM). CCSM is a tool designed by the US National Center for Atmospheric Research (NCAR) and the Department of Energy which simulates how a liquid released at the spill site would disperse and circulate. A complete list of tools is available at the NOAA web site [24].

Commercial models are also available, although usually this is achieved as a consulting service, and the user provides the relevant information to the company. One example is OilMap and OilMapDeep [25, 26]. Another is OSCAR which is available from the company Oil Spill Response Ltd. (OSRL) [27] and yet another is OSIS, available from BMT Cordah [28]. A common situation is for these companies to have a specialty developed in-house, but to have also several models at their disposal, often in common with their competitors. For example, BMT Cordah runs both OSCAR and OSIS and OSRL runs both OilMap and OSCAR. A short review of many models is provided by Foreman et al. [29].

Models should include key processes mentioned above, such as advection and spreading, three-dimensional hydrodynamics, evaporation, dispersion, sedimentation, emulsify-cation, and beaching. Their outputs should include the flow field of the region (ideally 3D), plume or slick trajectory, distribution of oil from surface to bottom, fate of oil (beached, degraded, evaporated, sedimented), and assistance to effectively plan defensive booming and/or skimming of the oil.

The MEDESS4MS project [30] is the most recent European effort regarding numerical oil-spill modelling. The objective of this project which ended in 2015 was to deliver an integrated operational multi model oil spill system in the Mediterranean by gathering and analyzing met-ocean data as well as data related to ship traffic, ship operations and sensitivity mapping, providing a useful tool for the early detection and efficient control of the oil spill at early stages. The MEDESS4MS Service (http://www.medess4ms.eu/) employs various oil-spill numerical models covering different areas of interest in the Mediterranean, such as MEDSLIK, MOTHY and POSEIDON OSM. A short manual is available at http://medess-dss.bo.ingv.it/medessWebRes/User_Manual_MEDESS_4MS.pdf.

1.1.3. Oil spill response policies and guidelines

The International Maritime Organization (IMO) is the UN global standard-setting authority for the safety, security and environmental performance of international shipping. As the custodian of the 1954 International Convention for the prevention of pollution of the sea by oil (OILPOL Convention), assumed responsibility for pollution issues. Over many years has adopted a wide range of measures to prevent and control pollution caused by ships and to mitigate the effects of any damage that may occur as a result of maritime operations and accidents.

Several maritime safety agencies, organizations and companies have produced a vast amount of documents, guidelines and manuals over the time that cannot be listed here. It is worth mentioning, however, recent technical papers series, such as for instance the OGP-IMO-IPIECA-CEDRE Good Practice Guide Series [31] that summarizes upgraded current views on good practice for a range of oil spill preparedness and response topics, or the Technical Information Papers (TIPs) collection produced by ITOPF [32]. In these and other documents, the efficiency of mechanical techniques for oil containment and recovery such as booms [33], skimmers [34] or sorbents [35] have been widely recognized. Also, the efficiency of chemical agents, still controversial in some countries, such as dispersants [36], widely applied in the Gulf of Mexico last accident is also treated. These documents, however, address traditional mechanical and chemical resources, which are not the focus of this document. We have identified a need to explore and develop underwater detection and monitoring with new technologies and discuss it below.

1.2. State-of-the-art of oil detection underwater technologies

1.2.1. In water oil *in situ* probes

Petroleum hydrocarbons may be present in seawater in liquid, dissolved, gaseous or solid phases. The liquid phase contains significant amounts of polyaromatic hydrocarbons (PAH) whereas the gas phase consists of mostly lighter alkanes such as methane. Hydrocarbons can be detected directly (e.g., gaseous and dissolved methane, PAH) or indirectly by through an anomaly in the temperature, salinity, or other parameters. According to several authors and reports and [37, 38], multiple sensors will be required to collect a complete picture of an oil spill (extent, location, movement, thickness, condition, and classification). Sensors that detect oil by coming into close contact with it are considered *in situ*. Most in situ sensors take advantage of the absorption, reflectance, or fluorescence by hydrocarbons at different wavelengths of in situ, much like for remote sensing. In this section, only in situ sensors for field measurements are discussed.

The OGP-IPIECA Oil Spill Response Joint Industry Project report [39] has summarized the recently-available sensors for in situ measurement into direct and indirect as follows. Direct sensors detect oil or byproducts directly such as fluorometers for PAH or crude/refined hydrocarbons - using different wavelengths - or infrared spectroscopy of methane. Fluorometric differences on crude or refined oil resides in the PAH's composition, with the aromaticity of the compound playing a key role in determining its fluorescence intensity. Oils are typically excited using ultraviolet wavelengths (300-400 nm) and fluoresce in the visible wavelength range from 400-600 nm. Physical properties such as weight of oil or API gravity also affects the fluorescence of crude oils [40]. The addition of additives will also affect the fluorescence properties of oils [41] and differences in crude and refined oil fluorescence is primarily due to the refinement process.

Indirect measurements can be made by conductivity-temperature-depth (CTD) units, turbidity meters, dissolved oxygen concentration, or NDIR of carbon dioxide (a byproduct of biodegradation). Other, less common sensors include mass spectrometers, total organic vapor monitors, toxic Ultra violet (UV) and Infra-Red (IR) absorption, imaging sensors (optical or thermal) [42]. It is often emphasized that because of the complexity of the mixture of oil and seawater in terms of phases and compounds, a combination of sensors should be used, hence some suppliers have developed sensor suites called "leak detection systems." These are a combination of direct and indirect sensors, often of significant size and with substantial power requirements.

Even more recently, acoustic echosounders have been used to measure bubble and oil droplet size distributions from backscatter [43, 44] and optically using submerged microscopes or light diffraction measurements [39]. It also possible to map oil that has settled on the seabed using multibeam echosounder backscatter systems [45, 46].

1.2.2. Autonomous underwater vehicles in oil spill response

In-situ detection of oil in the water column is well established with small, affordable fluorometers that have regularly been integrated into Autonomous Underwater Vehicle (AUV) systems. These in situ sensors detect oil directly, as discussed above, but the complexity of the signal and the risk of false positives implies that care must be taken. One way is to carry as many direct sensors as possible (different types of fluorometers). This is the logic behind the Turner Designs® C3 Fluorometer (Crude, Refined, and CDOM fluorometers) – many other brands of fluorometers are available- which was shown to respond as expected to known analytes, even though the role of ambient water conditions and the choice of calibration substance was critical to proper interpretation [47]. This also implies that it is also helpful to carry as many indirect sensors as possible (CTD, Chlorophyll fluorescence, oxygen, turbidity). Even then, the best result one can reasonably hope for is the confirmation or denial that hydrocarbons are present. Almost nothing can be said for the absolute concentration unless the following conditions are met:

- The sensor is calibrated with the same substance that is known to have spilled. This is required because different compounds respond differently to the excitation light. Since spilled oil is a mixture of compounds, the relative contribution of each is critical to determining the response.

- Effects of weathering and biodegradation can be ignored. This is required because the oil that is oxidized, degraded, or otherwise modified from its original state will not respond the same to the excitation wavelength.
- Effects of other substances can be removed. This is required because other (natural) substances also fluoresce at the same excitation/emission bands.

It is true that indirect sensors can help to describe the validity of the latter two conditions, but it is clearly nearly hopeless to expect those conditions to be met, or to expect that supplementary measurements can sufficiently quantify the weathering or influence of other substances. Indirect measurements can, however, eliminate false positives for detection when it is seen that one component varies in a way inconsistent with the others [39]. Remote systems can also aid in locating oil spills, but do not provide information below the surface (except in the case of airborne laser fluorometers, which may collect information as deep as 2 m). The only sure way to validate the in-situ measurements is to collect water samples and analyze them in a laboratory setting, using a mass spectrometer for example. Samples are typically done using a ship with a rosette system of bottles. Diercks et al. [48] show how this was done in conjunction with ship-based in situ sensors (direct and indirect) during the DeepWater Horizon blowout of 2010.

Another issue arising from detection of oil in the water column is that of geolocation. Satellite-based positioning is not possible underwater, so acoustic methods must be used to track the position of the vehicle. Such systems must be installed on demand and are normally limited to a few km horizontally. Typically, the Autonomous underwater vehicle (AUV) is not aware of its exact position until it surfaces and acquires a satellite fix, unless is equipped with specific equipment like DVLs. Operators monitor it from land using a real-time transmission system. Vertical position in the water column can very accurately be determined by the vehicle's pressure sensor. This adds to the complexity of measuring oil from AUVs.

An impressive effort has been carried out [39] to characterize the current state of measuring oil from autonomous vehicles. While both surface and subsurface vehicles are included there, we limit our discussion to subsurface because it relates directly to the objectives of this project. In particular, the state of the art in measuring oil from small AUVs is addressed. It is shown there, that even the largest AUVs are limited to relatively small payloads, both in terms of volume, net buoyancy, and power. Typically, no more than a few days of measurements are possible before recovery, making AUVs generally a rapid targeted response tools. One exception is the underwater glider AUV, which can sample for many months, but with a severely restricted payload. A comprehensive and detailed list of each available AUV is included in OGP/IPIECA [39] report, followed by a set of matrices describing how compatible each specific sensor model is with each AUV model. Naturally, small direct sensors (fluorometers) and indirect sensors (CTD, Dissolved Oxygen, optical) dominate the compatibility. Gliders are a special case and have been shown to be useful in long-term monitoring using a small subset of sensors, mostly indirect, during the DeepWater Horizon spill [49]. Because of their long endurance, it is possible to have gliders constantly sampling regions of interest as a precautionary measure. For currently available gliders, compatibility is low according to IPIECA [39], because of the capability of the very restrictive payload. However, a recently-funded European project called BRIDGES [50, http://www.bridges-h2020.eu/] aims to develop a deep hybrid AUV-glider with a specific payload for oil detection.

Finally, it is important to mention some applications of AUVs detecting oil in water. IPIECA [39] evaluated combinations of sensors and vehicles for five scenarios. Regarding in situ sensors and AUVs, they found that only in incidents offshore (oil tanker in transit offshore, offshore platform at 300 m depth, and offshore pipeline rupture or well blowout) and for fluorometers, CTD, optical dissolved oxygen, and turbidity sensors are AUVs suited. They also found that gliders are likely to be useful for monitoring spill large perimeters and extents.

1.3. Advantages of this technology

As stated above, building situational awareness and improving preparedness for oil spill response are mainly made through data acquisition and processing. However, current technologies are mostly focussed on oil detection at the sea surface. As previously review, these technologies include airborne and spaceborne remote sensors such as: IR video, photography and thermal imaging, synthetic aperture radar, UV sensors, airborne laser fluorosensors and airborne and spaceborne optical sensors. Available remote-sensing techniques are efficient and well developed for on water oil, but less useful for underwater releases before surfacing. The increase in deep water offshore activity have increased the public interest in countermeasures available for sub-surface releases of hydrocarbons. The 2010 Deepwater Horizon incident brought into the public eye the problems identifying and determining the extent of these large subsurface plumes. Since then, several initiatives have emerged to incorporate this issue into the preparedness and oil spill response policies.

Fluorometry is a technique widely used studying oceanographic processes. Fluorescent dyes, such as Rhodamine WT, are commonly used to track water flows since they are detectable at very low concentrations. One of the most effective techniques to determine the presence of oil in water - either remotely or in-situ - is fluorescence as PAH can be sensed with this technique. Development of the solid-state light sources in a wide range of wavebands, including the UV, has led to the introduction of new types of fluorescence probes to sense hydrocarbons. Nevertheless, to determine the spatial distribution of an oil spill and its temporal evolution the integration of this kind of probes in dynamic platforms is necessary. These platforms are able to sample large areas, including the water column and accurately geo-reference the recorded measurements. Potential robotic platforms are Remotely Operated Vehicles (ROVs) and AUVs. Deep-water-drilling companies routinely enlist ROVs to maintain and assemble equipment underwater. In the weeks following the explosion of BP's Deepwater Horizon oil rig, a dozen of working class ROVs descended into the Gulf of Mexico. Each one tethered to a ship by a combination of electrical and optical cable, the ROVs formed a fleet of unprecedented size.

Although the AUVs technology is mature enough, and commercially available, their use is still much restricted for military and scientific applications. Their use for environmental studies is steadily increasing, e.g. to measure pollution chemical signature, where source localisation or boundary tracking are the standard type of missions.

Unlike the ROVs, the AUVs are untethered vehicles and therefore do not require of large infrastructures or complex logistics to cover significantly larger area than ROVs can do. Moreover, as the AUVs missions are preprogramed and they are not remotely operated, they do not require a permanent attention of an operator (human-in-the-loop), but its supervision (human-on-the-loop), thus simplifying the operations. Also, unlike ROVs, they can operate in relatively adverse weather conditions, mostly limited by the deployment/recovery capabilities of a support vessel.

Autonomy brings the advantage of multi-agent collaborative robotic systems enabling to address the main issues in our targeted application. The main goal for these robotic systems is to provide information on sub-surface hydrocarbon concentrations and determine their extension. This technology can be either, used to find a slick, or to track and monitor oil in water slicks. Here we designed and use a fleet of several autonomous underwater vehicles with hydrocarbon sensing payload supported with unmanned surface and aerial vehicles. While the firsts directly measure in water oil, the surface and aerial agents serve as a communication gateway to make collected data available in near real-time wherever needed. Thus, the system provides information to improve reliability in the numerical modelling fate forecast of oil plumes not seen from the surface.

During the Underwater Robotics ready For Oil Spill – URready4OS- project, several kinds of assets working collaboratively allowed overcoming the limitations of one single robot at work. The system is enabled of detect and monitor subsurface oil plumes and feed tracking oil models to better forecast the spills trajectories below the water. This approach considerably simplifies the operations logistics and costs complementing current conventional techniques available for on water oil.

The capability of tracking subsurface oil plumes brings a new perspective in the spills monitoring not used before. The distributed intelligence of these devices across the slick enable us to build up a highly accurate and dynamic image to predict its movement. The URready4OS robotic system will enable the end-user to optimize the response time.

Here we summarize the system advantages by grouping them into three main categories: quality of the acquired data, maneuverability and system adaptability.

One of the major benefits of the system is its ability to collect a large amount of high-quality data in cost- and time-efficient way. A key of success for operations relay in the equipment manoeuvrability. Lightweight - one person portable (20-50kg) – AUVs, are easy to handle from land or small rigid haul inflatable boats (RHIBs) without requiring large and expensive infrastructures for logistic, deployment and recovery. The third main advantage resides in the flexibility enabling the system to operate with a few or a large number of robotics assets depending on the scale of the spill.

1.3.1. Quality of the acquired data

In oil spill emergencies, both data quantity and quality are equally important to determine rapidly its fate in the marine environment. As subsurface oil plumes can travel for long distances in short period of time, is of upmost relevance to increase the response time by feeding the fate forecast numerical models with dynamical information of the plume. In the scope of this project, AUVs equipped with sensors able to detect hydrocarbons (crude and refined oil) were the preferred platform for 3D data collection. Determining the fluorescence of oil in water column over space and time at high frequency gives a unique opportunity to model and monitor the spill in 4D.

Quality, accuracy and confidence of the recorded data directly influence the performance of the modelling procedures. Typically, the collected data consist in a set of AUV positions (Latitude, Longitude and depth) and the corresponding oil concentration measurement. The system provides accuracy of just a few meters in the horizontal plane and centimetres in the vertical with approximately 1 ppb for oil concentration measurements. Logging data at high frequency (10Hz) provide spatial resolution in tens of centimetres providing a high-density data grid. As an example, the AUV trajectory during one hour of operation can cover a distance of about 5,000 meters that distributed in some meaningful form - such as lawn mower, circle or straight lines - provide data for an impressive space-time area coverage. These data can be transmitted to operators either, at the end of the mission, or at near-real time at lower frequency due to restrictions of the acoustic modems.

Real-time availability of AUVs acquired data is a priority enabling us to feed the forecast trajectory model thus supporting decision makers with the information to re-plan and launch the most appropriate mission in a timely manner. Within the scope of this project, we tested two real-time communication options. The first with continuous data flow every few seconds, the second, based on an event driven data feed, transferring data only when oil-in-water was positively detected.

1.3.2. Maneuverability and operational costs

Use of URready4OS system significantly reduce the need for human intervention in the field. However, that does not mean that humans are not involved in operation. Their intervention is limited to vehicles handling, mainly during the deployment and recovery, and monitoring the system status and situation in the operational field to re-plan and launch new missions. It does not intend to eliminate the human in the process, but reduce their efforts providing better and faster data to support the decision making process.

Cost effectiveness of the system can be observed from three different perspectives when compared with large vessels operational cost. Firstly, the cost of the portable vehicles used here is reasonable in comparison to the cost of alternative solutions, e.g. ROVs. Secondly, vehicles can be deployed from shore or small support vessels only for deployment and recovery, otherwise available for other concurrent tasks, thus simplifying the operations being cost-effective. Thirdly, the URready4OS system is not a human-in-the-loop system where humans are involved in flying the vehicle and handling of the tether system throughout the operation, but a human-on-the-loop system, in which pilots monitors the operations and interferes only if and when needed, thus reducing significantly the human workload.

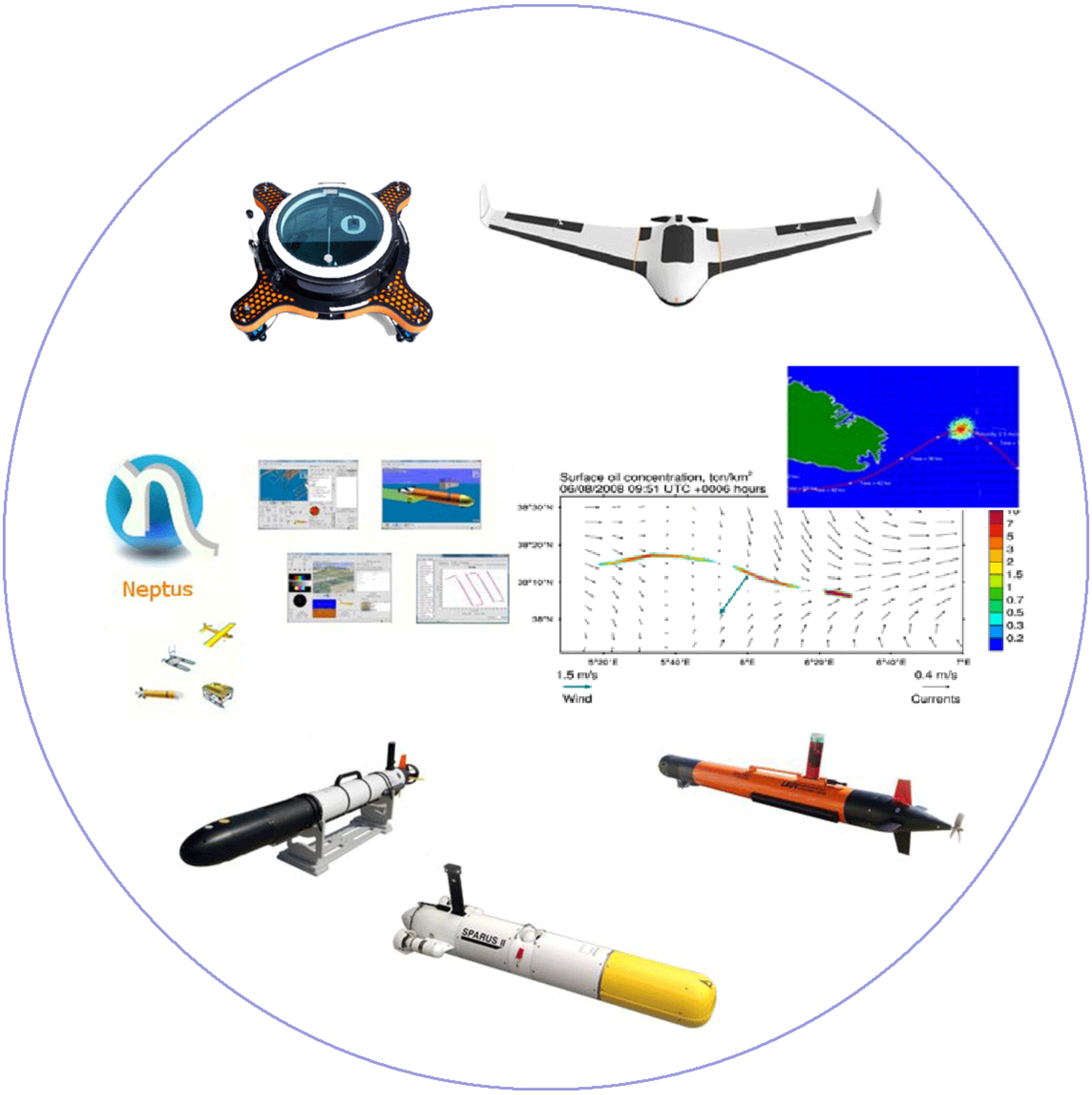
Operations involving a high number of specialists and trained crews increase considerably the cost of the operations cost. Operation of the system does not require additional certified personnel on board. Cost of training for a ship or rapid response crew is insignificant compared to the cost of certification of other platforms personnel, e.g. ROV pilots. Technical certified personnel for ROVs is a limitation overcame by the use of lightweight AUVs and other vehicles comprising the UReady4OS fleet. After the basic training, the fleet can be operated by fieldwork crew and with relatively simple logistics with supervision of a specialized engineer.

1.3.3. System adaptability

Environmental and financially speaking oil spill are extremely costly disasters. The spill of an oil tanker load can produce a slick of hundreds of square kilometers in size changing position and dimensions over time. The size of a spill does not necessarily indicate the damage it will cause by itself, largely depending on the location. An oil spill near the coast or in an area protected from the wind and waves, that would normally dissipate the oil, can cause a massive prolonged damage on the coastal biota. Although, large oil spills (over 75 km2) are relatively scarce in time, small spill (of less than 10 tons on average) are registered daily, with medium spills (between 10 and 1,000 tons) occurring about once a quarter.

The scalability of the URready4OS robotic system brings one of the largest advantages allowing to attend either small or large slicks at different spatial and temporal scales. The system, as designed, can be scaled up, to include numerous vehicles scanning large areas, or scaled down, to a single vehicle for small slicks, being cost effective.

From a heterogeneity point of view, the system is also expandable with AUV operations supported with other type of vehicles. Supporting of USVs provides real-time data extending reliably the AUVs navigation time under the water. Support of UAV extends the range of AUV operations in relation to the location of the control center and can provide high quality data of the surface slick extent when video streaming.



CHAPTER 2

URready4OS System Description

2. URready4OS System description

System components of the URready4OS project can be grouped into two categories: vehicles and software. Three different kinds of vehicles are involved: Autonomous Underwater Vehicles (AUVs), Unmanned Surface Vehicles (USVs) and Unmanned Aerial Vehicles (UAVs). While the AUVs measure the in-water oil, the USVs and UAVs increase the AUVs operational range acting as gateways for communication between the vehicles and the base station, either on land or ship, where near real time data are received.

Two separate pieces of software are also involved in the system: The command and control console and data visualization tool NEPTUS and an oil spill tracking and fate forecasting MEDSLIK or GNOME.

A representation of links between agents is shown in Figure 2.

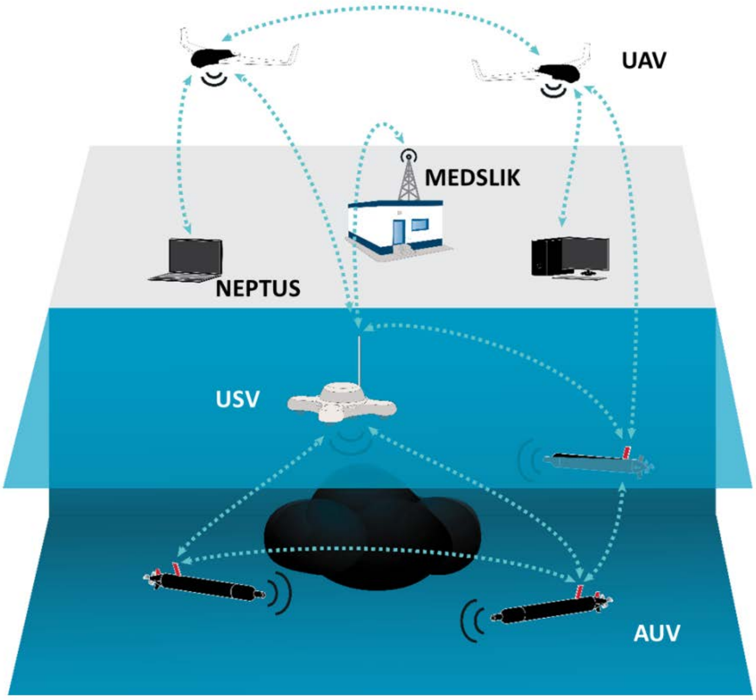


Figure 2. Sketch of system components and links between agents.

2.1. Vehicles technical specifications

An autonomous underwater vehicle (AUV) is a robot capable of traveling underwater without the need of an operator (they may also be referred to as Unmanned Undersea Vehicles – UUV). They cover a wide and diverse range of applications from inspection to intervention and mapping, depending on the sensor payload.

Here we used light AUVs with a size of 120 cm long, 20 kg weight and 60 meters depth rating -due to fluorescence optical sensors integrated. However, a deeper water -600 meters rated, larger and heavier- REMUS600 - and two SPARUSII - mid-range AUVs - vehicles were used. In total 8 AUVs from four different manufacturers took part in this project in different exercises: 3 Light Autonomous Underwater Vehicles (LAUVs), manufactured by OceanScan MST (Portugal); 2 IVER2, manufactured by L3OceanServer (US); 2 SPARUS II, manufactured by IQUA Robotics (Spain) and 1 REMUS600, manufactured by Kongsberg (Norway).

The robots that can travel autonomously on the water surface are usually called Unmanned Surface Vehicles (USVs). As the AUV, they are also programed to follow a specific path on the surface. Three different USVs, 1 PlaDyPos and 2 H2Omni-X, manufactured by H2O Robotics (Croatia) took part in the exercises. The unmanned aerial vehicles (UAVs) are robots able to fly autonomously. They can be equipped with autopilot to fully autonomous flights or can also be remotely operated by a pilot on land or ship. 2 X8 UAVs assembled at University of Porto were used in some of the exercises.

The marine robotics has a high background in military applications but is also extensively used in the scientific domain. With the popularization of this technology in the ground sector, and subsequent downscaling price, the number of maritime industry applications has also exponentially grown. Here three different system components in the underwater, surface and air are combined to detect and monitor oil in water. A technical description of these components is provided in the next sections.

2.1.1 LAUVs

The Light Autonomous Underwater Vehicle (LAUV) is manufactured by OceanScan MST (a spin-off company from the Underwater Systems and Technology Laboratory – LSTS - University of Porto) targeted at innovative standalone or networked operations for cost-effective oceanographic, hydrographic, security and surveillance surveys. Based on a modular design, the platform is built to be robust and reliable. The name of vehicles dedicated to this project were *Xplore-1* , *Lupis* and *Harald* for the ones of UP, UZ and NTNU respectively. They are shown in Figure 3 with some characteristics in Table 1.

Figure 3. LAUVs that took part in the URready4OS training exercises.

Table I. Basic characteristics of LAUVs.

Length	Starting at 95 cm to 240 cm	**Diameter**	14.7 cm
Weight	Starting at 19 kg to 32.1 kg	**Depth range**	100 meters
Communications	Wi-Fi, GSM/HSDPA Iridium Acoustic Modem	**Autonomy**	Lupis – 6 hours Xplore-1 – 24 hours Harald – 24 hours

The new nose section design and development by OceanScan for the LAUV Xplore-1 (Figure 4) enable the vehicle to accommodate sensors from different manufacturers. Besides the probes for Refined Oil, Crude Oil and Rhodamine, can also integrate many other sensors including a forward looking sonar. The electronics board that interfaces with the sensors is based in the AML's Metrec-X, that includes multiple analog input slots, to which the Cyclops C7 fluorometer probes were connected.

The Laboratory for Underwater Systems and Technologies (LABUST) at University of Zagreb performed the integration of the oil in-water probe in the Lupis LAUV from a different point of view. A wet connector was installed between the flooded nose (wet side) and the Doppler Velocity Logger (DVL) compartment (dry area) to install and connect the Cyclops C7 fluorometer directly on the connector as shown in Figure 4. On the dry side, the probe is powered by 12VDC from the AUV power distribution board and probe signal output (analog output) and range inputs are connected to the backseat PCU. From the software point of view, the backseat samples the probe measurement and automatically adjust the probe range. At the same time collects the position data from the front seat and internally log all this data together. In case of near real time data transfer, backseat communicate via acoustic modem with the surface transducer and handles the transfer. For targeted application, an USBL transponder/modem and a fluorometer facing forward were installed into the specially designed and manufactured new nose of the vehicle, whose exploded view is given in Figure 5. The integration solution for Harald is as shown in Figure 6.

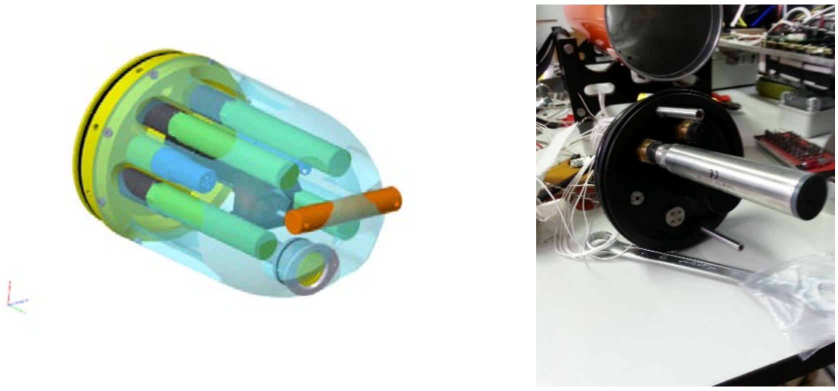


Figure 4. Left, sketch of the probe integration in the LAUV Explore-1. Right, laboratory test of the integration of the sensor in the LAUV Lupis

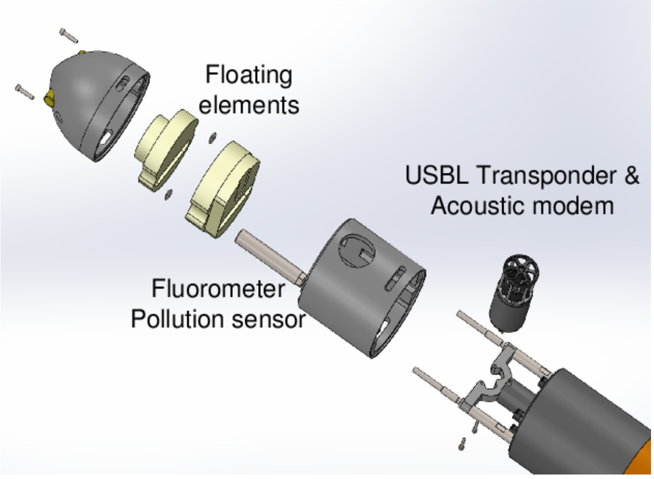


Figure 5. Modification of the off-the-shelf LAUV. Extension of the original flooded nose of the vehicle for fluorometer and acoustic modem integration.

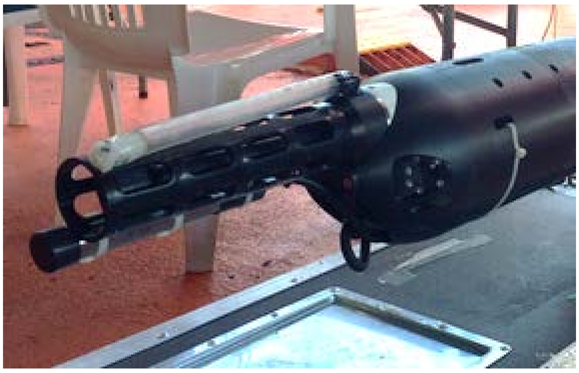


Figure 6. Solution from NTNU fluorometer integration in the LAUV Harald.

2.1.1. IVER2

The IVER2 AUV (Table II) is a small man-portable AUV manufactured by L3 Oceanserver. With a proven track record over thousands of missions, it is used for imaging and environmental surveys, including research, development, and OEM based applications. The IVER2 design allows for the integration of new sensors and capabilities.

Figure 7. IVER2 with two different fluorometer integrations.
White one for TUT, yellow for UPCT.

Table II. Basic characteristics of the IVER2 AUV.

Length	Starting at 110 cm	**Diameter**	15 cm
Weight	Starting at 18 Kg	**Maximum Depth**	100 meters
Communication	Wi-Fi, GSM/HSDPA Acoustic Modem	**Autonomy**	6 hours

A new nose was design and manufactured at the Technical University of Cartagena to integrate the Turner Cyclops Integrator in the IVER2 AUV (Figure 8) named Icue. This design implied the installation of a backseat PCU in the AUV where recorded oil and rhodamine data were stored and merged with the position parameters from the front PCU following a similar procedure carried out in LAUVs. The probe is also powered by 12VDC from the AUV power distribution board.

Figure 8. Left, Cyclops Integrator (Turner Designs) oil probe.
Right, IVER2 Icue, with the new nose and probe integrated.

Tallinn University of Technology found another way to integrate its oil in-water probe in the IVER2 (Figure 9). A single sensor - Rhodamine in this case, with plastic housing and shade cap - was integrated at the top of the vehicle, streamlined with the handle, a safe place for deployment and recovery. The Cyclops 7F optical sensors was external with its cable penetration potted with Scotchcast 2131 resin. As the Cyclops 7F optical sensors output an analog signal, the analog digital converter was kept inside the AUV body, connected via USB to its main board and plugged as another input to the 12V DC supply power.

Figure 9. IVER2 with the new Cyclops 7F optical sensor integrated.

2.1.2. SPARUS II

SPARUS II AUV is a multipurpose lightweight hovering vehicle with mission-specific payload area manufactured by IQUA Robotics (a spin-off company from the University of Girona). The payload area can be customized by the end-user and with an open software architecture, based on Robot Operating System (ROS), for mission programming. Two SPARUS II took part in one of the exercises, one from the University of Girona and another owned by the University of the Balearic Islands, referred to as Sparus and Turbot, respectively. SPARUS II taking part in the exercise are shown in Figures 10 and 11, with Table III giving some basic information. They are in the mid-range of weight and size so the need a crane to be deployed and recovered.

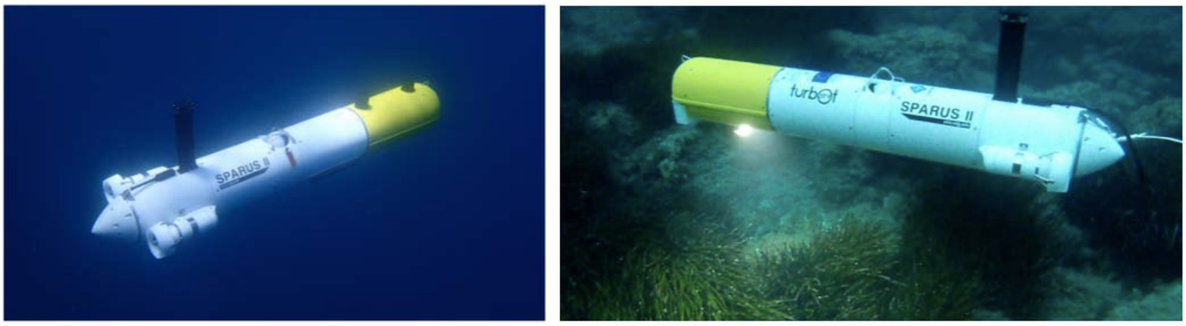
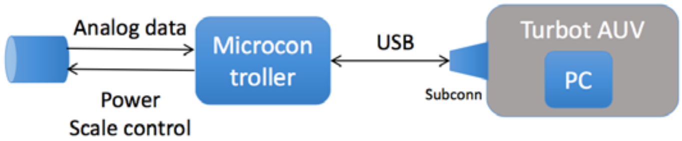


Figure 10. Right, Turbot AUV from University of the Balearic Islands. Left, Sparus AUV from University of Girona, both manufactured by IQUA Robotics.

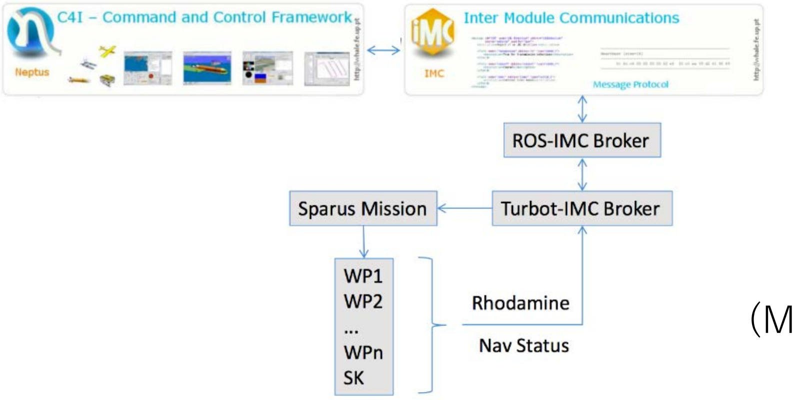
Table III. Basic characteristics of the SPARUS II AUV.

Length	1.6 m	**Diameter**	230 mm
Weight	Starting at 52 Kg	**Maximum Depth**	200 meters
Communication	Wi-Fi, GPS and flasher light, Acoustic Modem	**Autonomy**	8-10 hours

The UIB and UdG laboratories adapted the vehicle to accommodate the Cyclops C7 fluorometer probe without any irreversible change. The sensor is attached to the vehicle's structure on the payload area using a specially designed holder. The probe is powered with 5VDC from the AUV. The analog data and control lines are digitalized and serialized thanks to a dedicated microcontroller board and sent to the vehicle computer. The Rhodamine sensor readings are periodically gathered, time-stamped and stored with all the corresponding navigation data so they can be accessed by a base station in navigation time or downloaded at the end of the mission. Both Sparus and Turbot are equipped with an USBL transponder/modem and can be accessed from a base station while underwater. Once on surface, a Wi-Fi link is available.



(Electrical integration)



(Software integration)

(Mechanical integration)

Figure 11. Integration of the Cyclops C7 fluorometer in the SPARUS II vehicles. Right, Mechanical integration in Turbot AUV. Left, Diagrams corresponding to the electrical and software integration of the sensor.

2.1.3. REMUS 600

The REMUS AUV is a positively buoyant, 2m long, propeller-driven vehicle used for short-duration (max 10 hours), intensive surveys of the ocean down to 600 m over distances of around 70 km. The REMUS 600 SAMS vehicle, named Rebus, is designed to measure the amount of small-scale turbulent mixing in the ocean as well as temperature, salinity, water velocity and fluorescence. Rebus has been on missions around Scotland and the Arctic. Figure 12 shows the vehicle on the “Clara Campaomor” deck. Table IV shows main characteristics.

Figure 12. REMUS 600 AUV from the Scottish Association for Marine Science (SAMS).

Table IV. Basic characteristics of the REMUS 600.

Length	3.25 m	**Diameter**	32.4 cm
Weight	Starting at 220 Kg	**Maximum Depth**	600 meters
Communication	Acoustic modem, Iridium modem, Wi-Fi 2.4 GHz, 100 Base-T Ethernet	**Autonomy**	10 hours

2.1.4. USVs

The autonomous USV named after its initial purpose as a Platform for Dynamic Positioning (PlaDyPos) and shown in Table V evolved to the H2Omni-X vehicle (Figure 13). It is equipped with payload for navigation, SeaTrac acoustic system for

USBL localisation and communication with underwater agents and Wi-Fi for communication with control center. The navigation sensor set consist of a 9-axis Inertial Navigation System (INS) and high precision GPS. The surface platform has been developed at the Laboratory for Underwater Systems and Technologies at the University of Zagreb Faculty of Electrical Engineering and Computing, Croatia, and now is manufactures by H2O Robotis (a spin-off company form the University of Zagreb). It has been used for a number of different applications from diving support to underwater archaeology. It is over-actuated with 4 thrusters forming the X configuration. This configuration enables motion in the horizontal plane under any orientation.

Figure 13. H2Omni-X USV in two different exercises at sea.

Table V. Basic characteristics of the H2Omni-X USV.

Size (W x L x H)	707 x 707 x 350 mm	**Speed**	Up to 3 knots
Weight in air	25 kg	**Weight**	Starting at 18 Kg
Communication	Wi-Fi, Acoustic Modem		

The software architecture for this USV is based on the Robot Operating System (ROS) with a cascade low-level control system and an Extended Kalman Filter (EKF) navigation and target tracking. With a path and trajectory following integrated algorithm can also support NEPTUS mission planning.

2.1.5. UAVs

Although the Unmanned Aerial Vehicles (UAVs) have the ability to host video-cameras allowing a bird's eye view of an oil slick on surface, the main target for this vehicle in the system is to expand the communication range with surface and underwater vehicles while in surface. The Skywalker X8 is a low-cost COTS (Components Off-The-Shelf) vehicle that allows for quickly deployable surveillance missions (Table VI). It is a hand launchable vehicle perfected for low altitude reconnaissance scenarios with live video feed. This vehicle was enhanced at LSTS with a communications and computational stack that allows it to be part of a multi-vehicle network. Through the on-board Wi-Fi modem the vehicle can not only transmit data back to the operation station but can also extend an existing Wi-Fi network for field operation. These UAVs communicates with the USV and AUVs at surface to synchronize files and folders at distances up to 3 km (with our custom gear, omnidirectional Wi-Fi antennas). Using dish antenna with pan and tilt actuation that follows the UAV this distance can be expanded up to 10 km (also with video transmission).

Figure 14. Skywalker X8 UAV taking-of during the Cartagena exercise from the Underwater Systems and Technology Laboratory – LSTS - University of Porto.

Table VI. Basic characteristics of the Skywalker X8 UAV.

Wingspan	212 cm	**Length**	60 cm
Weight	Starting at 1.5 up to 3.5 Kg	**Endurance**	Up to 60 min
Maximum Altitude	600 m	**Wind tolerance**	Mean 14 Kts, Max 18 Kts
Communication	Wi-Fi 2.4Ghz	**Camera**	HD 720p on-board recording and streaming

2.2. Communications between agents

In a system like the URready4Os fleet involving four types of different agents (Operators, AUVs, UAVs and USVs) communication is key for the system coordination success. Two factors must be considered in the communication process:

- The mean by which the message transmitted that we call it here the pathway.
- The language, i.e. the set of protocols used for communication.

2.2.1. Communication pathways

Although not exclusively, communication between vehicles by air is performed trough Wi-Fi networks while underwater through acoustic modems. Figure 15 summarizes the URready4OS communication system.

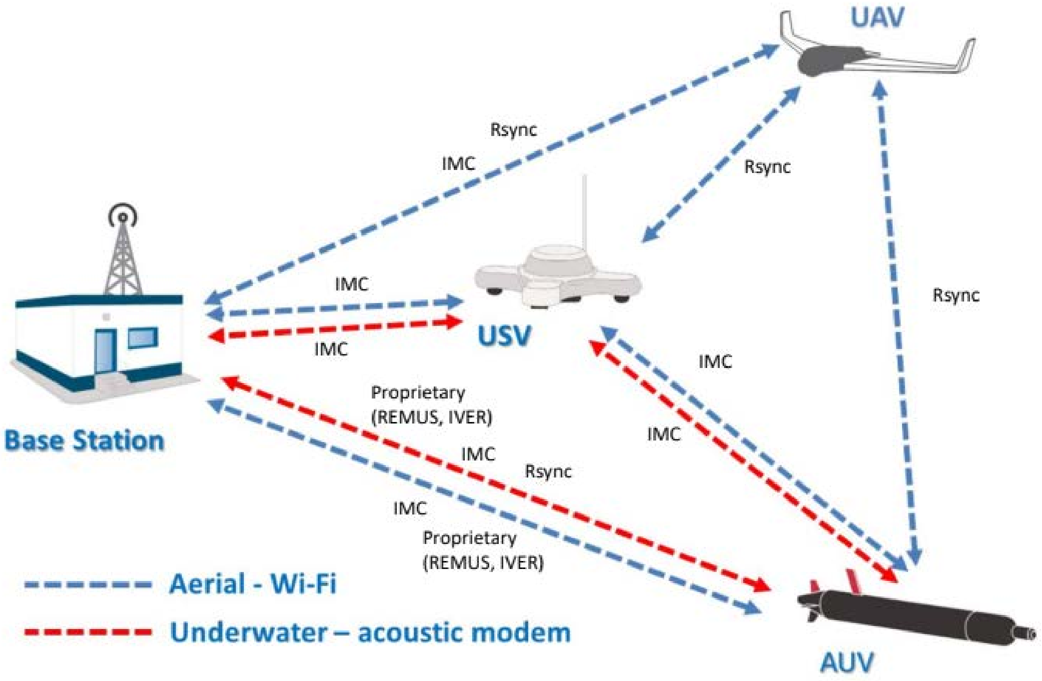


Figure 15. URready4OS system communication pathways.

Operators - fleet leader, vehicle's team leaders and vehicle pilots - must also be in perfect coordination. The team operating one (or several) vehicles is composed of a team leader and a pilot per vehicle. While the pilots receive orders from their team leader, they receive them from the fleet leader, which is permanently in contact with the captain of the ship (if the base station is at sea) or the decision maker (if on land). Figure 16 shows a sketch of the typical team organization. Operators communicate between themselves by radio (exceptionally by mobile phones if signal is available) or any other effective mean of wireless remote communication.

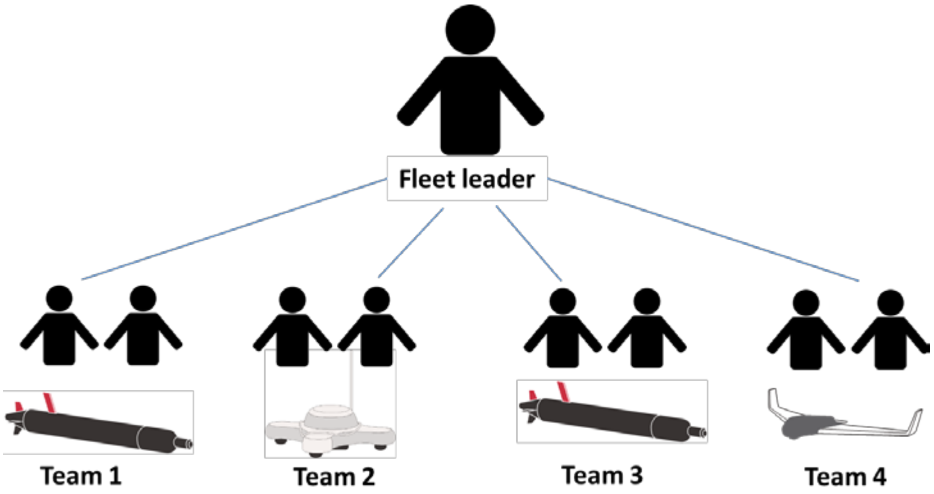


Figure 16. Operations team hierarchical organization.

Wireless communication using standard Wi-Fi routers or gateways is the main mean of contact between operator/s and one or several vehicles. The base station is usually configured as a Wi-Fi Access Point and vehicles as clients, constantly trying to connect to a Wi-Fi network with the same SSID. Although this is a common configuration employed in unmanned vehicles operations, the network is flexible enough, with routers configured transparently, to adapt to almost any mission requirement.

When the USV and AUV are in surface, but far away and out of the Wi-Fi range of the ship or land-based station to achieve a stable communication link, the fast moving in line-of-sight UAV can be used as gateway to pass information among agents. In this case, the UAVs are configured as Wi-Fi Access Point, with AUV and

USV as clients constantly trying to connect to a Wi-Fi network with the UAV SSID, which is most likely the default behavior for any AUV working with Wi-Fi.

The UAV carries a minimal open-source Linux distribution maintained by LSTS, named GNU/Linux Uniform Environment Distribution (GLUED) (http://lsts.fe.up.pt/toolchain/glued). In GLUED, Rsync is available and can run as a service daemon. The UAV 'rsync' a folder from a certain IP address (the one of the AUV and/or USV) with a folder on its storage disk, which means that any files on that specific folder from the AUV and/or USV will be synchronized with a folder on board of the UAV. Data prepared to be transferred from the AUV and/or USV must be placed inside that specific folder. Once the UAV return to the base station, a share folder on the base station computer ‘rsync’ with the UAV folder downloading all the data collected.

AUVs, on the other hand, communicate with the other agents via Wi-Fi only while on the sea surface. While underwater, AUV communicate with the USV/Base station via acoustic link. This link cannot be considered as standard off-the-shelf communication channel but rather as a custom link, meaning that AUV and USV need to be customized for this purpose. Customization includes hardware integration of the USBL system with communication possibilities or pair of acoustic modems on vehicles, communication protocols and software, customs made applications for data acquisition, transfer and processing. Attempts to use the AUV and USV which were not "paired" prior the campaign would result in communication failure.

The underwater communication channel can be set with several options in order to avoid the interference between the underwater acoustic modem used to:

- Send position and oil concentration at certain time interval.
- Send position and oil concentration only when it is detected.
- Send no information.

Finally, USVs exchange data and commands with the base station by aerial Wi-Fi, or through the UAV when far away of the base station Wi-Fi network.

2.2.2. Communication protocols

NEPTUS, the command and control software used to coordinate, plan and execute the vehicles missions, offers an API that is flexible enough to support different communication protocols. Most importantly, NEPTUS API can be extended through plugins, thus allowing interoperability between systems. All the vehicles involved in the fleet were either, modified to abide to the API, or the API was extended to integrate the new system. Once the systems are properly integrated, the human operator can view the vehicle position in the map, gather data from the system and execute some actions. The onboard command and control loops of the vehicles can be performed with any of the existing software solutions as long as the design of the mission is compatible with NEPTUS, allowing the full integration on it. The protocol followed for the command and control communication has been IMC (Inter Module Communication).

The Inter-Module Communication (IMC) is a message-oriented protocol designed and implemented at the LSTS to build interconnected systems of vehicles, sensors and human operators that can pursue common goals cooperatively by exchanging real-time information about the environment and updated objectives. IMC abstracts hardware and communication heterogeneity by providing a shared set of messages that can be serialized and transferred over different means. The protocol contrasts with other existing application level protocols by not imposing or assuming a specific software architecture for client applications. Native support can be automatically generated for different programming languages and/or computer architectures resulting in optimized code, which can be used both, for networked nodes and also for inter-process and inter-thread communication. The protocol has already been tested throughout various experiments led by LSTS UP where it has taken care of communications between vehicles, sensors and operator consoles.

In case of the IVER vehicle, the open source copyright of DUNE and IMC protocol has allowed to develop a DUNE branch (DUNE4IVER) to be installed on the backseat CPU aboard the vehicle. This branch allows to retrieve vehicle information requested by DUNE from the main CPU using a language parser between the IVER and IMC protocols. The main feature of DUNE4IVER is carry out by a new task developed in charge of bidirectional communication between the navigation software installer on the main CPU (UVC-Underwater Vehicle Control) and DUNE on the second one. This new task works as a parser, translating the IMC protocol to the IVER protocol.

The use of DUNE and IMC protocol in the IVER vehicle has increased the degree of integration using the same communication protocol on all the assets (AUV, USV and UAV) and has allowed not only to plot their position on NEPTUS but to send control command to it.

An example of the IVER communication protocol is shown in Figures 17 and 18.

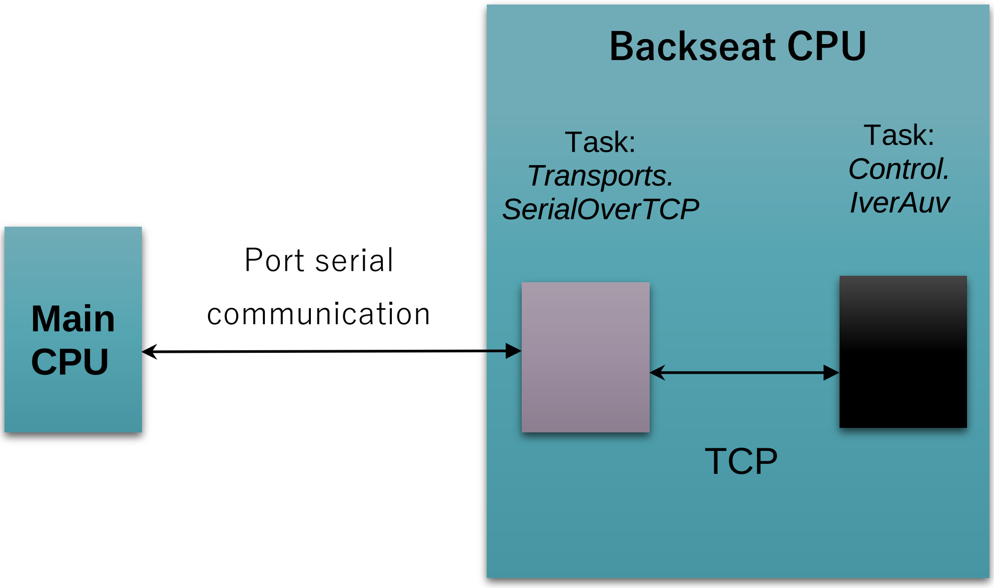
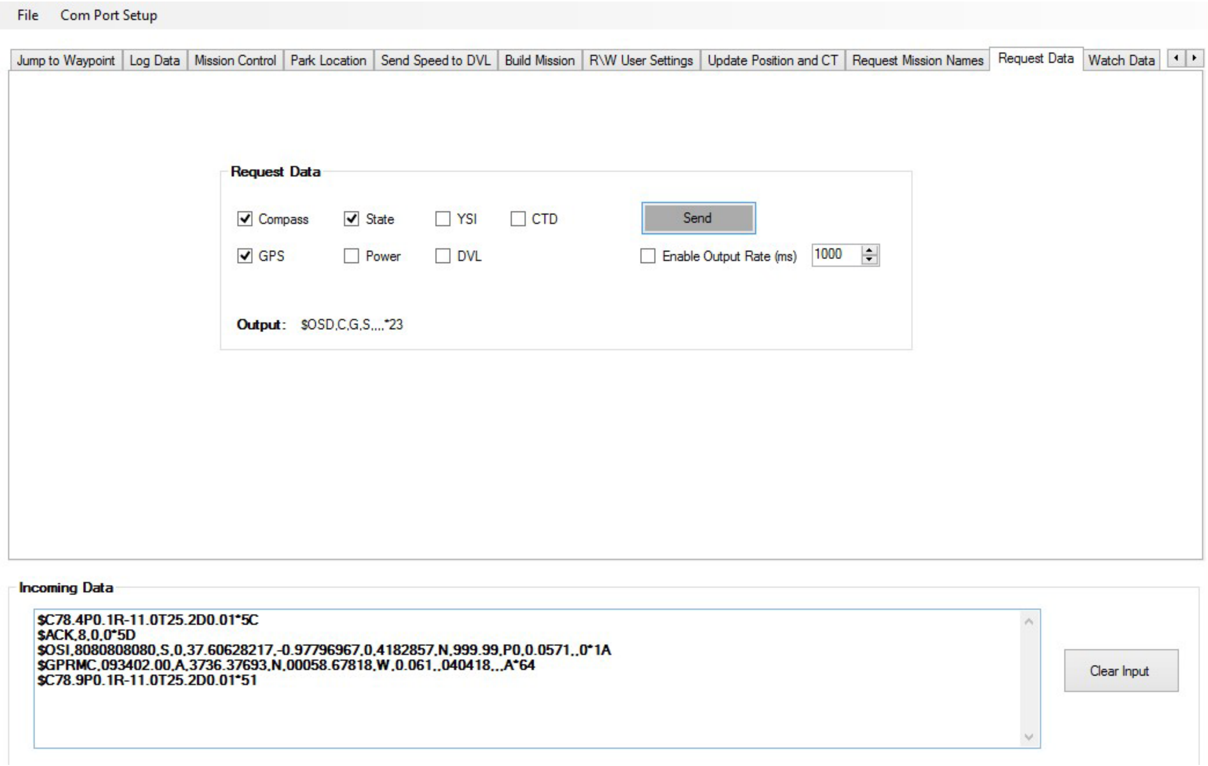


Figure 17. Scheme of the communication protocols.



Request Data

☑ Compass ☑ State ☐ YSI ☐ CTD

☑ GPS ☐ Power ☐ DVL

☐ Enable Output Rate (ms) 1000

Output: $OSD,C,G,S,...,*23

Incoming Data

```
$C78.4P0.1R-11.0T25.2D0.01*5C
$ACK,8,0,0*5D
$OSI,8080808080,S,0,37.60628217,-0.97796967,0,4182857,N,999.99,P0,0.0571,,0*1A
$GPRMC,093402.00,A,3736.37693,N,00058.67818,W,0.061,,040418,,,A*64
$C78.9P0.1R-11.0T25.2D0.01*51
```

Figure 18. Example of the IVER communication protocol.

The SPARUS vehicles has been integrated by an IMC broker that enables interoperability between ROS nodes and IMC capable systems (Figure 19).

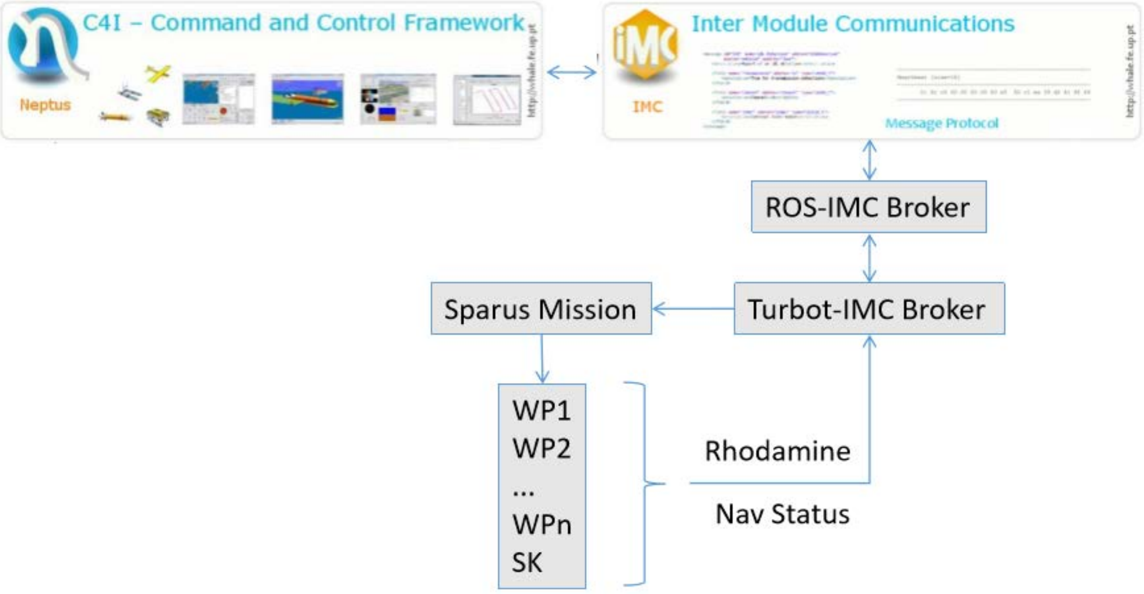


Figure 19. Example off the SPARUS II communication protocol.

The DUNE4IVER and ROS-IMC broker are opensource projects uploaded to the GitHub platforms. In case of the DUNE4IVER access should be ask to Paulo Dias (pdias@lsts.pt).

2.3. Software general description

In section two oil track and forecasting models are included. As mentioned in section 1.1.2. Numerical Modeling, we started using MEDSLIK II although many models are available. In order of overcome some of the limitations of this model, we started using in the second part of the project the GNOME suit. Here a brief description of how both were used within this project is given.

2.3.1. MEDSLIK II oil track and forecasting model

MEDSLIK II is an oil spill and trajectory 3D model that predicts the transport, fate and weathering of oil spills and the movement of floating objects in seas. The MEDSLIK incorporates the evaporation, emulsification, viscosity changes, dispersion in water column and adhesion to coast. The transport of the surface slick is governed by currents, waves and wind while its diffusion is modelled by a random walk model. Oil may be dispersed into the water column by wave action, but dispersed oil is moved by currents only (ref. Figure 1). The oil is considered to consist of a light evaporative component and a heavy non-evaporative component. Emulsification is also simulated, and the viscosity changes of the oil are computed according to the amounts of emulsification and evaporation of the oil. The pollutant is divided into a large number of Lagrangian parcels of equal size. At each time step, each parcel is given an advective and a diffusive displacement. Mechanical spreading of the initial slick is included with fate processes incorporated in the model as the evaporation of the lighter oil fractions and the mixing into the water column by wave action and emulsification [22]. Figure 20 shows an example of an output of an underwater oil spill and its forecasted surface concentration produced by MEDSLIK.

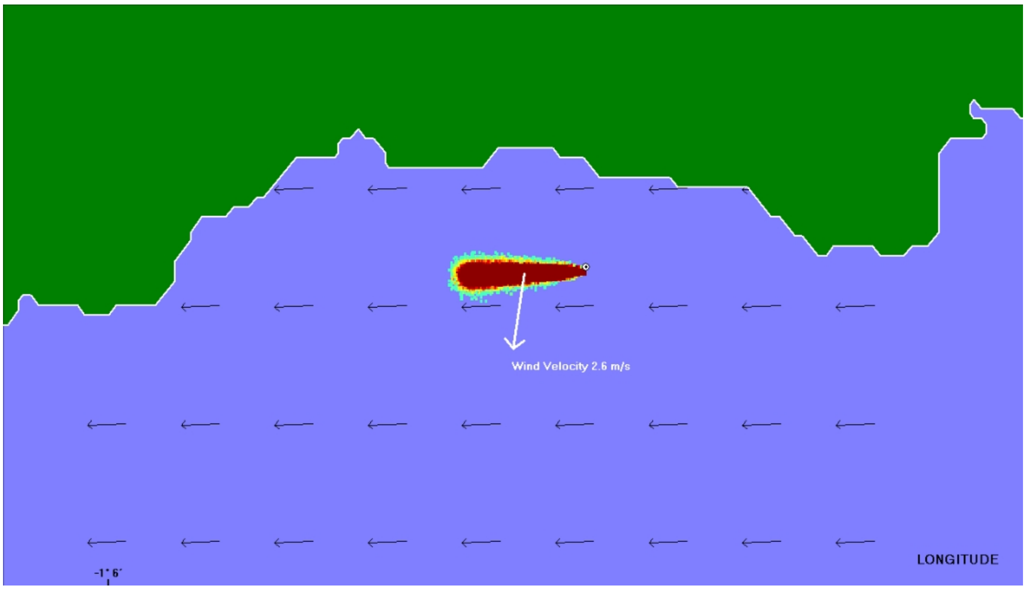


Figure 20. MEDSLIK model output of an underwater oil spill and its forecasted surface concentration off Cartagena (Spain).

Oil viscosity changes and beaching on the coast and absorption depending on the coastal type. MEDSLIK can be used for any user-selected region in the world if the appropriate map, bathymetry and forecast files are provided.

MEDSLIK consists of four modules:

- Setup module for model domain and parameters
- Visual interface for input of the spill data
- Run module that performs the simulation
- Visual interface for viewing the output

Other features of MEDSLIK include a built-in database (from REMPEC) of 230 oil types that are the most common in the Mediterranean Sea. It allows to switch from coarse to high resolution ocean forecasting data, when the oil slick passes from a course to a higher resolution domain. Also allows assimilation of observations, in-situ or aerial to correct the oil spill predictions. The effect of deployment of oil booms and/or oil skimmers-recovery can be examined. Continuous or instantaneous oil spills from moving or drifting ships whose slicks merge can be also modeled together. MEDSLIK II not only can perform hindcast simulations for tracking the source of pollution but also simulate sub-surface oil spills.

2.3.2. GNOME suit for oil spill modeling

GNOME is freely available and has all the features of MEDSLIK II, with the exception of sub-surface oil spills (limited in MEDSLIK II to 4 layers). Since it is more user-friendly, widely accepted and freely available, the GNOME oil spill fate model may be preferred. This model is being developed by the U.S. National Oceanic and Atmospheric Administration (NOAA), along with many supporting tools like a coastline generator, data service for winds and currents, and visualization tools (https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome.html). Besides providing input data files, GNOME also reads NetCDF from any forecasting or observing system using standard CF 1.0 convention. It also provides output in KML for easy plotting. Most importantly for this project, it allows a much finer precision of spill location and model output time steps without any changes to the source code. Figure 21 shows an output of the simulated oil spill off Cork (Ireland) during a training exercise within the project.

Figure 21. Example of GNOME model output every 30 min from 1100h to 1530h (overlaid). Floating oil parcels predicted to be at the yellow locations, with values of “least regret” in red.

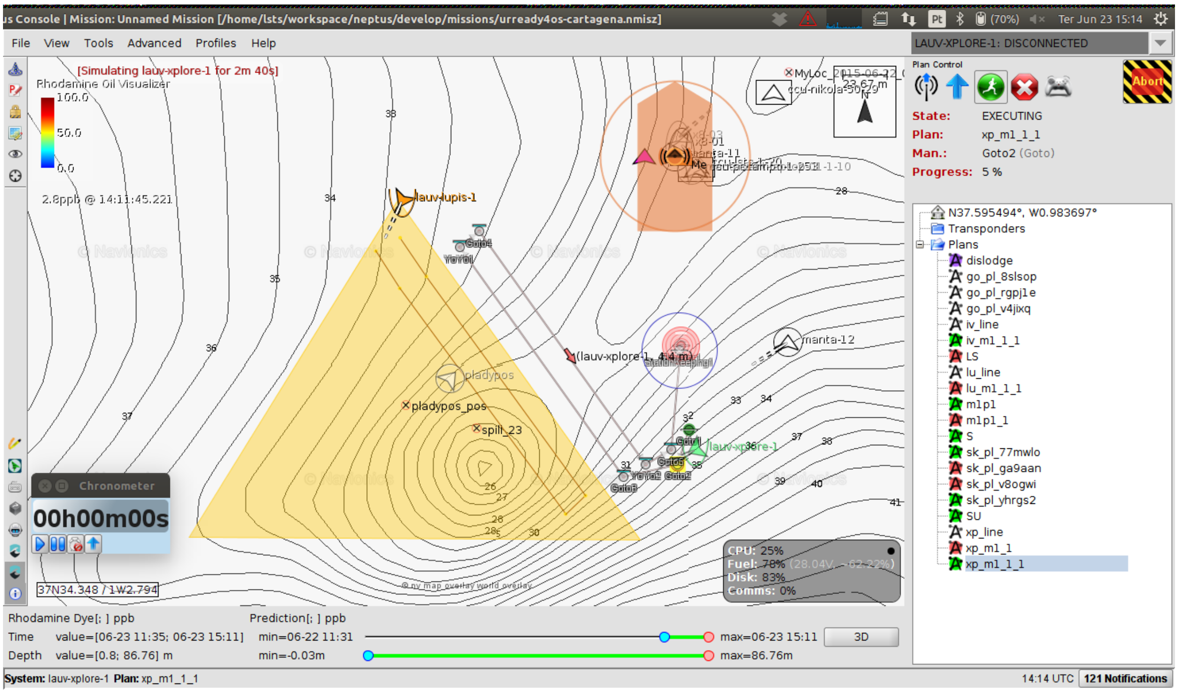
2.3.3. NEPTUS command and control software

The Command and Control (C2) and visualization software used in the URready4OS system is NEPTUS, a software written in Java that currently runs in Linux and Microsoft Windows operating systems that was developed and is used to command and monitor all vehicles at LSTS. Together with IMC and DUNE (Uniformed Navigational Environment, onboard control software) is part of the LSTS Toolchain for Autonomous Vehicles (http://www.lsts.pt/toolchain).

NEPTUS is a framework created from the scratch having in mind its adaptability and flexibility to encompass needs from diverse vehicles, scenarios and operator experiences. As a result, it provides the rapid creation of derived tools and can be customized according to operator and mission needs. IMC is the main communication protocol for NEPTUS, making it interoperable with any other IMC-based peer. IMC is a message-based protocol that defines a set of messages allowing the inter-communication of autonomous vehicles and the command and control interfaces. It is used to command a very heterogeneous kind of autonomous vehicles and sensors. Despite the heterogeneity of the controlled vehicles, NEPTUS provides a coherent visual interface to command all these assets.

This C2 software framework can be extended through a plugin infrastructure. A plugin can be developed independently of the main NEPTUS source and added as a compiled jar file. Thus, it can be extended by a third party with new components without the need of sharing source code among developers. Improvements for its use in the URready4OS project consisted in developing new plugins and building new visualization capabilities.

Figure 22 shows the NEPTUS main console interface, which is highly configurable, allowing to plan and execute missions on the vehicles, monitor their progress, and review the collected data.



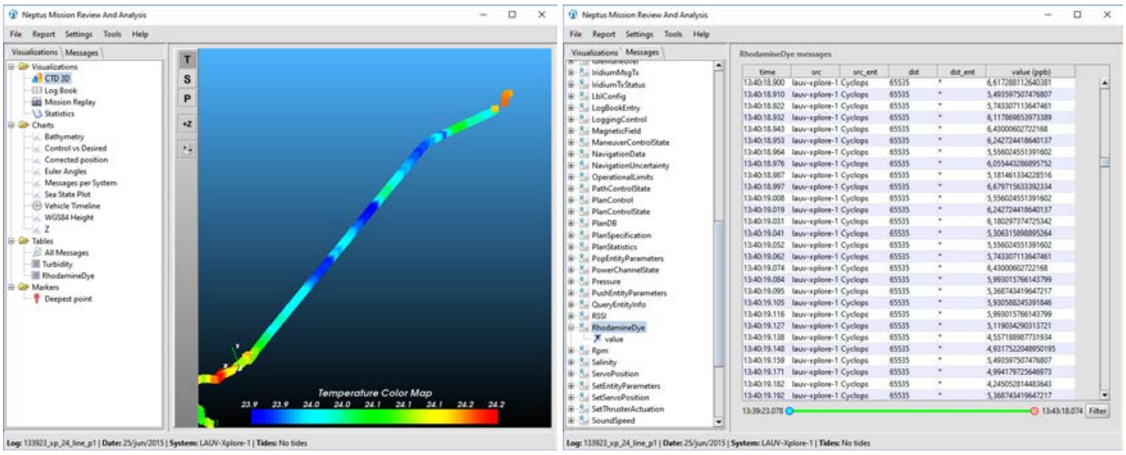
State: EXECUTING
Plan: xp_m1_1_1
Man.: Goto2 (Goto)
Progress: 5 %

Rhodamine Dye[;] ppb
Prediction[;] ppb
Time value=[06-23 11:35; 06-23 15:11] min=06-22 11:31 max=06-23 15:11
Depth value=[0.8; 86.76] m min=-0.03m max=86.76m

System: lauv-xplore-1 Plan: xp_m1_1_1

Figure 22. NEPTUS snapshot. Working area with USV and Rhodamine WT spill spot is the enhanced yellow triangle. Different AUVs positions and mission are drawn.

NEPTUS also has a data review tool, the Mission Review and Analysis (MRA) that allows the revision off all data collected by the vehicle. It is also extensible by plugins for dedicated visualizations or exporting. Figure 23 depicts some examples of the MRA tool.



Log: 133923_xp_24_line_p1 | Date: 25/jun/2015 | System: LAUV-Xplore-1 | Tides: No tides

Figure 23. MRA screen capture showing a temperature profile (left) and right Rhodamine WT value measured by the LAUV.

As mentioned above, NEPTUS natively is able to command and monitor vehicles talking IMC messages. Custom plugins can be built for other systems to accommodate the custom command languages as made for IVER2, SPARUS and LAUV AUVs within this project.

NEPTUS manual and detailed capabilities can be found at http://whale.fe.up.pt/neptus/manual/trunk/index.html .

2.3.4. Data formats

New data recorded by oil in water probes by vehicles, forecasted oil spill trajectories and concentrations provided by MEDSLIK II or another model need a specific format for their visualization on NEPTUS.

For oil spill concentration data, a simple comma separated values (CSV) format was used. The following shows a template of the header for this format, where '¶' represents a new line, and '%' is the character indicating a comment in the file:

```
%LAUV-LUPIS-1, Rhodamine, 10 Hz¶
%24/06/2015 07:05¶
%-1¶
%Time (unix time), Latitude (decimal degree), Longitude(decimal degree), Depth
(m), Rhodamine (ppb), Crude, Refined, Temperature (C)¶
```

The header is composed of four lines. The first line representing the mission: vehicle model, sensor name, sampling frequency (Hz). The second line is the date-time on which data was collected in UTC (the format is dd/mm/yyyy HH:MM). The third line is the non-valid value (in the example -1), and the fourth line the columns names (as seen above).

The MEDSLIK output format is the one from the MEDSLIK model. In this case, we use the TOT or LV* files with the same format:

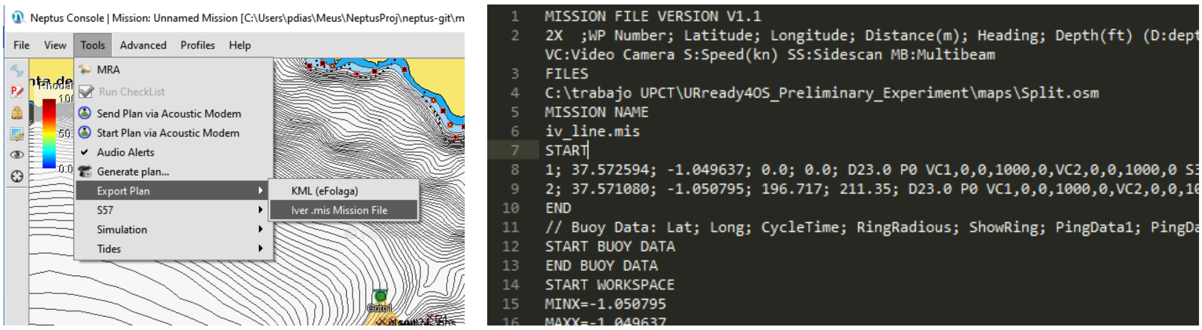
```
cu.m of pollutant at level 3 between depths
     4.0     6.0   metres below surface
   1     : Hours after start of spill
         1.  cu.m of pollutant released so far
  37.572  -1.049  : Lat & Long of spill location
  15.0    : Pixel size (m) for spill plotting
500.0 ppm         0.0   : Concentration & density of active pollutant
  1083     : Number of data points
    Lat      Lon      cu.m/sq km
```

The header consists of nine lines followed by the data (after that there may exist additional data used by the model not read here). First line is descripted and not read. The second line indicates the depths to which the data is valid. The third indicates the delta time passed from the first spill. The fourth is informative of how much pollutant is been released so far (not read). The fifth indicates the latitude and longitudes of the original spill in decimal degrees. The sixth is not used (is a graphical indication how to show the point data). The seventh line is not used also (indicates the concentration and density of active pollutant). The eighth indicates how many lines of data follows this header. The ninth line is the columns names.

2.3.5. Current development for IVER, SPARUS and MEDSLIK

L3 OceanServer, the manufacturer of IVER AUVs, provides with its own mission plan software, but format, telemetry and command language are not compatible with IMC. A not intrusive approach was taken to develop the IVER plugin in order to avoid any kind of interference with the navigation system of the vehicle. The planning interface does not need to be changed. So, the same interface is used to plan the missions for all vehicles. The approach used was to take the plan created in the interface and export it for the IVER language plan. This exported file is then sent to the IVER AUV for its execution. Figure 24 shows the process with visual access and sample mission file.

On one side, the positions of the vehicles (including the IVER, which plugin was developed here) feed the NEPTUS NMEA Plotter., which receives NMEA position sentences from all the external sources. Any georeferenced vehicles, including the vessel and auxiliary boats can send their position through the same channel.



```
MISSION FILE VERSION V1.1
2X  ;WP Number; Latitude; Longitude; Distance(m); Heading; Depth(ft) (D:dept
VC:Video Camera S:Speed(kn) SS:Sidescan MB:Multibeam
FILES
C:\trabajo UPCT\URready4OS_Preliminary_Experiment\maps\Split.osm
MISSION NAME
iv_line.mis
START
1; 37.572594; -1.049637; 0.0; 0.0; D23.0 P0 VC1,0,0,1000,0,VC2,0,0,1000,0 S3
2; 37.571080; -1.050795; 196.717; 211.35; D23.0 P0 VC1,0,0,1000,0,VC2,0,0,10
END
// Buoy Data: Lat; Long; CycleTime; RingRadious; ShowRing; PingData1; PingDa
START BUOY DATA
END BUOY DATA
START WORKSPACE
MINX=-1.050795
MAXX=-1.049637
```

Figure 24. Screen capture of the IVER mission export plugin developed for NEPTUS (left) and sample mission file (right).

MEDSLIK produces simulations of the spill evolution and fate. Once developed the visualization plugin for this model it can be activated in NEPTUS to navigate through the cloud of points produced in the simulation. Using sliders one can navigate through the prediction in time and depths. Also, a 3D view of the data is made available (Figure 25).

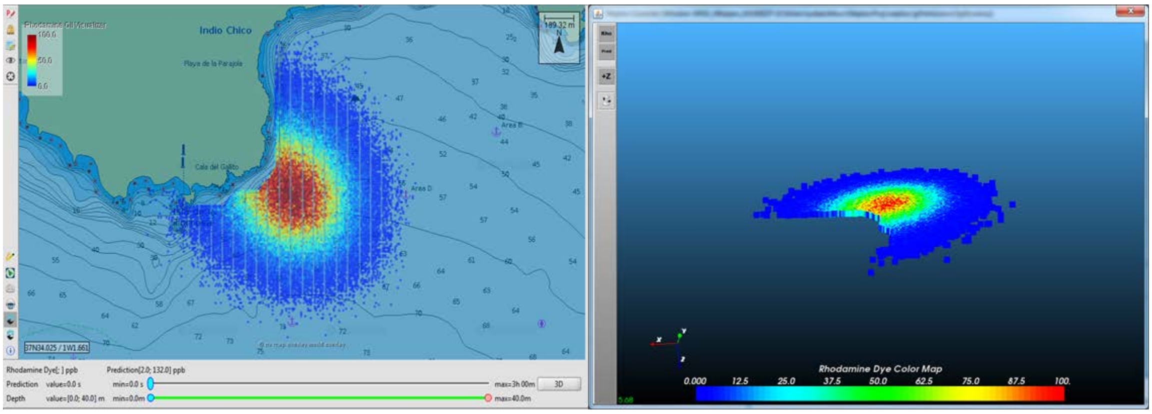
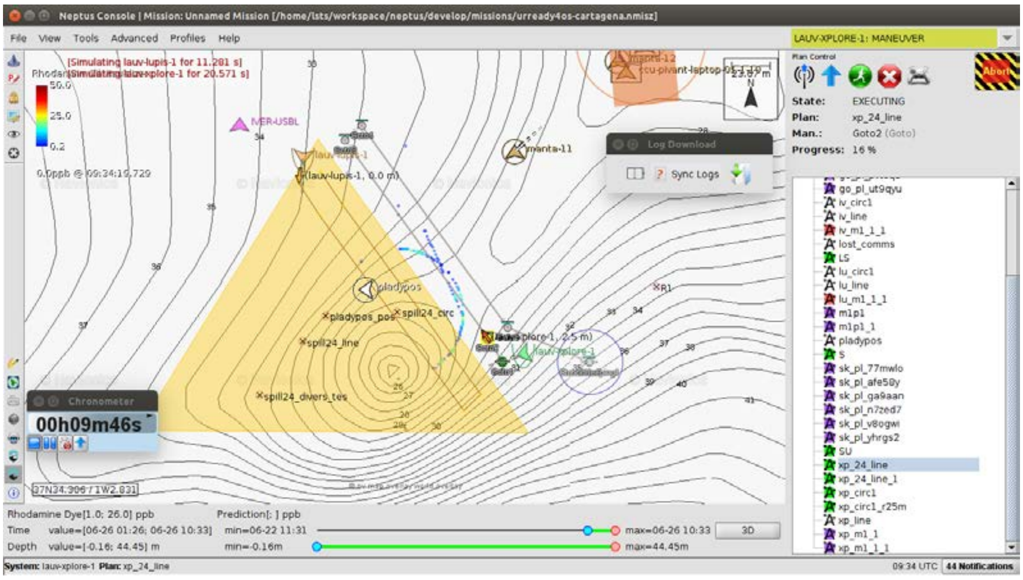


Figure 25. Left: MEDSLIK simulation of a Rhodamine spill showed on NEPTUS using the MEDSLIK visualization plugin. Time and depth sliders shown at the bottom. Right: 3D NEPTUS visualization of the simulated Rhodamine spill.

The MEDSLIK output is composed of CSV files with the format described above. The plugin that depicts the prediction is also capable of showing the recorded oil concentration by the AUVs that arrives to NEPTUS. A time slider is also available for the operator to go through the collected data over time and depths. The Figure 26 shows the NEPTUS Console with this plugin activated were Rhodamine concentration recorded by the AUVs (blue dots) are real-time received through acoustic modem and immediately made available to the operator.


Neptus Console | Mission: Unnamed Mission [/home/lsts/workspace/neptus/develop/missions/urready4os-cartagena.nmisz]

[Simulating lauv-lupis-1 for 11.281 s]
[Simulating lauv-xplore-1 for 20.571 s]

0.0ppb @ 09:34:19.729

LAUV-XPLORE-1: MANEUVER

State: EXECUTING
Plan: xp_24_line
Man.: Goto2 (Goto)
Progress: 16 %

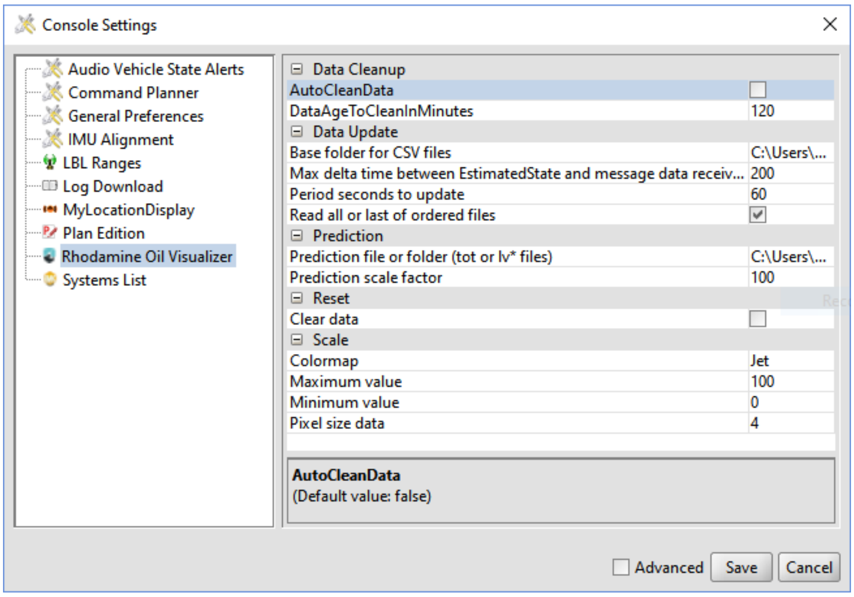
Rhodamine Dye[1.0; 26.0] ppb
Prediction[:] ppb
Time value=[06-26 01:26; 06-26 10:33] min=06-22 11:31 max=06-26 10:33
Depth value=[-0.16; 44.45] m min=-0.16m max=44.45m

System: lauv-xplore-1 Plan: xp_24_line
09:34 UTC
44 Notifications

Figure 26. Rhodamine WT data measured (blue dots line). All the agents of the system are showed in the map: working area , ship, AUVs and USV.

The plugin is also configurable for data location, old data cleaning policy, color maps and pixel size for representation of each data point. The configurations available are shown in Figure 27.

The SPARUS II vehicles taking part in some of the exercises run ROS (Robot Operating System). Because there is not one set of standard messages that would fit all implementations on ROS, the approach was to expose the IMC message protocol to ROS, and for that LSTS provided a bridge to NEPTUS. This bridge is the ros-imc-broker available in GitHub at https://github.com/paulosousadias/ros-imc-broker/tree/feature/vehicle-adapter .



Data Cleanup	
AutoCleanData	☐
DataAgeToCleanInMinutes	120
Data Update	
Base folder for CSV files	C:\Users\...
Max delta time between EstimatedState and message data receiv...	200
Period seconds to update	60
Read all or last of ordered files	☑
Prediction	
Prediction file or folder (tot or lv* files)	C:\Users\...
Prediction scale factor	100
Reset	
Clear data	☐
Scale	
Colormap	Jet
Maximum value	100
Minimum value	0
Pixel size data	4

AutoCleanData
(Default value: false)

Figure 27. Windows configuration of NEPTUS Oil Spill visualization plugin.

The implementation is using a vehicle adapter which creates the communication link to NEPTUS, and publishing and reading IMC messages from the ROS message bus. For more technical information on the connection, establishment visit https://github.com/LSTS/neptus/wiki/Neptus--to--Vehicles-Messages-Interface.

2.4. System functioning

After the deployment of the vehicles in the water, a series of interactions between agents and operators takes place (Figure 28). The positions of vehicles and oil recorded information by the AUVs are transmitted, either by air or underwater to the operators. As explained above, AUVs can transmit this information directly to the ship (or land base station) underwater via acoustic modem. They can also transmit the data to the USV underwater by the same system. The USV sends afterwards the information by air, via Wi-Fi, either to the ship, if in the Wi-Fi range, or to the UAV. The UAV can contact the USV aerial signal by low altitude flying over the surface vehicle. However, the AUVs can also store the information to be transmitted by air -

via Wi-Fi -, either to the USV, the UAV or the ship - if within the range -, when in surface. Although underwater communication has strong limitation due to bandwidth and distance, which at the same time depends on the water column characteristics, it is the best way of transmitting the information real time to the base station.

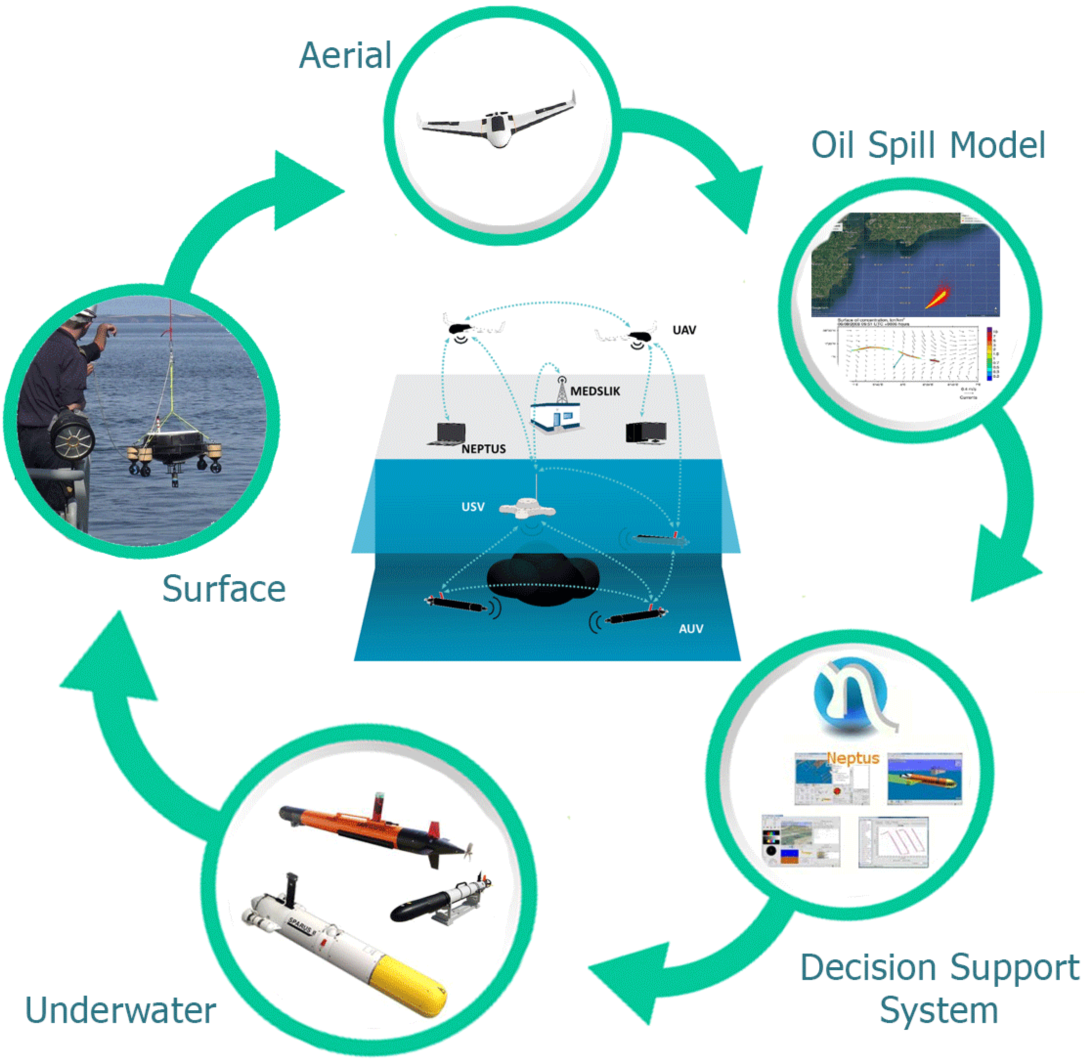


Figure 28. Chain of interactions between vehicles software in the URready4OS system.

The different types of communication and distance ranges provide the system with an extraordinary flexibility to design the operations. The first mission is obviously designed on the base of previous knowledge of the slick location. The numerical model (MEDSLIK or GNOME), driven by the available current and wind data, produces a forecast on which this first mission is based. Data recorded by AUVs in the first mission are then used by MEDSLIK to produce a new forecast. Second mission for the AUVs is based on the forecast, thus producing a loop between the model and the vehicles that allows for a better prediction of the spill trajectory underwater to determine the spill extent. This loop is described in Figure 29.

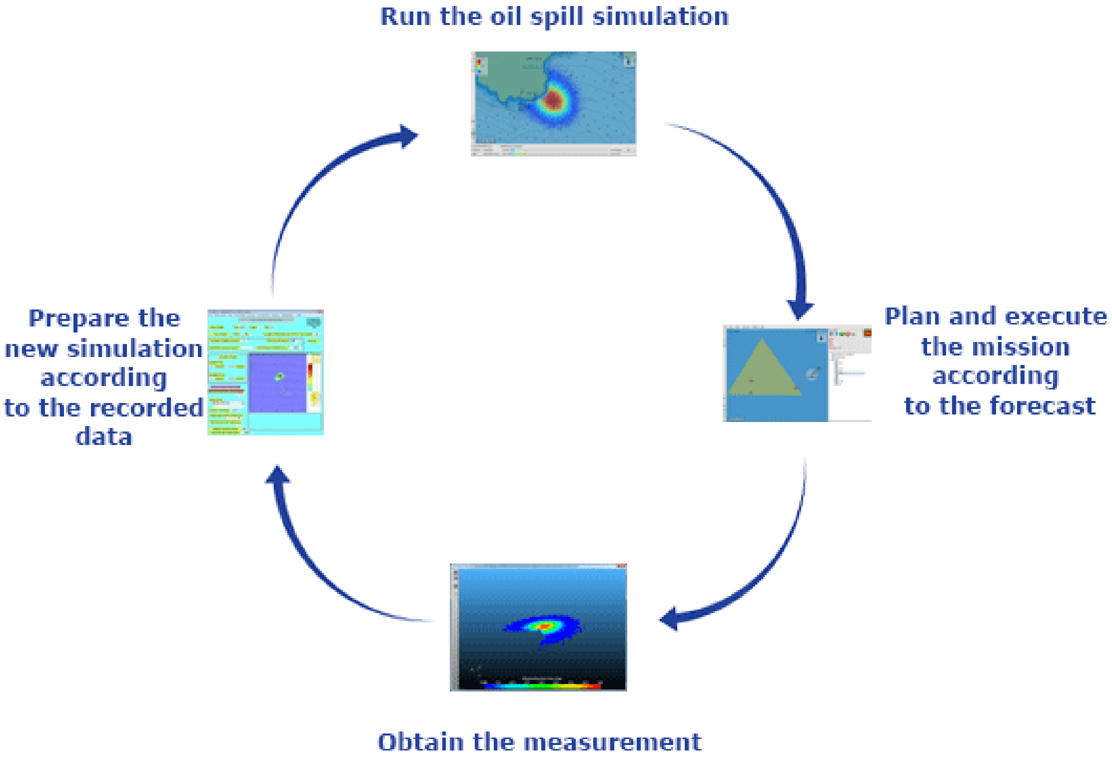


Figure 29. Integration of MEDSLIK model on the mission planning process.

2.5. Operational constrains

As described above, the system uses cooperative vehicles in the underwater, surface and air domain. Constraints for applying the URready4OS system derive from two main sources: The equipment itself and the environmental conditions.

2.5.1. Constrains by the equipment

The AUVs can be classified in three categories, with size and autonomy conditioning their depth rating. The AUVs able to dive deep down to 6,000 meters are the largest (up to 20 m long) and heavier (from 5 tons) with higher autonomy (over 72 hours). Medium range AUVs (up to 2,000 m depth rating) are usually over 2 m long and under 300 Kg weigh. Light - or portable - AUVs are under 2 m long with, less than 50 Kg weigh, under 24 hours autonomy and depth rating between 100 and 300 m.

Whereas the AUVs cost increase exponential with depth rating, their operability decrease. The URready4OS system has carried out exercises for the integration of both light and medium-range vehicles. The drawback encountered when integrating vehicles of more than 30 kg into the light fleet is that these vehicles need much more resources either for deployment and recovery, being detrimental to the operability.

As in the underwater domain, surface and air vehicles also depend on their size to sail or fly in adverse weather conditions. Operability is inversely proportional to the vehicles weight and size, so a trade-off in the operations design and equipment required is needed.

Unlike the ROVs, autonomous vehicle means being untethered, without direct real-time access to the vehicle during the operations. While underwater, neither AUV nor ROV have access to GPS or any other reliable source of absolute localization information. They rely on dead reckoning for navigation with the serious drawback that position error grows with time moving underwater. Therefore, AUV needs to surface periodically to acquire GPS signal and correct dead reckoning error. Introduction of acoustic system for simultaneous localization and data exchange solves both problems, ensures real-time data exchange and allows navigation corrections by bounding of dead reckoning error. Drawback of this approach is that requires permanent presence of a surface vessel, equipped with adequate acoustic system in the operating area thus introducing an additional element in the operation logistics.

Autonomy is also a technical limitation derived from the vehicles themselves. Standard autonomy for these light AUVs is 5 to 10 hours of continuous operation. However, they can be modified to achieve autonomies of up to 24-48 hours, or even longer. During the exercises carried out during the project, this time frame was proved to be enough for some of the envisioned scenarios and conveniently coincidental with the fleet operations personnel time frame.

Logistics play a key role in emergencies response. By using light vehicles in the three segments, the system does not need centralized storage while not in use. It can be easily shipped by any means of transportation. The only transport restriction by air is concerning the Li-ion batteries requiring special packaging by certified provider.

The equipment warehouse in the operational area should be a closed and dry space with regular power supply. Vehicles' pilots and operators will also need a minimum space for preparation, adaptation or small fixing and repair of the vehicles.

Being a decentralized fleet of light assets not stocked in one place, some minimal shipping time for vehicles and transport of personnel is required. It is estimated that a minimum of two days would be the time of the fleet arrival within Europe. Equipment can be shipped either by air land or sea. Figure 30 shows the equipment haven been transported to the Cartagena exercise in June 2017.

Figure 30. Left, two packaged AUVs being uploaded to the ship. Right, packaged equipment -one AUVs and one UAV – on deck.

The basic logistics required are summarized in Table VII.

Table VII. Basic logistic for all the agents involved in the URready4Os system.

AUV logistic	• Warehouse with electric power supply. • Ramp, low freeboard in a boat or low edge in a dock or crane (for deployment of AUVs)

UAV logistic	• Open area to place a net • Direct line of vision to the inspect area • Warehouse
USV logistic	• Warehouse • Ramp, low freeboard in a boat or low edge in a dock or crane (for deployment of AUVs)
Staff logistic	• Accommodations • Meeting room o Board, or equivalent to large screen or projector o Tables and chairs o Power electric supply • Working place (onboard or ashore for pilots) with visibility to the sea with shelter for sun, wind, rain, etc…) • Wi-Fi on the accommodations and working area. • Workshop on the working area. o with shelter for sun, wind, rain, etc... o Tables and chairs o Power electric supply
Model logistic	• Working area with shelter for sun, wind, rain, etc...

Light AUV have a typical depth range of 100 meters. Within this range, most of the envisioned scenarios could be covered by this fleet. However, an additional constrain derives from the fluorescence optical integrated probes (Turner Design® Cyclops 7 and Integrator™), whose depth range is set at 60 m depth - although manufacturer can supply probes up to 1000 m depth rate. With the integrated probes, the maximum operating depth of our AUVs is set at 60 meters.

Other limiting factor of light AUVs is their autonomy, usually between 6 to 10 hours of continuous operation, depending on speed and use of sensors, with 2 hours typical recharging battery time. Some light AUVs, however have enhanced autonomy up to 24 hours, as e.g. the OceanScan Xplore-1. Four to six hours are considered as a reasonable time to detect and monitor one, or even several, oil plumes depending obviously of their extent, spatial distribution and the position and time of the spill origin respect to the main ship or base station position.

2.5.2. Environmental conditions

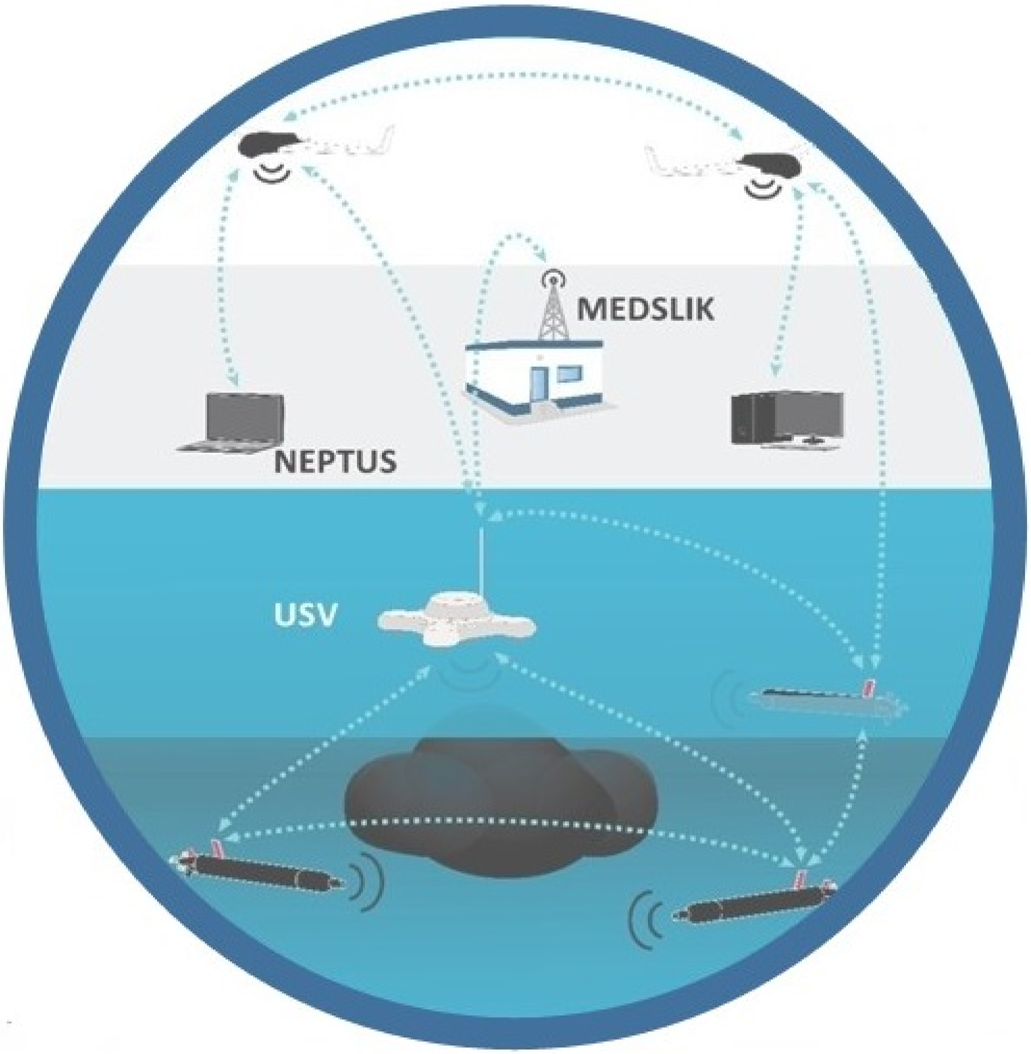
In alignment with our objectives - monitoring in water oil plumes - the AUVs operate underwater with lesser effect of weather or surface sea conditions than vehicles at surface or in the air. However, that does not mean that they can be deployed or recover in any weather conditions. Deployment and recovery are critical parts of the AUVs missions' planning. One of the main advantages brought by Lightweight AUVs is the easiness in these maneuvers.

A second constraint derives from the underwater speed currents. The Lightweight AUVs described and used here can reach a maximum over ground speed of 4 knots. However, navigation with speed currents over 2 knots can produce instability in the vehicle, putting at risk the maneuver, with vehicles not being able to dive against the current.

In the surface segment, where we used the PlaDyPos and H2Omni-X USV, the main limiting factor was due to waves height and surface speed currents. These USVs were designed to withstand waves up to 1.5 m. With 3 knots of maximum speed limit it has navigation problems with surface speed currents higher that 1 m/s. The autonomy limitation in the USV is not so much critical as it holds enough space for long endurance standard batteries that can easily and quickly replaced.

Wind is the main conditioning factor in the air segment. The X8 delta wing AUV can tolerate mean winds of 14 knots with maximum speeds of 18 Knots, but wind speed is not however the only atmospheric constrain for flying the AUVs. Air turbulences notably influence the piloting success, especially in the take-off and landing maneuvers. As in the launch and recovery of AUVs, these are also critical points in the mission. Direction of take-off and landing opposite to the wind brings additional constrains when carried out on a vessel. The emerged structure of the vessel where to take-off or land can also introduce local turbulence making advisable to deploy an auxiliary boat in case of failure or maneuver abortion.

With maximum endurance in the air of 60 min, 55 to 110 km/h speed range and 600 meters maximum altitude, this UAV can remain loitering in circles oversighting the surveillance area of surface and underwater vehicles. Transferring information in both directions - to and from the USV and AUVs while in surface – allow to receive the logged data in the ship or base station and transmit new missions to execute when vehicles are out of Wi-Fi range.



CHAPTER 3

Concept of Operations

3. Concept of operations

The Concept of Operations (ConOps) is a user-oriented stand-alone document that describes the characteristics for the system from the viewpoint of any organizational entity that will use it. Serving as a communications tool for informing end-users of the operational and support context for the system, is neither a specification nor a formal statement of requirements, which have already been discussed in the previous chapter. Here, a description of the operational and mission support, operating environment, interoperability and policies are analyzed intending to bridge the gap between the potential users' operational needs and system technical description. This chapter ends considering three main envisaged scenarios to derive functional capabilities of the system.

3.1. Operating Concept

3.1.1. Operational Description

The full multi-agent fleet configuration consists of three kinds of vehicles (AUVs, UAVs and USVs) with operational capability to perform underwater oil-spill detection, and monitoring. Defining the particular configuration and number of assets participating in the operation will largely depend on the spill type, its size and the specific environmental circumstances.

The URready4OS system scalability allows multivehicle operations independently of the assets characteristics - with minimum adaptation requirements. It can be deployed either from land - for a near shore slick - or from a vessel - for an offshore spill - and can operate with only one single AUV for a small slick, or with more vehicles for larger spill spatial coverage. It can also operate as a standalone system, regardless the number of assets, or integrated within other response networks using other types of means such as vessels and aircrafts.

The system - with its multi-vehicle operational command and control software - will enhance the overall mission performance whether it is acting alone or integrated within a larger response infrastructure.

3.1.1.1. Homeporting, transport and operating schedule

The URready4OS system homeporting is widely decentralized, with different institutions owning their respective vehicles. The assets that are lightweight vehicles that can be easily and quickly shipped elsewhere in Europe from their respective laboratories. The system can be gathered in a destination point with current standard commercial transport logistics almost as quickly as personal can reach the spilled area. Once on the scene, the whole system can operate from shore or be transported on a RHIB or boat to the operations vessels. However, the heavyweight vehicles, with highest operational requirements need additional infrastructures like cranes, etc. that need be set up well in advance.

The fleet can virtually operate all year long with no other restriction than that for its own regular maintenance. Routinely short time lapses are requested for recharging batteries, perform vacuum tests, or another regular tests during operations.

3.1.1.2. On-scene reporting

The URready4OS command and control systems allows to coordinate the activities of multiple underwater, surface and air robotic assets thus acting as an autonomous unit. Two pilots/engineers per vehicle compose the fleet team, one of them directly reporting to the fleet leader (see Figure 16, Chapter 2), which, has the authority to command, coordinate, and monitor the actions of the assets.

The team leader will report the underwater spill information collected to the on-scene commander throughout the appropriate ad hoc command chain stablished, which will obviously vary with the spill nature and size. For a small slick near shore, where there is no need to mobilize a large number of assets for instance, the leader may directly report to the on-scene commander. However, when the fleet integrates into a broader operational framework, the leader will report to the commander of the unit in which the fleet is integrated.

3.1.2. Mission Support Description

The overall URready4OS mission support will fall upon the responsibility of the on-scene commander, crisis cabinet, company or Maritime Safety Agency seeking for the team intervention.

3.1.2.1. People and training

Robotic assets pilots and engineers within the team are trained to cope with most of the problems, both hardware and software, that may emerge during operations. However, imponderable that cannot be solved outside the laboratories can arise during the maneuvers. Assets redundancy, when possible, will diminish its detrimental impact. The URready4OS team have accomplished together a number of training exercises with several operating conditions improving coordination for optimizing the system operability.

During operations all URready4OS team will reside in shore facilities, except when required to stay onboard overnight and the vessel habitability can provide adequate accommodation. Both, in shore or/and on-board facilities should be provided by the institution requesting the fleet services.

3.1.2.2. Equipment and supplies

As mentioned above, the systems do not belong to any single personal or legal entity but to several, who maintain the equipment and personnel with budget not specifically assigned for this application.

Oil in water probes and acoustic modems - or underwater positioning systems - do not require excessive time for their re-integration and calibration once removed to leave the assets available for other usage.

These constrains can affect the immediate availability of the vehicles if for whatever reason they are away engaged in another campaign, temporarily out of working order, or trained personal could not attend the emergency. Nevertheless, there is a clear willingness to cooperate when the fleet is requested, and technical expertise of pilots and engineers can solve many of the problems in the laboratory making the vehicles available in a short time period. On the other side, having redundancy of vehicles softens this constrain. At least eight AUVs with their corresponding pilots and engineering teams have performed training exercises. In case of urgent request, the closest geographically assets would arrive first thus providing at least one response team to attend the emergency whilst the other arrive.

After having expanded the fleet with new vehicles, the immediate availability issue has been substantially improving. It's now available the fleet with new trained vehicles from different countries, however, the training time with light vehicles should be increased, focus on improving response times and the location and extent of spills.

Accessory equipment to assist UAV flight, such as catapults and nets to UAV takeoffs and landings, whenever required, will be provided by the vehicles team.

Where no direct access to the sea were available, the support vessel services (e.g. auxiliary boats or cranes) for vehicles deployment and recovery will be provided by the institution requesting the fleet services.

3.1.3. Operating Environment

3.1.3.1. Description of the spilled area

An oil spill is, by nature, a complex and heterogeneous environment. Accordingly, operations in those areas are far from identical with particular challenges to overcome in completing the mission. A good knowledge of the working area will allow the vehicles team to prepare accurately the robotics assets missions. All the environmental information available should be therefore provided, preferably in digital format. Maps of the area, bathymetries and nautical charts, description of oil sensitive areas, marine protected areas, fixed or adrift fishing nets location, or any other relevant information will greatly benefit the quick missions design and will help avoiding further maneuvering issues.

Accurate, reliable and detailed oil spill data can significantly improve performance and efficiency of the multi agent operation with lack or data inaccuracy potentially leading to mission failure. Origin, type of oil, spatial scale, release flux, extent and total amount of oil spilled, is information used to configure the fleet elements and to feed the trajectory forecast model supporting the missions. Of the utmost interest is the climatological and oceanographic description of the area. Local research centers, port authorities or other related institutions quite often can provide relevant information concerning winds, currents, waves or other relevant environmental data.

Regional and global scale weather and ocean forecast services oceanographic information can be integrated in the NEPTUS command and control software, therefore importantly improving the in-water oil plumes detection and monitoring missions.

3.1.3.2. Potential threats and hazards

Maneuvering the URready4OS system does not add, in principle, new hazards beyond those inherent for deploying and recovery assets into/from the water and flying UAV. Nonetheless, doing so from a vessel may add new risks particularly in bad weather conditions. As robotics assets are autonomous and unless some unexpected problem arises, they do not need special maneuvering care once in the water.

UAVs takeoffs and landings require a minimum space for security reasons. When taking off from a vessel deck, wind direction is a critical factor and depending on the vessel freeboard turbulences destabilizing the UAV may occur. In critical weather and sea condition, the pilots will report to the fleet leader whether the conditions allow proceeding with the mission or requires its abortion.

3.1.4. Potential end-users

Designed for complementing the on-scene surface and aerial means in the fight against oil spill, the URready4OS system bridges the technological gap to detect and monitor oil in water plumes. Oil spill responders at any level are therefore the potential end-users of the system. Maritime Safety Agencies, port authorities, oil companies and oil spill responders' companies can benefit from the system advantages.

In this regard, three courses have been given to different Marine Safety Agencies (SASEMAR, Cyprus Civil Defense and IRCG), resulting in several documents (presentations and media file) available in the *Documents* section at the projects web site (http://www.upct.es/urready4os/?page_id=1509)

3.1.5. Policies, assumptions and constrains

Legislation for using maritime robotics assets either in the air, surface or underwater is still in its infancy. Up to our knowledge, there is no regulation for civil underwater autonomous vehicles yet, perhaps because of its navy exclusive and restricted use. Regardless of that, operations with AUVs should be notified to authorities in charge, either regional or national, and depending on the zone, extent, and maneuvers range should be notified to the navy officers in the area.

Unmanned surface vehicles are generically under the floating crafts legislations and restrictions may apply in territorial waters of different countries. Long distances maneuvers with USVs should be notified to the corresponding port authority (or navy officers) if applicable.

As aerial autonomous vehicles (usually known as drones) become democratized, regulations have evenly increased with an unequal effect between countries. While there is currently a legislative gap in some of them, in others it is not allowed flying UAVs, whereas some restrictions may apply depending on vehicle size, weight and flight distance for instance with special license and even airspace reservation required in some other countries.

The response team requesting the URready4OS services should provide the legal permits for operating with maritime robotics assets whenever applicable. All information required to obtain the corresponding permits should be provided to the URready4OS teams in a timely manner to ensure rapid response.

3.2. Potential scenarios

The URready4OS fleet can operate in most scenarios where underwater slicks cannot be seen through aerial or surface means alone. To derive system functionalities, three of the main system capabilities - detection, monitoring and inspection of in water oil spills - are described in this section with three most likely scenarios. Firstly, when the unknown origin position of a spill observed from the surface needs to be identified. Secondly, when an underwater plume needs to be monitored to determine its size and spatial evolution. Thirdly, when confirmation of a spill cessation is required.

The fleet capabilities allowing near real time recorded data reception at the base station reside on the system components described in Chapter two, summarized as follows:

- UAVs – enabled for measuring oil in water
- USV – expanding the real-time communication with submerged vehicles
- UAVs - allowing larger range remote downloading of AUVs recorded data
- NEPTUS Command and Control Software – managing the entire fleet
- Oil spill fate forecast model – to know the evolution of the spill

3.2.1. Detecting underwater oil spill origin

This first scenario traced is based on a simulated alert concerning a surface oil spill either from a wreck or a pipeline leakage at the sea bottom. It is assumed that position of the on-water slick is known but not the position of its origin - in any case no deeper that 60 meters (see section 2.5.1. Chapter 2).

Oil type, area on surface, estimated flux and amount spilled, time since the slick was noticed and other relevant information including the response time required should be carefully evaluated before deciding the number of assets involved in the operation. In this particular case, three AUVs and one USV would be requested if the estimated origin point were easily accessible.

A MEDSLIK II and GNOME back tracking simulation of the spill whenever meteorological and oceanographic data were available can be performed to draw the most likely location of the spill origin. This point would mark the destination of the USV as the epicenter of the operations. A wide circular perimeter would be traced in order to stablish a reasonable search limit. Within this perimeter each vehicle should carry out missions in concentric circles (50 m apart) at different depths as shown in Figure 31.

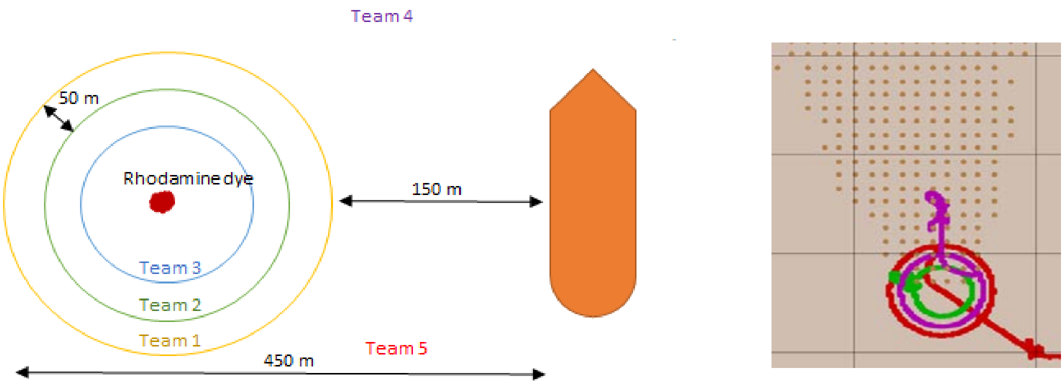


Figure 31. Left. Example of AUVs circle missions to detect direction on oil spill. Each colour line represents each AUV trajectory. Right. Trajectories performed by 3 AUVs on-scene (red, green, purple). Dots are the simulation trajectory output of the spill model, all view on NEPTUS screen.

If, as expected the spill origin was in the central position, the plume movement would be directed towards the same circumferences arch with AUVs sensing higher oil concentrations thus indicating the underwater spill origin. If, on the contrary, the spill origin was not located, none of the three rings would show any sensed signal. In which case, re-planning the same mission moving the epicenter out the surveyed area would be next option. This operation may be repeated as many times as needed, depending of the asset's autonomy, until detecting the leaking point.

With the dimensions in the Figure 31, and once the AUVs are in their defined parking positions, the mission would last for 20 – 30 minutes. Circular missions were tested with three AUVs and one USV during the training exercises carried out

The following functional capabilities would be implemented in this kind of mission:

- Sensing oil in water with AUVs
- Transmitting AUVs recorded information to the USV or base station underwater through acoustic modems
- Receive data in the base station either on shore or onboard
    - underwater through acoustic modems either from AUVs or USV
    - aerial via Wi-Fi through the USV when AUV are underwater
    - aerial via Wi-Fi from AUVs in surface when mission ended
- Running spill trajectory simulations with MEDSLIK II
- Planning missions and command and control AUVS and USV from NEPTUS
- Plotting AUVs trajectories and data recorded near real time with NEPTUS
- Quick missions re-planning.

3.2.2. Monitoring underwater oil plumes evolution

The following scenario is envisioned to determine the size and evolution over time of an underwater oil plume already identified. Oil in water measurements will validate the numerical model outputs allowing further improvement of reliable simulations to forecast the plume fate. Numerical model simulation would be performed whenever forcing data were available or could be collected on-scene (e.g. through Doppler current meters installed on the vessel, or meteorological data available).

Once the spill origin is identified, an imaginary line on the slick direction would be traced and AUVs programed for perpendicularly crossing this line with equidistant transects separated a fixed distance (e.g. 50 meters or more, depending of the estimated size) at several depths. Figure 32 shows a schematic representation of the imaginary line (orange color) with transect trajectories for two different AUVs (red and purple color lines).

Here it is assumed that the operations supporting vessel – or on shore base station - is out of Wi-Fi communication range with the vehicles, which means that recorded data would be captured by UAVs bringing them to the land/vessel base station.

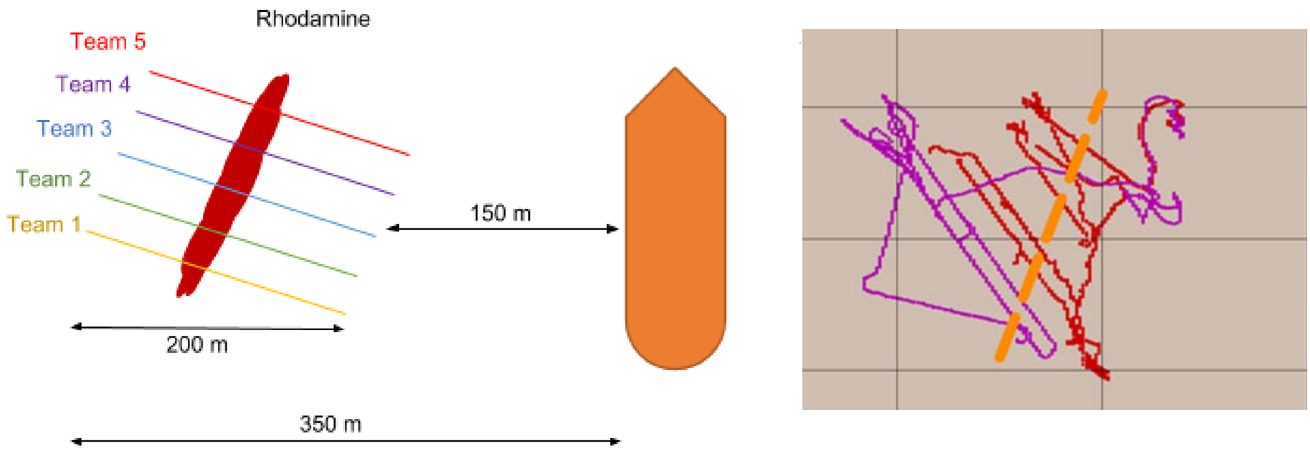


Figure 32. Example of AUVs parallel transects crossing an oil plume direction. Orange dotted line in the right is the hypothetical spill direction, red and purple lines are AUVs trajectories crossing it.

The AUVs would be deployed either, from an auxiliary boat or shore targeting their pre-fixed specific parking points designated on NEPTUS screen. Starting from these points, missions would end at the same or another also pre-fixed point, depending on distances traveled. After missions completed AUVs would surface and wait at the end mission in its parking point.

While AUV missions executes, UAVs would be prepared for takeoff and programmed for overflying the end mission points. They would upload in flight the AUVs recorded data to bring and download them when overflying the support vessel - or shore base station.

Once on NEPTUS, the spill data would be transferred to the numerical model (MEDSLIK II or GNOME) in order to perform a new simulation and re-plan the AUVs missions accordingly. The new AUVs designed mission could then be uploaded to the UAV in flight and downloaded to the AUVs again before landing. This loop can be repeated as many times as the vehicles autonomy allows.

If required one operator can re-plan de missions for each AUV on NEPTUS, almost instantly.

The following functional capabilities would be implemented in this kind of mission:

- Sensing oil in water with AUVs
- Upload AUVs recorded information to UAVs in flight
- Download data to the support vessel or shore station in flight
- Running spill trajectory simulations with MEDSLIK fed with measured data
- Re-planning AUV missions with NEPTUS
- Upload new AUVs mission from the support vessel or shore station to the UAVs inflight
- Download new AUVs mission from UAVs to AUVs in flight
- Execute new AUVs missions

3.2.3. Sizing the in water spill

The third scenario considered is envisioned to accurately determine the in-water spill size. In this case, although spill origin position and extent would be known, a quantification of the plume oil amount would also be required. Some system functional capabilities already shown in the previous scenarios may apply. Starting from the monitoring scenario, and once the plume was identified, missions can be traced with strait lines crossing diagonally the plume from many different angles. The more diagonals traced the more precise quantification of the extent of the plume would be performed. Fluorometric sensors provide concentration measurements, so the more at the spurs of the plume the lower concentration would be recorded. Having a large set of diagonals would provide an oil in water concentration map thus deriving the total oil amount within the plume.

In this scenario, functional capabilities already described for the identification and monitoring can be combined using the USV and/or the UAVs. Figure 33 show a sketch of this plan.

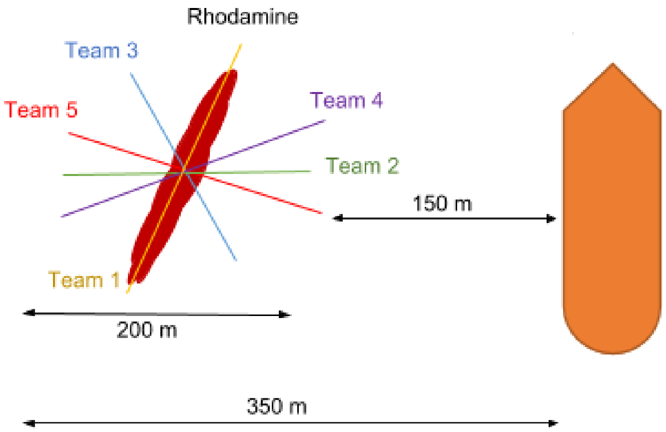


Figure 32. Example of AUVs diagonal transects crossing at different angels to size the plume.

CHAPTER 4

Training Exercises

4. Training Exercises

Several training exercises have been carried out during the URready4OS and e-URready4OS projects. The main aim of this exercises was to effectively coordinate the attending teams. Planned missions were executed by the in a near-real time scenario. All the protocols and systems previously developed worked together to address a simulated oil spill. In this chapters these exercises are described showing the fleet evolution during the projects, with achievements and lessons learned.

First training exercise was performed in Split (Croatia) 2014 – SplitEx2014 -, this was mainly performed from shore with a test on board of a small Croatian Navy surveillance vessel in the Bay of Split. Second and third exercises were held on board of SASEMAR Seagoing Tug “Clara Campoamor” off Cartagena (Spain) 2015 – CartEx2015 – and 2017 – CartEx2017-. The fourth one was held on board of the Irish Naval Service offshore patrol vessel LÉ Róisín, off Cork (Ireland) – CorkEx2018.

4.1. 1st Training Exercise - SplitEx2014

An initial exercise was carried out on shore in the Norther part of the Marjan peninsula in Split (Croatia), a place with easy access to the sea provided by the Croatian Navy. The exercise lasted from 22 September to 1 October 2014, in order to test communications and set up, both individually and collectively, the first vehicles of the fleet. In total, 20 people joined to take the first step within this project. Figure 33 shows a panoramic view of the site with the team and vehicles used.

Figure 33. Split bay panoramic view from the Marjan peninsula (above), team and vehicles (below).

The vehicles engaged in the exercise were: one LAUV (Xplore-1) and one X8 UAV from the University of Porto; one LAUV (Lupis) and one USV PlaDyPos from the University of Zagreb; And an IVER2 AUV (Icue) from the Technical University of Cartagena. The team from University of Cyprus was responsible for making predictions of potential trajectories followed by the simulated spills made with Rhodamine WT with the MEDSLIK oil spill model.

The aims and achievements of this exercise can be summarized as follow:

1. Individual probes integration test for each AUV. As mentioned above, integrating the probes in the vehicles was developed differently by each team. First step was to verify that the integration was done correctly. An intercomparison of Rhodamine WT recorded values was performed thereof, ensuring that the measurements between the probes were homogeneous. A dilution of 100 ppb of rhodamine, and a white sample (without dye) were used.
2. Communications Test between AUVs and UAVs. The three AUVs (Xplore1, Lupis and Icue) were overflight by one of the UAVs while on shore and in

surface waters. Files were correctly synchronized thus transferring information from underwater vehicles to aerial ones.

3. Underwater Communications Test between USV and AUVs. 5 to 10 seconds was the time interval that Lupis took to send the information to the base station while submerged through the USV PlaDyPos. The Xplore1 performed this task differently. Its signal, also acoustic, was sent directly to a submerged receiver located at the ground station.
4. Positioning test for all vehicles in Command and Control Console (NEPTUS). After checking comms, knowing the position of each vehicle at any time is the following crucial step. NEPTUS allowed verifying and checking the location of all the equipment simultaneously near real time.
5. Integration of data in NEPTUS. All info recorded by vehicles - positions, water temperature, etc.- were received and plotted by NEPTUS
6. Test of protocols for communication. Before this test, each vehicle was using its own protocol that should be unified. During this exercise we worked on integrating the Icue IVER2 into the system.
7. Test of protocols for operations. A template-like for concept of operations was drawn from experience gained in this exercise to be used in the following ones.
8. Operational test with several vehicles deployed at a time. Coordination of missions between agents was one of the main challenges for this first time exercise. Although there were many lessons learned, we succeed having rhodamine readings with the AUVs and plotting them by NEPTUS, knowing the position of each asset at any time.

4.2. 2nd & 3rd Training Exercises – CartEx2015 & CartEx2018

Two exercises were carried out in waters off Cartagena aboard the Spanish Maritime Safety Agency (SASEMAR) seagoing tug “Clara Campoamor”. Both exercises were carried out off Cartagena (Spain) in the South Western Mediterranean Sea (Figure 34).

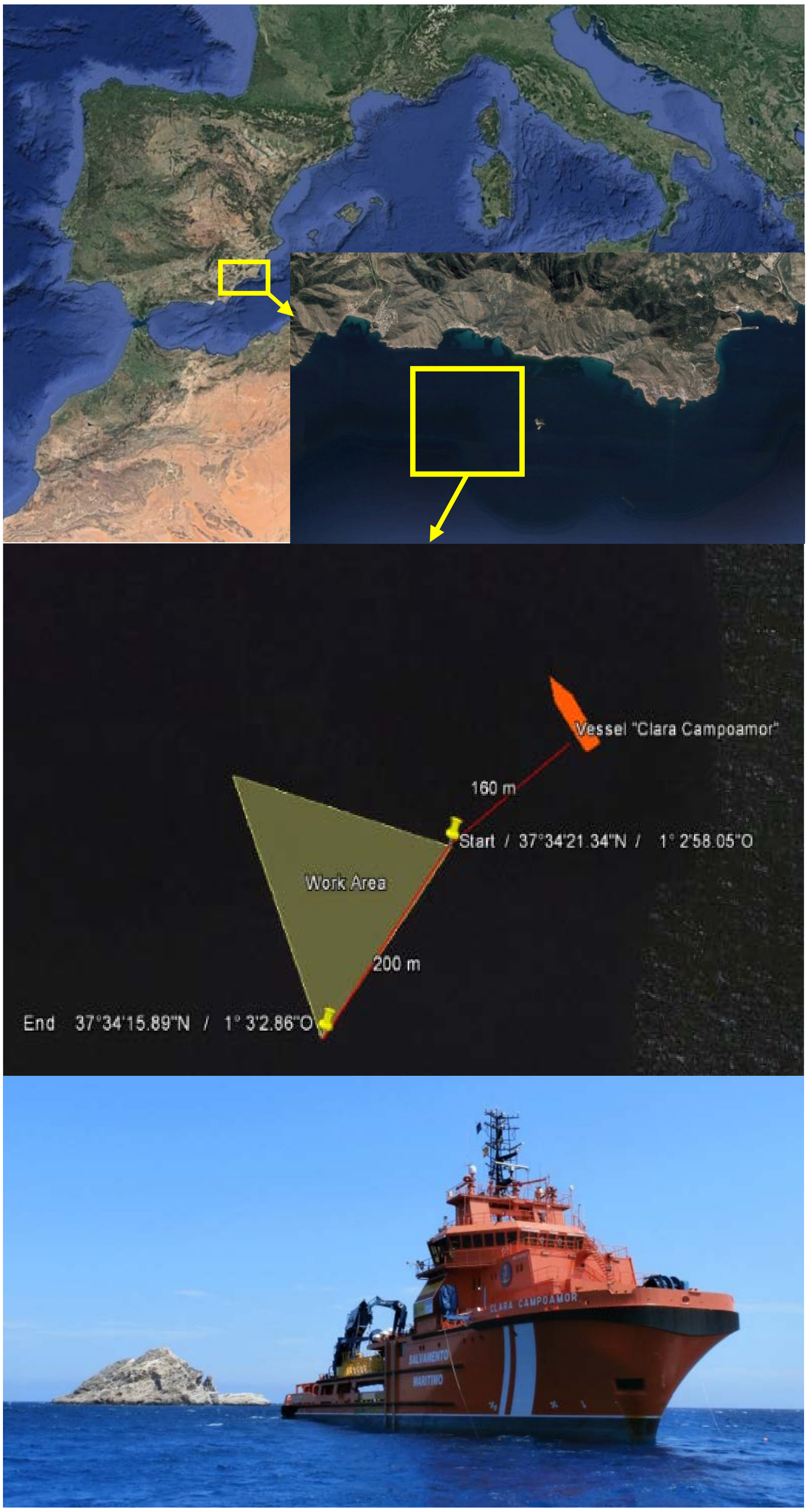


Figure 34. Location of the exercises and SASEMAR vessel “Clara Campoamor”.

While the CartEx2015, was performed from 22 to 26 of June 2015, the CartEx2017 was held from 5 to 9 of the same month in 2017.

The main goal of CartEx2105 was verifying the validity of the protocols and software developed for a fleet of aerial, surface and underwater autonomous vehicles to identify, quantify and monitor a simulated oil spill made of Rhodamine WT. Five vehicles took part (Figure 35): one LAUVs (Xplore1) and two X8 UAVs from the University of Porto, the LAUV (Lupis) and the USV PlaDyPos from the University of Zagreb, and an IVER2 AUV (Icue) from the Technical University of Cartagena. In addition, the team from University of Cyprus made numerical predictions of the pollutant cloud evolution, which aided in mission planning and adaptation. In total, a team of 20 people joined over 7 days to carry out the suite of experiments needed to meet objectives of the project.

Figure 35. AUVs taking part of the 2nd training exercise CartEX2015. Sorted from left to right: IVER2 Icue (UPCT), LAUV Lupis (UZ), LAUV Xplore1 (UP).

In the CartEx 2017 the project's fleet demonstrated the ability to increase with new vehicles. A part from the AUVs shown in Figure 35, a new LAUV (Harld) from NTNU, another IVER2 from TUT and one REMUS600 from SAMS joined together with one USVs (H2Omni-X) and 2 X8 UAVs. As in previous editions, the team from the Oceanographic Centre (University of Cyprus) run the MEDSLIK model feed with met stations data and currents profiles from the ship. In total 6 AUVs, 1 USV and 1 UAV were operating at the same time in the water with a team of 26 people working together over 5 days refining protocols, new teams integrating in the operations and coordinating assets maneuvers (Figure 36).

Figure 36. Teams and vehicles taking part in the CartEX 2017.

New plugins for NEPTUS were developed and installed in each one of the vehicles allowing a better integration of the fleet. In both exercises, a week-long schedule was created to generate and monitor a simulated oil spill plume. In order to maintain a constant spill of rhodamine WT at certain depth a pumping system was designed allowing to produce a rhodamine WT plume underwater made of two lines flowing at a rate of 17 l/min (Figure 37).

Figure 38 shows a screen capture of NEPTUS showing the bathymetry, positions of each vehicle at its parking points, auxiliary boat producing the spill, and main vessel location. The MEDSLIK model output provided information allowing to predict where the spill would go and its expected spatial coverage.

Following the potential scenarios from section 3.2, three kind of missions were carried out. Some of the results obtained, although not conclusive, are shown in Figures 39 – 41.

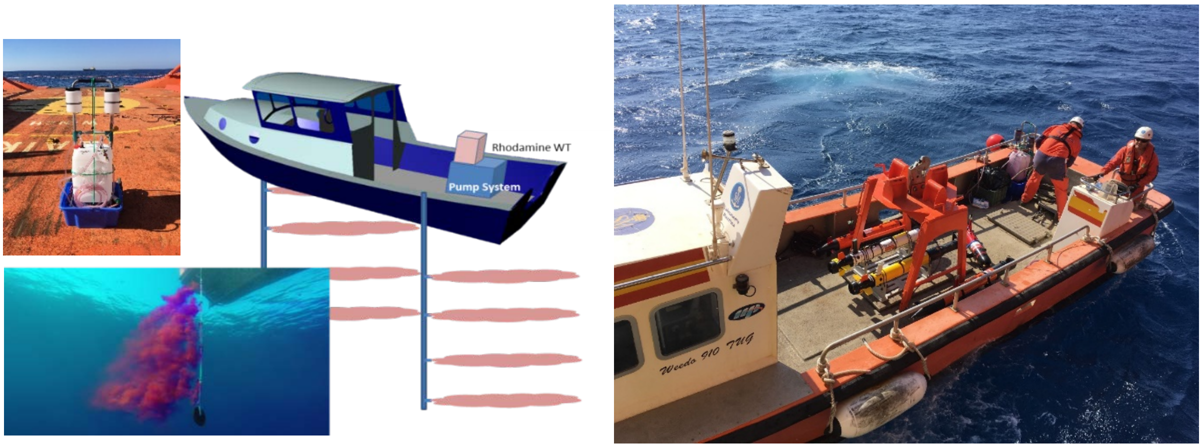
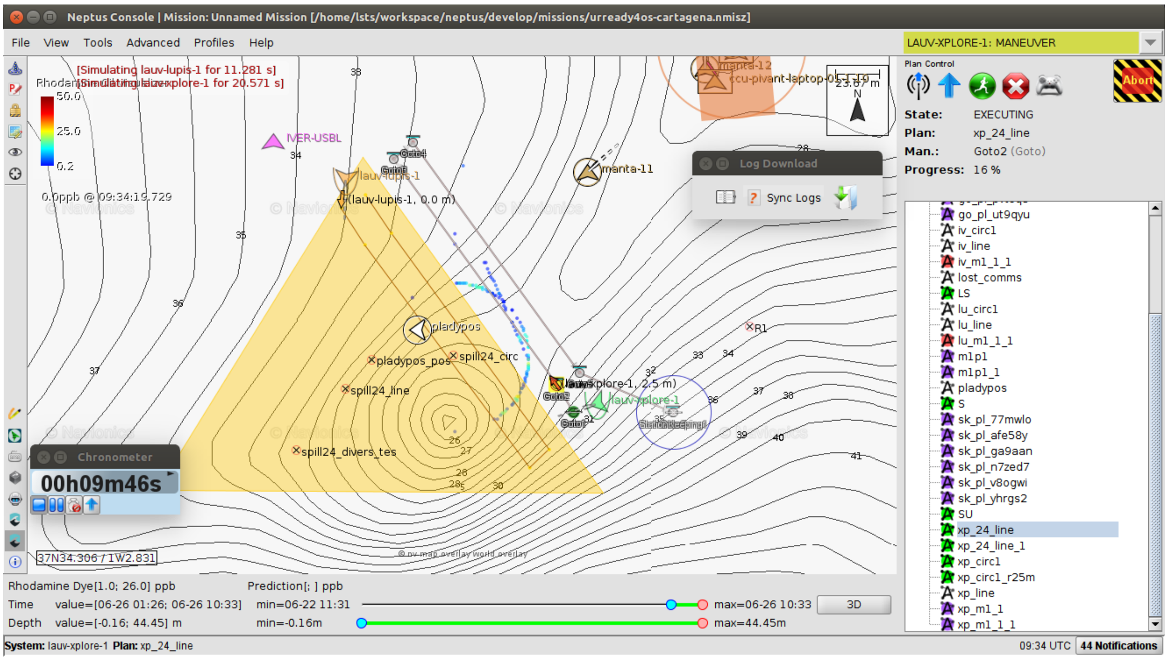


Figure 37. Rhodamine WT pumping system design producing an in water plume from a Clara Campoamor auxiliary boat with five AUVs ready to deploy.


Neptus Console | Mission: Unnamed Mission [/home/lsts/workspace/neptus/develop/missions/urready4os-cartagena.nmisz]

LAUV-XPLORE-1: MANEUVER

[Simulating lauv-lupis-1 for 11.281 s]

State: EXECUTING
Plan: xp_24_line
Man.: Goto2 (Goto)
Progress: 16 %

0.0ppb @ 09:34:19.729

00h09m46s

37N34.306 / 1W2.831

Rhodamine Dye[1.0; 26.0] ppb
Prediction[;] ppb
Time value=[06-26 01:26; 06-26 10:33] min=06-22 11:31 max=06-26 10:33
Depth value=[-0.16; 44.45] m min=-0.16m max=44.45m

System: lauv-xplore-1 Plan: xp_24_line
09:34 UTC
44 Notifications

Figure 38. NEPTUS screen capture showing the bathymetry, the area where the missions were executed in yellow, the location of the main vessel in orange and parking positions for AUVs. Note that blue dotted lines show rhodamine concentration sensed by one of the vehicles.

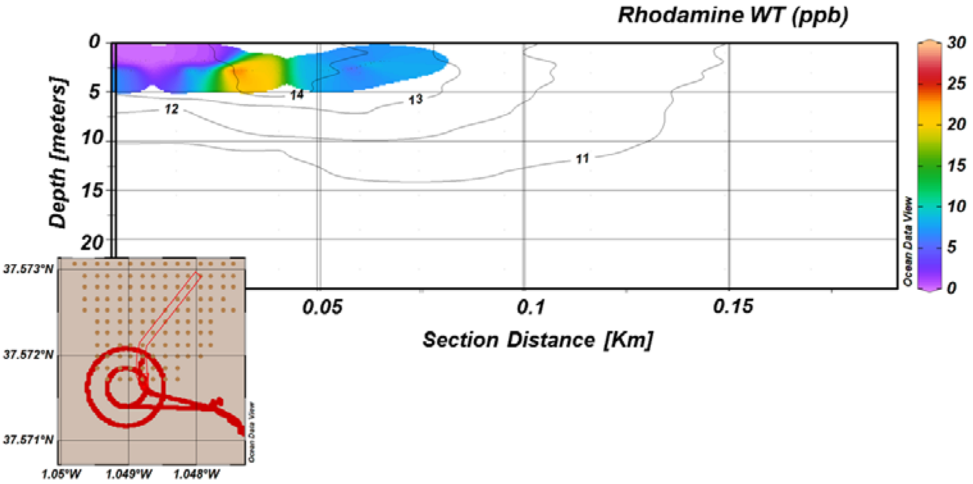


Figure 39. Rhodamine concentration (ppb) measured by vehicles. Brown dots at the lower left panel shows MEDSLIK output.

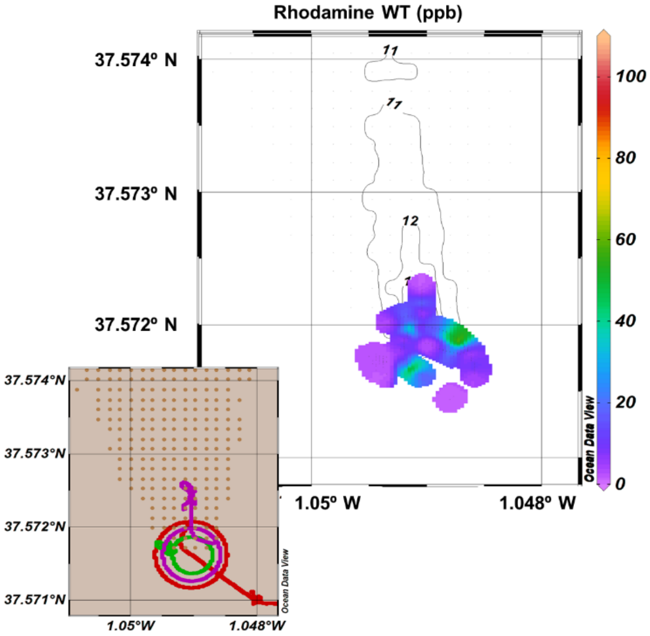


Figure 40. Rhodamine concentration (ppb) and MEDSLIK. Colours in lower left panel show trajectories by Icue (green), Lupis (purple) and Xplore-1 (red).

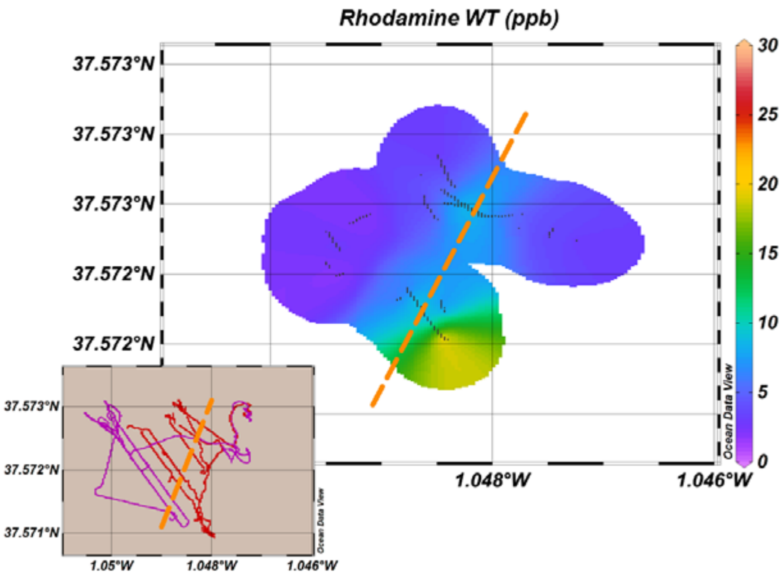


Figure 41. Rhodamine WT concentration (ppb) measured and trajectories by vehicles (lower left panel).

It must be taken into account that integration of new vehicles and teams in the system was the main goal of these exercises. In the CartEX2017 it was made clear very soon that having a larger fleet implies a higher coordination level, thus requiring a progressive training for newcomers. Different kind of vehicles used at a time, like REMUS600 and LAUVs, brings a large value added to the fleet, however, heavier vehicles need different deployment systems. Whereas several light AUVs can be deployed at a time from an auxiliary boat (see e.g. Figure 37), heavier vehicles need dedicated cranes (see e.g. Figures 12 and 13) taking longer time and resources to be deployed, thus implying delays in maneuvers. A trade-off between pro and cons, depending on the particular situation, must be carefully evaluated in order to take upmost advantage of the system configuration flexibility.

4.3. 4th Training Exercise – CorkEx 2018

The last training exercise took place in Cork (Ireland) from 23 to 26 July 2018 on board the Irish Naval Service offshore patrol vessel “LÉ Róisín” coordinated by Irish Coast Guard.

Figure 42. The Irish Naval Service vessel “LÉ Róisín” during the training exercise.

The training operations for this exercise were carried out in an area to 5 miles S/SW off Naval Base, Haulbowline, Cork in the Atlantic Ocean (Figure 43).

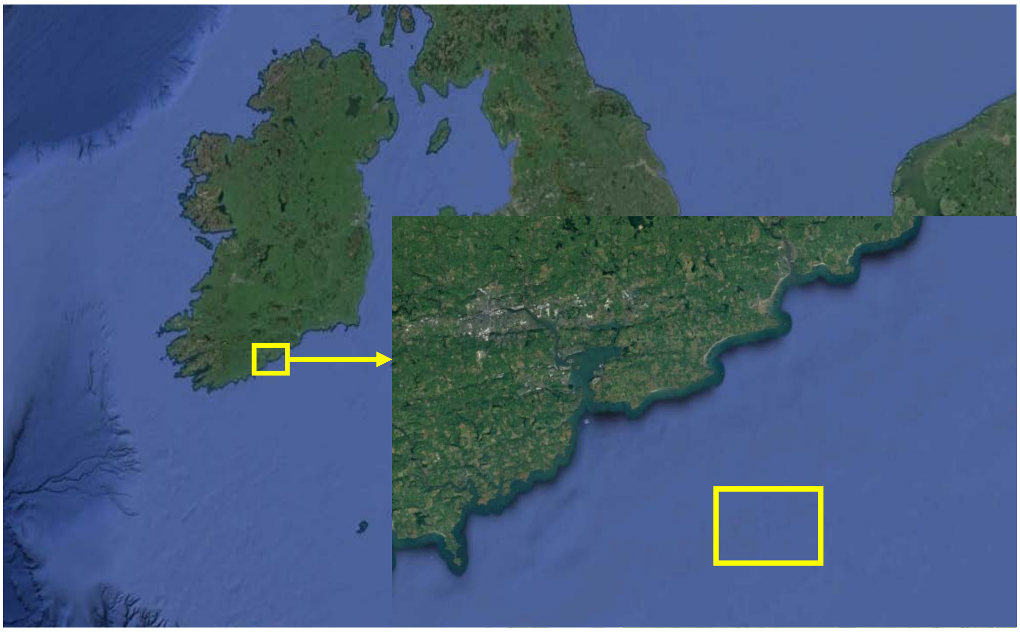


Figure 43. Area where the training exercise was carried out.

5 AUVs participated in this exercise: One LAUVs (Xplore2) from UP, one IVER2 (Icue) from UPCT, one LAUV (Lupis) and one USV (H2Omni-X) from UZ and two SPARUS II (Sparus and Turbot) from UG and UIB respectively (Figure 49).

Figure 49. AUVs participating in the CorkEX 2018 training exercise.

In this exercise two new teams were enrolled: one from the University of Girona and the other one from the University of the Balearic Islands (both in Spain), with SAPRUS II type vehicles taking part for first time in these series of exercises. Both teams have been tightly working with the UP team in order to adjust protocols and communications with the console NEPTUS. These types of vehicles are based on ROS (Robotic Operative System), different to Linux and Microsoft, used in the other AUVs of the fleet. As described in section 2.1.2 a new strategy was followed in order to integrate these vehicles in NEPTUS.

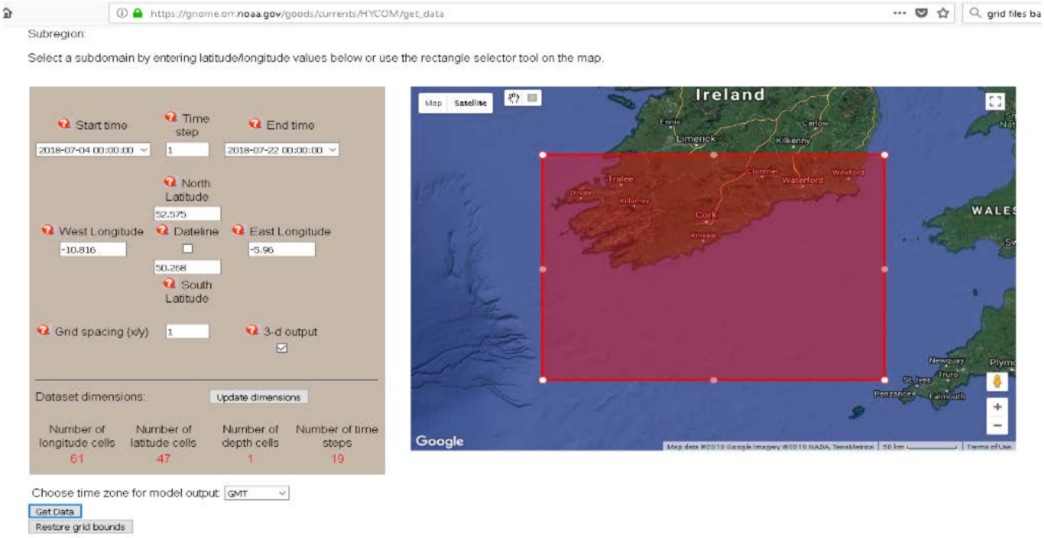
The SPARUS II is over 50 Kg weigh and 1.6 m long, thus requiring a crane for deployment and recovery (Figure 50). The abovementioned disadvantages this entails were made evident with wind force 3-4 and strong drifting current against the wind.

Following section 2.5 of Operation constrains, in this exercise both, by the equipment and the environment met. On one side, rough weather made maneuvers more difficult with delays in operations, on the other side, the main vessel had to be moving forth and back along a line to avoid drifting. However, and as vehicles also drifted in opposite direction, Wi-Fi range fell short in these circumstances therefore losing direct contact with them. A RHIB was needed to recover them back to their parking points.

Figure 50. SPARUS deployment

In addition, predictions of the plume made with the same with the same pumping system were performed here with GNOME to overcome some of the limitations found with MEDSLIK. The procedure used for this exercise may be summarized as follows:

1. Generate and download coastline, using online tool. https://gnome.orr.noaa.gov/goods then click on “Global custom map generator” at https://gnome.orr.noaa.gov/goods/tools/GSHHS/coast_subset. File has extension “bna.” (for this exercise an screenshot is given in Figure 51)


https://gnome.orr.noaa.gov/goods/currents/HYCOM/get_data

Subregion:

Select a subdomain by entering latitude/longitude values below or use the rectangle selector tool on the map.

Start time: 2018-07-04 00:00:00
Time step: 1
End time: 2018-07-22 00:00:00
North Latitude: 52.575
West Longitude: -10.816
Dateline: ☐
East Longitude: -5.96
South Latitude: 50.268
Grid spacing (x/y): 1
3-d output: ☑

Dataset dimensions:

Number of longitude cells	Number of latitude cells	Number of depth cells	Number of time steps
61	47	1	19

Choose time zone for model output: GMT

Figure 51. Screen capture of location area for the CorkEx 2018

2. Download sample winds, using online tool “GOODS” but this time clicking Winds/NCEP GFS, then choose ½ deg, 2 weeks plus forecast, then press “submit.” Use the same domain as the coastline. Maximum time range (about 2 weeks) and minimum time step (6 h) are set. File has extension “nc.”
3. Download derived currents, again with “GOODS” but this time clicking “Derived Currents/SSH,” then choose date and spatial range to be same as winds. Time interval of 1 (1 day). Tidal and HF radar currents are not available in the Atlantic or Med regions. File has extension “nc.”
4. Download model currents from Global Hycom system. Using online tool “GOODS” but this time clicking “Global Ocean Current Models”, then Hycom (1/12 deg). Use same region and minimum time interval of 1h, same start date to maximum range in time. Surface and 30 m (click “3-d output”). File has extension “nc.”
5. Repeat above step for RTOFS. Only surface currents are available, and only nowcast or 1-week forecast. Choose to forecast (e.g. on 16 July 2018 the output is from 15th at 0300 to 23rd at 0000). File has extension “nc.”

6. Download technical documentation, including data formats, as well as sample windows data files at: https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/resources/gnome-technical-docs.html
7. Read tips on setting up a region at: https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/resources/setting-gnome-your-region.html. In particular, documentation of the input file format (NOAA standard trajectory). Since all of the necessary input data are downloaded, open GNOME, go to diagnostic mode, and load the map, currents, winds, then save as “Save File” not as “Location File.”
8. Download and install GNOME. On left side double click “movers” and later “spills” to enter in info or choose data files or values. Note that for latitude, the highest resolution is 0.01 min or about 20 m. (it rounds to nearest). Recommend using deg, min, sec.sss since it seems to allow positioning down to about a meter.
9. Wind can be entered in constant or variable. Netcdf from NOAA also works automatically.
10. Currents from NOAA (HYCOM and RTOFS) work automatically but can also manually enter through a text file with extension “.cur.”

```
[GRIDCUR]
NUMROWS 100
NUMCOLS 100
STARTLAT 33.8
STARTLONG -120.4
DLAT .008
DLONG  .01
row col u v
1 1 .10 .10
1 2 .10 .10
1 3 .10 .10
…………..
100 100 .11 .15
```

    The user may create a file for constant current to match the bna file. It is also constant spatially, and on an arbitrary grid. This could be generated from a model or other source, but for now quick way to specify a constant current in the area in time and space. An easy way to make time variable (but still spatially constant) is to use hdr file referencing a series of files (here choose the S Irish Coast is chosen):

    S-Irish-Coast_hdr.cur--------------⊠ S-Irish-Coast_hdr_yymmddhh.cur, …

    The user can also create a file with extension “.ossm” which gives magnitude (only) of the current as a function of time, with direction given by current field.
11. A wind file can also be created with similar structure, but the easiest is to use the OSSM (On Scene Spill Model) option for a time series only (assumed spatially homogeneous automatically). Can create through GNOME dialog boxes (constant or

steady in time). Easier to edit the file S-Irish-Coast.wnd (few lines for time series of wind at boat location).

12. Set diffusion or use default 100,000 cm2/s (a “mover”).
13. Can spray the spill location, with the total mass specified in dialog box.
14. Output is made available in KML format by default, for easy viewing in GoogleEarth (besides GNOME itself). The user must convert ms4 (MOSS file 4, average) and Ms6 (least regret estimate) to a usable format if other visualization tools are needed. It contains positions of elements, not concentration. Note that MOSS files 5/7 contains the mass of the splot and the concentration (g/cm3), respectively. An example plot from GNOME interface is in Figure 52.

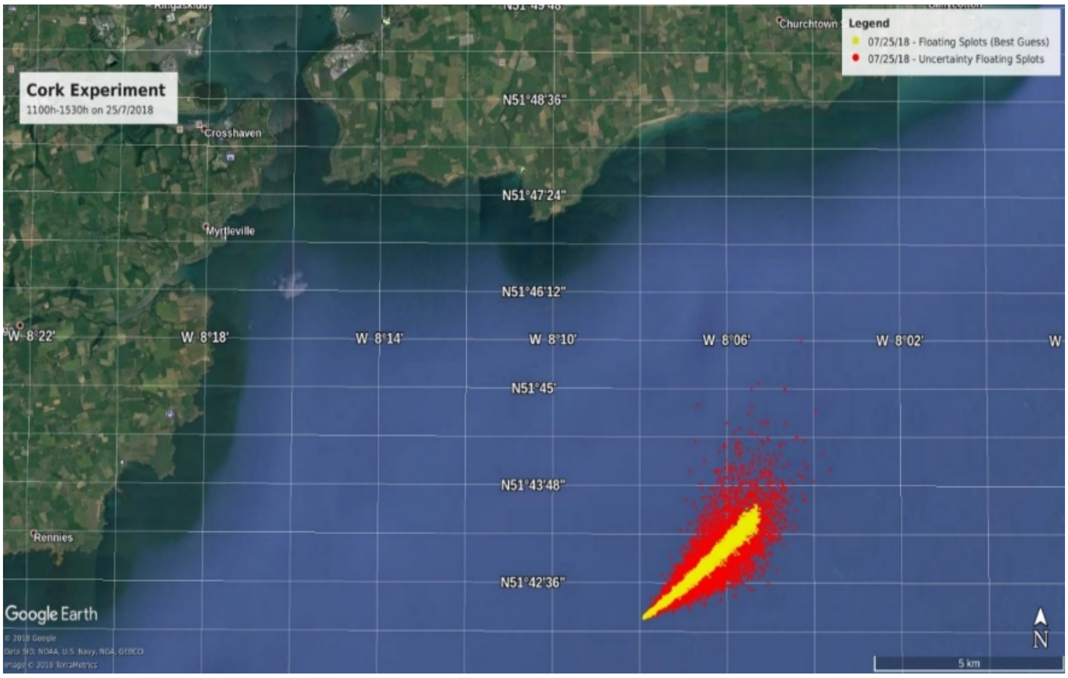


Figure 52. An example plot from GNOME interface.

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6. Acronims

ACT - Association for Coastal Technology

ADIOS - Automated Data Inquiry for Oil Spills from NOAA

API - American Petroleum Institute - http://www.americanpetroleuminstitute.com/

AUV – Autonomous Underwater Vehicle

BMT - http://www.bmtcordah.com

C2 – Command and Control

CCSM - Community Climate System Model

CEDRE - Centre of Documentation, Research and Experimentation on Accidental Water Pollution - http://wwz.cedre.fr/

CLS – Cleansea.net

ConOps – Concept of Operations

COTS - Components Off-The-Shelf

CSV - comma separated values

CTD - Conductivity-Temperature-Depth

DUNE – Uniformed Navigational Environment, onboard control software

EMSA – European Maritime Safety Agency - http://www.emsa.europa.eu/

ERD - NOAA Emergency Response Division

ESA – European Space Agency

GLUED - GNU/Linux Uniform Enviromment Distribution- http://lsts.fe.up.pt/toolchain/glued

GNOME - GNU Network Object Model Environment - https://www.gnome.org/

GPS – Global Position System

Hz – Hertz

IMC – Inter-Module Communication Protocol

IMO – International Maritime Organization - http://www.imo.org/

IP – Internet Protocol

IPIECA - Global oil and gas industry association for environmental and social issues http://www.ipieca.org/

IR – Infrared wavelength

IRCG - Irish Coast Guard

ITAR - The International Traffic in Arms Regulations - https://gov-relations.com/itar/

ITOPF - International Tanker Owners Pollution Federation - http://www.itopf.com/

IVER - http://www.iver-auv.com/

LABUST - https://www.fer.unizg.hr/zari/labust

LAUV - Light Autonomous Underwater Vehicle

LBL – Long Base Line
LSTS - http://lsts.fe.up.pt/
MEDESS4MS - http://www.medess4ms.eu
MEDSLICK – Mediterranean trajectory and forecast oil spill model
MODIS - Moderate Resolution Imaging Spectroradiometer – http://modis.gsfc.nasa.gov/
MRA – Mission Review and Analysis
NCAR - National Center for Atmospheric Research
NIR – Near-infrared wavelength
NMEA - National Marine Electronics Association
NOAA - National Oceanic and Atmospheric Administration's – http://www.noaa.gov/
NTNU - Norges Teknisk-Naturvitenskatelige Universitet
OSRL – Oil Spill Response Limited
PAH - polyaromatic hydrocarbons
PAH - Polycyclic Aromatic Hydrocarbons
POSEIDON OSM
ppb – part per billion
REMPEC – Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea
ROS – Robot Operating System
SAMS - Scottish Association for Marine Science
SAR – Search and Rescue
SAR - Synthetic Aperture Radar
SASEMAR - Spanish Maritime Safety Agency –
http://www.salvamentomaritimo.es/spanish-maritime-safety-agency/
SLAR - Side-Looking Airborne Radar
TUT - Tallinn University of Technology
UAV - Unmanned Aerial Vehicle
UC – University of Cyprus
UG - University of Girona
UIB - University of the Balearic Islands
UN – United Nations - http://www.un.org/
UP – University of Porto
UPCT – Universidad Politécnica de Cartagena
URready4OS – Underwater Robotics ready for Oil Spill
USBL - Ultra Short Base Line
USV – Unmanned surface vehicle
UV -Ultra Violet
UZ – University of Zagreb

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How to cite this document:

López-Castejón, F. & J. Gilabert (Eds). 2019. Underwater Robotics ready for Oil Spill. Technical Paper URready4OS Project. 98 pp.

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Acknowledges

We thank the Captains and crews of the “Clara Campoamor” and “LÉ Róisín” for their enthusiastic and professional contribution to this project during the exercises at sea.