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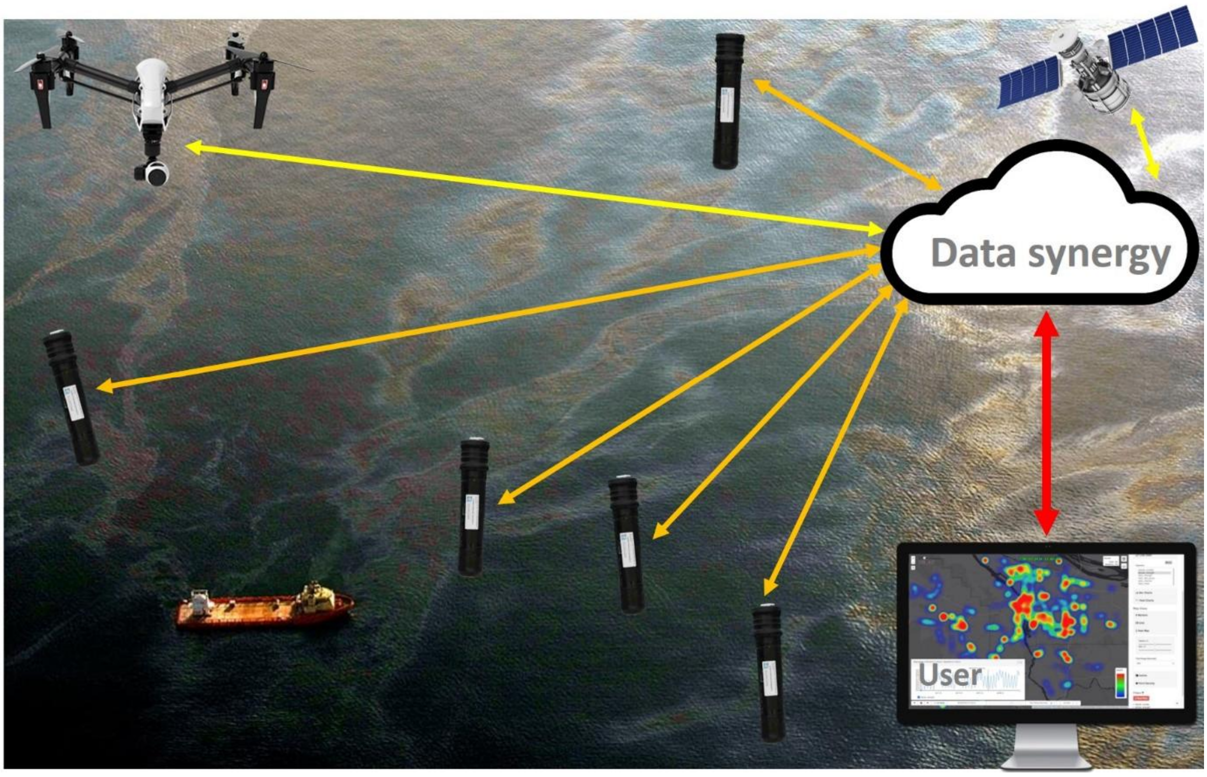
Application of UAV-s for oil detection and monitoring, combined with drifters

D1.7

WP1: Oil spill detection, monitoring, fate and distribution



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Executive summary

Drone aircrafts, also known as an Unmanned Aerial Vehicles (UAV) or Unmanned Aircraft Systems (UAS)) are gaining more and more importance in environmental monitoring as well in oil spill response, all over the world. Drone aircrafts have the potential to deliver information quickly and economically for areas of difficult access and have the potential to fill an important gap in surveillance capability. UAS cover wide range of scales of applications for oil spill response, from strategic (MALEs and HALEs) through tactical (TUAVs) to close-tactical (MUAVs) and so can in principle be matched to operational requirements, helping to form a hierarchy of observation scales.

Airborne oil spill remote sensing is normally divided into two different modes of operation: far-range detection from satellites and near-range monitoring from different aircrafts. Far-range detection often uses imaging radar systems, which usually cover swaths of several tens of kilometers and are insensitive to weather or natural illumination. Near-range monitoring of oil spills includes mapping of relative and absolute oil layer thickness, as well as classification of the type of oil. Different type of oil sensors are: aerial photography and video, multispectral optical and thermal sensors (visible-, UV-, thermal-IR-, UV-IR sensors), microwave radiometers, hyperspectral sensors, laser, radar and integrated airborne sensing systems.

Performance of different UAV-s and attached sensors is evaluated based on available technical information as well actual field tests on Estonian and Finnish coasts. Operational capabilities of different AUV-s and sensors were demonstrated in case of physically simulated oil spill in winter, icy conditions in Rahja harbor, NW Finland, March 2016. Different UAVs and oil sensing systems such as LIDAR instrument, VIS/NIR sensor, thermal infrared camera and hyperspectral camera were tested.

Drifters have a long history of use for purposes ranging from mapping large-scale ocean currents to following oil spills to aiding search and rescue operations. In case of an oil spill, decision makers are in need of in-situ information in order make optimal decisions, minimizing environmental damage. A drifter buoy can be used to track oil spills during response operations providing the response teams with real-time, accurate information related to speed, position, direction and etc. of the pollutant. Real-time environmental data as well as oil slick observations are crucial if a spill trajectory forecast is to be accurate. There are several oil tracking buoys specially designed for oil spill response in mind, like: the iSPHERE, AIS Drifter Buoy, Fastwave Voyager Oil Spill Tracking Buoy and prototype oil detecting drifter by Tallinn University of Technology.

The properties of local wave field is a very important driver for oil spill distribution, both horizontally and vertically. On the other hand, however, local wave height and period is poorly represented by existing systems, both measurements and modeling. Based on UAV imaging there are possibilities to acquire wave information locally, with very high spatial and also temporal resolution such as wave velocity field from SPOT5 and wave height from IR imagery.

Combined usage of AUV-s and drifters and relevant web-based expert system was tested in the field by monitoring the spread of suspended matter from dredging operation in harbor, which well simulates the oil spill behavior, as oil spills of such range is not possible to reproduce in real. Real time monitoring of the suspended matter plume included an on-line monitoring buoy and regular AUV flights over the polluted sea area, images and videos recorded. Similar to oil pollution, suspended matter distribution is well observable on the sea surface, showing also similarities to oil slick dynamics, sensitive to weather conditions, mainly wind, currents, waves. The extent and area of suspended matter distribution was assessed, and a method was introduced to derive distribution of

suspended matter concentration from drone images from 4K video camera, using linear relationship between measured TSM concentrations and pixel digital number. Two-band ratio between red and green was used from the image raw data to establish the linear relation.

Drones can also be used to monitor localized oil pollution such as oil leakage from shipwrecks. As an experiment, a shipwreck named MS VOLARE, close to the Estonian coast, was chosen to be monitored. The wreck was already salvaged and bigger oil sources removed, but the aim was to study, is there still some oil leak around the wreck, and UAV was an ideal work tool for that. During the UAV survey, some small oil slicks were still discovered.

Concept of tactical scale oil spill response support system is proposed, based on drifters and AUV-s.

Introduction

This deliverable focuses on oil spill detection and monitoring from unmanned aerial vehicles (UAV) or drones, combining those remotely sensed data with in situ measurements from drifter buoys to increase situational awareness of oil spill situations at the sea. This methodology address first of all in situ sector, most demanded data in oil spill response, as well local high resolution monitoring, data highly demanded specially in coastal sea and in presence of ice, where oil spill response is most complicated.

The basic aim of using UAVs is to estimate the areal extent of the oil at sea surface in limited range from starting position, in high resolution. UAVs have the potential to fill the gap in surveillance capability and widen monitoring capability of oil combatting and monitoring vessels. There are many different UAV and sensor technologies available but they are evolving fast, costs are reducing, and models and capability are, and will be, overtaken by new developments in data processing and visualization

In case of an oil spill, decision makers are in need of in-situ information in order make most optimal and best decision in particular conditions and minimize the environmental damage. The drift of the oil in water is influenced by surface currents driven by winds, tides and other circumstances, river outflow for example. Traditionally, oil spill monitoring is done by helicopters, airplanes and ships, and now recently by more modern UAV-s. A drifter buoy can be used to give additional information to the aerial systems - track oil spills during response operations providing the response teams with real-time, accurate information related to position, speed and direction of its drift of the pollutant. Real-time environmental data as well as oil slick observations are crucial if a spill trajectory forecast is to be accurate. Also, recorded data can be assimilated into dynamic models to improve the accuracy of the model predictions.

Remotely sensed data from AUV and from in situ drifters, synthesized together, give a new perspective for local scale oil spill situational awareness, furthermore satellite technologies add larger area context. In situ data and AUV images form an on-line system to get simultaneous ground truth information of certain area at the sea of oil spill, opening new perspectives for decision support.

1. Unmanned Aerial Vehicles (UAV-s)

Drone aircrafts (also known as an Unmanned Aerial Vehicles (UAV) or Unmanned Aircraft Systems (UAS)) are currently being evaluated for oil spill response, all over the world. Drone aircrafts have the potential to deliver information quickly and economically for areas of difficult access and have the potential to fill an important gap in surveillance capability extending from scales traditionally associated with fixed wind aircraft down to almost in-situ scales. Some can fly at very low altitudes, with high degrees of flight flexibility and with no human exposure. The more quiet nature of small drone aircrafts may make this also an attractive tool for reconnaissance near biological sensitive areas such as shorebird roosting sites and colonies. They have become complementary to manned aircraft and to satellites.

UAS represent a quite new technology in the civilian domain. In report provided for IPIECA and OGP [1] outline of their potential (but not necessarily realized) benefits as are given as follows:

• UAS cover a range of scales of application for oil spill response, from strategic (MALEs and HALEs) through tactical (TUAVs) to close-tactical (MUAVs) and so can in principle be matched to operational requirements, helping to form a hierarchy of observation scales.

• UAS have degrees of flexibility that are not available to manned platforms. They are able to fly at low altitudes, under clouds for example; they are less restricted than many manned aircraft as they can be launched from many different platforms (for example, from vessels, or even by hand); they can fly in hazardous situations where manned flight may be undesirable, for example in the Arctic, or in areas which might require tight maneuvering (as along some coasts). Flight patterns can be pre-programmed in many cases using satellite positioning or more complex dynamic automation.

• Some UAS have endurance. They are able to be operated remotely by pilots who can operate in shifts if necessary.

• Some UAS have long operational lifetimes because they can be retrofitted with new state of the art sensors on top of a short development cycle (typically 1-2 years).

• There are significant health and safety benefits to not deploying manned aircraft in some areas, such as the Arctic. Pilots need less onerous training and none of the health checks associated with pilots, although UAS still require the deployment of a team of operators on the ground near the area to be surveyed to launch and recover the UAS, and the operator team still require standards of support to carry out their tasks, in sometimes remote locations.

• Some UAS can be used as communications platforms as well as remote sensing platforms.

However, it is important to note that these benefits do not apply to all types of UAS and there remain key constraints such as in relation to the regulatory environment for their operation and in providing launch and recovery under certain situations. The technology is evolving fast, costs are reducing, and models and capability are, and will be, overtaken by new developments. Many of the current models are in experimental or otherwise pre-commercial form.

1.1 UAV systems

In the report by Polar Imaging Limited [1], an extensive overview of the different classes and types of UAVs and are presented in this section.

UAS have three components: the platform (UAV) with sensors, communications system and ground control station. These components can range from backpack portability, to large systems which require large vehicle transportation. Larger UAVs require satellite communications via an on-board terminal as well as a GNSS link.

Some can fly at very low altitudes, with high degrees of flight flexibility and with no human exposure. UASs come in a range of classes, defined in terms of their endurance/range, their vertical range of operations and their payload capacity.

1.2 Larger UAV systems

Larger UAV systems have similarities to manned aircraft in terms of their size and other characteristics. Their engines are often piston engines, turbofan or two stroke and there is a requirement to incorporate sense and avoid systems. Their payload capacities can be excellent, supporting a suite of remote sensing instruments, including the larger sensors such as laser fluorosensors, synthetic aperture radar and hyperspectral sensors. In principle, larger UAS can be used for flexible and persistent (strategic) wide coverage surveillance, and can operate well above the altitudes of local response platforms.

Medium Altitude / Long Endurance (MALE) UAVs tend to operate at altitudes up to about 15,000m. Their fuel capacity allows them to carry out surveillance lasting many hours, with resultant flight range of hundreds of kilometers.

Figure 1 Long endurance UAV Insitu integrator [2]

High Altitude / Long Endurance (HALE) UAVs can operate at altitudes up to about 20,000m. They are typically used for major scientific studies and are designed specifically for long endurance. HALE systems tend to be used for large-scale scientific programs, as spearheaded by NASA in the 1990s.

Figure 2 High Altitude/Long Endurance (HALE) UAV - Boeing Phantom Eye [3]

Tactical Unmanned Aerial Vehicles (TUAVs) fill the capability gap between the short range mini-UAVs and the long range, extended endurance MALE and HALE UAVs, combining the flexibility of the smaller platforms with the longer endurance of the higher-end platforms.

Figure 3 Tactical Unmanned Aerial Vehicle (TUAV) - “Flying Fish” unmanned aircraft takes off and lands on water [4]

1.3 Smaller UAVs

Smaller classes of UAVs, typically less than about 25kg in mass, being extremely flexible, often using electric propulsion (and thus are quiet and create no pollution) and do not ordinarily need to comply with air traffic control. They are often provided with high quality digital camera and/or video systems (often with IR for night). Their capacity for payloads is in some cases very limited, but some can take miniaturized sensors, including FLIR, hyperspectral, thermal and SAR sensors. They can be very useful for surveillance in hazardous locations (where manned flight would be considered undesirable or dangerous); areas where extreme maneuverability is required (e.g. coast lines); situations in which near continuous loitering over small areas is required. They also have uses which can relate to OSR such as wildlife surveillance (helped by low noise) and search and rescue. Their close-tactical capabilities enable them to be useful for support in dispersant application and follow-up, real time assessment of spill evolution, detailed assessment of structures (e.g. pipelines) and air quality sampling (subject to available sensor). They are also in most cases readily deployed from most locations, from vessels, by hand, from the ocean surface or from vertical takeoff. On the other hand, they tend to have low endurance (and therefore limited range) and limited altitude due to battery life, regulatory limitations such as maximum flying height and the need to remain within sight of the operator at all times, and so for OSR, there is an argument for access to 2-3 platforms to support continuous operation.

Micro and Mini UAVs (MUAVs). MUAVs are potentially able to be transported in backpacks, weighing typically up to 6kg. They operate at low altitudes with limited battery capacity leading to flight times in many cases of the order of 5 to 30 minutes, sometimes more. These typically have color video payload systems.

Vertical take-off and landing (VTOL) UAVs are particularly useful in areas where takeoff or landing runs are impossible, and they are also portable. The high power consumption for hovering flight tends to limit their flight duration (typically to one hour, based on electric motors and rechargeable batteries), although the largest platforms can accommodate larger fuel capacity. Control is typically via line-of-sight and for a quick analysis. They are readily deployable using a one or two man crew from vessels, and the most challenging onshore environments.

Figure 4 Typical VTOL Mini UAV - DJI Phantom 3 [5]

1.3.1 Smaller class AUV DJI Inspire 1

Tests to apply commercially available small AUV DJI Inspire 1 for detection and monitoring of oil spills were made by Marine Systems Institute at Tallinn University of Technology.

Depending on the design of the UAV, a variety of sensors could be installed on board – from commercial optical digital cameras, multispectral infrared sensors or thermal cameras to small LIDAR sensors. The main advantages of smaller AUV-s is the availability on market, which means comparably low cost and easiness to operate. This model of the commercially available UAV, Inspire 1 from DJI, is professional tool for photographers and videographers. It can shoot videos up to 4K resolution. To the build quality, size and shape of the UAV make it very stable in windy conditions, which frequently is case in sea conditions. DJI Inspire 1 is capable of flying up to 22 minutes with one battery in calm conditions. Yet, flying time is very dependent of the wind speed, air temperature and extra weight as another sensor for measuring that it might carry. Standard camera integrated to UAV has been used first of all, other sensors, like infrared and UV sensors are already available. More experiments are needed to decide which extra sensors on board this particular drone give best extra value for dataset. DJI Inspire 1 is drone potentially covering wide range of applications and most importantly proven by large amount of users, well developed flight automatics, simple and robust construction.

DJI Inspire 1 is a professional aerial filmmaking and photography platform that is ready to fly right out of the box. Featuring an onboard camera equipped with a 20mm lens and 3-axis stabilized gimbal, it shoots sharp 12mp stills and stable video at up to 4K. Its retractable landing gear pulls up out of view, giving the camera an unobstructed 360-degree view of the world below.

An advanced flight controller makes the DJI Inspire 1 stable, safe and easy to fly in different weather conditions. The brand new Vision Positioning System gives it the power to hover in position at low altitudes even without GPS. Like all DJI flight controllers, it is also able to return home if remote controller signal is lost or if the low battery warning is triggered.

Figure 5 DJI Inspire 1 drone [5]

1.3.1.1 At sea operations of DJI Inspire 1

With the current technology, it is possible to investigate water quality parameters, as well oil pollution from regular camera image User may also want to attach necessary imaging sensors onboard however it would be inconsistent with guarantee agreement. The biggest advantage of DJI Inspire 1 has been its mobility. It can be brought to research vessel and by doing that, the search radius will enlarge immensely. As also tested, the search radius on the sea would be at least 2.5 km if even more. The only problem would be to find suitable space to lift off and land the aircraft. Another critical aspect with vessels with metal body is that compass calibration operations are not doable onboard although calibration should be done in every new location and before every new flight (not between battery replacements). To overcome the problem, it is suggested to perform calibration operations on ground away from large metal objects which includes wharfs, which are enforced with metal structures.

When already on the vessel, the most spacious area must be selected for liftoff. Most probably there are lot of objects on the vessel, which is why it is suggested to fly away as fast as possible to avoid any collisions. Small test flight and aircraft inspection (listen motors the first moments of flight while hovering close-by, inspect and tighten screws if necessary etc.) should be done a priori to boarding to ship. For landing, it is probably safest to catch the aircraft from air. The vessel itself should be stable for both takeoff and landing. User should be extremely careful while flying over the open water and carefully monitor the battery drainage to avoid emergency situations. The return to home location should be selected to be the remote controller. By default, the home-point is the liftoff location.

With current devices it is also possible to monitor long transects of shoreline. It would be useful when the pollution has already propagated nearshore. With one flight, it would be possible to acquire information up to 6 km of shoreline. The distance could even be increased when user walks to the same direction as the aircraft is piloted. Home-point should again be selected to be the remote controller.

Figure 6 Operating the DJI Inspire 1 drone from a small vessel. As there was lack of landing space on board such a small vessel, the hand landing of the UAV was performed. Left panel shows preparations for hand landing – trying to keep the drone as steady as possible. Small drift from the waves and wind complicated the process. Right panel shows successful catching of Inspire 1 from the air.

1.3.1.2 Operation of the drone DJI Inspire 1 in winter/arctic conditions

Properties of the sea ice cover are major relevance for climate studies as well as for operational monitoring. These properties include for example: ice type distribution, ice concertation and thickness, frequency size and distribution of leads and polynyas, ice deformation and ice motion

Sea ice monitoring helps to improve the accuracy of the operational ice charts. More detailed knowledge of the ice conditions would also be useful for the forecast models, eventually producing more accurate ice forecasts, which will benefit the icebreaking authorities in cold climate well as the large number of merchant vessels transiting there. Information about changes, like maximum and minimum ice extent, location and structure of the ice edge, new ice and melt ponds etc. are also highly relevant for climate studies.

In addition to using a drone for monitoring over open water as described in previous chapter, experimental flight series of ice conditions mapping and observations have been performed with DJI Inspire 1 at the West Estonian coast. During these flights, information about local ice conditions were gathered, also valuable experience of piloting the UAV in winter conditions was gained.

Figure 7 Operating the drone in winter/arctic conditions, from ice cover

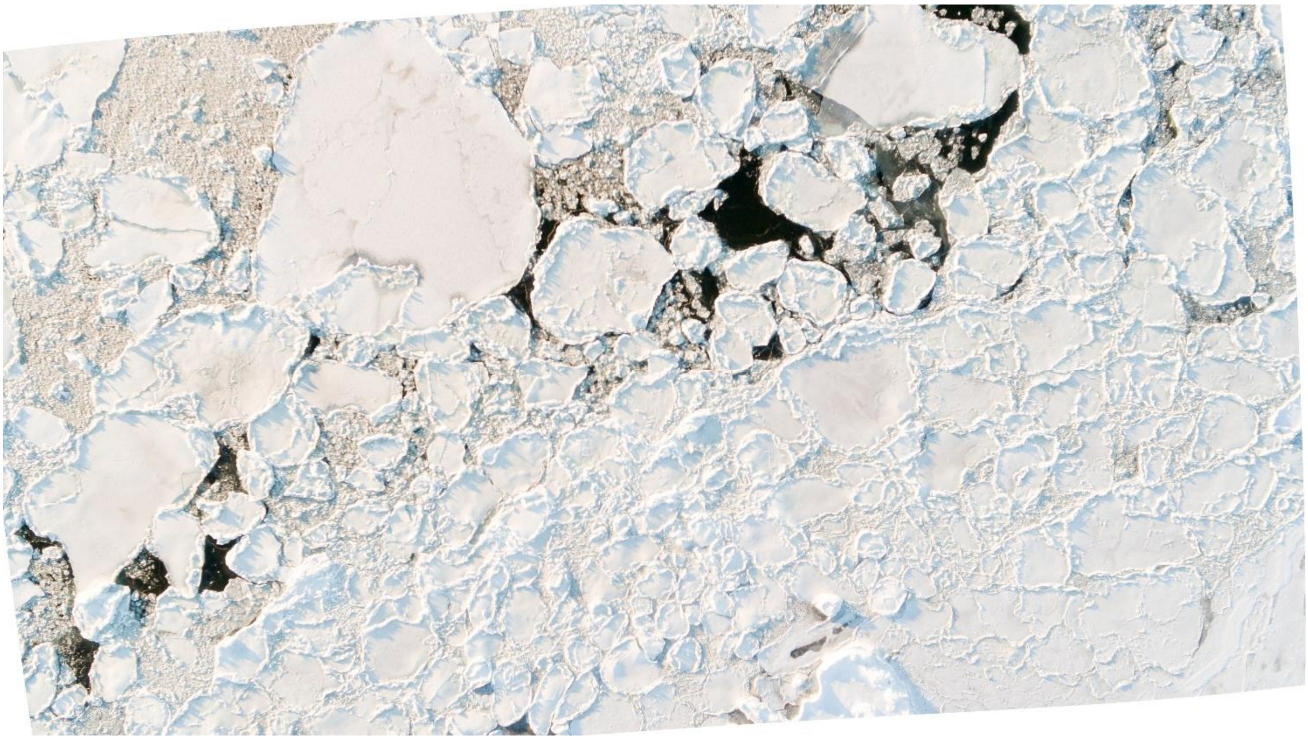

Figure 8 Fine scale structure of the ice field obtained from UAV flight, image taken with down-looking camera, size of ice floes as well open water areas between ice could be well detected

Figure 9 General view on the ice covered sea, over larger sea area, from UAV flight, giving ice conditions for certain sea area

Oil spill in ice is a challenge to be met in ice covered sea areas, having intensive ship traffic in the area. Domination by drift ice makes the situation very dynamic and novel methods needed for situational awareness of oil spill accidents, also response strategies and techniques should be reviewed. Oil booms may be hindered by the ice drift; the oil may be frozen and captured in growing ice or spread below a solid ice sheet. Ice can also act as a natural boom that prevents the oil from spreading out over vast distances, as happens in open-water spills. In addition, at colder temperatures, oil is more viscous and diffuses less quickly. Lower temperatures also expand the window of time for oil recovery. The fate and behavior of oil relates to how different types of oil weathers under different ice conditions.

The technologies for detecting and mapping spilled oil in icy waters are rapidly improving. Experiments with drone Inspire 1 with ice observations and mapping well support the idea to use such drones in case of oil spills, improving remarkably the situational awareness of oil response operations.

When flying in winter conditions, several things must be taken to account:

- Battery drainage is quicker due to cold weather and because of that, also the flight time and search radius can be shorter.
- With colder temperatures more problems that are technical may occur.
- More problems with signal between mobile device and drone, being weak or lost.
- When snowing quality of video/photos may decline.
- With degrees +5°C and lower, insulation stickers must be added to batteries.
- With thicker snow cover, sufficient area for takeoff and landing must be cleared.

2. Sensors for airborne oil spill remote sensing

The past 20 years have seen major advances in satellite and airborne sensor technologies that allow study of the Earth's surface at a number of radiative frequencies suitable for classifying the type of surface and allowing regular mapping of a number of parameters including, but not limited to, land use, sea ice cover and ocean color [23].

Airborne oil spill remote sensing is normally divided into two different modes of operation: far-range detection and near-range monitoring. Far-range detection often uses airborne imaging radar systems, which usually cover swaths of several tens of kilometers and are insensitive to weather or natural illumination. Suspicious structures detected by airborne radar are subsequently investigated on-site using near-range sensors. Near-range monitoring of oil spills includes mapping of relative and absolute oil layer thickness, as well as classification of the type of oil. This mode of operation is typically limited to swaths of several hundreds of meters at flight altitudes in the range of 300–1,000 meters. There are a number of well-established near-range sensors, such as infrared (IR)/ ultraviolet (UV) sensors, visible sensors, camera systems, microwave radiometers (MWRs) and laser fluorosensors (LFSs). [1]

The API have provided an overview of the advantages and disadvantages of many of these remote sensing instruments [6].

It is also important to note that there are a number of additional surface observations that can be made by remote sensing that are not directly related to oil spills, but are still important for OSR, for example measurement of waves, surface currents, sea surface temperature and hazards that may be impacting on oil spill response, for example, sea ice [1].

In this section we present an overview of the different airborne oil detection sensor types.

2.1 Aerial photography and video

Aerial photography and video provide important support to human eye observers and can be used in conditions under which a human observer can't reach. The sensors are often easy to operate and have a relatively low cost. Guidelines on the use of photographic and video imagery are provided by IPIECA [7]. Cameras come with a range of qualities now that are expected, including the following [7]:

- Very high resolution (>10 megapixels);
- Video/still switch;
- Capability for high speed (depending on platform, from 1/500° to 1/2000°);
- Aperture f.8 to f.16 for maximized depth of field (focusing across the oil spill);
- Moisture resistant;
- Dust resistant;
- GNSS tagged for location (either from the aircraft or separately);
- Time and date tagged and other metadata provided;
- Polarizing filter to assist with visualization of thin oil layers;
- Anti-UV filter;
- 200 or 400, or even 800 ISO for poor visibility conditions;
- Live data transfer

As light diminishes below a certain level, some cameras can automatically switch to night mode to make use of near infrared (IR) light to deliver high-quality, black and white images. During the day, the camera filters out IR so that it does not distort the colors of images as the observer sees them. As well as some cameras providing the ability to collect photography in NIR, some cameras are used for photogrammetric applications and collect stereoscopic imagery (with sufficient overlap between frames). However, photogrammetric cameras usually have no live feed capability and require several hours of post-processing before they can be exploited

Light field cameras have possibilities to extend the diurnal sampling range of the sensors and to support flexible post-shot processing to focus to the spill (called plenoptic processing). Cameras separately record the color, intensity and vector direction of all the light rays reflected towards them. It is then possible to manipulate the image after the photo has been taken via an algorithm that operates on all the data, so that the user can choose between having the foreground, middle, or background subjects in focus, or they can select all three together. Light field technology also allows pictures to be taken in lower light (because all of the light is used), shutter lag is greatly reduced (because the camera doesn't have to focus), and both 2D and 3D images can be obtained from the same shot.

Video cameras are often used in conjunction with filters to improve the contrast in a manner similar to that noted for still cameras. This technique has had limited success for oil spill remote sensing because of poor contrast and lack of positive discrimination. With new light- enhancement technology, video cameras can be operated even in darkness. Tests of a generation III night vision camera showed that this technology is capable of providing imagery in dark night conditions [8].

Hyperspectral imaging is a growing area in remote sensing in which an imaging spectrometer able to collect hundreds of images at different wavelengths for the same spatial area. Hyperspectral images are extremely complex, and require advanced processing algorithms to satisfy near real-time requirements in applications such as, mapping of oil spills and chemical contamination of surface water.

Data in the visible has been subject to many efforts to use mathematical techniques to help distinguish oil from water. At this time no automatic processing algorithms are used in the oil spill industry [8]. Overall, the visible area remains an active research area as well as a practical means of monitoring oil spills.

Figure 10 Light reflection off the sea can sometimes be a problem when taking aerial photographs; UV and polarizing filters may help to sharpen the visual definition of oil [14]

2.2 Multispectral optical and thermal sensors

Multispectral sensors generate images of the surface at several discrete optical wavelengths (typically 3 to 7, sometimes more). They are not limited to the visible part of the electromagnetic spectrum, and so often record at NIR and sometimes SWIR as well. Thus, as well as generating "true color" images, they are able to generate "false color" images. These sensors provide digital imagery in various spectral bands at ground sampling distances that can vary between a few centimeters and 1 or 2 meters (depending on the platform altitude and lenses used).

Some sensors are used for digital photogrammetry and collect stereoscopic imagery in each of the spectral bands - usually visible (RGB) and near-infrared bands. This allows us to develop digital elevation models and ortho-photography in coastal areas, which can help in modelling and mapping applications. Typical ground sampling distances for these cameras are 5-30cm, depending on the flying height and the focal length of the lens used. This provides mapping scales ranging from 1:500 to 1:5000 (with appropriate ground control).

The advantages of multispectral sensors are as follows:

- They help to remove false alarms in cases where a larger number of spectral bands are available (by identifying differences between oil spill and false alarm signatures).
- They extend the range of applicability of surveillance across environmental conditions or valid measurement ranges (e.g. extending observations into dusk in case of SWIR), or detecting thinner (<10 μm) and thicker oil.
- They can often provide additional environmental information that supports OSR, such as sea surface temperature from TIR.

Visible image sensors record true color imagery, but as in the case of aerial photography, they are useful for recording oil spill identifications by observers and distributing this information to relevant parties. They can also be used to support enhanced quantification of basic oil spill parameters including location and extent.

UltraViolet (UV) sensors are sensitive to very thin sheens of oil (as little as 0.01μm in thickness, though dependent on sea surface conditions) because of strong refractivity at these frequencies. The contrast increases as oil thickness increases. Some UV sensors have a bandwidth that may include violet (0.390-0.450 μm) and blue (0.450-0.480 μm) that increases their sensitivity to solar induced fluorescence from crude oils, but reduces the sensor's ability to detect very thin oil. There is some capability also to detect emulsified oil.

Thermal Infrared (TIR) sensors are useful for detection of oil during day and night and for classifying oil thicknesses more than >10μm. The ability of thermal sensors to detect oil depends on its thickness, type, degree of emulsification and time of day, and will not be effective during rough weather. Some sensors have high spatial and thermal resolution (sub-meter/0.05deg Kelvin), allowing for the determination of subtle variations in sea surface temperature that are related to surface oil. As well, any materials on or at the surface of the water / land with a large enough difference in emissivity will also be apparent even if they hold the same apparent temperature. The system is designed for large-scale area coverages and can operate day and night under clouds or clear skies. TIR sensors are also useful for measuring sea surface temperature, estimation of marine mammal activity as well in search and rescue operations at sea.

Thermal sensors are available as cooled (cryogenic) or un-cooled sensors. Cooled sensors depend on the availability of liquid nitrogen which limits their operational life to several hours ([9]); newer systems are based on gas expansion which gives them a longer operational life, and un-cooled systems are becoming available in smaller models, with easier maintenance and operation, [7]. Thermal sensors can be divided into nadir (TIR sensors) sensors or forward-looking infrared (FLIR sensors). Detection is better suited to the latter, while quantitative mapping is more appropriate for the former.

UV-IR sensors are now standard tools for oil spill response, being used typically to generate a thematic map of oil thickness categories in sea surface. They combine the benefits of the UV and TIR bands for detecting a wide range of oil thicknesses.

The two sensors are normally as follows:

- Optical UV detector, in the range of 0.32 to 0.38μm;
- A TIR detector in the range of 8 to 12μm.

Basic mapping of local characteristics of oil spills is normally carried out using UV-IR sensors. These devices are bi-spectral cross-track scanning sensors that are capable of mapping relative oil thickness within a swath of about 500 meters at a platform altitude of 330m. In the thermal IR, oil spills can be detected if the oil layer thickness exceeds approximately 10μm, and in the near-UV the lower limit of detection is approximately equal to 0.01μm.

There are a wide range of commercial available sensors that are designed for general surveillance or applications such as search and rescue or vessel tracking that have applicability to OSR.

Some multispectral sensors are able to generate information in real time from the data, but in most cases value-added analysis of the data needs to be carried out using post-flight data on the ground. This creates a delay in the application of the data to OSR which can be significant. This includes the analysis of multispectral information to resolve false alarms.

Figure 11 Multispectral sensing system - the Icaros IDM600 sensor [16]

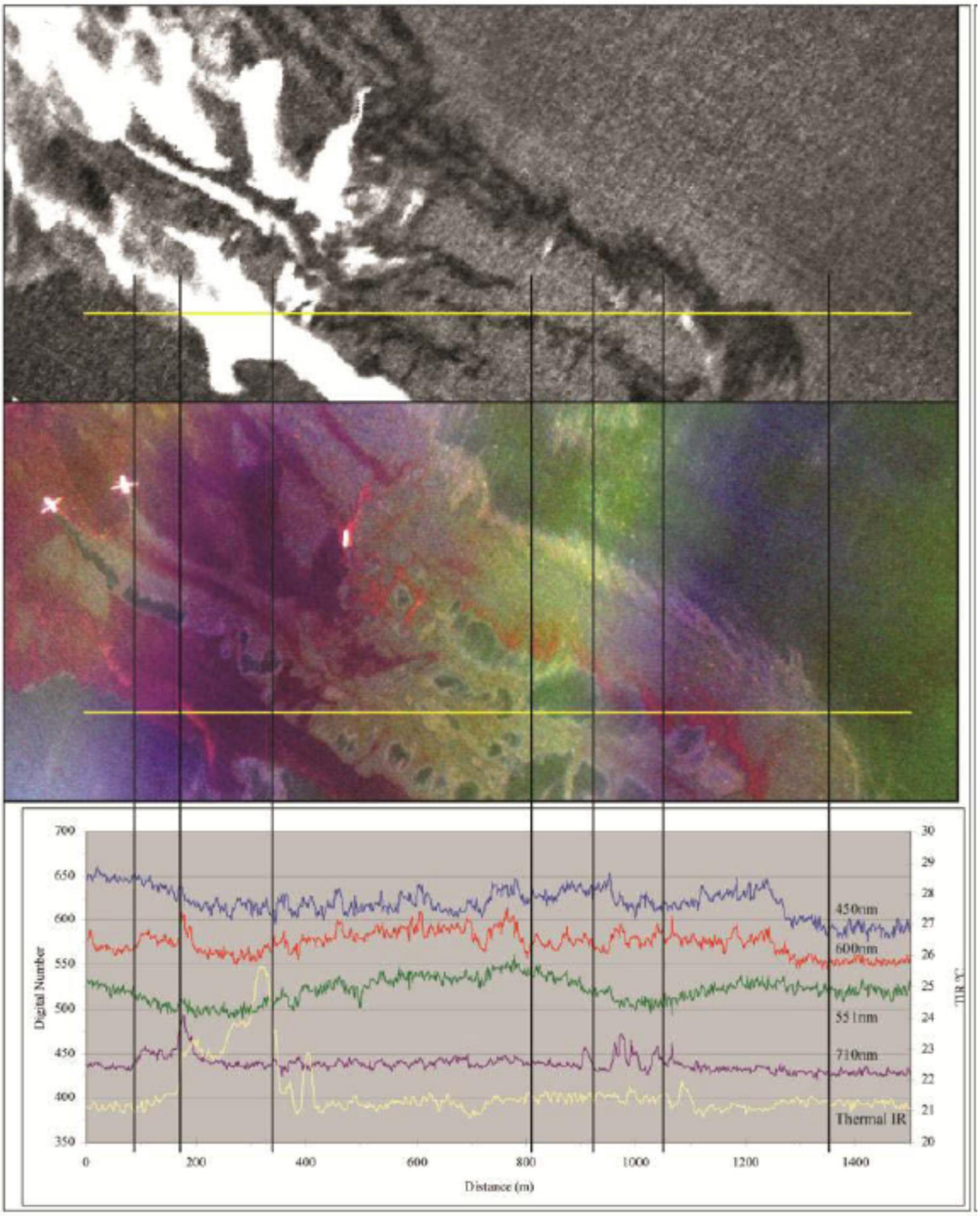

Figure 12 Thermal IR (top) and 450, 551 and 600nm color rendition of a large area of emulsified oil during the Deep Water Horizon spill as imaged by Ocean Imaging's aerial system. The graphs on the bottom show spectral reflectance/emission profiles along the yellow transect line. The thickest emulsions show the highest heat emission (white areas in top image) while thinner emulsions appear cooler (darker) than surrounding water due to petroleum's lower emissivity properties. [15]

2.3 Microwave radiometers

Microwave radiometers are very useful in being able to map oil thicknesses greater than about 0.05mm. Airborne MWR Sensors are mounted to the lower side of the aircraft. The parabolic scan antenna, protected by a dome-shaped cover, has a free field of view in nadir direction. The scan mechanism provides a sinusoidal scan line on the ground. The radiation collected by the antenna is fed through the horn into the receiver where it is amplified and filtered, to extract the desired frequency.

While airborne MWR systems operate in principle between about 1 and 100 GHz, in practice airborne systems tend to operate at particular frequencies including 18GHz, 36 GHZ and 89 GHz. These are complementary, and have differing spatial resolutions and oil thickness sensitivities, ranging from sensitivity to relatively thin (~50µm) oil at higher frequencies (89 GHz) to enhanced spatial resolution at lower frequencies (18 GHz).

In practice, there is complexity involved in using the microwave brightness temperature to estimate oil thickness through the impact of absorption on upwelling radiation. There are interference effects imposed on the upwelling radiation by the interfaces between the oil and water and oil and air. Multiple scattering of the signal between these two interfaces acts to set up a process of constructive or destructive interference in the signal, creating an ambiguity in the thickness estimation.

2.4 Hyperspectral sensors

Some imaging sensors are able to sample a very large number (>100) of spectral wavelengths across the optical part of the electro-magnetic spectrum, typically extending well into the IR band. These hyperspectral imaging sensors have typical surface resolutions of 0.5-12m, depending on altitude. The advantage of these sensors is that the spectral resolution is high enough to enable the unique signatures of particular compounds to be matched to reference library signatures, leading to the possibility of using hyperspectral sensors not only to detect oil, but to characterize the oil in terms of type and condition. These sensors can also be used for oil spills in coastal environments and on land, where their ability to extract unique spectral signatures is useful in compensating for the more complex backgrounds against which oil needs to be detected. In general, hyperspectral sensors can be used with all types of oil, except very light oils. Observations in the SWIR are useful in order to resolve hydrocarbons from other organic matter identified in the VNIR. Spectral signatures can be compared to library signatures for the identification of unique compounds.

Figure 13 Hyperspectral camera embedded on OnyxStar HYDRA-12 UAV from AltiGator

2.5 LIDARs

Light Detection and Ranging (Laser, or "Light Amplification by Stimulated Emission of Radiation") sensors LIDARs are widely used for topographic and bathymetric mapping applications, but some have been adapted for OSR. They are designed to exploit very short optical wavelengths to detect not only surface materials, but also atmospheric constituents, which can be indicative of oil spills. In principle, LIDARs can also detect submerged oil within the penetration depth of the radiation. The use of LIDARs in near real time, however, has yet to be fully proven. Laser fluorometers (LFS) use a more sophisticated method of hydrocarbon detection involving the transmission of a UV signal towards the surface and recording of the return signal in the visible range. The analysis is typically carried out on the aircraft. These are the only sensors that can discriminate between oil types. Most sensors operate in the 0.3 to 0.355µm range.

LFS systems can also be used to classify oil type. As a by- product, LIDAR systems can also potentially provide other hydrologic observations such as turbidity.

Laser Raman spectroscopic systems can also be used to quantify the suppression of Raman scattering signal by oil to estimate the oil thickness for oils between 0.5 and 10µm in thickness [10]. The conversion to thickness depends on knowledge of the absorption coefficient of the oil at the relevant frequencies, and this depends on the type of oil. These systems can also be used to detect compounds indicative of oil such as ethane/methane.

Power limitations mean that LFS systems generally need to be operated below about 500m altitude. More powerful lasers will be able to operate at higher altitudes. Coverage is also limited to relatively narrow swaths, so the technology needs to be deployed efficiently. The number of pulses is also limited by power consumption, so resolution on the ground tends to be fairly coarse. An LFS having consuming 5 kW of power can feasibly consume 50% of the total electric power available aboard the aircraft.

Laser fluorosensors have shown high performance in practice and are now becoming essential tools in many remote sensing packages. The information in the output is unique and the technique provides a unique method of oil identification [8].

2.6 RADARs

Imaging RADAR can be deployed or data from exiting RADAR to detect oil spills some distance away, through off-nadir imaging at significant angles. They are therefore useful as a wide coverage, initial response airborne sensor. Imaging radars are able to observe the surface during day and night, and during poor weather conditions. As such, its operation is limited only by conditions that might restrict deployment of the platform (e.g. very poor weather) rather than to operate the sensor.

Side-looking airborne radar (SLAR) uses a relatively long antenna to obtain good spatial resolution in the direction of movement of the platform. Synthetic aperture radar (SAR) achieves high spatial resolution by using the motion of the aircraft to synthesize a large antenna in the direction of travel, thus enabling the use of smaller antennas. Thus, it combines the ability to observe the surface during day and night, and during poor weather conditions, with the ability to resolve the surface in great detail. VV surface is generally considered the best polarization, and the most experience is with C band.

Imaging RADAR systems do not discriminate between different thicknesses of oil, and provide very little information on the oil itself, at least from single polarization signals. They are also subject to many potential false alarms in all environments.

Imaging RADAR data are extremely difficult to interpret, requiring significant expertise in all environments. Given challenges in relation to false alarms, it is also important to have ancillary information available that can help with identifying false alarms.

Imaging RADAR involves significant image processing and data quantities. Given this and the challenges identified above, it can be difficult to use SAR effectively in near real time without significant advance planning.

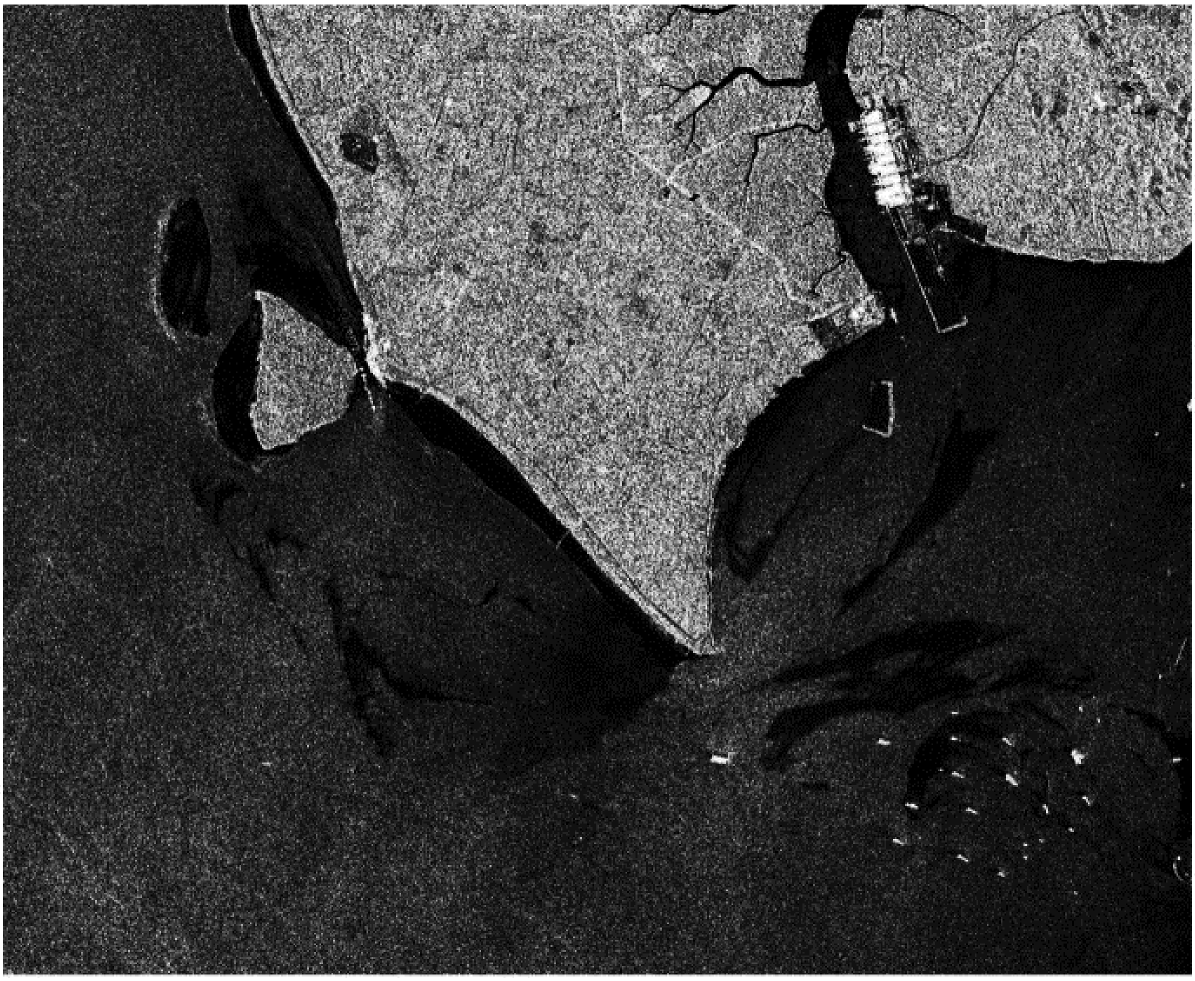

Figure 14 SAR (Synthesized Aperture Radar) image (RADARSAT-1) of oil spill in Strait of Malacca [17]

2.7 Integrated airborne sensing systems

A number of suppliers are now offering integrated airborne sensing systems, to provide end users with the following:

- The ability to use multiple sensors together to identify false alarms because false alarms are not normally present across the electro-magnetic spectrum, and to provide a more complete set of oil spill and ancillary observations (no one airborne sensor provides all the oil spill information that is required);
- To provide the ability to extend the range of applicability of surveillance diurnally or across environmental conditions or valid measurement ranges (e.g. extending observations into night, or detecting a wider range of thicknesses of oil).
- To offer integrated communications across sensors, for example via satellite communications;
- To enable a single ground station to be used for processing and distribution of the data and images;
- To support the potential for multiple sensor data fusion to enhance the quality and range of oil spill products from airborne sensors.

The use of data from multiple sensors is clearly an advantage for oil spill detection and monitoring, but has associated challenges in terms of combining the data effectively in near real time, so the integration implies significantly more than providing access to different sensors on a single platform. Effective integration requires skill to operate the sensor package, a suitable custom software environment, communications and effective physical integration (e.g. shared components where appropriate). In addition, it is important that the configurations of the sensors are suitable for oil spill response and there should be knowledge about how best exploit and present the data in combination, so that the potential of the multiple observations is fully realized.

2.8 Estimation of local wave field properties from drone images, proof of the concept

Properties of local wave field is very important driver for oil spill distribution, both horizontally and vertically. On the other hand, local wave field properties are poorly represented by existing systems, both in terms of measurements and modelling. Based on UAV images, we propose technology to acquire wave information locally, with very high spatial and temporal resolution. Wave properties retrieval technology could be applied on images obtained from UAV Inspire 1 flights (Fig. 15).

Firstly, wave velocity field from SPOT5 satellite data, applicable directly to DJI Inspire 1 images. In the presence of surface wind waves, the sun light reflected by the wave slopes produces glints according to the relative positions between the sensor, the wave front geometry, and the Sun azimuth and elevation. In principle, wave propagation does not produce horizontal displacements of the medium. But given a fixed Sun-wave-sensor geometry, as the waves propagate, the sunlight will produce a glint on the slope of the waves that are in distinct positions. To start, a set of two scenes acquired few seconds (different frames from video or picture file) apart and use the subpixel phase correlation technique to track the glint over time, therefore measuring the phase velocity field of ocean waves [20]. The basis of this operation would be the Fast Fourier Transform (FFT) which is main processor of image spectrum related applications.

Secondly, wave height could be retrieved from IR imagery. Computation of wave height spectra from optical images requires ambient environmental parameters and spatial power spectra derived from the optical images. A demonstration of wave height calculations from infrared images are brought out in [22]. They have developed a modulation transfer function (MFT) and use Fourier transform in together. Another demonstration of usage of infrared images to obtain wave parameters is brought out in [21]. The approach is to assemble a sequence of images in a temporal stack that preserves the spatial coordinates on the mean surface, and to calculate 3-D frequency-wavenumber (*w*-*k*) spectra to ascertain the physical mechanisms responsible for the modulations. These mechanisms are identified in the spectra by the location of the modulation energy. If assumed that the existence of a local *k*-*w* transfer function between the IR return and wave height, then energy would be expected to lie on the 2-D surface.

Figure 15 Photo from vertically down-looking camera of DJI drone, sun light reflected and scattered glints are clearly visible and could be used for wave retrieval for this local sea area.

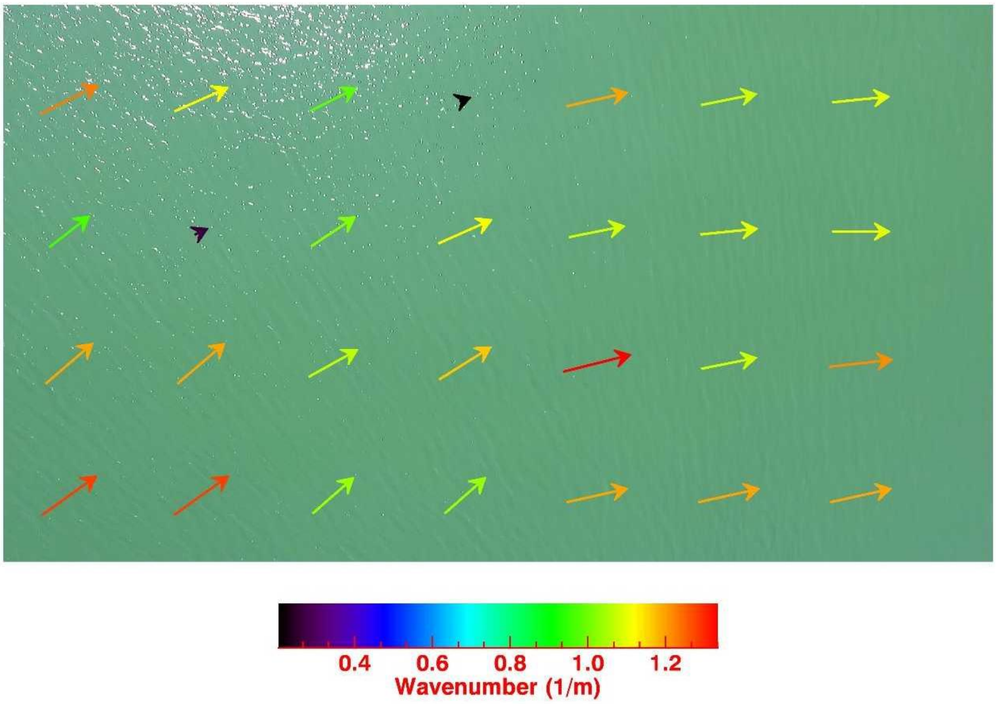

Figure 16 Local wave field obtained from vertically down-looking camera of DJI drone. The Sun light reflected and scattered from the wave slope is recorded by the sensor as glints and different shades of grey (in case if color channels are separated). In principle, a wave passing through a medium does not displace matter horizontally, but as glints form for a given Sun-wave-sensor geometry, the glints

stick to the wave slope as it moves. Therefore, by measuring the glint offsets and dividing it by image acquisition time lag, the wave's velocity can be measured, wavenumber presented on image.

2.9 Case study of UAV-s and sensors performance for oil detection in Arctic conditions

The event was organised by SYKE (Finnish Environment Institute) to demonstrate and/or find operational UAV technology system to study performance of UAV based systems in day and night conditions with different sensors to monitor oil pollution on land and in water in winter conditions.

The technology would benefit many organizations such as border control, police or search and rescue teams as well as scientists. Testing event took place in Kalajoki harbour, North Western Finland on March 14-15, 2016. The ambient temperatures were around 0 °C with slight overcast.

Figure 17 Test fields: each pool contained seawater, oil, ice block and snow in a predefined manner.

Figure 17 shows the test field created for the event. There were three containers in a row with approximate size of 12x4m each containing oil contaminated soil, water, snow and ice. The situation inside the containers were closely imitating oil pollution in ice conditions were under the top oil-ice layer regular seawater was.

Figure 18 Heavy duty drone by Air Intelligence Finland Oy.

Preparation of the first heavy duty drone by Air Intelligence Finland Oy. As seen from the Figure 18 the drone has 8 engines which would make it possible to carry up to about 5 kg payload in favorable environmental situations. The gimbal on the flight machine has two-axis stabilization and regular Video camera is currently installed. Due to the weather conditions, the first flight remains relatively short of about 5 minutes in consideration that we (MSI) have had experiences of up to about 20 minutes of flight time with up to 8 km distance with one battery with lower grade UAV.

Figure 19 LIDAR instrument from LDI Innovations OÜ (EST) in the grey case attached to the copter and ready for uptake.

LIDAR instrument (Fig. 19) by LDI Innovations OÜ (EST), weighs about 50 kg. The instrument has been on Hurtigruten cruise ships in Norway coast to test the instrument and monitor oil pollution at sea. It takes more time than anticipated to start up the LIDAR since the inverter in the copter was not powerful enough. In the end, the warming system was turned off, power consumption was reduced and that way, the measurements were completed.

The LIDAR measurements were successful. The software identified oil pollution right away and with spectral analysis, specific type was determined. Depending on the water conditions, the LIDAR is able to measure pollution up to 30m deep as reports LDI Innovations OÜ.

Figure 20 First flight with VIS/NIR sensor on the drone over oil contaminated snow

The first flight with a VIS/NIR (VISual/Near InfraRed) sensor presented on Figure 20. The sensor itself is one-wavelength-sensor, which has complicated filter system in front of it. The system is able to save up to 30 spectral channels in couple of seconds in wavelength interval from 350nm to 950nm. Since the electronics are more suited for warmer weather conditions, the device was covered with polyester insulation material to secure its working condition.

Another similar device tested has analogous configuration, but has RGB and the hyperspectral information is achieved by using complicated filter system. However, in this configuration, the post processing is much more demanding than for VIS/NIR sensor.

The measurements with these devices were made at 10, 20, 30 and 50m height. However, to save all the spectral information, the drone operator had to stay at each height level for about 10 seconds.

Figure 21 First flight of the copter with the LIDAR on-board.

The flights were made in 30 and 50m height with different speeds. Everything was successful according to the words of the LIDAR operator.

Figure 22 Thermal infrared camera attached to the drone.

On Figure 22, thermal infrared camera from Infradex Ltd is presented. The device needed special power and data cable to communicate with the UAV. A setup procedure to calibrate the sensor was also needed. Hence it took more time than anticipated to set up the system.

Figure 23 UV Fluorescence sensor developed by LDI innovation OÜ (EST)

Another device developed by LDI Innovations OÜ (EST) works in UV Fluorescence area of the spectrum, about 320nm where the backscattering from the oil pollution should be best. The device will determine whether there is a pollution or not without doing spectral analysis like the LIDAR does.

This device worked best from 10m height and lower, therefore more suited for stationary monitoring stations such as harbors. Sensor accommodated also GSM modem for real time data transfer.

Unfortunately, the drone was not able to fly very long with the sensor due to the weather conditions and the weight of the device which is about 3 kg. The LiPo battery of the drone had low voltage error from the minute it got into the air and measurements were cancelled.

In the evening, the LIDAR measurements were done once more with the copter and another measurements were made with the thermal infrared camera. Rest of the sensors were not tested in the dark.

On the 14th of March, the containers with oil water/ice mixture were covered with fresh snow in order to imitate realistic and more complicated conditions in nature.

Figure 24 The test fields were covered with fresh snow layer to complicate the oil detection situation.

Figure 25 Thermal infrared camera was first to fly over the oil contaminated ice and snow containers.

Thermal infrared camera was first that was tested over the snow-covered containers. Closer view of the hyperspectral camera inside of the insulation box can be seen on Figure 26. Since the ambient temperatures were around 0 °C, the camera system needed warming. The hyperspectral camera was first tested with UAV and later it was attached to copter (Fig. 27). Flights with the copter were performed at different heights in relatively low speed. However, some of the spectral bands were not sharp due to the copter movement and shutter time. Moreover, since the camera needs time to capture all the spectral information, it would fit best to slow moving areal platforms.

Figure 26 Hyperspectral camera inside the insulation box.

Figure 1 Hyperspectral camera of Jussi Soukkumaki design attached to the copter and ready for uptake.

Figure 2 Infrared camera with the larger lens and smaller device for object detection.

Regular infrared camera attached to a UAV is presented on Figure 28. The smaller camera system on the left is regular RGB camera for object detection purposes since objects from infrared cameras might not be identifiable. The video from infrared camera system was also broadcasted to distant screen. This system would be beneficial to e.g. fire fighters where they would have important heat information before the fire extinguishing action.

3. Autonomous drifting buoys, drifters, for oil spill monitoring

Drifting autonomous buoys or drifters have a long history of use for very different purposes ranging from mapping large-scale ocean currents to following oil spills to aiding search and rescue operations [24].

In case of an oil spill, decision makers are in need of in-situ information in order make the correct decisions and minimize the environmental damage. The drift of the oil spill is influenced by surface currents driven by winds, tides and other circumstances, river outflow for example. Traditionally, oil spill monitoring is done by helicopters, airplanes and ships, more modern by UAV-s. A drifter buoy can be used to track oil spills during response operations providing the response teams with real-time, accurate information related to position, speed and direction of its drift of the pollutant. Real-time environmental data as well as oil slick observations are crucial if a spill trajectory forecast is to be accurate. Also, recorded data can be assimilated into dynamic models to improve the accuracy of the model predictions.

Oil spills can be tracked using specially-designed buoys to follow the oil's movement. The same buoys have been used to simulate the oil spills spread in various sea areas in order to improve preparations for potential oil spills in the area. Such tracker buoys have been used in the past also during oil spill exercises. In this sections some of such oil tracking buoys are described.

3.1 The iSPHERE drifter buoy

The iSPHERE is a unique buoy designed for oil spill tracking. Offered as an alternative to the standard ARGOSPHERE drifter, this new-generation buoy uses the bi-directional Iridium satellite system to communicate and to transmit essential scientific data. Iridium telemetry is the most cost-effective means of transmitting data for environmental applications. The Iridium modem provides the end-user with lower transmission costs and an increase in data throughput. The two-way communication allows for customized data. [11]

Figure 29 The iSPHERE [11] oil tracking buoy

3.2 AIS/IRIDIUM Marking and Tracking Buoy 4950B.AIS/IR-F

This second generation AIS Drifter Buoy with optional IRIDIUM transponder is designed to mark and track oil spill and other floating objects. The marker buoy is designed for quick and easy deployment in an event and its robust design allows for drop launching this marker from up to 30 meters above sea surface, i.e. from helicopters, platforms or elevated decks. Improvements over the previous generation include a magnetic activation switch also indicating AIS status, low self-discharge rechargeable NiMh batteries and an optional integrated LED strobe (for the -F versions) and the optional IRIDIUM transponder.

IRIDIUM communication is especially useful for tracking in remote regions or if the drifters are not to be followed permanently. It is also possible to operate the drifter in IRIDIUM only mode significantly extending the lifespan up to one year making it suitable for applications in marine research like surface current tracking. [11]

Figure 30 AIS Drifter Buoy with optional IRIDIUM transponder for oil tracking [11]

3.3 Fastwave Voyager Oil Spill Tracking Buoy

The Voyager transmits GPS position, sea surface temperature and battery voltage and delivers the data to Fastwave's secure servers. From there it is decoded and made accessible through an on-line data management portal, or data can be delivered directly to clients applications. The Fastwave management system enables clients to send commands to the Voyager to change reporting intervals (2 min - 24 Hour) to be set up. Additional sensor options, e.g. fluorometer, turbidity, compact weather station and AIS enabled version for local vessel alerting and tracking options are available. Voyager Drifter Buoy features include, Long endurance – e.g. around 300 days at three hourly reporting, Re-useable, User replaceable, long shelf-life, flyable D-Cell alkaline battery pack. Robust, compact design - drop launch from up to 15m without parachute, Simple to deploy with magnetic on/off switch, LED and vibration alert for on/off and remotely adjustable reporting interval (2 Min - 24 Hrs.) Additional accessory options include Marker flag and strobe light to assist in recovery, Drogue for sub-surface tracking, Parachute for airborne deployment and a Transport Case.

Unlike spherical drift buoys, the Voyager's unique fin design and low freeboard ensures close coupling with the ocean surface layer and minimum wind influence. The Voyager has very simple operation and deployment procedures, making it ideal for oil spill response and emergency Search and Rescue (SAR) applications. Robust construction allows the Voyager to be dropped overboard from vessels or offshore platforms, or deployed from aircraft using an optional parachute. [12]

Figure 31 Fastwave Voyager Oil Spill Tracking Buoy [12]

3.4 Prototype of oil detecting drifter by Tallinn University of Technology

A prototype of the drifter with oil detecting capability is developed by Tallinn University of Technology (Fig. 33). Motivation for this development was technologically open architecture of the buoy, so that different technical and software scenarios, also adding other sensors could be played through, which not possible with ready made products from the market. The buoy is equipped with GSM/GPRS based two-way communication, thus the buoy operation is programmable during the mission, very cost effective communication in the Baltic Sea conditions.

The buoy is about 1m long, with diameter of 110 mm and weighs about 10kg. Inside the buoy there are three sections. The upper section contains electronics, data collection unit and motion sensor. The middle section is for buoyancy and the bottom one is for a battery back. Inside the top lid there are sensor for air temperature, GPS/GSM antenna and in bottom section connector for the oil sensor, commonly UV fluorescence type and water temperature sensor. Water and air temperatures are both essential parameters to estimate oil transformation during its fate. Oil sensor show presence of oil in location of the buoy and wave properties derived from buoy movement.

Properties of the local wave field nearby the drifter buoy not directly measured by sensors on board the buoys, but using accelerometer in upper part of the buoy recording motion of the buoy on waves, measuring the heave acceleration or the vertical displacement of the buoy hull during the certain time period. A Fast Fourier Transform (FFT) is applied to the data by the processor on board the buoy to transform the data from the temporal domain into the frequency domain. Note that the raw acceleration or displacement measurements are not transmitted shore-side. Obtained wave data are to be accounted for both hull and electronic noise and resulting is non-directional spectral wave data (i.e., wave energies with their associated frequencies) are derived. Along with the spectral energies, measurements such as significant wave height, average wave period, and dominant wave period are also derived from the transformation.

The data transmission can be set on-line, from 5 minutes to 24 hour periods. Data is transmitted in real time via GSM networks, using GPRS protocol, if it is available. If GSM service is not available, position of the buoy and other data are still recorded on the memory card of the buoy and transmitted when the buoy is again in area with GSM coverage. Even when drifter is lost, data can be retrieved.

The format of the data communication fits with the existing operative oceanographic data transfer protocol of Marine Systems Institute, according to which data is received in the institutes FTP site in ASCII format. Communication with the buoy is two-way and data logger fully programmable during the mission. Drifter buoy has also a “lost function”, which switches buoy into economy mode, in case when buoy’s battery goes down and the buoy has no access to GSM networks, allowing to achieve longer lifetime and download data when the buoy is available again in GSM network.

For oil detection functionality the UviLux UV- fluorometer from Chelsey Technology Group (UK) is added to the buoy. The oil detection is done by proxy of Polycyclic Aromatic Hydrocarbon (PAH) concentration (in terms of Carbazole) with unit μg/L. The UviLux uses a deep UV LED light source and a miniature photomultiplier detector to provide state-of-the-art measurement sensitivity at the parts-per-trillion level.

Figure 32 UviLux UV fluorometer from Chelsey Technology Group (UK) [18]

Figure 33 Autonomous drifter buoy developed by Tallinn University of Technology

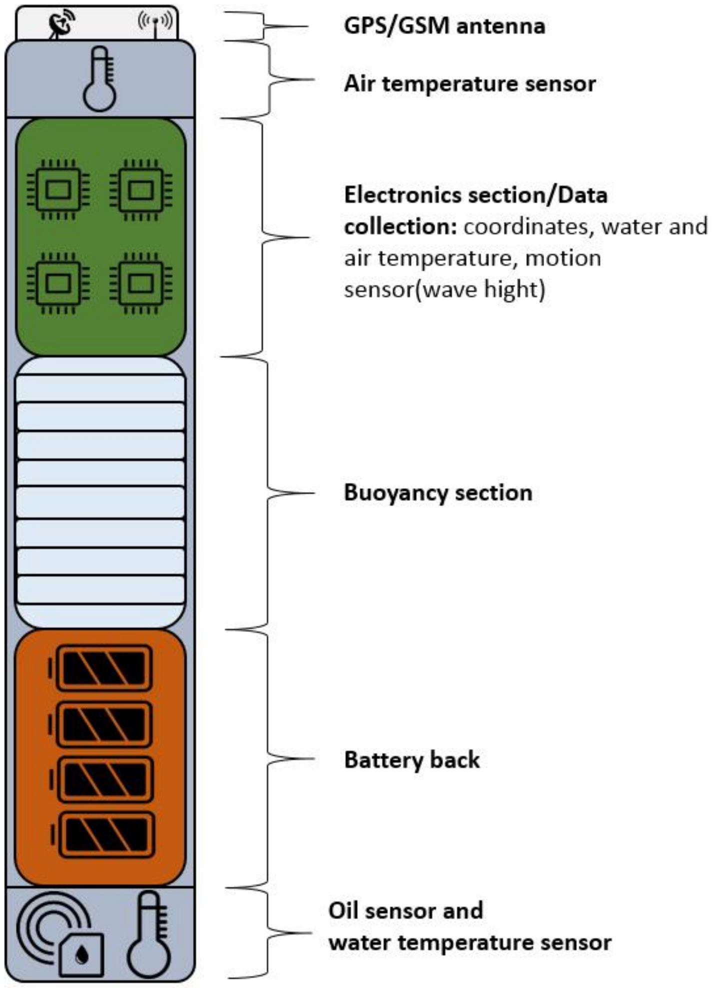

Figure 34 Rough schematics view of the oil detecting drifter buoy prototype.

Figure 35 Deploying the drifter from the boat (left panel) and drifter in working position (right panel)

4. Combined use of drifters and AUV-s to improve oil spills situational awareness in tactical scale.

Oil spill response is local, tactical scale operation. Up to now data used during response operations are large scale satellite images, with some addition of aerial surveillance. The system definitely lack in situ data. We propose systems with on-line oil sensing drifters and AUV-s, giving needed in situ data and decreasing the costs of aerial surveillance.

4.1 Case study - monitoring of suspended matter distribution

As oil slicks that can be observed at sea, occur rarely we performed a test of the system consisting AUV and one drifter buoy with a plume of suspended matter from dredging operations. The observed parameter is concentration of Total Suspended Matter (TSM) in water, originating from dredging operation in Pärnu harbor, Gulf of Riga, the Baltic Sea. The plume of the suspended matter spreads in a quite similar way as an oil slick, in the surface layer of the sea and we used it as a case study of pollution dynamics in certain sea area, this case river mouth (Fig. 38). As in case of oil spills also suspended matter shows different concentrations of the material and quite similar sensitivity to weather conditions, mainly wind. Dredging operations in coastal waters affect water quality through an increase in the concentration of suspended matter, which is naturally influenced by spring bloom, cyanobacterial bloom, resuspension, and river inflow. Waves and currents can also cause resuspension of sediments in shallow coastal seas. To monitor TSM concentration in real-time, a monitoring buoy, equipped with SEAPOINT turbidity sensor, also optical sensor like in case of PAH measurements. The on-line buoy was placed near the dredging area, about 1.5 km from the coast and 600 m from the end of the bulwarks (Fig. 41).

During dredging period, three monitoring flights were done. The monitoring program of the dredging operations in the Pärnu harbor included also the independent in situ water turbidity observations (Sechhi depth), as well water samples taken for laboratory analyses and on-line buoy measurements of water turbidity in certain monitoring point.

The aircraft was operated at the altitude of 500m and at the distance of 3 km from the flight operator.

The extent and area of suspended matter distribution could be assessed and the suspended matter plume could be well estimated from the drone photos/videos, also other peculiarities like different concentrations inside the cloud (Fig. 37 and 38) can be measured by an online buoy. Both the plume of suspended matter and the oil slick are forced by local wind conditions, which create certain dynamics in both of these – UAVs and online measuring buoys are suitable assets for monitoring the dynamics of the pollution plume.

It is clear that UAV imaging gives useful information about spatial extent of the pollutant visible on sea surface, still ground truth data are needed explaining the visuals. In case of operations during the Pärnu Bay dredging, this is TSM (Total Suspended Matter) concentration, which was recorded by special on-line monitoring buoy (Fig. 39), whereas data presented via web-based user interface.

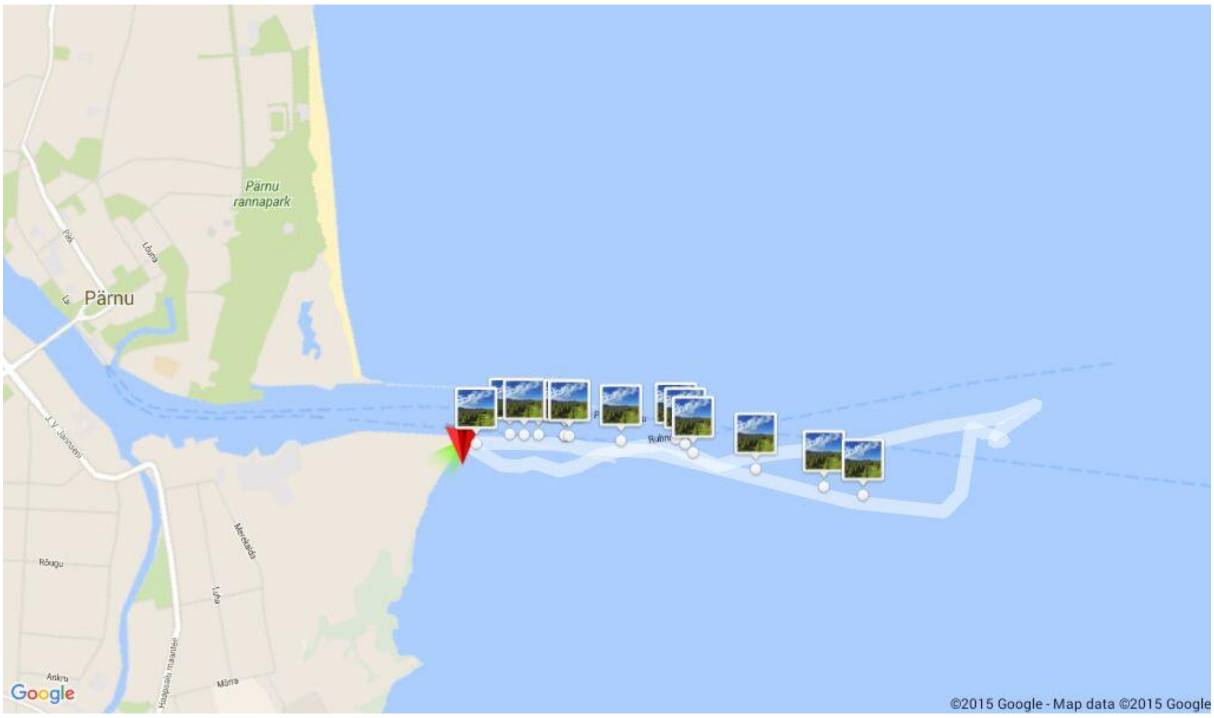

Figure 36 Travel trajectory of drone flight on the Pärnu Bay with locations where images were taken

Figure 37 One of the images from the flight presented in Figure 36

Figure 38 Image showing suspended matter distribution in the dredging zone, dredging vessel between bulwarks, leaving cleaner trail behind what tells that suspended matter is located mainly on surface

Figure 39 On-line buoy for measuring Total Suspended Matter (TSM)

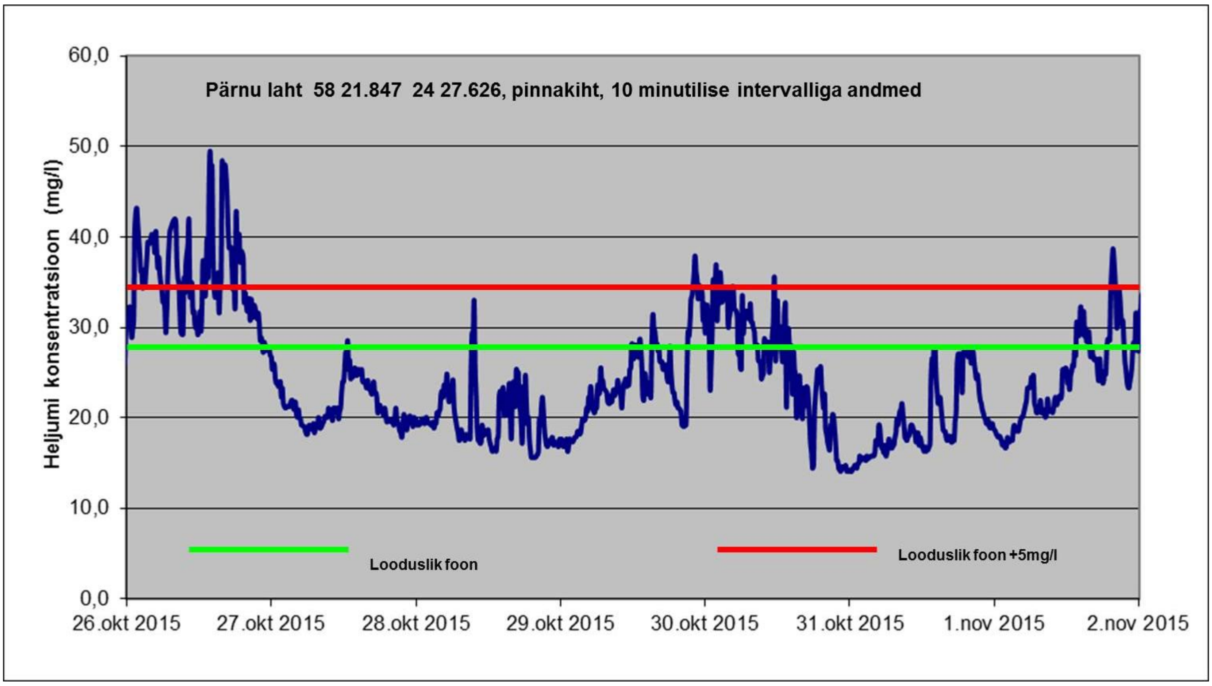

Figure 40 Temporal variation of Total Suspended Matter (TSM) concentration in water column as measured by on-line monitoring buoy in certain location in the Pärnu Bay in the period when also UAV flights were made. Green and red lines denote natural background and +5mg/l of TSM

Figure 41 View on the suspended matter cloud from the boat. On-line measuring buoy is near the navigation buoy seen on the photo, AUV is up in air

Values of TSM concentration showed a clear trend of increase towards the end of the dredging (Fig. 40), it was dependent on consistency of dredged material as well variability of forcing conditions. In the beginning of dredging period port area was dredged and between bulwarks a rise in the TSM concentrations could be seen. The reason for that can be bottom sediments with smaller fraction and/or the fact that there are no waves and currents in the harbor and between piers that would disperse the sediment plume. The second part of the dredging showed higher TSM concentrations (Fig. 40) exceeding critical levels. This is due to the effect of two factors, firstly, the suspended matter plume exiting from between the piers, and secondly the wave intensity and the consequent re-suspension of bottom sediments of the shallow Gulf of Pärnu. The high spikes on the graph are probably caused by dredging vessel passing the buoy and taking sediment plume with her. TSM values that exceeded the critical level for longer periods from the middle of the dredging period are probably caused by dredging nearer to the buoy. In addition, the end of the October and the beginning of November were quite windy with southern winds, which increases the sea level of the Pärnu bay and higher waves that causes local resuspension of sediments.

4.1.1 Quantitative estimate of suspended matter concentration from UAV images and drifter data, proof of the concept

Unmanned Aerial Vehicles (UAV) systems offers great potential to monitor the sea surface. In addition to retrieving regional information about TSM distribution and extent, application of mapping Total Suspended Matter (TSM) in high resolution from with a standard 4K video camera is presented.

To calculate the TSM concentration from UAV images, linear relationship between measured TSM concentrations and pixel digital number was found. According to Doxaran and Froidefond, 2002 [19], a two-band ratio between red and green was used from the image raw data to establish the linear relationship. The red and green pixel values were selected from the images closest to the measurement station at the end of the pier. Using the collocated dataset of pixel digital numbers and measured TSM concentration, the linear relation with the correlation coefficient of 0.93 was used.

To demonstrate the application, two examples are brought out in Figure 42 and Figure 43. On Figure 13. an example from 6 October 2015 07:00 UTC is brought out. The TSM concentration calculated from the image data corresponds well with the measured TSM readings of 20.4 – 31.3 mg/l.

The second example represents the situation at the end of the piers on 28 October 2015 11:00 UTC (Fig. 43). It is well seen from the image that the dredger ship has suspended more material between the two piers. This indicates that most of the fine matter is at the depth of the propeller which suspend the matter to the surface. Another explanation is that the piers are limiting the normal spread of the suspended matter. In contrast, on the example presented on the Figure 42, where the sea is more opened, the process is converted.

However, TSM acts in certain conditions similarly as light oil pollution. In situations where the light oil pollution is on the surface, the developed drifter buoy might not detect any pollution since the measuring sensor is at about 1 m depth. In addition, oil pollution warnings from satellite radar (SAR) images might not be true in very calm weather conditions. Thus, UAVs could be used to confirm if any pollution exist. If true, the UAV imagery would give short term information about the location of the pollution, as well as gravitational spread and distribution.

In contrast, there is no opponent to drifter buoys in medium or high sea state situations (wave height above about 1 m) to give data about oil pollution. Depending on the wind speed, SAR data might give false results on oil detection. Even if oil pollution is detected from SAR, it is only global snapshot of the situation and does not give knowledge about the spreading and drifting. Since the oil sensor on the drifter is at 1 m depth, it would also give data about oil spreading in the water column. Thus, the drifter would be the only solution that could detect and monitor the oil pollution. Of course, if pollution is detected by the drifter buoy or from SAR data, UAVs would be a valuable tool to monitor the extent and spatial distribution of the pollution in between times where satellite data is not available.

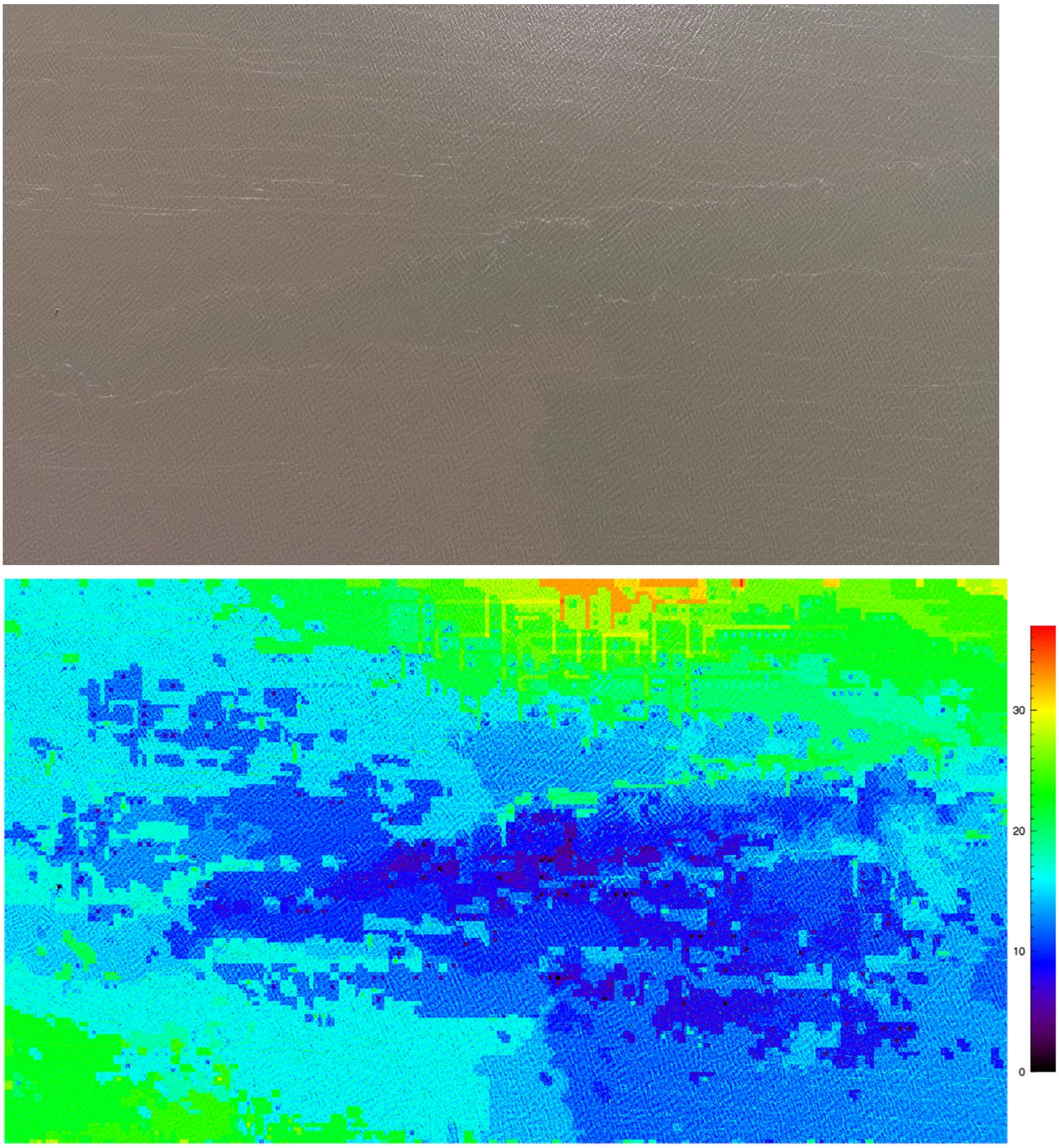

Figure 42 Example from 06 October 2015 07:00 UTC above and TSM concentration calculated from the image data. Measured TSM concentration was between 20.4 – 31.2 mg/l, which well agrees with buoy data (Fig. 40).

On Figure 42 an example from 6 October 2015 07:00 UTC is brought out. The TSM concentration calculated from the image data corresponds well with the measured TSM readings of 20.4 – 31.3 mg/l.

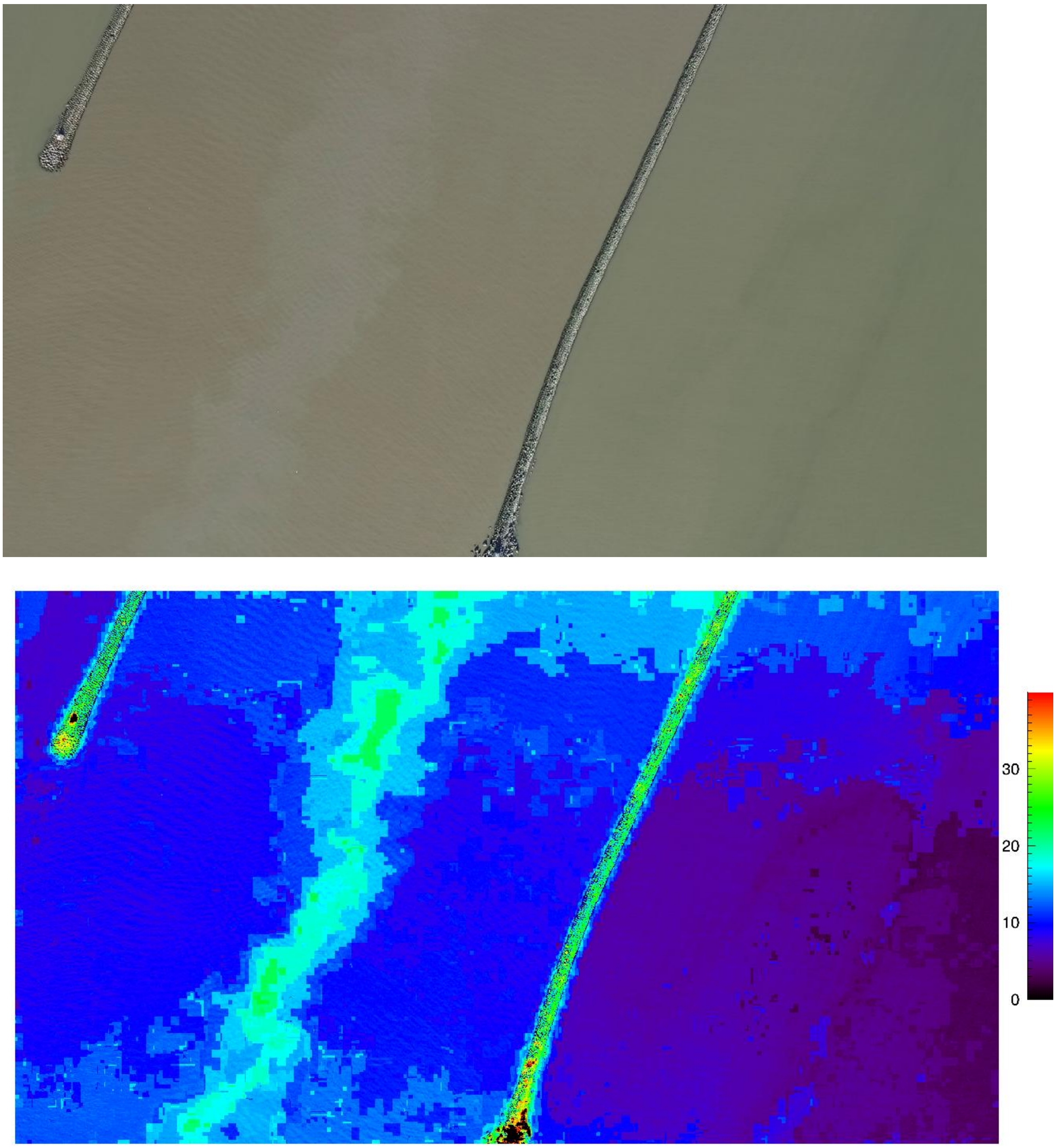

Figure 43 Example of TSM concentration calculated from the image data on 28 October 2015. Measured TSM values varied between 18.0 – 19.2 mg/l, agrees well with buoy data (Fig. 40).

4.2 Case study - monitoring of oil leaking shipwrecks

UAV and its camera functionality was tried with real oil slick. It is usually almost impossible to predict presence of oil slick at the sea, but sunken ships and wrecks having oil on-board form a potential risk for oil pollution and around these, almost permanent oil slick could be found.

As an experiment, shipwreck named MS VOLARE (Fig. 44) was chosen to be monitored for purpose of investigating shipwreck that had caused environment pollution for almost 20 years. The wreck was salvaged and bigger oil sources removed. The aim was to study, if there is still some oil leak around the wreck, and UAV was an ideal work tool for that. Flights were operated from board small rowboat. Oil survey flights at MS VOLARE wreck site were performed approximately a month after the salvage operation took place, so accidental leakages should have been already washed away and if an oil slick was still to be found, it should originate from the wreck. During the survey some small oil slicks were detected near the main engine of the wreck (Fig. 45).

For better overview of the situation a combination of a (online) survey buoy to get information about the oil concentration (and leakage intervals) and use a drone to identify the areal of the pollution.

Figure 44 View of the shipwreck from the side

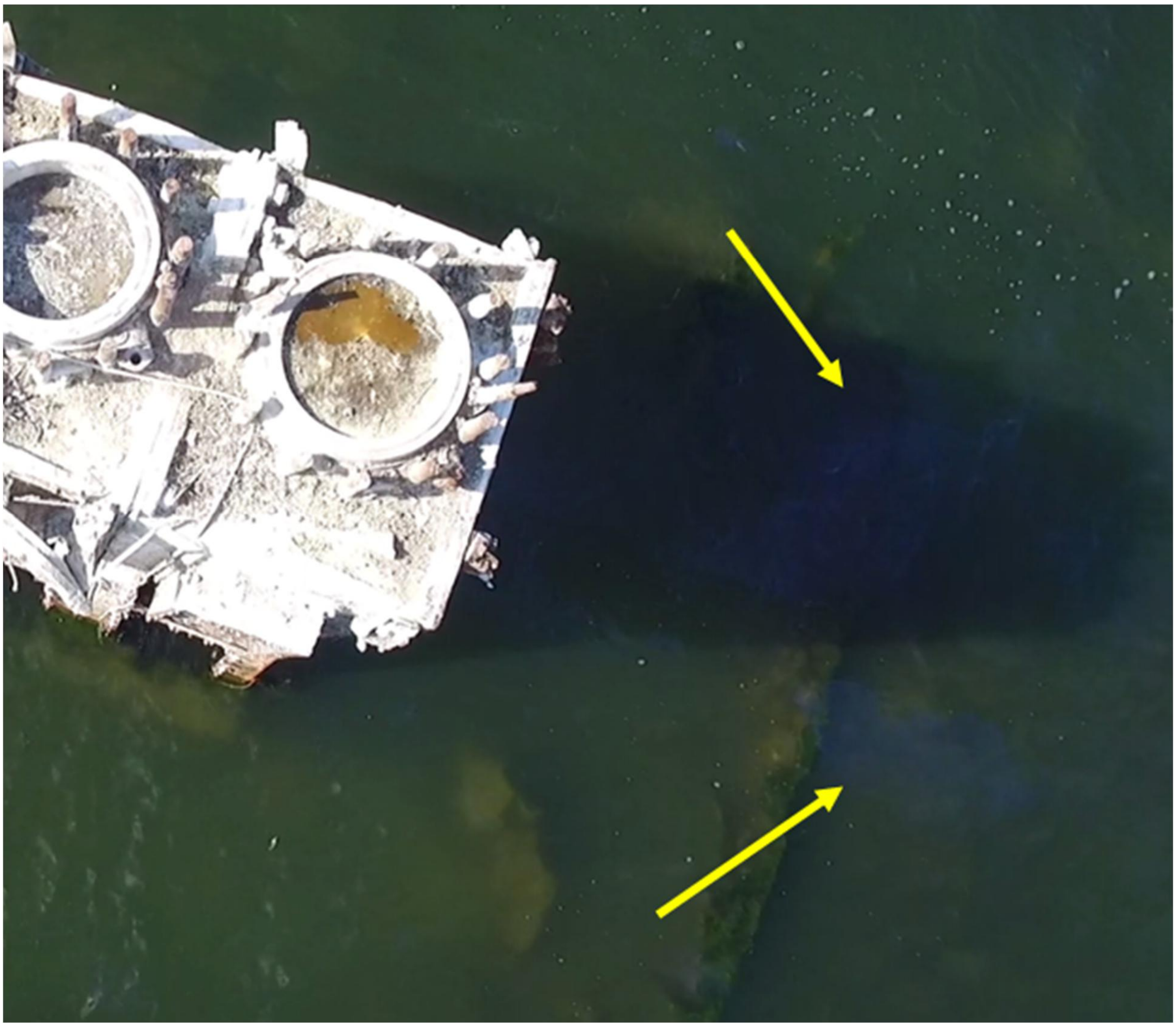

Figure 45 Drone photo from above, viewing remainings of the main engine of MS VOLARE wreck, arrows point on detectable oil slicks originating from the wreck

4.3 Tactical scale system supporting oil spill response locally

UAV systems together with in situ component, drifter buoys, is a cost-effective way to monitor different marine parameters in case of oil spill improving considerably situational awareness of operations. DJI's Inspire 1 aircraft together with drifter buoys have proven the usability of monitoring the spread and dynamics of pollution plume, similar to oil spill. It was found that UAV images give good local scale overview of situation dynamics in high resolution and buoy data contribute with in situ ground truth knowledge. Moreover, aerial image data can be extended to give various other parameters like local wave field, ice conditions in high resolution and concentration of the polluting matter. Most productive application for such system could be cost effective monitoring of oil leaking shipwrecks, which stay in same position and oil pollution can be localized more easily.

General layout of the tactical scale oil spill response support system is given on Figure 46 and consisting of number of drifters, one or more UAV and satellite images for general overview over larger sea area.

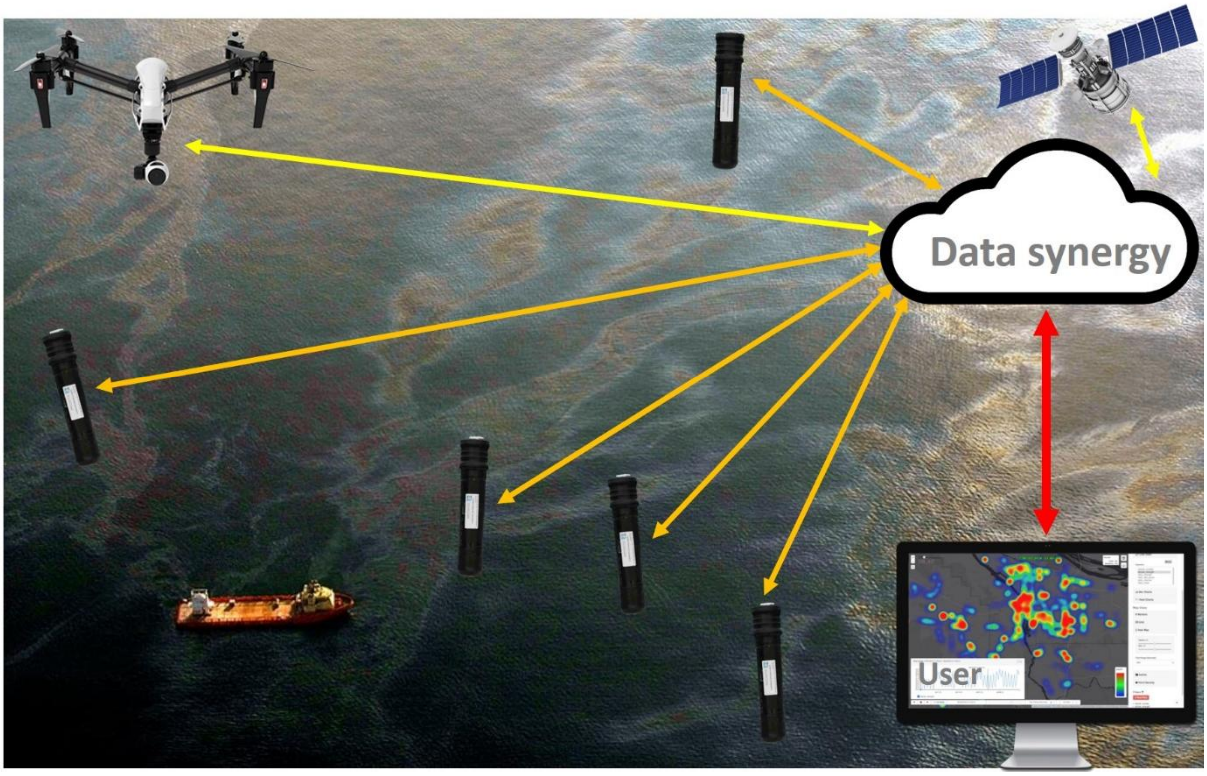

Figure 46 Concept for an on-line/real-time system that combines information from UAVs and drifters (and satellites, if possible), in case of an oil spill

References

[1] Partington, K. 2015. An Assessment of Surface Surveillance Capabilities for Oil Spill Response using Airborne Remote Sensing. Polar Imaging Limited

[2] www.insitu.com

[3] www.boeing.com

[4] www.umich.edu

[5] www.dji.com

[6] American Petroleum Institute. 2013. Remote sensing in support of oil spill response: planning guidance. API Technical Report 1144

[7] IPIECA-OGP / IMO / CEDRE. 2014. Aerial observation of oil pollution at sea: An operational guide. IPIECA-OGP Good Practice Guide series

[8] Fingas, M., Brown, C. 2014. Review of oil spill remote sensing. Marine Pollution Bulletin 83 (2014) 9–23

[9] Puestow, T., Parsons, L., Zakharov, I., Cater, N., Bobby, P., Fuglem, M., Parr, G., Jayasiri, A., Warren, S., Warbanski, G. 2013. Oil spill detection and mapping in low visibility and ice: surface remote sensing, OGP/IPIECA JIP Final Report 5.1

[10] Piskozub J., Drozdowska V. & Irczuk M. 1998. A water extinction lidar system for detecting thin oil spills preliminary results of field tests, Oceanologia 40(1), 3-10.

[11] www.metocean.com

[12] https://www.iridium.com

[13] Vahter, K., Pärt, S., Siitam, L., Kõuts, T. 2015. Pärnu sadama süvendusaegne seire 2015. Marine Systems Institute in Tallinn University of Technology

[14] Impact PR & Design Limited. 2011. AERIAL OBSERVATION OF MARINE OIL SPILLS. Canterbury, UK

[15] Svejkovsky, J., Lehr, W., Muskat, J., Graettinger, G., Mullin, J. 2012. Operational Utilization of Aerial Multispectral Remote Sensing during Oil Spill Response: Lessons Learned During the Deepwater Horizon (MC-252) Spill. Photogrammetric Engineering & Remote Sensing Vol. 78, No. 10, pp. 1089–1102.

[16] www.icaros.us

[17] Jha, M.N., Levy, J., Gao, Y. 2008. Advances in Remote Sensing for Oil Spill Disaster Management: State-of-the-Art Sensors Technology for Oil Spill Surveillance. Sensors (Basel, Switzerland). 8(1):236-255.

[18] www.chelsea.co.uk

[19] Doxaran, D., Froidefond, J. M., Castaing, P. 2002. A reflectance band ratio used to estimate suspended matter concentrations in sediment-dominated coastal waters. International Journal of Remote Sensing Volume 23

[20] Marcello, D. M., Leprince,S., Thiébot, J., Raucoules, D., Binet, R. 2012. Direct measurement of ocean waves velocity field from a single SPOT-5 dataset. Remote Sensing of Environment 119: 266-271.

[21] Dugan, John P., Henry H. Suzukawa, Charles P. Forsyth, and Morton S. Farber. 1996. Ocean wave dispersion surface measured with airborne IR imaging system. Geoscience and Remote Sensing, IEEE Transactions on 34, no. 5: 1282-1284.

[22] Gelpi, C. G., Schuraytz, B. C., Husman, M. E. 2001. Ocean wave height spectra computed from high-altitude, optical, infrared images. Journal of Geophysical Research: Oceans (1978–2012) 106, no. C12: 31403-31413.

[23] Wilkinson, J., Beegle-Krause, CJ., Evers, K-U., Hughes, N., Lewis, A., Reed, M., Wadhams, P. 2017. Oil spill response capabilities and technologies for ice-covered Arctic marine waters: A review of recent developments and established practices. Ambio, 46(Suppl. 3):S423–S441

[24] Lumpkin, R., Özgökmen, T., Centurioni, L. 2017. Advances in the Application of Surface Drifters. Annu. Rev. Mar. Sci. 9:59–81