GRACE grant no 679266

Oil detection using oil sensors on Autonomous Underwater Vehicles

D1.5

WP1: Oil spill detection, monitoring, fate and distribution

Cover Photo by Ben Allsup, Teledyne Webb Research

Prepared under contract from the European Commission
Contract n° 679266
Research and Innovation Action
Innovation and Networks Executive Agency
Horizon 2020 BG-2014-2015/BG2015-2

Project acronym:	GRACE
Project full title:	Integrated oil spill response actions and environmental effects
Start of the project:	01 March 2016
Duration:	42 months
Project coordinator:	Finnish Environment Institute (SYKE)
Project website	http://www.grace-oil-project.eu

Deliverable title: Oil detection using oil sensors on Autonomous Underwater Vehicles

Deliverable n°: D1.5
Nature of the deliverable: Report
Dissemination level: PU

WP responsible: WP1
Lead beneficiary: TUT

Due date of deliverable: 31.08.2017
Actual submission date: 31.08.2017

Deliverable status:

Version	Status	Date	Author	Approved by
1.1	draft	21.08.2017	Siim Pärt, Tarmo Kõuts, Kaimo Vahter	WP members 28.08.2017
1.2	final	29.08.2017	Siim Pärt, Tarmo Kõuts, Kaimo Vahter	Steering group 31.08.2017

Contents

Executive Summary 4

1. Autonomous Oceanographic Vehicles (AOV-s) 5

1.1 Autonomous Underwater Vehicles (AUV) 5

1.1.1 Man-Portable AUVs 7

1.1.2 Lightweight Vehicle (LWV) and Heavyweight Vehicle (HWV) AUVs 8

1.1.3 Large Displacement AUVs 9

1.2 Gliders 10

1.3 Wave and Wind Powered ASVs 12

1.4 Autonomous Surface Vehicles (ASVs) 13

1.5 Vehicle considerations and vehicle compatibility considerations for oil spill detection and monitoring 15

1.6 Teledyne Webb Research Slocum glider 16

1.6.1 Slocum G2 glider MIA of Marine Systems Institute at Tallinn University of Technology 18

1.6.2 Standard oil sensor for Slocum gliders 18

2. Autonomous underwater vehicles in oil spill detecting and response 19

2.1 Capabilities and Uses of Sensor-Equipped Ocean Vehicles for Subsea and Surface Detection and Tracking of Oil Spills 20

2.2 Autonomous Underwater Vehicles (AUV-s) in oil spill response 22

2.3 AUV based mobile fluorometers: system for underwater oil-spill detection and quantification 23

2.4 Oil spill detection and mapping under Arctic sea ice using autonomous underwater vehicles (AUV-s) 23

2.5 Oil spill detection and mapping using gliders 25

3. Specificity of glider operations in the Baltic Sea 25

4. Experimental study with oil detection sensor in glider mode 28

4.1 Location of the measurement area 28

4.2 Plan of the experiment 29

4.3 Results of the experiment 33

References 41

Executive Summary

An AUV (autonomous Underwater Vehicle) is a robot able to travel underwater, autonomously, without requiring input from an operator. Vehicles range in size from lightweight man-portable AUV-s to large diameter vehicles of over 10 meters in length. Primarily oceanographic tools, AUV-s carry sensors to navigate autonomously and map features of the ocean. Still even the largest AUV-s 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 and they still often require a vessel nearby during the monitoring run, making AUV-s generally a rapid targeted response tools. One exception are the quite new underwater gliders, which can sample for many months, but the problem is that they has severely restricted payloads and due that the compatibility of different sensors is low. Still gliders have been shown to be useful in long-term monitoring using a small subset of sensors, mostly indirect. Gliders use small changes in its buoyancy in conjunction with wings to convert vertical motion to horizontal, thereby propelling itself forward with very low power consumption. They operate under extremely tight power constraints—and travel thousands of kilometers in the ocean.

Available remote-sensing techniques are efficient and well developed for on water oil, but less useful for underwater releases before surfacing. To determine the spatial distribution of an oil spill and its temporal evolution the integration of AUV-s in dynamic platforms is necessary. The 2010 Deepwater Horizon incident brought into the public eye the problems identifying and determining the extent of these subsurface plumes. Nowadays, several initiatives and projects have come to being also using autonomous vehicles to deal and study these issues.

Gliders have matured to standard oceanographic instruments in the world ocean within last two decades or so. This is, however, not yet the case in the Baltic Sea, where only few glider surveys have been done. As the Baltic Sea is a multi-basin, small, shallow and brackish sea that has partly very lively marine traffic, operating gliders in the Baltic Sea is quite different when doing it in the ocean.

Marine Systems Institute (MSI) at Tallinn University of Technology (TUT), owns and uses the Slocum G2 glider MIA. This particular glider is suited for subsurface hydrophysical and hydrobiological sampling at a regional or larger scale in the Baltic Sea. Glider can be programmed to patrol for weeks or months at a time and if surfacing to transmit their data into shoreside servers, while downloading new instructions for operation. Glider is cost effective compared to traditional ship-based research methods. This report analyzes different aspects the usability of AUV-s broader and gliders particularly, for oil spill detection and monitoring.

The glider MIA used by MSI is not compatible with the Uvilux UV fluorometer, oil detection sensor we have available within GRACE project (see D1.1, D1.2 and D1.6). We describe glider operation and oil detection separately, in simulated glider mode with towable sensor rig from aboard a boat. System consista of the Sea-Bird CTD profiler and the UviLux UV fluorometer as an oil sensor. Location of the experiment was chosen in Tallinn Bay, area of heavy marine traffic intensity and high oil pollution probability could be expected. Three surveys were made, one with only the UviLux sensor, second with the towable rig , giving wide range of other parameters of marine environment and a third one with the rig and Uvilux sensor in a flow-through chamber, to lessen the effect of sunlight to the sensor on the surface layer. First test consisted of two transects, second test of two transects (5 and 10 “sawtooth” profiles) and five vertical profiles in fixed position and third test of two vertical profiles.

Results of the experiments showed that AUV-s are useful platforms for mapping of oil spills and surrounding marine environment in high resolution both vertically and horizontally. Measurements of

PAH concentrations, both vertical profiles and towing in glider mode, showed similar pattern of the variability in case of different profiles and transects. Drawback during the first two test was that UV fluorometer readings were influenced by UV component of the sunlight in surface layer of the sea, which lead to necessity to improve the measurement methodology with a flow-through dark chamber where sensor was accommodated during third test. Eliminating the influence of direct sunlight variability of UviLux sensor output values in terms of carbazole stayed between 1,7 and 2,2 µg/L.

Based on available from literature information and results of our experiments, one could be pointed out that gliders are platforms suitable to monitor distribution of oil components in larger sea area, as their autonomy is longer and classic AUV-s more locally, as they need presence of support vessel nearby and are less autonomous. In case of both, classic AUV-s and gliders we have very useful and cost effective tools for monitoring oil concentrations underwater, both in open water and beneath the ice thus applicable also in arctic conditions.

1. Autonomous Oceanographic Vehicles (AOV-s)

This section summarizes the range of autonomous oceanographic vehicles (AOVs) available for use as hosts for subsea oil detection sensors, including autonomous underwater vehicles (AUVs) and autonomous surface vehicles (ASV), and their potential suitability for various mission applications. Data were collected from a survey of vehicle manufacturers and information available, referred from the OGP/IPIECA [1] report. In this report a massive work has been done to give an overview of the current state of detecting and measuring oil (oil compounds) with autonomous vehicles. 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 and they still often require a vessel nearby during the monitoring run, making AUVs generally a rapid targeted response tools. One exception are the quite new underwater gliders, which can sample for many months, but the problem is that they has severely restricted payloads and due that the compatibility of different sensors is low, according to IPIECA [1]. Still gliders have been shown to be useful in long-term monitoring using a small subset of sensors, mostly indirect, for instance during the DeepWater Horizon spill [3].

1.1 Autonomous Underwater Vehicles (AUV-s)

An AUV is a robot that travels underwater, autonomously, without requiring input from an operator. AUVs constitute part of a larger group of undersea systems known as unmanned undersea vehicles (UUVs), a classification that includes non-autonomous remotely operated underwater vehicles (ROVs) controlled and powered from the surface by an operator/pilot via an umbilical or using remote control. In military applications AUVs are more often referred to simply as UUVs.

The AUV market is effectively split into three areas: scientific (including universities and research agencies), commercial offshore (oil and gas etc.), and military application (mine countermeasures, battle space preparation). The majority of these roles use a similar design and operate in a cruise (torpedo-type) mode. They collect data while following a preplanned route at speeds typically between 1 and 4 knots. Most AUVs follow the traditional torpedo shape as this is seen as the best compromise among size, usable volume, hydrodynamic efficiency, and ease of handling. Some vehicles use a modular design, enabling components to be changed by the operators.

Hundreds of different AUVs have been designed over the past 50 or so years but only a few companies sell vehicles in significant numbers. Several companies sell AUVs on the international market, including Bluefin Robotics, Hydroid (now owned by Kongsberg), International Submarine Engineering (ISE) Ltd., Kongsberg Maritime, and Teledyne Gavia (previously known as Hafmynd).

Vehicles range in size from lightweight man-portable AUVs to large diameter vehicles of over 10 meters in length. Large vehicles have advantages in terms of endurance and sensor payload capacity; smaller vehicles benefit significantly from lower logistical burden (e.g., support vessel footprint; launch and recovery systems).

Primarily oceanographic tools, AUVs carry sensors to navigate autonomously and map features of the ocean. Typical sensor payloads include compasses, depth sensors, sidescan and other sonars, magnetometers, thermistors, and conductivity probes. AUVs can be monitored from a distance, from a small vessel, or they can in many cases operate completely autonomously. In general, the following modes of operation can be defined:

- Autonomous – the AUV executes its mission without any interaction during mission execution. This typically requires some prior knowledge about the area of operation, such as a general idea of the bathymetry, currents, and threats (e.g., trawling nets and complex obstacles). When operating completely autonomously, the AUV will surface and obtain its own GPS fix. Between position fixes and for precise maneuvering, an inertial navigation system on board the AUV measures the acceleration of the vehicle, and Doppler velocity technology is used to measure rate of travel. A pressure sensor measures the vertical position. These observations are filtered to determine a final navigation solution. In case of a serious malfunction, the AUV will rise to the surface if at all possible, and transmit its location.
- Semi-autonomous – the AUV is in intermittent contact with its support ship, through satellite, radio frequency (RF) or acoustic links. The support ship is free to perform other tasks during the AUV mission.
- Supervised – the AUV is in near-continuous contact with the support ship through acoustic links. In this mode, the operator can change nearly any aspect of the mission execution and monitor data recorded by the payload sensors. The support ship needs to stay within a few hundred meters to a few kilometers to the AUV, depending on the conditions.
- Long Baseline (LBL) – the AUV navigates using an underwater acoustic positioning system. When operating within a net of sea floor deployed baseline transponders, this is known as LBL navigation. When a surface reference such as a support ship is available, ultra-short baseline (USBL) or short-baseline (SBL) positioning is used to calculate where the subsea vehicle is relative to the known (GPS) position of the surface craft by means of acoustic range and bearing measurements.

Transitions between different modes of operation can occur; the AUV may start and end its mission in supervised mode and switch to autonomous mode later (pre-planned, or when receiving a command from the support vessel).

Weather limits for AUV launch and recovery (L&R) operations depend on many factors. The size of the AUV, the use of a dedicated launch and recovery system (LARS), and the type of dedicated ship or ship of opportunity are all factors in determining the sea state that AUVs can be launched and recovered. Many recovery operations require small boats to connect a lifting line to the AUV. Dedicated LARS allow the AUV to be recovered without launching small boats into the water, thereby extending the sea state conditions in which operations can take place.

1.1.1 Man-Portable AUV-s

Man-portable AUVs are appropriately named due to their small sizes and weight. The vehicles can be deployed from most vehicles or shore sites, but are typically deployed by a few personnel in inflatable boats. The displacement of these vehicles is generally up to approximately 80 kilograms (two-person lift) though a few configurations can be heavier. This class of vehicle exhibits the following characteristics:

- Endurance ranges from < 10 hours to 20 hours depending on speed and hotel (including sensors) power load
- Payload volume is modest < 0.007 m^3

Figure 1 Man-Portable AUVs [1]

1.1.2 Lightweight Vehicle (LWV) and Heavyweight Vehicle (HWV) AUV-s

LWVs are larger in terms of size and weight compared to man-portable AUVs. This vehicle size is defined as nominally 33,4 cm in diameter and typically includes cylindrically-shaped vehicles. This size fills the need for a vehicle with extended endurance and ease of handling. HWVs are nominally 53,3 cm in diameter and are also typically cylindrical shaped.

These classes of vehicle exhibit the following characteristics:

- LWV: – typically 33,4 cm in diameter and approximately 227kg in weight though heavier configurations exist
- endurance ranges from 10 hours to 40 hours depending on speed and hotel (including sensor) power load
- payload volume is on the order of 0.03-0.08 m^3.
- HWV: – are typically 53,3 cm in diameter and weighing up to 1361 kg
- endurance ranges from 20 hours to 80 hours depending on speed and hotel (including sensor) power load
- payload volume is on the order of 0.11-0.17 m^3

Other than select vehicles with discrete payload compartments or bays, these vehicles are generally constructed as cylindrical modular vehicles broken into sections that are joined together to comprise the entire vehicle. As such, payload sections can be of variable length largely constrained by overall weight, balance and control limits of the vehicle design and the handling and storage limits of the on-deck cradle, launch and recovery equipment. Most manufacturers have a catalog of “standard” payload sections for their vehicles, though most can be customized for specific sensor integrations.

These classes of AUVs are typically launched from board of the vessel using an A-frame or boom type of crane system, a launch and recovery ramp, or specialized launch and recovery system equipment developed specifically for AUV L&R. Launch and recovery consists of a free-floating vehicle actively swimming off the surface and being recovered while drifting on the surface. The AUVs are configured with recovery straps (lifting points) and nose recovery bails that are installed on the AUV. This equipment is kept on during operations and used for hook- based (e.g., crane or davit) L&R. This method requires dexterity with equipment and manpower. The use of people very close to (touching) the vehicle, small boats and cantilevered hoists require relatively calm sea-states for safe and controlled L&R. Alternately, the recovery bail and main lifting point on the AUV can be attached at sea by shipboard operators using a long (~9 meter) carbon fiber pole.

Most of these AUVs can also use a LARS that eliminates the close proximity “pole hooking” approach. In this case the recovery consists of the crew securing the AUV recovery line from a distance, manipulating the ship into a towing position, and a winch operation that retrieves and lifts the AUV onto a cradle by the nose.

Figure 2 LWV and HWV class AUV-s [1]

1.1.3 Large Displacement AUV-s

This vehicle class is the largest size in operation. The driving factor for the large size is endurance and payload capacity. In order to travel long distances (>160 km), and to have long times on station (>1 week), their energy capacity must be significant. This class of vehicle exhibits the following characteristics:

- Typically greater than 91 cm in diameter and weighing up to 9070 kg
- Endurance greater than 100 hours depending on speed and hotel (including sensor) power load
- Payload volume on the order of 0.4-0.8 m^3

Payload is carried in discrete payload bays designed into the overall vehicle arrangement. L&R is similar to that indicated for the LWV and HWV AUV classes, but scaled-up to reflect the size and weight of these vehicles. Due to their size and cost, these vehicles have not been produced in great numbers, though the vehicle manufacturers are reputable companies that have been in the maritime industry for a considerable period of time.

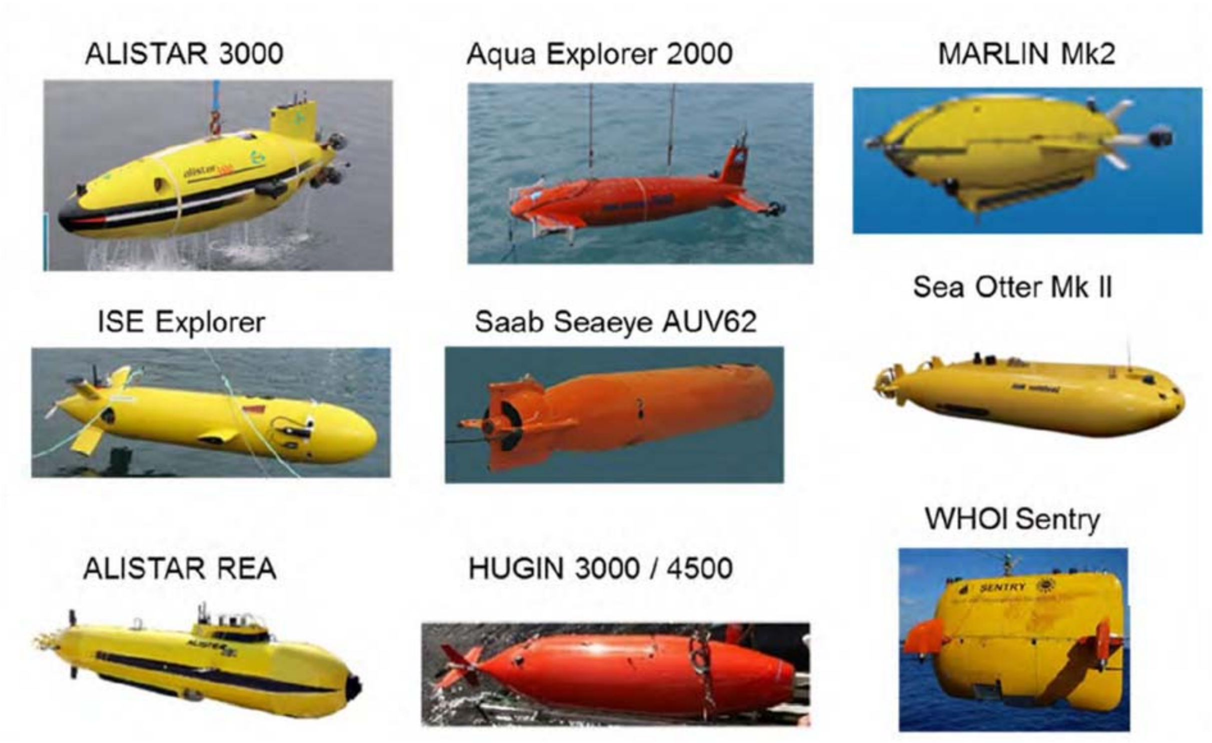


Figure 3 Large Displacement AUV-s [1]

1.2 Gliders

An underwater glider is a type of AUV that uses small changes in its buoyancy in conjunction with wings to convert vertical motion to horizontal, thereby propelling itself forward with very low power consumption. Gliders operate under extremely tight power constraints—they travel thousands of kilometers in the ocean consuming about 1 W for propulsion and about the same for hotel. Minimizing drag, and maximizing lift/drag of lifting surfaces, is essential to achieving range and endurance, which are typically considered the most important glider characteristics. This class of vehicle exhibits the following characteristics:

- Slower than conventional AUVs (0.4-0.7 kts vs. 3-5 kts)
- Significantly increased endurance and range (from hours to weeks or months, and to thousands of kilometers)
- Following an up-and-down profile through the water (often referred to as a sawtooth), typical glide slopes, on the order of 1:4, are much steeper than the slope of oceanic distributions, so each leg of a glider sawtooth produces the equivalent of an ocean profile.
- The shallowest points on the sawtooth are at the surface where satellite navigation and communication are carried out, eliminating the need for in-situ tracking networks.

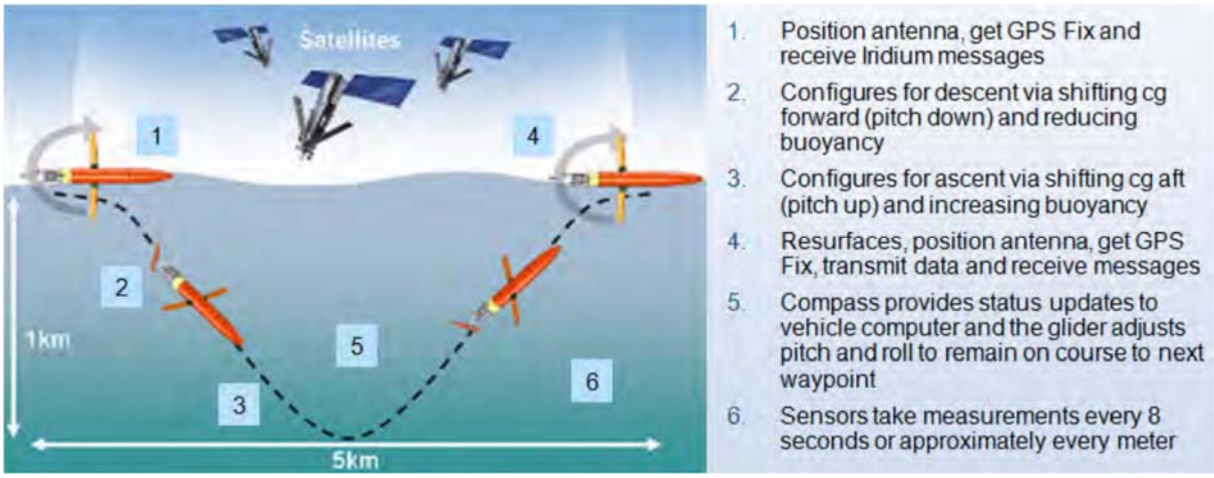
Four basic sampling modes for gliders have presented themselves:

- Forward motion can be used to counter ambient currents and maintain position, allowing gliders to sample virtually as a vertical array of moored instruments

- Moving from place to place yields a highly resolved section, although the slowness of advance mixes time and spatial variability
- Multiple gliders controlled remotely from a research vessel can form an array to describe a spatial and temporal context for intensive measurements
- The long operating lives and ability to sample densely suit gliders to missions where unusual events are sought and then studied intensely when found.

Scientific payloads for gliders are limited by size, flow disturbance, and power requirement considerations. Gliders achieve their low overall power consumption by using low-power electronics and sampling schemes that limit the duty cycle of sensors. The relatively slow glider speeds allow sampling intervals of 8-10 seconds to achieve a vertical resolution of 1 meter. Sensor systems must fit within the payload fraction of the vehicle and, because gliding involves modest buoyancy forces, ballast and trim are paramount considerations. In general, sensors must be hydrodynamically unobtrusive, lest they spoil gliding performance by adding drag. Streamlining can be achieved by using sensors that are small or mounted flush to the vehicle hull. Outward-looking acoustic and optical sensors conveniently fit this requirement and have been used on the gliders described here.

Figure 4 Gliders [1]



1. Position antenna, get GPS Fix and receive Iridium messages
2. Configures for descent via shifting cg forward (pitch down) and reducing buoyancy
3. Configures for ascent via shifting cg aft (pitch up) and increasing buoyancy
4. Resurfaces, position antenna, get GPS Fix, transmit data and receive messages
5. Compass provides status updates to vehicle computer and the glider adjusts pitch and roll to remain on course to next waypoint
6. Sensors take measurements every 8 seconds or approximately every meter

Figure 5 Representative glider mission profile [1]

1.3 Wave and wind powered ASV-s

This is a new class of wave-propelled, persistent ocean vehicles. The key innovation of these vehicles is the ability to harvest the abundant energy in ocean waves to provide essentially limitless propulsion. A wave powered vehicle can be regarded as a small, self-propelled (albeit slow) buoy capable of an average forward speed of about 1 m/s (1.5 knots) in seas with 0.5 m – 1 m wave height.

The Wave Glider is a hybrid sea-surface and underwater vehicle comprised of a submerged “glider” attached via a tether to a surface float. The AutoNaut is a more conventional sea-surface vehicle that has similar planes on the bow and stern. The vehicles are propelled by the conversion of ocean wave energy into forward thrust, independent of wave direction. The wave energy propulsion system is purely mechanical; electrical power is neither generated nor consumed by the propulsion mechanism.

As a surface vehicle the Wave Glider can maintain continuous GPS and Iridium communication, allowing it to be controlled in real-time. The current graphical interface provides the operator with two distinct modes of operation: mission planning and direct control. Mission planning is waypoint navigation based on geographical references provided by GPS; direct control allows the operator to effectively “drive” the vehicle (within the operator’s line-of-sight) to aid in L&R operations or to navigate harbors and other confined waterways. Wave Glider L&R is similar to that of a LWV-class AUV, being typically deployed using a small crane. Deck stowage would be in the form of a cradle. The Wave Glider has two dry payload bays on the float and payload mounts on the glider body. The payload mounts are suspended ~ 7 meters below the float and can be used for sampling. Payload power is provided by the batteries which are recharged by solar panels. It is also conceivable for a payload to be suspended or towed from the glider body.

The Saildrone is an autonomous rigid foil sailboat that uses the wind for propulsion and solar panels to provide additional electrical power for steering and sensors. Saildrone is constructed from high-strength carbon fiber to create a strong and durable structure. While delicate in appearance, Saildrone is engineered to be fully submerged and rolled in extreme waves. The Saildrone’s hydrodynamic design is a hybrid, combining the features of mono- and multi-hulls. The result is a fully self-righting platform that also benefits from high righting moments for speed and wave piercing capabilities to reduce pitching and energy absorption from waves. Saildrone has two payload bays and external payload attachments, configurable to serve varied mission requirements. Total payload weight capacity is currently 100 kg, and can be expanded with larger craft as required. Various power options and sampling solutions are offered depending on the mission specific tasks.

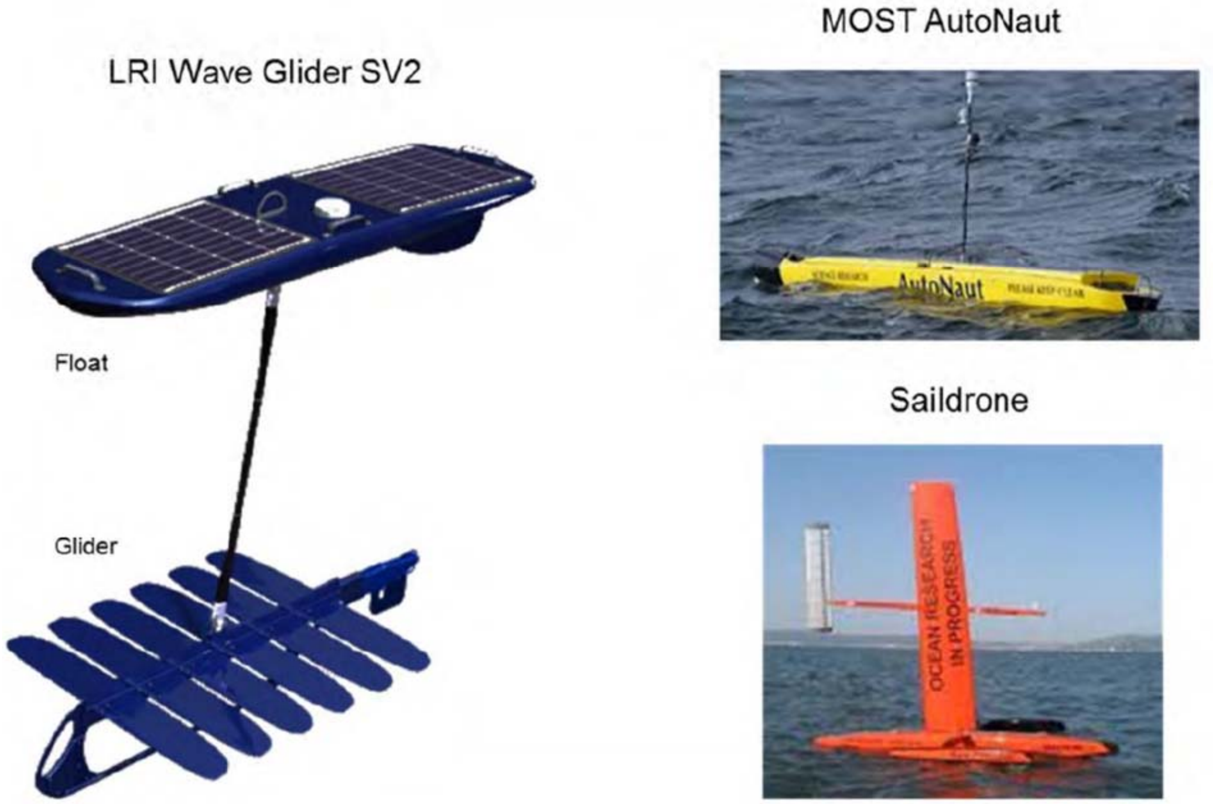


Figure 6 Wave and wind powered ASVs [1]

1.4 Autonomous Surface Vehicles (ASVs)

The term ASV or unmanned surface vehicle (USV) refers to a vehicle that operates on the surface of the water without a crew. ASVs have been tested since World War II but have been largely overshadowed by other AOVs. Navies around the world are developing, testing, and using autonomous surface vehicles today. They are reliable, fast, and highly maneuverable, allowing the conduct of a wide range of missions, including patrols of the coast, without endangering personnel. ASVs are also used in oceanography as they are more capable than moored or drifting weather buoys, far cheaper than the equivalent weather ships and research vessels, and more flexible than commercial-ship contributions. ASV payload integration for subsea operations is either hull-mounted, uses a mechanical boom extension, or uses a dipper or a tow-fish on a winch. The term "dipper" refers to a sensor suspended on the winch line without great regard for stabilization. Of these approaches, only the dipper and tow-fish can achieve significant water depth. Arguably, any method of sensor employment suitable for small boat operations and capable of being automated is useable from an ASV, though it may not be considered standard equipment from the ASV manufacturers.

As a surface vehicle, an ASV can maintain continuous communication with the operator allowing the ASV to be controlled in real-time via either satellite GPS and Iridium communication or line-of-sight radio communication. The operator possesses two distinct modes of ASV operation: mission planning and direct control. Mission planning is waypoint navigation based on geographical references provided by GPS; direct control allows the operator to effectively pilot the vehicle (within the operator's line-of-sight) to aid L&R operations or to navigate harbors and other confined waterways. Research is ongoing to develop ASVs that will operate under minimal supervisory command and control for long durations, with shore bases intermittently monitoring performance and providing high-level mission objectives through beyond line-of-sight communications links. These vessels will be provided with advanced autonomous navigation and anti-collision features to keep them within maritime law and the International Regulations for Preventing Collisions at Sea.

Figure 7 Small ASVs [1]

1.5 Vehicle considerations and vehicle compatibility considerations for oil spill detection and monitoring

In this section general considerations and words of advice from the OGP/IPIECA [1] report for AOVs are given to help guide the priority recommendations for oil spill scenarios.

- Most AOVs are developed for either military or scientific purposes.
- Larger AOVs become more desirable for extended missions as spill duration increases and spills get deeper and farther from shore.
- Man-portable AOVs become less useful in deeper waters due to limited operational duration, depth, and maneuverability.
- AOVs are generally preferred over manned vessels for the purposes of reducing costs and reducing risks of personnel exposure to hazards during spill response.
- It is generally desirable to engage a mix of surface and subsea vehicles for spill detection and tracking.
- Gliders have limited on-board power and might have to operate direct sensors (which typically consume more power than indirect sensors) intermittently rather than continuously using a power management system.
- Gliders are release-and-forget type vehicles that are likely to be useful for monitoring spill perimeters and extents.
- Wave/wind powered ASVs were designed as open water vehicles and are likely to be less effective close to shore.
- In most locations, manned surface vessels are likely to be readily available while any type of autonomous vehicle would likely require a day or longer to deploy in the spill area.
- Small ASVs can operate in protected bodies of water such as ports and harbors but are not designed for open seas.
- Wave gliders and ASVs are more useful than AUVs when the majority of the spill is at or near the water surface.
- AUVs are not practical or economical close to shore where the water is shallow and a range of surface vessels are likely to be readily available.

1.6 Teledyne Webb Research Slocum glider

Conceived by Douglas C. Webb and supported by Henry Stommel and others, the class of Slocum gliders is named after Joshua Slocum, the first man to single handedly sail around the world. These platforms are a uniquely mobile network component capable of moving to specific locations and depths, and occupying controlled spatial and temporal grids. The gliders are driven in a sawtooth vertical profile by variable buoyancy and can move horizontally and vertically. Long-range and satellite remote sensing systems are being realized in the ocean measurement field. These systems are being used to quantify currents, sea surface height, temperature, and optical properties of the water, enabling modeling and prediction of ocean state variables in the littoral zone. A similar nested grid of subsurface observations is required to maximize the impact and ground-truth of the more extensive surface remote sensing observations. The long-range capabilities of the Slocum gliders make them well suited for subsurface sampling at a regional or larger scale. These gliders can be programmed to patrol for weeks or months at a time, surfacing to transmit their data to shore while downloading new instructions at regular intervals, at a substantial cost savings compared to traditional ship-based research methods. The small relative cost and the ability to operate multiple vehicles with minimal personnel and infrastructure enables small fleets of gliders to study and map the dynamic (temporal and spatial) features of our subsurface coastal or deep ocean waters 24 hours daily, 365 days a year.[3]

Figure 8 Slocum G2 Glider [7]

Technical features of the Slocum glider [8]

- Exchangeable 6L payload capacity
- Independent processor for data acquisition
- Customized for a variety of acoustic, optical and chemical sensors
- Multi-depth capability with a single glider: User exchangeable nose pump sections result in quick optimization for changing mission depths
- User exchangeable depth section
- Nose recovery system
- Recovery strobe light
- Extendable payload bay for sensors or
- additional energy requirements

Capabilities of the Slocum glider [8]

- Waypoint transect
- Water column monitoring
- Virtual mooring
- Gateway glider acoustic link
- Storm sampling
- Coordinated fleet
- As part of Teledyne Marine, access to engineers and technology for advanced sensor capability and future sensor developments

Table 1 General specification of Slocum G2 glider [8]

Deployment	Versatile, maneuverable deployment with 1-2 people
Power	Alkaline (A) or Lithium (L) batteries
Range	600 - 1500 km (A) / 4000 - 6000 km (L)
Deployment length	15-50 days (A) / 4 - 12 months (L)
Configuration options	(4 to 200m) or (40 to 1000m) operating depth range
Navigation	GPS Waypoints, Pressure Sensor, Altimeter
Communication	RF Modem, Iridium (RUDICS), ARGOS, Acoustic Modem
Speed	0.35 m/s (0.68 knot) Average Horizontal
Mass	54 kg
Dimensions	Vehicle Length: 1.5 meters; Hull Diameter 22 cm

1.6.1 Slocum G2 glider MIA of Marine Systems Institute at Tallinn University of Technology

The Glider “MIA” used by the Marine Systems Institute is meant to gather data from the depth up to 200m. It registers the profiles of temperature, salinity, chlorophyll-a fluorescence, oxygen and turbidity [11].

Configuration of the glider is specially tuned for use in the Baltic Sea:

- the glider repeatedly traverses between 2-3 fixed points
- one measurement cycle consist of three dives and returning to the surface
- sensors record data at each diving with the frequency once every two seconds (0,5 Hz)

The MIA has carried out five surveys in August 2014 in the Muuga Bay, in July 2015 in the mouth of the Gulf of Finland (between Osmussaare and Hiiumaa), in October 2015 in the Gotland Deep, in May 2016 in the Gulf of Finland near the Keri Island and Kolga Bay and in 2017 near the Åland.

1.6.2 Standard oil sensor for Slocum gliders

The Sea-Bird Scientific SeaOWL UV-A™ SLC has introduced a new in-situ oil-in-water sensor specifically designed for integration into the Teledyne Webb Research Slocum glider, which bases on registration of UV fluorescence. Based upon the WET Labs’ ECO sensor, Sea-Bird Scientific has developed oil detection technology creating a 5X optical resolution improvement over its predecessor. [12]

SeaOWL UV-A™ SLC measures crude oil-in-water using UV-A excitation and blue emission wavelengths (370 nm EX/ 460 nm EM). The SeaOWL UV-A™ SLC improves the resolution and range of the ECO with a greater depth of field, optimized electronics and dynamic gain stage modulation. The new dynamic gain provides sensitivity across a large detection range making saturation unlikely in even the most heavily impacted environments. The compact SeaOWL UV-A™ SLC design also includes chlorophyll fluorescence and 700 nm backscattering measurements to discriminate crude oil from phytoplankton and other natural sources of FDOM.[12]

General features of the SeaOWL UV-A™ [12]

- Industry leading optical resolution.
- Wide dynamic gain prevents measurement saturation even within heavily impacted environments.
- Three parameters in a single sensor: chlorophyll, backscattering, and Fluorescent Dissolved Organic Matter (FDOM).
- Backscattering and chlorophyll fluorescence provide discrimination of crude oil from phytoplankton and other natural sources of FDOM.

Figure 9 SeaOWL UV-A™ SLC (Sea Oil-in-Water™ Locator SLC) [12]

Sensor is integrated in glider by manufacturer in their factory, taking care that buoyancy balance of the glider will stay in needed frames. No literature leads was found about actual usage experience and measurement results with SeaOWL UV-A™ sensor.

2. Autonomous underwater vehicles in oil spill detecting and response

Current technologies are mostly focused on oil detection at the sea surface. These technologies include airborne and spaceborne remote sensors such as: IR video, photography and thermal imaging, synthetic aperture radar, UV fluorescence sensors, airborne laser fluorosensors and airborne and spaceborne optical sensors [2]. Available remote-sensing techniques are efficient and well developed for on water oil, but less useful for underwater releases before surfacing. To determine the spatial distribution of an oil spill and its temporal evolution the integration of AUVs in dynamic platforms is necessary. These platforms are able to sample large areas, including the water column and accurately geo-reference the recorded measurements. 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 localization 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 preprogrammed 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. [2]

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 subsurface plumes.

Nowadays, several initiatives and projects have come to being also using autonomous vehicles to deal and study these issues. In this section some of these are described.

2.1 Capabilities and uses of sensor-equipped ocean vehicles for subsea and surface detection and tracking of oil spills

This OGP/IPIECA report [1] evaluates a range of oil detection sensors and oceanographic vehicles and their overall compatibility for detecting and tracking oil in water. Oil detection sensors include in situ contact sensors that utilize either direct or indirect sensing methods and surface remote sensors that utilize either passive or active sensing methods. Oceanographic vehicles include autonomous underwater vehicles (AUVs), autonomous surface vehicles (ASVs), and manned surface vessels.

To assess the compatibility of candidate oil detection sensors and oceanographic vehicles, a general qualitative assessment was performed at an overview-level as gaps in both sensor and vehicle payload interface data precluded a detailed quantitative comparison. With these limitations in mind, general observations are made regarding the combination of sensors and vehicles for oil detection at sea.

Several direct oil detection sensors are commercially available that focus on detecting either polyaromatic hydrocarbons (PAH) or refined and crude hydrocarbons (HC); a methane detection sensor is also available. Multiple commercially available indirect oil detection sensors are available to detect the changes between the properties of baseline local environment seawater and modified properties in the presence of oil, such as conductivity, temperature, turbidity, and presence of dissolved gases. The direct and indirect oil detection sensors measure the water at essentially a single local point; mapping the extent of hydrocarbons over a large geographic area and/or water column depth requires a large number of readings to be made.

Multiple viable combinations of direct and indirect oil detection sensors can be hosted on each of the classes of unmanned vehicles evaluated. Autonomous underwater vehicles (AUVs), gliders and autonomous surface vehicles (ASVs) have different strengths and weaknesses for their use as host vehicles for sampling the seawater environment. Principal among these are their launch and recovery (L&R) requirements and endurance which drive manning requirements. Many of the vehicles will likely have some amount of non-recurring engineering (NRE) associated with accommodating novel sensor configuration (one which the manufacturer has not already performed). This is due to the need to maintain and verify that overall vehicle trim and balance and hydrodynamics are maintained within acceptable design tolerances. This is especially true for the smaller AUVs and gliders. Different sizes and configurations of AUVs, gliders and ASVs are available commercially though some have only been produced in limited numbers. Direct and indirect oil sensors can also be deployed from almost any manned surface vessel provided that the vessel has a winch or similar device for raising/lowering or towing the sensor.

Several types of commercially available, passive remote sensors can be used to detect oil on the surface by exploiting phenomenologies that result in a distinct contrast between oil and the seawater background in the sensor image. These types of sensors include ultraviolet (UV), visible, and thermal infrared (IR) imagers, many of which have very common and widespread commercial applications. Active remote sensors include radar and fluorescence LIDAR which rely on post-processed images of returned energy to detect oil on water. Radar is a mature technology that is commonly available on many surface vessels and has been demonstrated to be useful for oil detection on water while fluoresce LIDAR is far less common and remains relatively unproven for oil detection from a surface vessel.

Passive imaging sensors can be either handheld or mounted and impart few if any requirements on the surface vessel. Radars can operate on most surface vessels but require installation and power for several components. However, many surface vessels already have built-in navigation radar and require only an additional back end processor to utilize for oil detection. Fluorescence LIDARs are large, expensive, and require significant power resources to operate and must therefore be used on a relatively large surface vessel.

Following the evaluation of oil detection sensors, oceanographic vehicles, and their overall compatibility for oil detection and tracking, these evaluations were applied to two oil response studies. The first study related these evaluations to guidance provided by the U.S. National Response Team (NRT) on atypical dispersant operation. The second study used these evaluations to determine priority recommendations of sensor and vehicle combinations for five specific oil spill scenarios.

The NRT guidance was developed in response to the Deepwater Horizon event, in which dispersants were applied at subsea depths greater than 300 m and for prolonged durations (>96 hours) on the surface. Neither of these scenarios is addressed in pre-existing dispersant application and monitoring guidance documents. For subsea, the 300m depth requirement is the critical issue, and most direct (fluorometers) and indirect (CTD, particle size, turbidity, dissolved O2) detection systems can be coupled with larger AUVs (light, heavy, and large displacement) to monitor oil during dispersant operations. For prolonged surface application, passive imaging sensors (visible, infrared, ultraviolet) as well as direct and indirect sensors meet specific NRT monitoring needs and can be integrated onto any surface vessels (manned or unmanned).

Priority recommendations of sensor and vehicle combinations were applied to five oil spill scenarios identified by the OSR-JIP: a release at a coastal terminal, an oil tanker in transit offshore, an offshore oil platform, an offshore pipeline rupture, and a deepwater well blowout. Combinations of oil detection sensors and oceanographic vehicles were assigned a high, medium, or low prioritization for each scenario depending on the operational capabilities and limitations for conducting emergency response operations.

As many viable combinations are plausible, a larger view of the entire concept of operations including host ship interfaces, time-on-station, manning requirements and constraints, and the duration for operation sustainment would need to be developed to determine the optimal number and type of sensors and vehicles required relative to the type of hydrocarbon spilled. The results of this study may be used as a screening tool to narrow the range of possibilities and prioritize combinations worthy of further consideration. In this regard, this study can be used to help identify those criteria that have the best probability of success relative to each specific mission scenario.

2.2 Autonomous underwater vehicles (AUV-s) in oil spill response

European Commission, Directorate General Humanitarian Aid and Civil Protection co-financed project UReady4OS [2] was dealing with usage the AUV-s in oil spill response and forces were joined to make AUV technology 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 recently been brought into the public eye during the 2010 Deepwater Horizon incident. 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.

During the URready4OS project two experiments where performed to prove the concept. The first one was held in Split, Croatia, to test the communications and set up of the fleet. The second one was held on board of the Spanish Maritime Safety Agency (SASEMAR) “Clara Campoamor” in waters off Cartagena, Spain.

The purpose of the white paper project was to show some technical characteristics of the developed system to track and monitor underwater oil in water plumes.

Firstly, it focuses on knowing what oil spill tools are available today. The goal 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.

Secondly, it describes the system, the diverse kinds of vehicles covering the underwater, surface and air segments. Also in that chapter the communications between agents – operator and robots between them – are described, the communication pathways and the protocols. In third, the software involved are described. The MEDSLIK II trajectory and forecast model was chosen for that 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 implemented in the project. Adaptation for new vehicles like IVER or fate and forecast models like MEDSLIK are now integrated in the platform that will be expanded in the future.

Thirdly, it describes briefly the experiment performed in waters off Cartagena in which all vehicles were working collaboratively to detect and monitor an underwater oil plume made of Rhodamine WT.

Teams from four European countries participated in this project: The Underwater Vehicles Laboratory (LVS) from 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.

2.3 AUV based mobile fluorometers: system for underwater oil-spill detection and quantification

The paper [3], performed in the framework of the European Commission EC-ECHO (Civil Protection) funded project ”Autonomous underwater vehicles ready - UReady4OS”, analyzed and tested application of Autonomous Underwater Vehicles (AUV) with integrated submersible fluorometer for underwater detection of hydrocarbons. Also a set of experiments were carried out in Kastela bay in 2014. summer-fall timeframe. Although the main scope of that project was to detect oil in water, it was not permissible to create oil pollution in reality. For that reason, Rhodamine WT red fluorescent dye was chosen as harmless, non-toxic oceanographic tracer, in order to simulate the oil spill situation.

First objective of thouse experiments was to detect the Rhodamine in water column and find the plume. The second objective was to geo-reference, log and visualize measured data. The third objective was to spatially map the plume.

The results of the experiments showed that fluorometers, when integrated on a dynamic platform such as AUV, can be efficiently used for in-situ spatial detection and quantification of a pollutant of interest. System, the AUV with integrated fluorometer, generally provided reliable measurements if adequate flow of water and protection from the ambient light are ensured. However, some false positive readings caused by ambient light were recorded close to the surface. They pointed out that special attention should be paid when using auto-gaining mode due to the time required for stabilization of readings. Still, many applications could benefit from auto-gaining feature, allowing users to detect a wide range of concentrations in best resolution. In applications where continuity of measurement is crucial, static gaining is recommended. Furthermore, fusion of concentration measurements with spatial and temporal data provides opportunity to visualize spatial distribution of the pollutant concentrations in a relatively static plume. But if the plume is transient, sole geo-referenced concentration data is not sufficient for reliable mapping of a plume though it represents valuable contribution to the development of the numerical model of the pollution.

2.4 Oil spill detection and mapping under Arctic sea ice using autonomous underwater vehicles (AUV-s)

Capabilities of Autonomous Underwater Vehicles (AUV-s) to operate under Arctic sea ice for the detection and mapping of oil spills has been studied earlier in a study [4] funded by Bureau of Safety and Environmental Enforcement (BSEE), U.S. Department of the Interior.

An integrated study of both AUV and sensor suite performance for oil spill response in ice-covered waters was performed. That had two key, complementary foci:

- a suite of three laboratory experiments were performed to determine the efficacy of three sensor modalities (sonar, digital imagery, and laser fluorescence) for detection of oil beneath, and encapsulated within sea ice,

- AUV missions to test the feasibility for extension of the existing under-ice capability of the Seabed Class AUV to oil spill mapping scenarios in variable, drifting ice conditions and under fast ice in shallow water.

Sensor evaluation included testing of a laboratory broadband sonar system, a high-fidelity high-frequency narrowband sonar, digital cameras, and development and testing of a laser fluorosensor prototype system. This suite of instruments was proven to be effective at detecting oil under sheet ice, and encapsulated within the ice to a thickness of up to 15 cm, depending on the sensor. Of particular interest, the acoustic scattering from the basal layer of sea ice was seen to be highly variable and distinct from that of the oil. Both broadband and narrow band sonar techniques proved effective in detecting and quantifying the thickness of oil under sea ice. Experiments demonstrated a clear benefit of acoustic systems is their potential for detecting the thickness of an oil layer, both under the ice, and to some degree encapsulated within the ice, based on detection of multiple acoustic scattering interfaces when oil is present. This thickness, when combined with observations of the spatial extent of the oil (provided by any or all of the sensor systems tested herein), allow quantification of the oil volume. The efficacy of oil detection under differing conditions (e.g. oil thickness, depth of encapsulation) is dependent on a variety of parameters (e.g. pulse width, range resolution). They concluded that determination of the most appropriate system configuration, or suite of systems, will require further experiments and analysis of performance under more complex ice conditions typical the variable Arctic ice cover. Also, broadband sonar techniques have several potential advantages for oil detection; Based on the results presented in that document the development and testing of compact AUV- based broadband systems seems warranted.

Laboratory based experiments, during this project, provided a unique opportunity to examine the efficacy of undersea oil detection techniques in different young ice types that occur in the Arctic Ocean. They found that detection of oil with sonar was more complicated in frazil and pancake ice types, although in these cases digital imagery and laser fluorescence proved effective. Results of these experiments suggested that the best solution for oil detection under ice would involve a combination of each of these sensors. Despite the success of these experiments, sensor efficacy under more realistic, highly variable ice conditions was needed, and would require both AUV missions to fully characterize the under ice environment, and further oil spill experiments in more complex ice conditions.

AUV missions in the Great Lakes and the Beaufort Sea demonstrated that rapid, entirely ship-based operation of the AUV under highly varied ice conditions would be possible. Long-range acoustic communication capability demonstrated in the shallow water fast ice environment at Prudhoe Bay will permit relatively large scale AUV surveys. AUV navigation techniques that combine inertial, bottom tracking, and acoustic positioning should permit precise large-scale mapping missions in varied sea ice conditions.

These results demonstrated the potential for development of a complete sensor suite and AUV platform for oil spill response in ice-covered waters. In particular, with directed investment, potential exists to advance AUV capabilities for routine large-scale oil spill mapping missions under the full range of ice condition encountered on the Beaufort/Chukchi continental shelf. A path towards this capability should include both further development of under ice AUV capability and evaluation of expected sensor performance under these conditions. For the former, development of long-range and long-endurance capability while maintaining accurate navigation and real-time communication are key to extending current capability to scenarios where rapid response to large spills under variable pack ice is required, or for routine monitoring for leaks from subsea pipelines.

Furthermore, they suggest that further testing and analysis of sensor performance in realistic conditions, including at longer ranges and in complex under-ice morphologies is necessary so that the expected characteristics of the signal response and required capabilities of each sensor system in this environment can be better determined. Given that each sensor system will have different performance capabilities in different ice and oil scenarios, it is expected that an operational system will combine several, or all the sensor modalities. Techniques for fusion of data from multiple sensors for the most reliable detection of oil should also be developed.

2.5 Oil spill detection and mapping using gliders

Gliders have been shown to be useful in long-term monitoring using a small subset of sensors, mostly indirect, during the DeepWater Horizon spill [9]. 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 [1], because of the capability of the very restrictive payload. They also found that gliders are likely to be useful for monitoring spill large perimeters and extents.

Also, recently-funded European project called BRIDGES [10] aims to develop a hybrid AUV-glider with a specific payload for oil detection which should exceed the existing state of the art.

3. Specificity of glider operations in the Baltic Sea

The Baltic Sea is a multi-basin, small, shallow and brackish sea that has partly very lively marine traffic. The water masses are horizontally and vertically strongly stratified. Some parts of the Baltic Sea resemble large estuaries. Also the topography is very variable. The dynamic scales, including scales of eddies and fronts, are variable and depend on the local stratification in the basins.

Traditional monitoring by research ships, gives a general impression on the conditions, but that impression is not detailed unless towed instruments are used. Use of towed instruments, like many institutes around the Baltic Sea e.g. in Estonia, Poland and Russia have for decades done, has been a good approach to resolve the processes. Those studies have shown the interaction of different scales and shed light on the multi-scale variability. However, in the present world, research ship time is a limited resource and new cost-effective observation methods are needed to increase the amount of observations. Gliders have matured to standard oceanographic instruments in the world ocean within last two decades or so. This is, however, not yet the case in the Baltic Sea. [5]

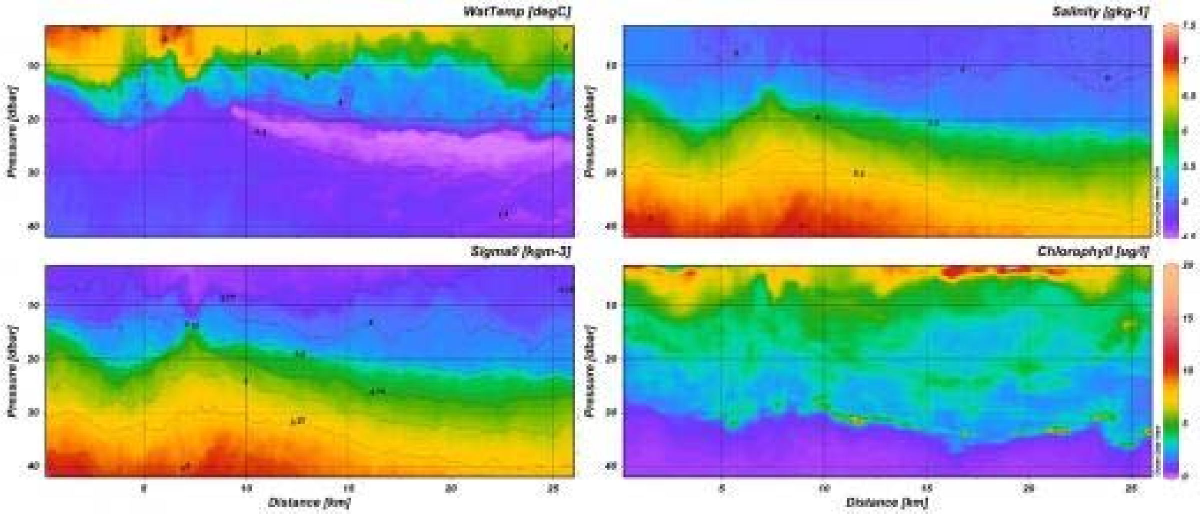


Figure 10 Distribution of water temperature, salinity, density and chlorophyll-a content in one section of the Keri - Kolga Bay survey, Gulf of Finland, recorded by Slocum glider MIA [11]

In a paper [5], describing the use of gliders for studies of multi-scale variability in the Baltic Sea, Baltic Sea was identified to be an area where gliders are not yet in routine use. At the time of writing of that paper, five scientific glider experiments in the Baltic Sea are known. In one of those the glider disappeared and no data was got. In the other the glider had difficulties to penetrate through the strong pycnocline, which led to conclusion that the instrument was not worthwhile using. German scientists did the first successful glider study in 2010 at Boknis Eck [6] in Western Belt Sea. FMI conducted the next successful experiment, or an experiment pair, under GROOM in September 2013 in Bothnian Sea and Archipelago Sea in co-operation between FMI and Plataforma Oceánica de Canarias (PLOCAN) from Spain. Also a short technical test of a Slocum shallow sea type glider in 2014 done by Marine Systems Institute of Tallinn University of Technology, Estonia. Finnish Meteorological Institute (FMI) and Plataforma Oceánica de Canarias (PLOCAN) organized a joint experiment to Bothnian Sea and Archipelago Sea, two sub-basins of the northern Baltic Sea, to study the use and potentials of gliders in these shallow, low-salinity environments.

In the paper [5], the GROOM Baltic Sea glider tests are described – a close co-operation between FMI and PLOCAN. The experiment strategy was to put the glider in mission and to do at the same time ship observations along the glider section and at the glider virtual mooring. The former ocean glider was carefully ballasted to the target areas brackish water. Glider was used in section mode in an open sea area and as a virtual mooring in a semi-enclosed small basin within an archipelago. The horizontal length scale of the glider observations in 100 m deep waters was about 200m. Their conclusions were that their two glider tests in the Baltic Sea were successful and reached their goals, proved the usefulness of gliders in these sea areas both in a section mode and in a virtual mooring mode. They got experience on the resolution of observations, on the energy consumption of the glider, on the characteristics of the missions and on many other details. The careful ballasting of the instrument before the missions was crucial step to successful use of the gliders in the Baltic Sea. Another important aspect was the altimeter. It is a necessary sensor onboard and worked as expected. The glider avoided collisions with the bottom and followed the bathymetry nicely along its mission. The ship traffic is very dense in certain parts of the Baltic Sea. They chose our study area so that there is not too much other traffic there. Therefore the glider was not in danger of collisions with ships during the short missions.

As mentioned above the first successful glider study in the Baltic Sea was a study of summer upwelling events in Southwestern Baltic Sea in 2010 [6]. During the experiments two consecutive summer upwelling events, each lasting for less than 24 h, were surveyed in high temporal and vertical resolution close to the Boknis Eck time-series station (BE) in the western Belt Sea (Baltic Sea) in summer 2010 with an autonomous glider. The glider was commanded to operate in a "virtual mooring mode", defined by two waypoints separated by about 750m and located at the 20m isobath. Occasionally the glider left the virtual survey line due to short-term current events and drifted into water of different depth (up to 25m toward the southeast and less than 10m towards the northwest). The deployment was prepared by utilizing BE time- series data suggesting that the glider should be ballasted to be neutrally buoyant for a density of 1011 kg m^{-3} and that a vertical density range of 8 kg m^{-3} was expected. The survey area is marked as a "restricted area" in the navigational charts and as such no ship traffic was expected during the operation. The glider was a shallow depth (configured for 30m water depth) SLOCUM G1 electric glider. The scientific payload included a SeaBird SBE41 "temperature, conductivity, pressure" probe, a turbidity/chlorophyll a (fluorescence) WetLabs ECO FLNTU Puck, and an AADI oxygen optode 3830. The scientific data were recorded with a sample rate of 1Hz (oxygen with 0.5 Hz) and approximately 700 000 (oxygen 350 000) data points of each variable were collected during the survey. On three occasions the glider ventured into shallow waters where it stranded at the sea floor. It remained there until a time-out (4 h) was triggered and the glider's autonomous system decided to change the buoyancy to let the vehicle ascend to the sea surface again. From a technology point of view they were able to demonstrate that an autonomous glider can be navigated in the shallow Belt Sea, which has a comparably large vertical density gradient. It can provide high temporal and spatial resolved data to support time-series data interpretation. The monthly ship visits made it possible to collect many other parameters, not accessible by autonomous instrumentation.

As an outline, some points must be taken into consideration, when operating gliders in the Baltic Sea

- In In the Baltic Sea, gliders must be optimized to operate in shallow and brackish water
- Temporal and spatial autonomy of the glider may be shorter
- Because of heavy ship traffic, special attention must be given to ship avoidance strategies
- Legal issues – gliders cannot leave the water of the country (countries) where the mission takes place

4. Experimental study with oil detection sensor in glider mode

4.1 Location of the measurement area

Location of the experiment was in Tallinn Bay in the Gulf of Finland. It is situated between Suurupi and Viimsi peninsulas, between Naissaar and Aegna islands, with an area about 250 km^2 and with a maximum depth of more than 90 m. The location was chosen because presence of heavy ship traffic, which increases the probability of finding residues of oil contamination and the differences in readings of the UviLux sensor at different depths.

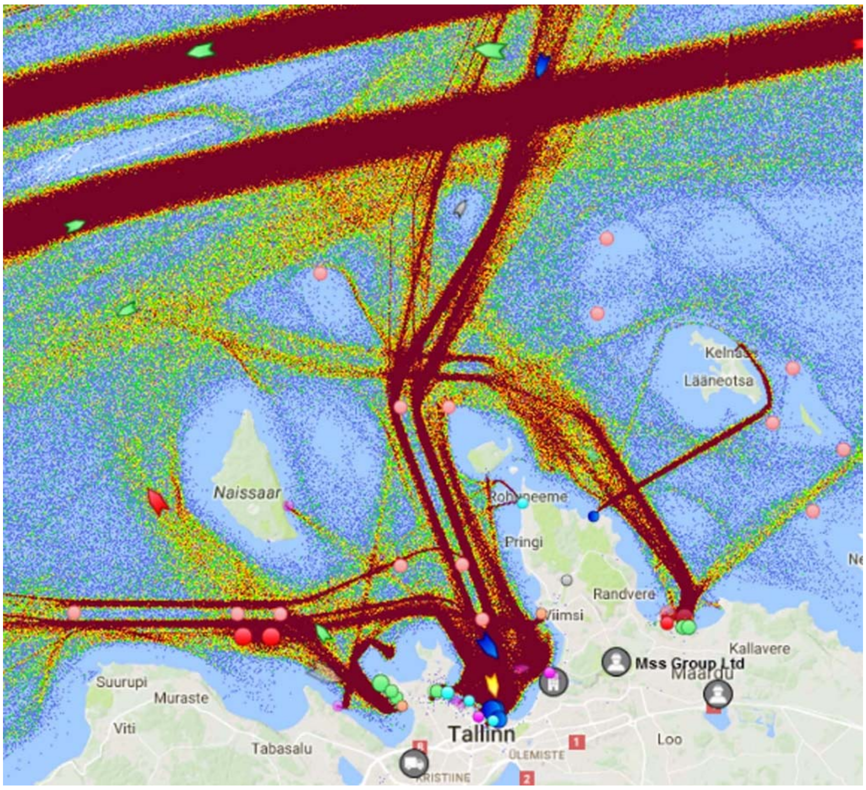


Figure 11 Ship traffic intensity in Tallinn Bay [13]

4.2 Plan of the experiment

Available resource for oil detection we have is the UviLux UV fluorescence sensor from Chelsey Technology Group (UK), described in D1.1 [15], previously used in FerryBox system (D1.2) [15]. UviLux fluorometer has been tested on a flow-through system and on the field and through testing some experience gathered. In D 1.6 a comparability tests of in situ fluorescence detection (FLD) to the laboratory methods used in HELCOM monitoring. Namely three different sensors tested, among these the Uvilux sensor. Experience gathered so far with the UviLux sensor showed its stable operation in different field conditions and that its performance and output signal could be used for oil detection, not in absolute units but relative scales through the patterns of the parameter variability registered by UviLux sensor. However some drawbacks was found during long term operation, firstly dependence of measurement chamber shape and (bio)fouling.

As the Slocum glider MIA used in MSI is not compatible with the Uvilux UV flouorometer and adding of external weight ruins the glider buoyance stability, it was decided to test UviLux sensor simulating its movement in glider mode. The towable measurement rig was constructed, consisting of a Sea-Bird CTD profiler and the UviLux sensor (Figure 16), for PAH measurements. Data logging of UviLux sensor was realized in on-line mode, so first analysis of data was possible practically immediately.

First test was made on 10.08.2017 with only the UviLux sensor (equipped with extra weight). Weather was cloudy, with southwestern winds blowing 3-6 m/s with gusts up to 10 m/s. Air temperature was around 21°C. Wave height on the sea was about 0,4 m. The sensor was towed behind a vessel for transect, both with ten “sawtooths” (Figure 12), what we call the glider mode (see also Figures 26- 28).

Second test was done on 15.08.2017. Weather was mostly sunny with occasional clouds, south and southwestern winds were blowing 3-5 m/s. Air temperature was about 21 °C. Wave height on the sea was about 0,1-0,4 m. During the second test, two transects and five profilings were made in other side of the Tallinn Bay (Figure 13).

During the first transect, the rig was lowered and hoisted for five times (Figure 13). Length of the transect was about 6,2 kilometers and average horizontal speed of the system 8 km/h, which is close to what glider does.

During the second transect, the rig was lowered and hoisted for ten times (Figure 13). Transect distance was about 8 kilometers and average speed proceeding on transect, 8 km/h, in glider mode.

Between two transects, 5 vertical profilings were made to the depths down to 25 meters (Figure 13)., to study performance of UviLux in profiling mode.

Third test was done on 23.08.2017. Weather was cloudy and northern winds were blowing 9-11 m/s. Air temperature was 14 °C. Wave heights on the sea were about 1 m. During the third test, two profilings were made on the Tallinn Bay (Figure 14), from surface to the depth of 20 m. As during first two tests influence of UV component of the sunlight was noted in surface 5m zone, different sensor compartment was constructed. UviLux sensor was put into dark chamber and measurement was performed in flow-through regime (Figure 18). Measurement rig contained still the Sea-Bird CTD probe, which pump was used to activate continuous water flow through dark chamber with UviLux sensor.

Variables measured by the rig consisting Sea-Bird (SBE19plus) and oil sensor UviLux:

- Pressure/Depth
- Temperature

- Conductivity/Salinity
- Fluorescence
- Turbidity
- Oxygen concentration
- Oil contamination in terms of PAH compound (in terms of Carbazole)

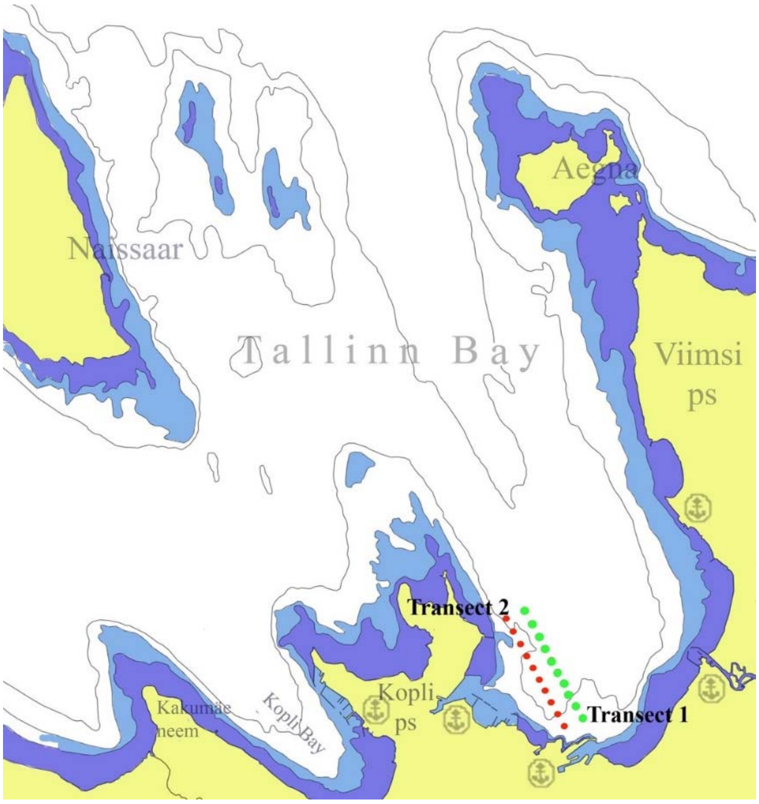


Figure 12 First survey with the Uvilux oil sensor in glider mode, August 10, 2017

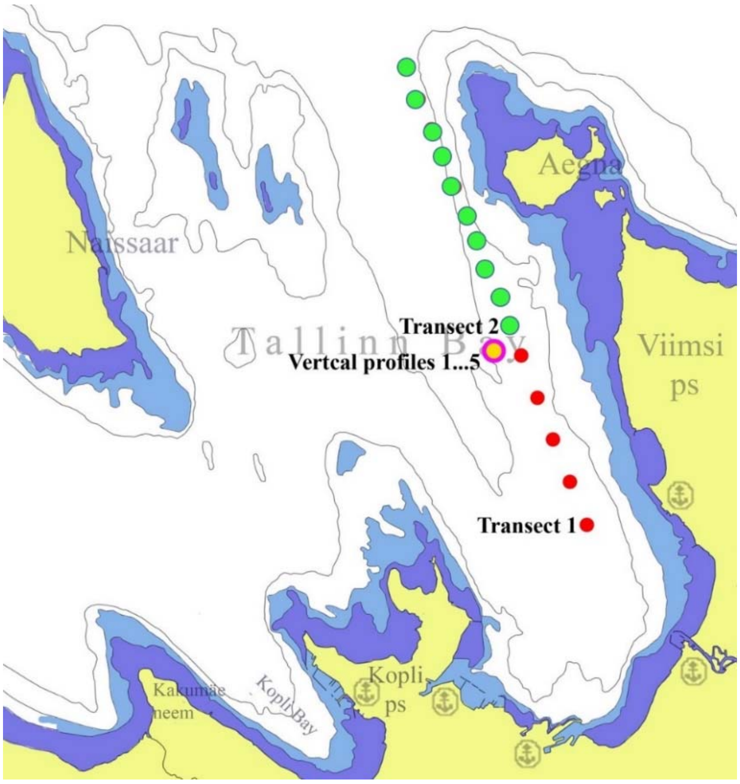


Figure 13 Second test with the towable rig, consisting of a Sea-Bird CDT profiler and the UviLux sensor in glider mode, August 15, 2017

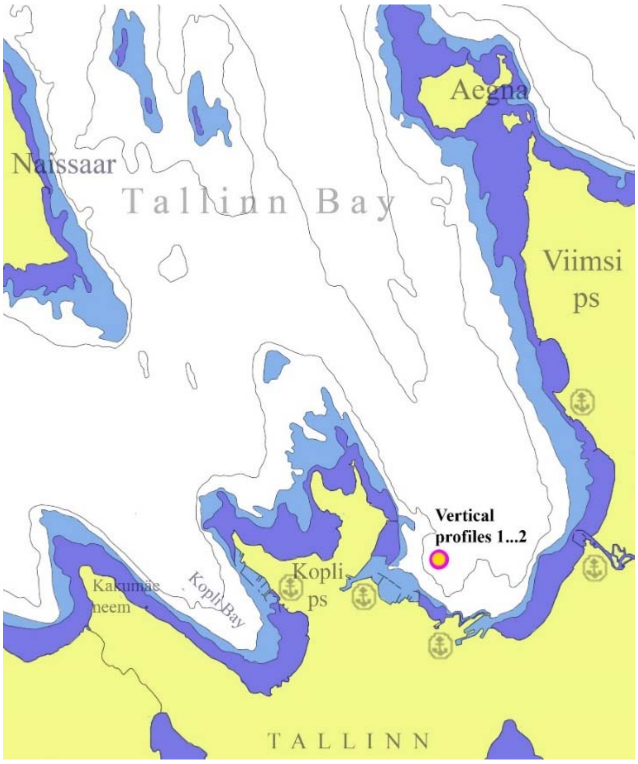


Figure 14 Third test with the rig, consisting of a Sea-Bird CDT profiler and the UviLux sensor in flow-through dark chamber, August,23, 2017

Figure 15 Workboat used for field experiment

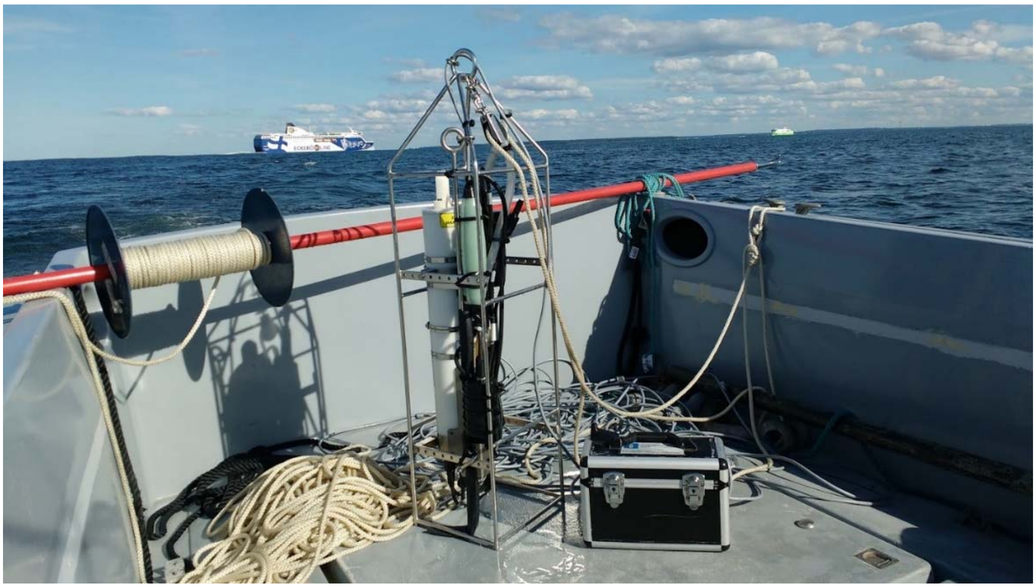


Figure 16 Towable rig, consisting of a Sea-Bird CDT profiler and an UviLux sensor in the workboat

Figure 17 Towing the measurement rig in glider mode

Figure 18 Uvilux UV fluorometer in flow-through dark chamber

4.3 Results of the experiments

Results of the PAH measurements from the profiling and towing experiments were, that the pattern of the variability of PAH was registered. That pattern showed consistency in every profiling and transect. PAH values stayed between 0,05 and 2,2 µg/L. The vertical distribution of the PAH seems quite steady, except on the surface, where the UV component of sunlight probably affects the readings of the optical UviLux sensor. As seen from the graphs (Figures 19-26), water temperature stays between 17,7°C at the lower depths to almost 19°C at the surface. Variability of the salinity was low, being close around 6,2psu (Figures 19-25) and oxygen concentration around 4,2ml/L. Larger was vertical variability of chlorophyll-a concentration, in terms of chlorophyll fluorescence, ranging in 4-22 mg/m3 – higher in surface and lower near bottom (Figures 19-25).

Towable measurement rig was tested for the first time. As there were no real-time data about the depth of the rig during the towing, there were no certainty how deep does the rig go. Later it was found out that the maximum depth was only about six meters, vertical profilings reached depths 25m.

The Uvilux sensor was cleaned before every profiling and transect, except profiling number five.

Recorded depth movement of the measurement rig shows that it moved with same manner as a glider (Figures 26-28 and Figure 5), system was recording data in 0.5Hz frequency in case of CTD probe and once per minute in UviLux case. Measurement results are presented on Figures 22-24, and similar pattern of vertical variability of parameters was obtained, as in case vertical profilings (Figures 19-26). Horisontal resolution of profiles is about 250m, similar as gliders. If eliminating the influence of direct sunlight on the sensor readings, the distribution of oil compound PAH was even along the transects as well in depth, where it was even in the entire measurement area. No oil concentration anomalies were found. Experiment showed that compact and rugged oil sensors, like UV fluorometers, could be used on board AUV-s as well gliders and these measurements can give data about oil distribution below the sea surface, with high special resolution. Some problems are still needed to be taken care of, first one known already earlier- the (bio)fouling (see D1.2) and secondly, what was found during this experiment, the influence of sunlight's UV component. Improving the measurement cell, where UviLux is placed in a flow-through chamber can overcome these problems as can be seen from the third test (Figures 24 and 25).

Eliminating the influence of UV component of the sunlight in the surface layer of the sea output values of the UviLux sensor were quite stable, ranging between from 1,7 to 2.2 µg/L of carbazole, as this is calibration standard in case of UviLux. Values were slightly higher near to sea surface and lowered towards sea bottom (Figures 24 and 25).

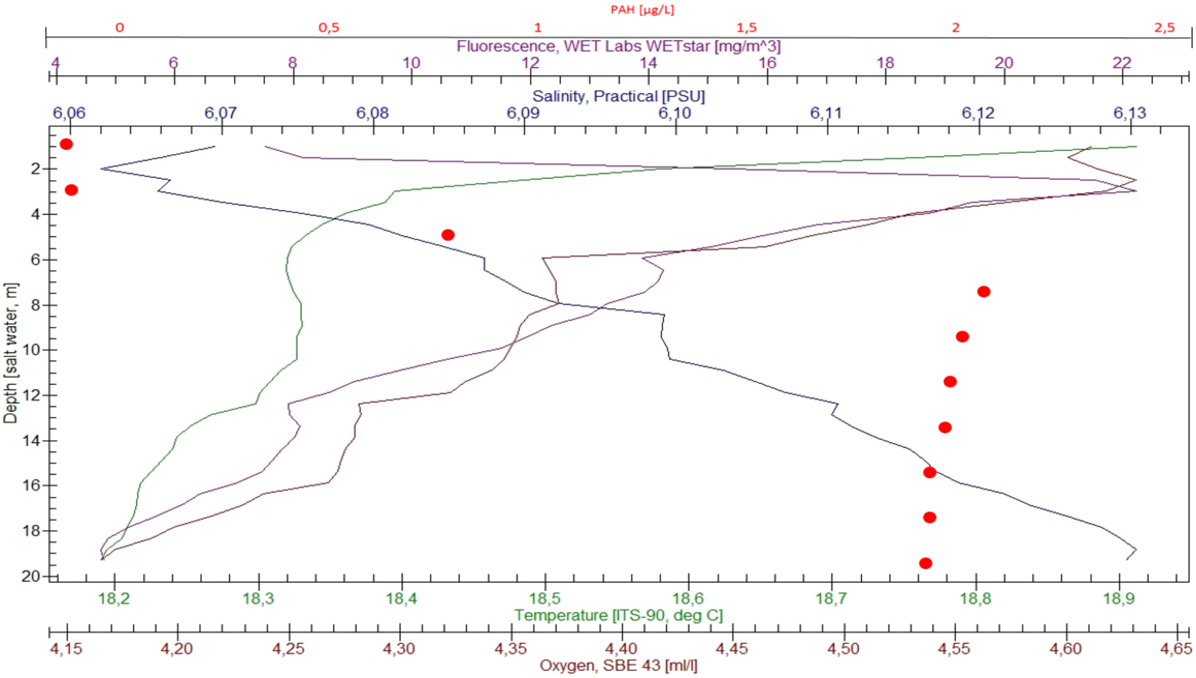


Figure 19 Vertical profiles of seawater temperature, salinity, oxygen content and CHL-a in first station. Red dots mark PAH concentrations from UviLux sensor. Coordinates of the station are 59.32,9262 N 24.44,6947 E in the Tallinn bay

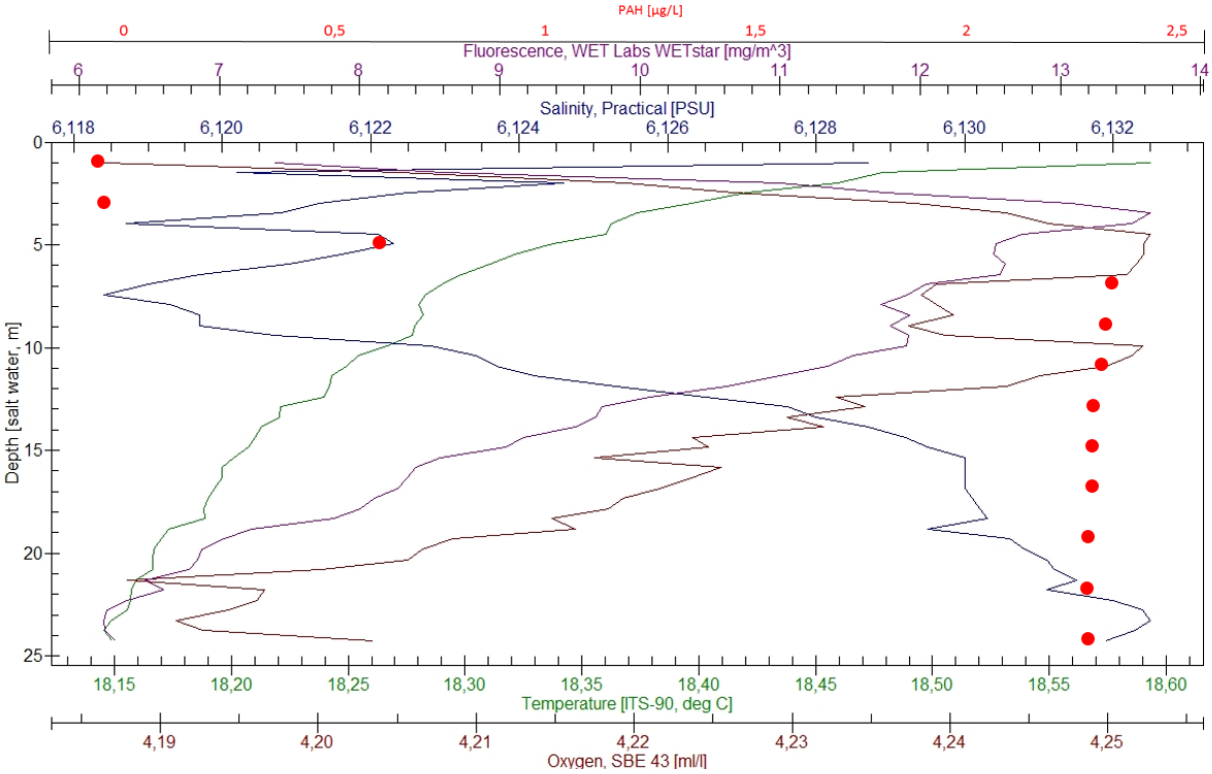


Figure 20 Vertical profiles of seawater temperature, salinity, oxygen content and CHL-a in second station. Red dots mark PAH concentrations from UviLux sensor. Coordinates of the location are 59.32, 8516 N 24.43,8925 E in the Tallinn bay

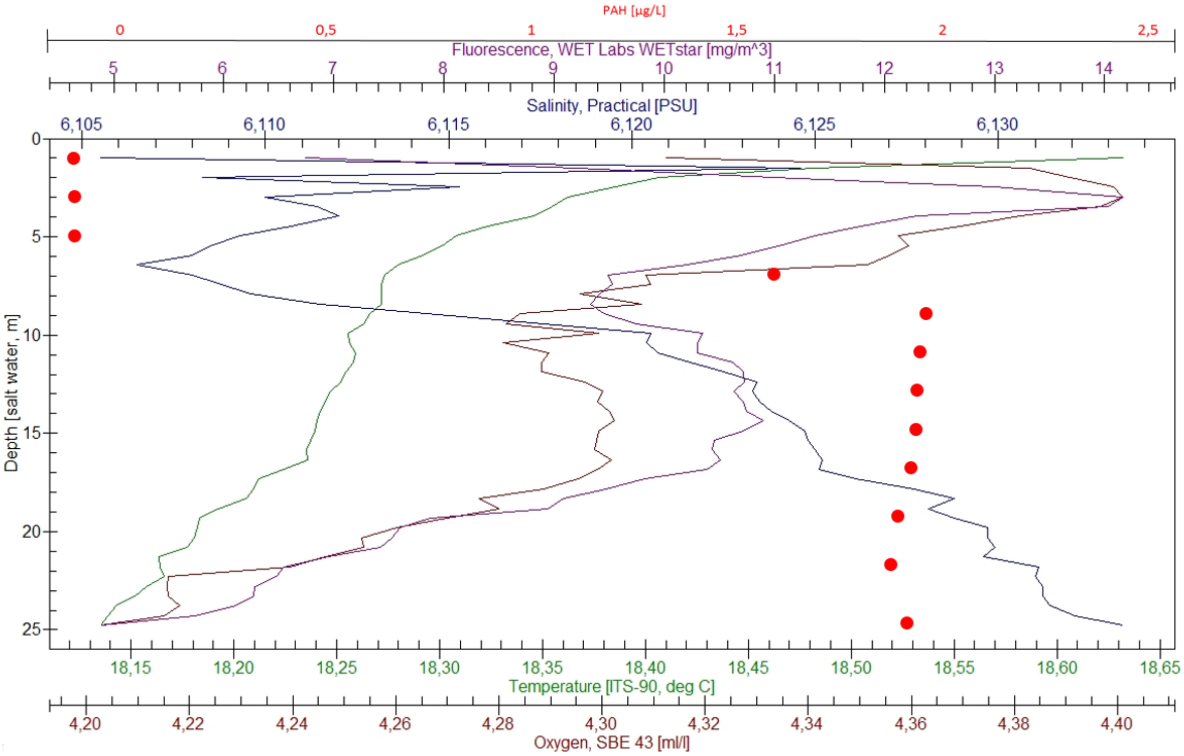


Figure 21 Vertical profiles of seawater temperature, salinity, oxygen content and CHL-a in third station. Red dots mark PAH concentrations from UviLux sensor. Coordinates of the location are 59.32,8277 N 24.43,9732 E in the Tallinn bay

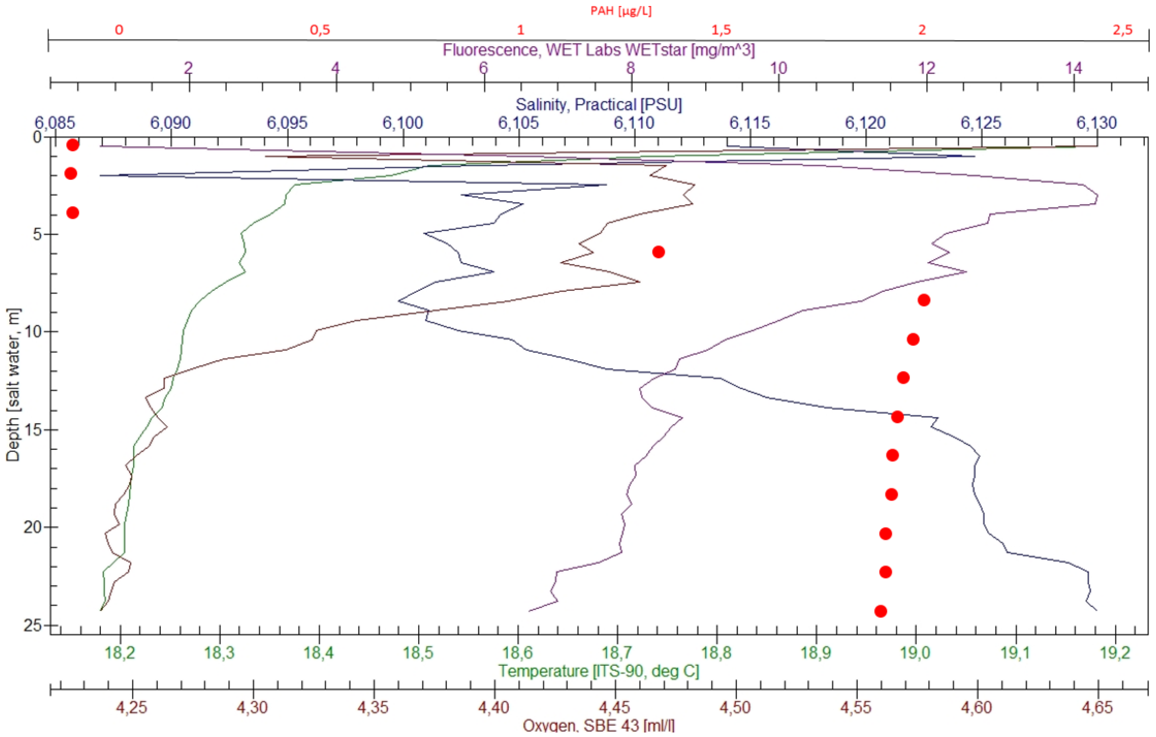


Figure 22 Vertical profiles of seawater temperature, salinity, oxygen content and CHL-a in fourth station. Red dots mark PAH concentrations from UviLux sensor. Coordinates of the location are 59.32,7769 N 24.44,0264 E in the Tallinn bay

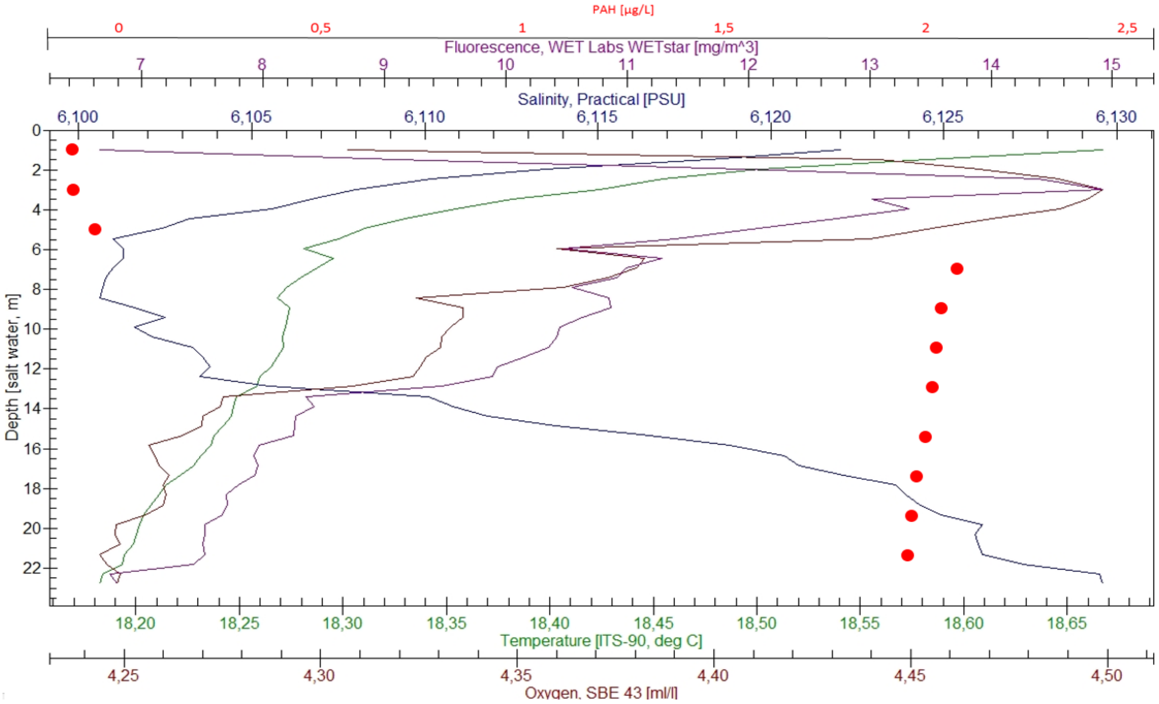


Figure 23 Vertical profiles of seawater temperature, salinity, oxygen content and CHL-a in fifth station. Red dots mark PAH concentrations from UviLux sensor. Coordinates of the location are 59.32,7287 N 24.44.0777 E in the Tallinn bay

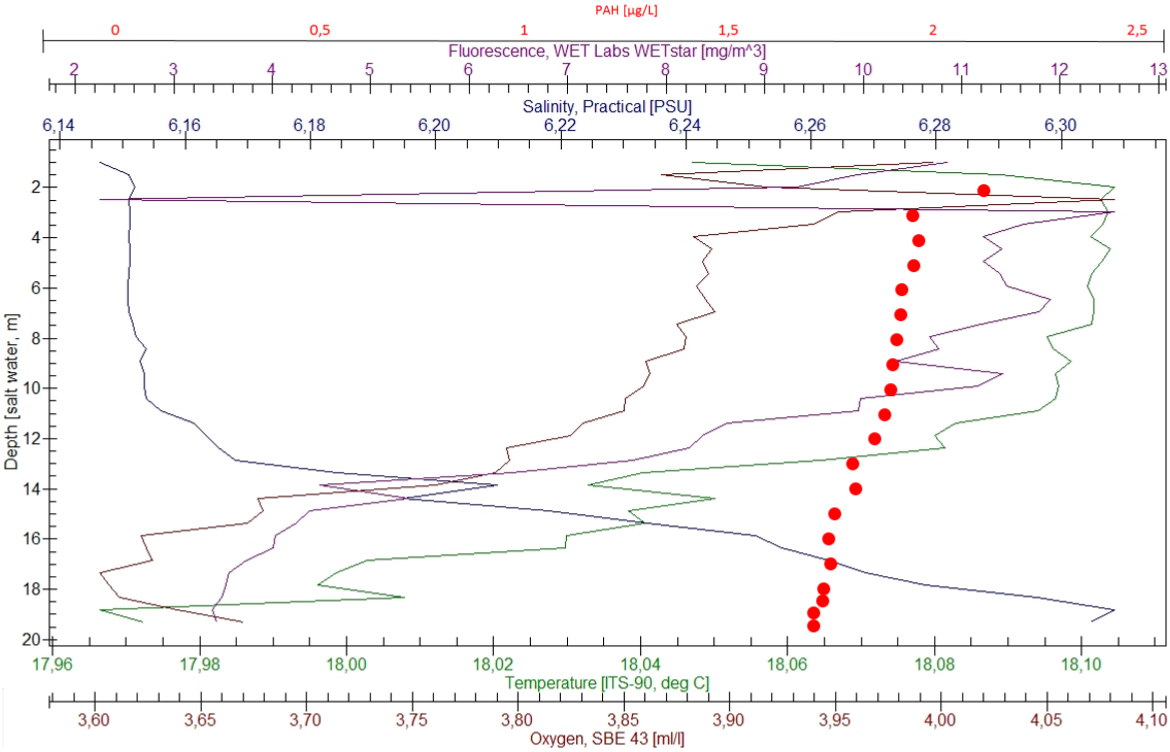


Figure 24 Vertical profiles of seawater temperature, salinity, oxygen content and CHL-a, during the third test in first station. Red dots mark PAH concentrations from UviLux sensor in flow through dark chamber. Coordinates of the location are 59.28,0576 N 24. 44,8642E in the Tallinn bay

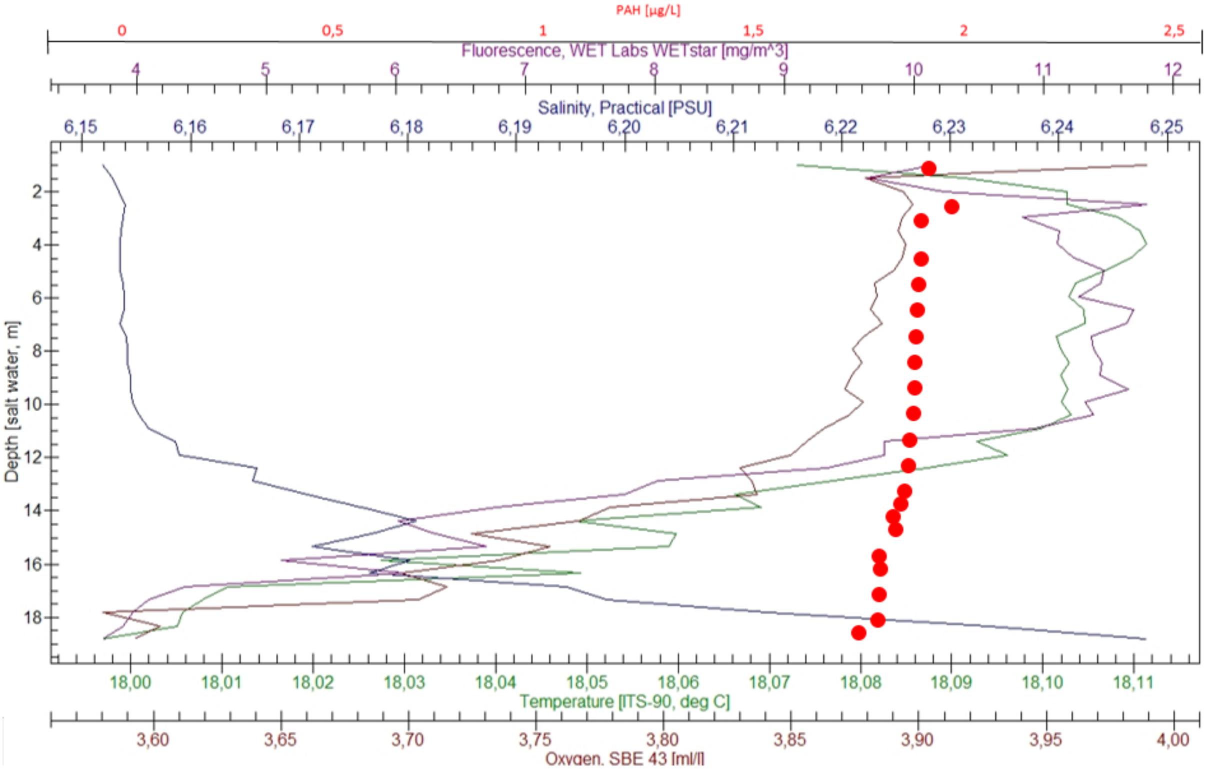


Figure 25 Vertical profiles of seawater temperature, salinity, oxygen content and CHL-a, during the third test in second station. Red dots mark PAH concentrations from UviLux sensor in flow through dark chamber. Coordinates of the location are 59.28,0375 N 24.44,9076 E

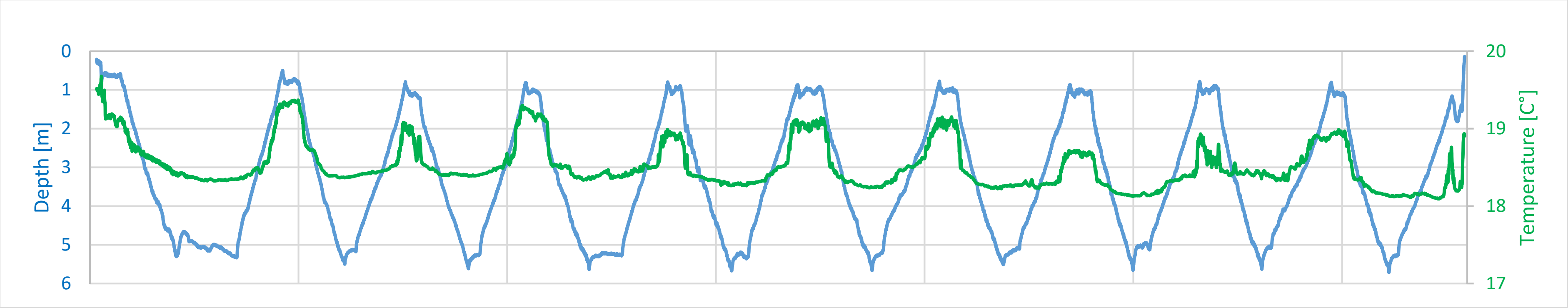


Figure 26 Movement of the measurement rig in glider mode between surface and 6m depth along the second transect (Figure 13) - blue line. Variability of temperature along the transect is given with green line. Change in water temperature can be seen in correlation with the rig's "sawtooth" movement

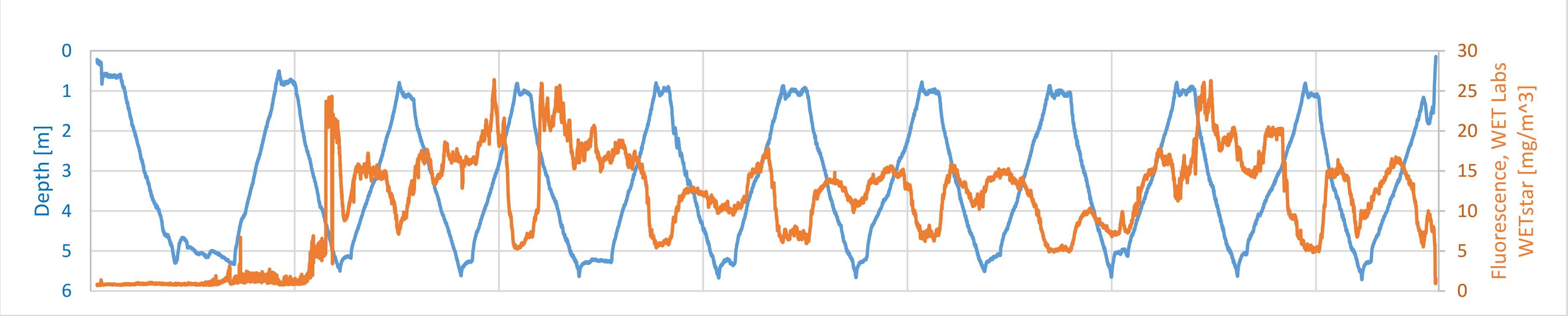


Figure 27 Movement of the measurement rig in glider mode between surface and 6m depth along the second transect (Figure 13) - blue line. Variability of fluorecence along the transect is given with orange line. Fluorescence values change between 0,7 and 26 mg/m^3

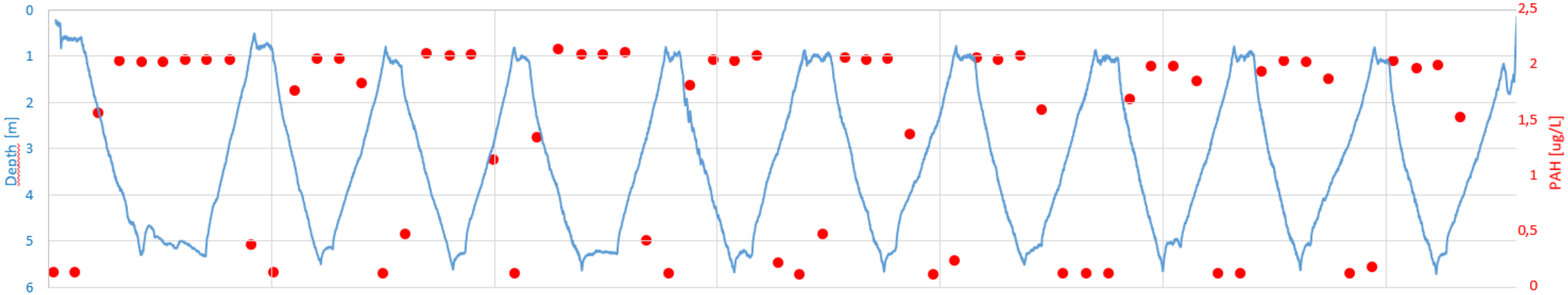


Figure 28 Movement of the measurement rig in glider mode between surface and 6m depth along the second transect (Figure 13) - blue line. Variability of PAH along the transect is given with red dots. PAH reading were between 0,04 and 2,2 µg/L. Same kind a pattern as in profilings can be seen - PAH readings go to near 2 µg/L over depths of 4 meters.

References

[1] OGP/IPIECA. 2014. Capabilities and uses of sensor-equipped ocean vehicles for subsea and surface detection and tracking of oil spills. Oil and Gas Producers Association / International Petroleum Industry Environmental Conservation Association. Oil Spill Response Joint Industry Project: Surveillance, Modelling & Visualization. Work Package 1: In Water Surveillance. 233 pp.

[2] URready4OS. 2016**.** Autonomous underwater vehicles in oil spill response. Project White paper. 79pp.

[3] Vasilijevic, A., Stilinovic, N., Nad, D., Mandic, F., Miskovic, N., Vukic, Z. 2015. AUV based mobile fluorometers: system for underwater oil-spill detection and quantification. Autonomous underwater vehicles ready for oil spill- UReady4OS. 6pp.

[4] BSEE. 2014. Oil spill detection and mapping under Arctic sea ice using autonomous underwater vehicles. Final report. 99p.

[5] Alenius, P., Tikka K., Barrera C.2013. Gliders for studies of multi-scale variability in the Baltic Sea. Gliders for Research, Ocean Observation and Management (GROOM). 6pp.

[6] Karstensen, J., Liblik, T., Fischer, J., Bumke, K., Krahmann, G. 2014. Summer upwelling at the Boknis Eck time-series station (1982 to 2012) – a combined glider and wind data analysis. Biogeosciences, 11, 3603–3617. 15pp.

[7] Teledyne Webb Research Slocum G2 Glider Operators Manual. P/N 4343. 2012

[8] Teledyne Webb Research Slocum G2 Glider Datasheet

[9] White, H.K., R.N. Conmy, I.R. MacDonald, and C.M. Reddy. 2016. Methods of oil detection in response to the Deepwater Horizon oil spill. Oceanography 29(3):76–87

[10] http://www.bridges-h2020.eu/deep-sea-solution.php

[11]https://www.ttu.ee/instituut/meresusteemide-instituut/laborid-ja-teenused-7/aparatuur/glider/glider-2/

[12] http://wetlabs.com/seaowl-uv-a-slc

[13] www.marinetraffic.com

[14] GRACE. WP1: Oil spill detection, monitoring, fate and distribution. Deliverable 1.1: In-situ oil detection sensor – technology overview and experiment design

[15] GRACE. WP1: Oil spill detection, monitoring, fate and distribution. Deliverable 1.2: Integration of oil detection functionality to FerryBox system