D5.1 IRA-MAR Preliminary bibliographic research on the Best Available Technologies for the use of drones in maritime emergency response surveys.

WP 5: Studies for the integrated response to pollution accidents: the use of UAS (Unmanned Aircraft System) in emergency response

Task 5.1: Research on Best Available Technologies (BAT) for shoreline use

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D5.1 IRA-MAR Preliminary bibliographic research on the Best Available Technologies for the use of drones in maritime emergency response surveys.

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Disclaimer

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Glossary

- ACE Adaptive Cosine Estimator
- AI Artificial Intelligence
- API gravity / °API gravity The American Petroleum Institute gravity using to express the relative density of petroleum liquids to water
- AVIRIS Airborne Visible/Infrared Imaging Spectrometer
- AT Aerial Triangulation
- BA Bundle Adjustment
- BATs Best Available Technologies
- BLOS Beyond Line Of Sight
- BRLOS Beyond Radio Line-of-Sight
- BVLOS Beyond Visual Line of Sight
- CASI Compact Airborne Spectrographic Imager sensor
- CEM Constrained Energy Minimisation
- CCFP Circular-Cylindrical Flight Planning
- CFP Corridor Flight Planning
- CG Centre of Gravity
- CNN Convolutional Neural Network
- DCNN Deep Convolutional Neural Network
- DEM Digital Elevation Model
- DSM Digital Surface Models
- DTM Digital Terrain Models
- EASA European Union Aviation Safety Agency
- EMSA European Maritime Safety Agency
- FAME Fatty Acid Methyl Esters
- FI Fluorescence Index
- FOSS Free and Open Source Software
- GCP Ground Control Points
- GSD Ground Sample Distance
- GPS Global Positioning System
- GPU Graphics Processing Unit
- HALE High Altitude, Long Endurance UAS
- Hazmat Hazardous Materials
- HI Hydrocarbon Index

- HDI Hydrocarbon Detection Index
- HNS Hazardous and Noxious Substances
- HSE Health and Safety Environment
- HTOL Horizontal Take-Off and Landing
- IR Infra Red
- INS Inertial Navigation System
- LALE Low Altitude, Long Endurance UAS
- LAOS Look-Alike Oil Slick
- LASE Close Low Altitudes Short-Endurance UAS
- LD Laser Diodes
- LDA Linear Discriminant Analysis
- LiDAR Light Detection and Ranging
- LOS Line of Sight
- LWIR Longwave Infrared Radiation
- MALE Medium Altitude, Long Endurance UAS
- MAVs Micro or Miniature Air Vehicles
- MWIR Medium Wave Infrared
- NAVs Nano Air Vehicles
- NCP National Contingency Plan
- NN Neural Networks
- NRCS Normalized Radar Cross Section
- NDOSI Normalised Difference Oil Spill Index
- NIR Near InfraRed
- PAV Pico Air Vehicle
- PCA Principal Component Analysis
- PLS Partial Least Squares regression analysis
- RADAR Radio Detection and Ranging
- RLOS Radio Line-of-Sight
- RPAS DC Remotely Piloted Aircraft Systems Service Data Center
- RPSA Remotely Piloted Aircraft Systems Service
- RX-UTD Reed-Xiaoli Uniform Target Detector
- SAM Spectral Angle Mapper
- SAR Synthetic Aperture Radar
- SCAT Shoreline Monitoring and Assessment Technique
- SEBC Standard European Behaviour Classification
- SID Spectral Information Divergence

- SFJTC Spectral Fringe-Adjusted Joint Transform Correlation
- SfM Structure from Motion
- SLAR Side-Looking Airborne Radar
- SORA Specific Operations Risk Assessment
- SOx Sulphur Oxides
- SSFIN Spectral-Spatial Feature Integrated Network
- STOL Short Take-Off and Landing
- SVM Support Vector Machine
- SWIR Short Wave InfraRed
- TIR Thermal Infrared
- UAS Unmanned Aerial System
- UAV Unmanned Aerial Vehicle
- UV Ultra Violet
- VIS VISible
- VTOL Vertical Take-Off and Landing
- µUAV micro Unmanned Aerial Vehicle
- WebGIS Web Geographic Information System

Introduction

The aim of this technical guide is to gather information and knowledge on the more advanced techniques and technologies, and related gaps, in the use of drones in marine environmental emergencies.

Activity are part of the Work Package 5 “Studies for the integrated response to pollution accidents: the use of UAS (Unmanned Aircraft System) in emergency response” (Task 5.1), of the IRA-MAR project (“Improving the Integrated Response to pollution Accident at sea and chemical risk in port” project).

IRA-MAR is a DG-ECHO co-funded project that aims to support the countries from the Western Mediterranean and Atlantic regions (France, Italy, Malta, Morocco, Portugal, Spain and Tunisia) in improving preparedness for marine pollution events through an integrated approach to response, both at sea, on the shoreline and in ports. It will also support beneficiary countries in better planning and preparation for chemical risks in ports.

This technical guide is particularly dedicated to authorities appointed in National Contingency Plan (NCP) to coordinate survey of areas affected by a maritime a pollutant spill following an environmental emergency.

An Unmanned Aerial Vehicle (UAV), commonly known as a drone or as a Remotely Piloted Aircraft System (RPAS), is an aerial vehicle without a human pilot onboard. The combination of the platform, its control segment, and its payload is sometimes referred to as the Unmanned Aerial System (UAS). In the text, therefore, when discussing aerial vehicles remotely piloted, it is alternatively reported as drones, RPAS, UAVs, or UAS.

UAS is considered, overall, a viable option to acquire high-quality inspection data while minimizing Health and Safety Environment risks (HSE risks) associated with conventional methods of access (confined spaces) or polluted areas.

Generally, a UAS is then a flying platform that can be maneuvered remotely or autonomously, typically carrying a payload to assist the mission. A pilot at a ground station controls the remotely operated UAS, while an onboard autopilot system is responsible for maneuvering an autonomous UAS. A hybrid approach involves, then, the pilot at a ground station remotely controlling the take-off and landing, while the autopilot system controls the UAS during the rest of the mission; the UAS payload consists of a range of sensors.

Recent developments in sensor technology and navigation systems have made drones a powerful and reliable basis for professional data acquisition. Indeed, drone technology offers a great potential to improve the mapping, monitoring, inspection, and surveillance procedures during a coastal and marine emergency due to a spill of oil or Hazardous and Noxious Substances (HNS). In particular, the application of these technologies provides a faster, safer, and more cost-efficient way to achieve data and information.

The use of drones therefore has enormous potential in improving the response to an environmental emergency at sea. Its technology has been rapidly developing over the last decade, with enormous potential to revolutionise the maritime emergency interventions by providing a more efficient, fast, safe, and cost-effective way to carry out various field activities. Therefore, the time is ripe for this type of survey to be considered in Contingency Plans to tackle accidental pollution at sea.

The combined use of drones, with 'conventional' manned vehicles (airplanes and helicopters) and satellites, allows for a faster and more effective response. The real-time sharing of results produced by drone overflights improves information sharing between stakeholders, allowing for a more holistic and integrated approach between the maritime and land institutions.

This bibliographic research mainly gives a review of the common UAV platforms and sensor systems available, based on information reported in scientific papers, previous similar projects, and past maritime incidents where UAVs have been employed. The advantages and challenges of using the different possible assets are also highlighted.

On this subject, authors observe that some projects, including EMSA RPAS Service, are more concerned with observation and detection at sea with assistance of drones weighing more than 20 Kg (see *paragraph 5.3 EMSA Remotely Piloted Aircraft Systems Service (RPAS)*). On the other hand, so-called "small drones" (i.e. drones weighing less than 20 kg) appear to be most widely used in coastal areas, this includes nano, micro and mini drones. Small drones are, in fact, those typically used by authorities in marine environmental emergencies.

The paper presents the state of the art of the main technological aspects of this useful and promising technology, which will be covered in specific sessions on: types of drones, sensors, data processing. It will also present the main results of projects on this topic, as well as the aspects to be considered in the different scenarios for the effective use of drone technology in maritime emergencies.

Executive summary

This document focuses on the main results of the bibliographic research carried out to identify the Best Available Technologies (type of most appropriate UAS, sensors, image analysis software, etc.) as well as main gaps for carrying out surveys in coastal areas during a maritime emergency response, considering the properties and characteristics of products spilled in the marine environment, as well as the environmental impact on habitats and wildlife. In this document, drones are alternatively referred to by the following acronyms:

- UAV = Unmanned Aerial Vehicle.
- RPAS = Remotely Piloted Aircraft System.
- UAS = Unmanned Aerial System.

The use of drones in maritime emergency response must have the following objectives:

1. Improve response capacity to marine pollution incidents standardizing *UAS*s based surveys.
2. Facilitate inspection of remote areas, reducing risks of exposure to pollutants.
3. Give instructions to create georeferenced thematic cartography to be used by authorities.
4. Develop synergies and exchange of information between maritime authorities and civil protection for the use of UAS in coastal areas.
5. Notify, inform and reassure the public on the development of an emergency response, making available photographic and video evidence.

Keeping in mind the objectives for which the use of drones is advisable, the following scenarios can be schematically identified in which UAVs can be used following a spill of oil or other hazardous and noxious substances:

1. Detection and tracking of slicks/drums/containers on the water.
2. Guide recovery vessels to the slicks.
3. Identification and mapping of atmospheric plumes.
4. Inspection of remote areas (e.g. cliffs, coastlines, estuaries, remote islands).
5. Survey of a hazardous environment.
6. Shoreline Monitoring and Assessment Technique (SCAT).
7. Wildlife population monitoring.

There is no ideal drone/sensor/software asset for all scenarios. Ideal asset depends on several factors as: position area to be inspected (shoreline vs open sea); type of pollutants (oil vs HNS); period of the survey (day vs night); size of the area to be inspected; payload of sensor(s).

The Chapter *6 The integrated response to pollution accidents: the use of drones in maritime Contingency Plans* of this document specifies these aspects in more detail and suggests for each scenario how include this topic in National Contingency Plan (NCP).

UAVs are cheaper, smaller, lighter, practical, and more user-friendly than airborne manned systems and satellites. However, the use of one platform does not exclude the others; each has strengths and disadvantages to consider. Depending on these circumstances, it is often advisable to use the three platforms in combination. Strategic planning is based on satellite imagery that provides a synoptic view of the pollutant spill, whereas airborne sensors are used for short-term or tactical responses. Aerial surveillance could be improved significantly by introducing drones because a quick assessment tool for spill accidents.

Drones have been classified based on performance characteristics such as flying height and range, size (wingspan), speed, endurance, landing mechanism, and weight (take-off weight). Bibliographic research focuses on the use of so-called "small drones", i.e., those weighing less than 20 kg and thus including nano, micro and mini drones. Small drones, in fact, are those that are usually used by authorities intervening during an environmental emergency at sea.

Based on airframe, drones are divided into two types: fixed-wing (aeroplane) and rotary-wing (helicopter), usually multi-rotor. However, some fixed-wing aircraft are now capable of Vertical Take-Off and Landing (VTOL). The most popular multi-rotor configurations are quadricopters, hexacopters and octocopters, named on the base of number of rotors that produce thrust.

There are, two primary landing mechanisms, namely Horizontal Take-Off and Landing (HTOL) and VTOL, whose use can be advantageous depending on a number of factors such as: speed and fly time, distance from the base, flight duration, the sensor type aboard, legislation, and lastly the mission objective and the type of information required.

Generally, the fixed-wing UAVs are more stable and can fly longer at higher speeds, hence would cover larger areas in a single mission; however, fixed-wing UAVs are not as flexible as rotary-wing drones and need a runway to facilitate take-off and landing. As these types of drones cannot be launched from ships or other offshore structures, their use in the open sea is limited. Multicopters, on the other hand, have lower speeds and shorter ranges, but can carry heavier payloads and remain operational in high wind conditions, as well as offering better maneuverability and the ability to fly at a constant altitude. Fixed-wing VTOL UAVs, often use a vertical propulsion system at the front of their fuselage and have cross-wings. This type of drones can take off and land vertically and do not need a runway for take-off.

Flight mission planning is a critical aspect of conducting a proper photogrammetric survey of the mission with a UAV. Therefore, flight planning carried out through specific software, consists of the process in determining the area to be flown over, defining the relevant tracks to be followed, and the actions to be performed by the UAV.

A rapid and effective response to acute marine pollution requires a rapid assessment of the extent of the spill and monitoring of its behaviour and fate in the marine and coastal environment. This could be carried out using drones mounting dedicated, suitable, and selected sensor(s). Drone technology stands at the intersection of conventional airborne/spaceborne remote sensing and portable, hand-held sensors/detectors. Accordingly, there are available different sensors specifically tailored for drones, ranging from high-resolution photography and thermal infrared (TIR) cameras to hyperspectral imaging systems, Radio/Light Detection and Ranging (RADAR/LiDAR), Laser technology and gas detectors (sniffers/imagers). It is possible to classify sensors into two categories: passive and active. Passive sensors, such as optical visual sensors, measure the natural radiation that is reflected or emitted by the target materials. Active sensors, such as laser and radar, are those that have their own source of light or illumination. This implies that the active sensors have two major components: an emitter and a detector. Due to the bulk power source and extra hardware required to emit radiation onto the target, the typical weight of active sensor systems is higher than passive sensor systems. Therefore, active sensors are less versatile for use in UAS than passive sensors.

It should be stressed that the choice of a particular sensor depends on a number of factors. These include the target composition (oil vs. HNS), its quantity/concentration range, its spatial extent, the necessity to obtain a quick response, the working time (day vs night) the operating environment (weather, temperature, wind, etc.), cost and, above all, the size, in particular its payload capability. In practice, however, more than one sensor should be used to meet all the requirements of a survey.

One aspect to be considered when planning the use of drones in a marine environmental emergency is the “data processing method”. When deciding on the type of data processing to be used, a number of critical factors need to be considered, namely: the time required for acquisition, the volume of data to be managed, the interchangeability and understandability of the data obtained. Data processing is the manipulation of digital data to produce meaningful information.

Note that the density and frequency of data collection is rapidly increasing with the use of UAS for large-scale surveys. It is therefore challenging to manually review and analyze this volume of data to detect anomalies such as pollutants on the water or along the shoreline. Therefore, automation of data interpretation using specialized computer software tools, supported by artificial intelligence, is required to derive maximum benefit from the collected data.

The document underline the relevance to make available a web server for data collection and user’s management. This approach can be useful when the data are too large to store locally and when multiple users need to access the same data at the same time, as could happen during a maritime emergency.

Over the last decade, the use of drones in oil and HNS spill response has become increasingly common, mainly due to technological developments and the miniaturisation of sensors. In almost all cases, the UAVs have been rotorcraft with visible imaging capabilities and have been used in a number of offshore oil spill incidents.

Considering all the publications consulted, there are advantages and challenges, which are summarised below.

Benefits:

- reassure the public about the development of a response;
- enable coastal monitoring;
- reduced cost and time;
- high versatility along different types of coastline;
- validate contaminant trajectory maps;
- improve worker safety, minimise HSE risks;

Challenges:

- optical equipment limitations;
- regulatory constraints;
- bad weather limitations;
- limited sensor payload;
- short battery life;
- large data management.

As reported in the IRA-MAR project proposal, two projects that tested the use of drones following oil and HNS spills were analyzed: IPoMaC and HazRunoff projects.

HazRunoff project - "*Integration of sensor and modelling technologies for early detection and monitoring of of hazmat and flood hazards in transitional and coastal waters*".
In WP1 Action 1.3 "*Integration of Unmanned Aerial Vehicles*", Cedre, in collaboration with the French authorities and the Port of Nantes-Saint-Nazaire, organized trials of oil spill containment equipment specifically designed to operate in fast-flowing waters. The equipment tests took place in October 2018 and provided an opportunity to assess the benefits of using a drone as an aerial support (e.g. surveillance, data transmission, asset positioning) for response operations in estuarine waters.

The project gives the opportunity to appreciate that drones are useful for many purposes, in particular:

- detecting and tracking slicks on the water;
- guidance of recovery boats to the slicks to facilitate efficient recovery of pollutants;
- facilitating information to the authorities and the command centre through the rapid transmission of images;
- facilitate the rapid delimitation of the pollution on the banks of the estuary through the photomosaic process.

IPoMaC project – “*Intervention sur Pollution Marine par Products Chimques*”

The main objective of the tests carried out as part of the IPoMaC project, led by the French Navy's CEPPOL (*Centre d'Expertises Pratiques de lutte antipollution*), was to evaluate the ability of remote sensing sensors to visualise the presence of chemical spills at sea in a controlled manner. Six chemicals were selected to provide a representative overview of the sensors' detection capabilities: butyl acetate, acetone, heptane, methanol, toluene, and a mixture of xylene isomers. In particular, a FLIR DUO PRO XT2 thermal camera mounted on a quadricopter drone (DJI Matrice M210) was tested and demonstrated its ability to detect all the spills. However, gas detection was not successful. The evaporation process of the products into the atmosphere was only detected by the FLIR E75 42° hand-heald, which was deployed manually from the stern of the ship.

This document therefore describes the RPAS service that is provided free of charge by EMSA (European Maritime Safety Agency) to all EU Member States, Candidate Countries and EFTA Member States, or other Member State Authorities through the European Agencies FRONTEX and EFCA.

In detail, EMSA describes its service as follows:

1. the RPAS service has been developed to support the traditional coastguard functions of maritime surveillance, ship emission monitoring, search and rescue, and pollution prevention and response.
2. The aircraft currently available range in endurance from 6 to 8 hours and in weight from 25 kg to over 150 kg. Three types of RPAS are available to meet different operational requirements:
   - medium size aircraft with “Long Endurance and long or medium-range”;
   - medium size VTOL aircraft;
   - lightweight VTOL aircraft (i.e. quadcopter).
3. RPAS can be used as aerial platforms for sensors such as:
   - optical cameras in the visible and infrared (IR) spectral ranges for night and day maritime surveillance;
   - IR sensors for oil slick detection and analysis;
   - radar for maritime surveillance, and oil spill detection;
   - gas sensors (“sniffers”) to measure of the SO_x levels in a plume emitted by a ship to be able to calculate the percentage of sulphur in the fuel burned by the ship.
4. The RPAS Data Centre (DC) service provides various users with access to archived or real-time collected video and data. The information is provided through the same web interface and combined with other EMSA maritime systems (e.g., CleanSeaNet, EMSA's satellite-based oil spill monitoring and detection system).

5. The following are the main scenarios for which drones are provided by EMSA:

- maritime patrol and general surveillance;
- marine pollution (monitoring and response support);
- surveillance of illegal fishing, anti-drug trafficking, or other illegal activities;
- emission monitoring;
- surveillance of port activities;
- search and rescue.

The last part of this document provides guidance on how to consider the use of drones in a National Contingency Plan (NCP) governing environmental emergencies at sea. Indeed, the use of drones is an activity that cannot be organised at the beginning of an environmental emergency, but must be planned before. The use of drones implies the involvement of various institutions and the mobilisation of personnel and equipment that must be available in the shortest possible time. Drones should be used, particularly, in the survey and monitoring phase, as a complement to the use of satellite data and data from 'conventional' aircraft.

With regard to the use of drones, the NCP must therefore contain:

- objectives and use of the data obtained;
- possible scenarios;
- institutions involved;
- type of drones and sensors to be used;
- their location;
- the procedures to be followed and the time required for the operation.

The NCP must clearly identify the authority responsible for monitoring and coordinating the use of drones. In this context, it is necessary to specify that there are two possible approaches to the management of the drone fleet:

1. The competent authority establishes a branch (UAS service)
2. The management of the fleet of drones is entrusted to one or more private companies, which are activated in the event of an environmental emergency

The NCP must consider the procedures to be followed so that the drones can be effectively deployed in the shortest possible time once an environmental emergency has started. Basically, 7 steps can be defined schematically:

Step 1 - Define the scope of the intervention.

Step 2 - Asses the field conditions.

Step 3 - Estimate the flight distance or area and distance from land.

Step 4 - Review international and national regulation.

Step 5 - Select the platform and sensor payload.

Step 6 - Select data processing tools.

Step 7 - Apply for permission to operate

1 The state-of-the-art in the use of drones in marine environmental emergency: purposes and objectives

1.1 Objectives

The overall objective of the use of drones during a maritime environmental emergency involving the spillage of hydrocarbons or other HNS is to improve the effectiveness of the response in terms of the time and quality of the acquisition of the information needed to understand the event, its extent and to rapidly define the best counter-strategies.

This paper reports on the results of a bibliographic search aimed at identifying the Best Available Technologies (BATs) for monitoring an area affected by a spill of oil or other HNS at sea. The BATs are presented on the basis of the types of drones, sensors, navigation software and post-processing software that can be used.

It is important to emphasise that the bibliographic research focuses on the use of so-called "small drones", i.e. those weighing less than 20 kg, which includes nano, micro and mini drones (see ***Errore. L'origine riferimento non è stata trovata.Errore. L'origine riferimento non è stata trovata.****"Drones categorization(…)"*). In fact, small drones are those usually used by the authorities intervening in the event of an environmental emergency at sea, and therefore the authors consider it more appropriate to indicate how to optimise their use.

The use of drones in maritime emergency response must have the following objectives:

- improve response capacity to marine pollution incidents by standardising UAS-based surveys;
- facilitate the inspection of remote areas, reducing the risk of exposure to pollutants;
- provide guidance for the production of georeferenced thematic cartography for use by authorities;
- develop synergies and information sharing between maritime authorities and civil protection for the use of UAS in coastal areas;
- notify, inform, and reassure the public about the development of an emergency response, providing photographic and video evidence.

1.2 Scenarios

Keeping in mind the objectives for which the use of drones is advisable, schematically, the following scenarios can be identified in which UAVs can be employed, following a spill of oil or HNS:

- detection and tracking of pollutant slicks/drums/containers on water, verifying extension, volume and drifting;
- guidance of the recovery boats toward the slicks to facilitate an efficient collection of pollutants as well as examination of pollutant response equipment conditions and efficiency;
- identification and mapping atmospheric plumes of pollutants;
- inspection of remote areas (e.g., cliffs shoreline, estuarine areas, remote islands);
- survey a dangerous environment, where human health would be put at risk;
- SCAT - Shoreline Monitoring and Assessment Technique producing cartography through the application of photogrammetry techniques;
- monitoring of wildlife populations to verify their size and distribution and to check their risk of contamination.

There is no ideal drone/sensor/software asset for all scenarios; as an example, the setups needed may be different if:

- a survey must be carried out on open seas or along the coast;
- the pollutant is oil or an HNS;
- the intervention is at night or during the day;
- specific detailed observations or a survey of a large area is required;
- the use of a sensor with a high payload is required.

Chapter *6 The integrated response to pollution accidents: the use of drones in maritime Contingency Plans* specifies these aspects in more detail and suggests the best available assets for each scenario.

1.3 Drones vs airborne manned systems and satellites

Among their many uses, UAVs can be employed for earth observation, agriculture, environmental monitoring and sampling, general scientific research, meteorology, etc.. UAVs are cheaper, smaller, lighter, more practical, and easier to use than any other earth observation equipment. In addition to their ability to provide a variety of equipment with economic efficiency as a mobile operator, they are preferred by researchers for their many other features, such as their ability to provide high-resolution imagery without requiring large organisations in confined spaces. Recent developments and environmental entrepreneurship in UAV technology have created a new paradigm in the field of geo-information technologies (*Colomina et al., 2008*). Drones can overcome some of the limitations of other means of aerial and in-situ observation. They can provide a possible alternative to traditional manned and satellite platforms for the acquisition of high-resolution remote sensing data at lower cost, with greater operational flexibility and versatility (*Domaille and Campion, 2018*).

While the manned airborne systems are more flexible and can provide datasets with higher spectral and spatial resolution, they are resource-intensive and costly, making them unsuitable for the repeated data acquisitions desired for monitoring purposes. The use of small unmanned aerial platforms dramatically reduces costs. However, satellite observations can be limited by the spatial and spectral resolution of the sensor, atmospheric conditions, revisit time and cost. High spatial resolution satellite data are now available, but the high-resolution (< 10 cm) and frequent, flexible overflights offered by drone sensors are more suitable for a wide range of applications, such as tracking oil slicks (*Klemas, 2015*).

In early environmental impact assessment, UAS can replace low altitude manned aircraft and collect high-resolution aerial imagery, video, and point cloud data to produce dense topological maps and 3D models of the area of interest. In addition, it is often unsafe to frequently deploy manned aircraft (helicopters) to survey, identify and locate HNS leaks. These limitations can be mitigated by deploying UAS equipped with appropriate sensor payloads, which may include highly sensitive optical, multi-spectral and gas detection sensors to effectively detect and locate gas leaks (*Wanasinghe et al., 2020*).

UAS can fly at altitudes of 75-100 meters, whereas conventional manned aircraft must fly at altitudes of 500-1500 meters. Combining the lower altitude with tighter grid patterns, the UAS can acquire the geophysical measurements at high-resolution. The UAS's onboard sensors can map and reconstruct the damaged facility or vessel in 3D, allowing the response team to identify safe entry and exit points and routes to rescue trapped personnel. Real-time video (visual and thermal) feedback from the UAS would assist the emergency responder in assessing the condition of the field personnel and the situation around them in order to prioritise rescue attempts (*Wanasinghe et al., 2020*).

On the other hand, recent developments in sensor technology (i.e., miniaturisation) and navigation systems have made drones a powerful and reliable basis for professional data collection. Drones provide a versatile and flexible platform that can be equipped with any type of sensor to characterise a target in real-time, day or night. Operating at low altitudes (i.e., <120m), they are not obstructed by clouds and therefore remain available for surveillance at all times. Drones could be easily deployed from virtually any platform on land or at sea (e.g., cars, ships/vessels, etc.) (*Asadzadeh et al., 2022*).

Due to the dynamic nature of a marine pollution incident (e.g., an oil spill), the timely delivery of remote sensing data is considered critical. Responders on the ground need to know the exact locations of the slicks in order to plan countermeasures more effectively and reduce the impact of the pollution: this gap can be largely filled by drone-based remote sensing. Drone technology could, to a large extent, replace or augment the current manned systems (e.g., helicopters) used for aerial surveys of spills, reducing safety risks while improving the efficiency of collecting critical data during an emergency response (*Allen and Walsh, 2008*).

A number of factors are expected to hinder the industry-wide application of this technology. These include the accessibility of the appropriate sensor system (due to high prices), weight constraints of the UAV payload (prohibiting the attachment of specific sensors or a large number of sensors), battery life and flight time, weather constraints (e.g., wind, humidity, ambient temperature, dust and rain), scalability issues, and regulatory barriers (e.g., line-of-sight rules) (*Asadzadeh et al., 2022*).

In conclusion, the use of one platform does not exclude the others; each has strengths and disadvantages to consider (*Table 1-.1-1*). Depending on these circumstances, it is often advisable to use the three platforms in combination. In addition to their advantages in hazardous conditions, UAVs then provide a tool that complements other remote sensing technologies (*Özdemir et al., 2014)*. A combination of satellite and airborne sensors is used for oil spill monitoring in many countries in northern Europe. Strategic planning is based on satellite imagery, which provides a synoptic view of the oil spill, while airborne sensors are used for short-term or tactical responses.

Table 1-.1-1 Summarising the comparison of the three platforms.

Characteristics	Satellite	Manned airplain	Drone
Costs	High	High	Low
Difficulties for deployment	High	High	Low
Resolution data	Low	Medium	High
Covered area	Wide	Medium	Limited
Relevance of cloud cover	High	Medium	Poor
Risks in dangerous environment	None	High	Scarse
Repeatability of overflight	Periodic	Intermittent	Continuous
Payload	High	High	Low
Response time	Medium	High	Short

For rapid response and intervention, EMSA has proposed the use of drones as a complementary system to satellite maritime surveillance (see *paragraph 5.3*). Aerial surveillance could be significantly improved by the introduction of drones as a rapid assessment tool for oil spills.

References Cap. 1

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2 Drones typologies

An UAV consists of a flying platform, the navigation system and the sensor(s) to achieve the mission objective, together with the acquisition and transmission of data (details of sensors are given in *Chapter 3*).

Drones have been classified based on performance characteristics such as flight altitude and range, size (wingspan), speed, endurance, landing mechanism, and weight (take-off weight) (*Shakhatreh et al., 2019*). Based on weight, drones are generally categorised into three classes. Class I is then divided into four categories. The classification based on weight and range may differ from country to country (*Table 2-1*).

Table 2-1. Drones categorization based on their weight and maximum range (Hassanalian and Abdelkefi, 2017; Wanasinghe et al., 2020).

Class	Type	Weight range (kg)	Maximum range (km)
Class I (a)	Nano drones	W ≤ 0,2	5
Class I (b)	Micro drones	0,2 < W ≤ 2	25
Class I (c)	Mini drones	2 < W ≤ 20	40
Class I (d)	Small drones	20 < W ≤ 150	150
Class II	Tactical drones	150 < W ≤ 600	150
Class III	Strike drones	W > 600	1500

Watts *et al.* (2010) described a wide range of platforms. They classified drone platforms for civil, scientific and military use based on characteristics such as size, endurance and capabilities. Their classification of drones *(Figure 2-1)* included MAVs (Micro or Miniature Air Vehicles), NAVs (Nano Air Vehicles), VTOL (Vertical Take-Off and Landing), LASE (Low Altitude, Short-Endurance), LASE Close (Low Altitudes Short-Endurance, specifically are small UAS that require runways, but whose larger size and weight confer increased capabilities), LALE (Low Altitude, Long Endurance), MALE (Medium Altitude, Long Endurance) and HALE (High Altitude, Long Endurance).

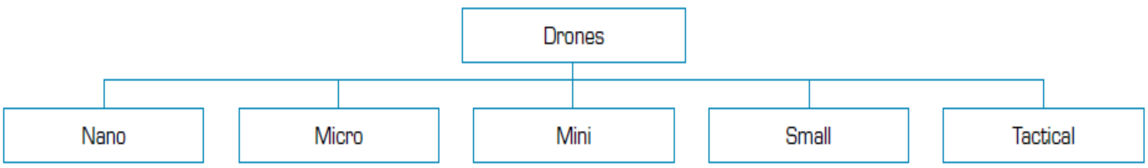


Figure 2-1. Diagram on categorization of UAVs based on size.

The 2-2 refers to another classification of different categories of drones, again based on size types: micro unmanned aerial vehicle (μUAV), Micro Air Vehicle (MAV), Nano Air Vehicle (NAV) and Pico Air Vehicle (PAV). In general terms, as mentioned above, this document refers to small UAVs as a whole: aircraft typically less than 200 cm in length and less than 5 kg in weight (in particular s and MAVs).

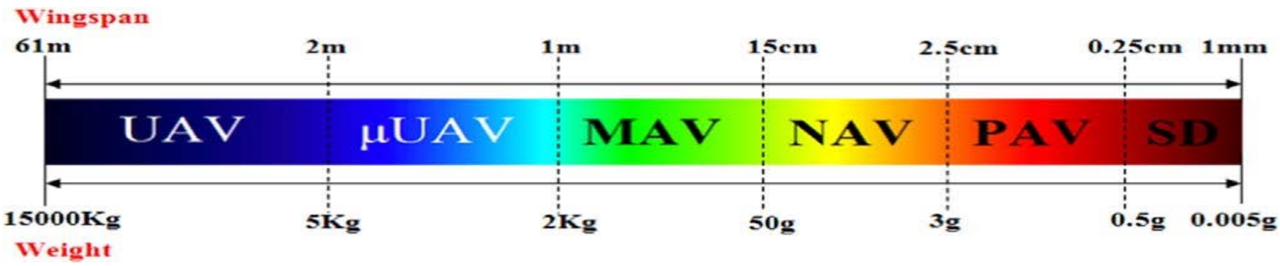


Figure 2-2. UAV Classification scheme by size (source: Hassanalian and Abdelkefi, 2017).

One of the important advantages of MAVs compared to other drones, such as UAVs, is their small size, which allows them to fly in confined spaces (*Joshi, 2015*). This is particularly true for rotorcraft MAVs, which can hover and have high manoeuvrability (*Schauwecker, 2012*).

The smaller UAVs could be hand-launched, while the larger ones are more suitable for long-endurance flights and larger payloads. Their sensor carrying capacity (payload) is proportional to their size (*Klemas, 2015*). The smaller platforms can therefore be easily deployed (hand-launched), while the others are more suitable for endurance flights and larger payloads (*Pereira et al., 2009*).

Based on the airframe, drones are divided into two types: fixed-wing (aircraft) and rotary-wing (helicopter), usually multi-rotor.

However, some fixed-wing aircraft can now perform VTOL (*Hassanalian and Abdelkefi, 2017*). The most popular multi-rotor configurations are quadricopters, hexacopters and octocopters, named after the number of rotors that generate thrust.

UAS use two primary landing mechanisms, namely Horizontal Take-Off and Landing (HTOL) and VTOL. HTOL UAS can have a very high cruising speed, but they are difficult to manoeuvre for landing on a specific point and their vertical movement or hovering is not possible. In contrast, VTOL UAS can fly, land and hover vertically, but are not suitable for higher cruising speeds (*Wanasinghe et al., 2020*).

The vast majority of drones (~96%) use batteries as a power source. The lightweight platforms for civil applications (class I(b) and I(c)) typically have a flight endurance of <1 h (typically 5-30 min) at an altitude of <250 m, with a maximum range of about 10 km. The major constraint on the flight endurance of these platforms is, of course, the battery supply. For this reason, there is an increasing demand for technological advances in battery capacity. Recently, the low energy density of current batteries (even the high-end lithium polymer ones) has led some developers/users to turn their attention back to gasoline or hybrid propulsion systems as an alternative source of electric power for drone platforms.

There are also other less common types such as ducted fan, flapping wing and other rotary-wing, etc. Today, there are several types of hybrid drones, including tilt-rotor, tilt-wing, tilt-body and ducted fan UAVs. In tilt-rotor UAVs, the rotors are initially vertical in vertical flight, but are tilted forward by 90° for cruise flight. In tilt-wing UAVs, the engines are usually attached to the wings and tilt with the wing. In this type of UAV, the angle of the entire wing is changed from zero to 90° to change the flight mode from horizontal to vertical. Both configurations flew successfully as drones, but the tilt-rotor UAV was the most efficient at hovering and the tilt-wing UAV was the most efficient at cruising.

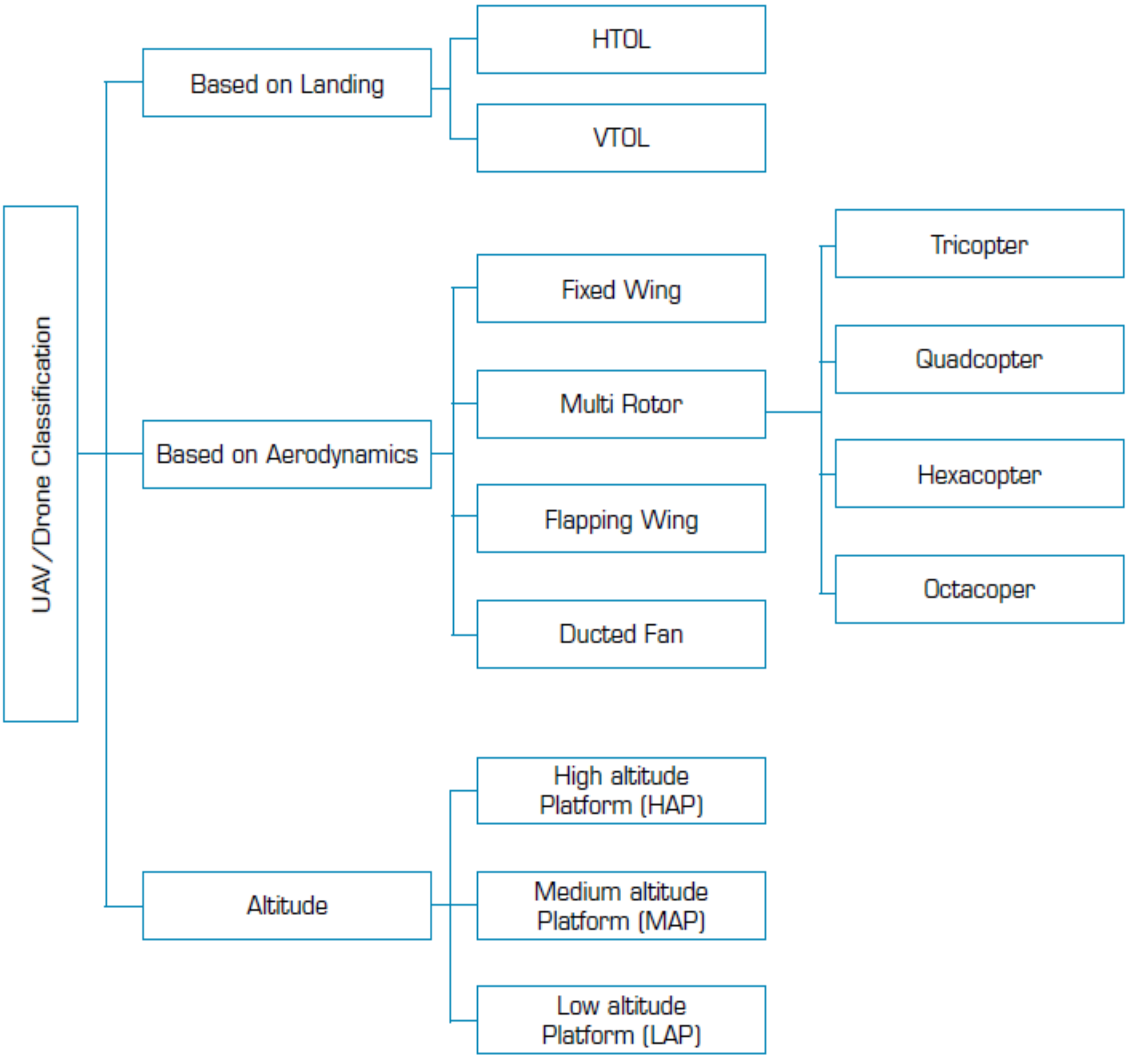


Figure 2-3. Different typologies of drones based on Landing, Aerodynamics and Altitude.

The free wing tilt-body UAV is a new type of drone, different from fixed-wing and rotary-wing drones. It is neither fixed-wing, nor rotary-wing, nor any combination of the two. In this type of UAV, the wing is completely free to rotate around the pitch axis and the fuselage is a lifting body. Both the left/right wing pair and the central lifting body are free to rotate about the spanwise axis, free with respect to the relative wind and free with respect to each other. The tilt-body is also an unconventional attachment of a boom type to a fuselage in such a way that it changes its angle of incidence relative to the fuselage in response to external commands. The advantages of this type of

UAV are Short Take-Off and Landing (STOL), low speed hovering, and reduced sensitivity to centre of gravity (CG) variations (*Ro et al., 2010*).

The ducted fan UAVs are drones in which the 'engines' are enclosed in a duct. The engine of these drones is called a 'fan'. This fan consists of two contra-rotating elements to minimise the rotation of the body by a resulting torque. Ducted fan UAVs can not only take off and land vertically, but can also hover and be controlled by two counter-rotors and four control surfaces (vanes) (*Austin, 2011*; *Ko et al., 2007*). Although the transition to and from cruise flight is easy, flow separation from the duct is a concern (*Austin, 2011*).

*Figure 2-4 Different types of UAVs, (a) HTOL, (b) VTOL ,(c) tilt-rotor UAV, (d) tilt-wing UAV , (e) tilt-body UAV, (f) ducted fan UAV, (g) helicopter, (h) heli-wing, and (i) unconventional UAV (*source: *Hassanalian and Abdelkefi, 2017).*

Today, researchers are designing and building various types of unmanned helicopters for vertical take-off, landing and hovering flight. There are four types of helicopter UAVs, namely single-rotor, coaxial-rotor, tandem-rotor and quad-rotor. Heli-wing UAVs are other types of drones that use a rotating wing as a blade. They can fly vertically as helicopters and also as fixed-wing UAVs (*Pace 2003*; *Sing et al., 2006*).

UAVs that do not fit into previously defined categories are considered unconventional UAVs. Bio-inspired flying robots are usually included in this group. For example, the FESTO AirJelly, which was inspired by jellyfish.

2.1 Fixed-wing UAVs vs rotary-wing UAVs

The choice of drone depends on a number of factors, including the area to be covered, the distance from the base, the flight time, the type of sensors carried, the terrain, the legislation and, finally, the objective of the mission and the type of information required. In general, fixed-wing UAVs are more stable and can fly longer at higher speeds, allowing them to cover larger areas in a single mission. For this reason, fixed-wing UAVs are considered the ideal choice for aerial surveys (e.g., photogrammetry). In most cases, fixed-wing UAVs are available at a higher cost than rotary-wing UAVs (*Asadzadeh et al., 2022*).

However, fixed-wing UAVs are not as flexible as rotary-wing drones and require a runway to facilitate take-off and landing. In contrast, multi-copters have lower speeds and shorter flight ranges, but can carry heavier payloads and remain functional in strong wind conditions, in addition to offering better manoeuvrability and the ability to fly at a constant altitude (*Asadzadeh et al., 2022*). Thus, the most attractive advantage of using multi-copters is the ability to fly at a constant altitude and also to hover at a single location while directing its orientation to a desired target (*Wanasinghe et al., 2020*). Therefore, rotary-wing UAVs are much more accessible to small businesses and the general public (*Domaille and Campion, 2018*).

Unmanned helicopters are available in many different configurations. One popular, stable design is the quadcopter, a multi-rotor helicopter that is lifted and propelled by four rotors. Quadcopters use two sets of identical fixed-pitch propellers: two that rotate clockwise and two that rotate counterclockwise. Control of the vehicle's motion is achieved by changing the rate of rotation of one or more of the rotor discs, thereby altering their torque load and thrust/lift characteristics. Quadcopters use an electronic control system and electronic sensors to stabilise the aircraft. They have several advantages over single-rotor helicopters. The four-rotor design allows quadcopters to be relatively simple in construction, yet highly manoeuvrable and reliable. They do not require mechanical linkages to vary the pitch angle of the rotor blades as they rotate. This simplifies the design and maintenance of the vehicle. The use of four rotors allows each rotor to have a smaller diameter than the equivalent helicopter rotor, minimising damage in the event of a crash. Typical flight times are in the tens of minutes before the battery needs recharging. Quadcopters are the most commonly used UAVs due to their vertical landing or rapid manoeuvrability, low-cost and compact size. Hexacopters and octocopters can carry heavier cameras, cost tens of thousands of dollars and are often used in film/TV applications. New systems capable of carrying multi-spectral, hyperspectral imagers or RADAR/LiDAR sensors are being developed to observe specific details of an oil spill (e.g., accumulation of pollution in remote coastlines) (*Asadzadeh et al., 2022*; *Klemas, 2015*).

Fixed-wing VTOL UAVs often use a vertical propulsion system at the front of the fuselage and have cross-wings. This type of UAV can take off and land vertically and does not require a runway for take-off. In the hovering flight mode, VTOL drones are more efficient than HTOL ones. They are limited in cruise speed due to the stalling of the retractable wings, but typically longer-range missions require UAVs with higher cruise speeds. However, the ability to take off and land vertically is valuable. These limitations have led to the idea of having a type of UAV that combines the capabilities of both VTOL and HTOL types (*Austin, 2011*).

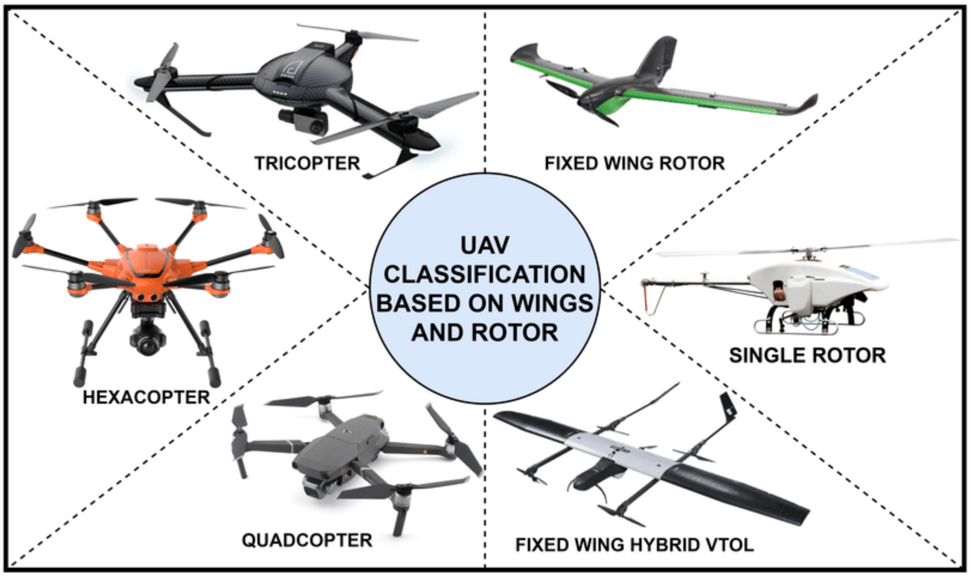


Figure 2-5 Classification of UAV-based on wings and rotors (source: Chamola et al., 2021)

Figure 2-6. An example of fixed-wing VTOL UAV (https://wingtra.com/)

Table 2-2 Recap of unmanned aerial vehicle classification based on size, range, properties and applications.

Type	Weight range (Kg)	Operating alt. (m)	Range (km)	Payload (kg)	Flight time (min)	Example model	Flying mechanism	Description	Applications
Nano	W ≤ 0,2	< 120	5	< 0.2	28-30	DJI Mini/2,3,SE DJI Mini 3 PRO EVO Nano + Kogan Nano	Multi-rotor	Easily manoeuvred and reach remote locations	Recreation
Micro	0,2 < W ≤ 2	< 120	47 30 7,5	0.2–0.5	90 45 60	eBee X eBee Geo Trinity F90+	Fixed-wing Fixed-wing VTOL	Operated on low altitudes with limited space for fuel and battery	Recreation, Military Spying task Survey
Mini	2 < W ≤ 20	< 120	32 / 15 25	0.5– 2,7	45 55 41 40	DJI Mavic 3 E DJI MATRICE DJI M30 Autel EVO Pro II	Multi-rotor	Maintain line of sight between the aircraft and the ground station.	Photography and Media, Military, Spying task, Survey
Small	20 < W ≤ 150	< 1500	150	5.0– 50.0	180	Scout- B330 UAV Helicopter	Multi-rotor	Operated at low to medium altitudes and longer loiter capabilities	Transferring goods Military, used in remote locations
Tactical	150 < W ≤ 600	< 3000	200	25.0– 200.0	1800	Predator B	Fixed-wing	Operated at high altitudes, provide tracking or monitoring	Armed investigation Target acquisition

2.2 Features of drones for a good maritime survey

The main characteristics of the different types of drones that need to be considered when using them in a maritime survey are highlighted below: the considerations apply to all small UAVs.

Speed and flight time.

Small UAVs can fly at speeds of less than 15 m/s. In contrast, large UAVs can fly at speeds of up to 100 m/s. If a UAV is to follow an intended trajectory to increase its spectral or energy efficiency, its speed needs to be properly checked at different turning points of that trajectory (*Rosa et al., 2010*). While the flight time of a UAV refers to the maximum time, it can fly until its battery is discharged. Size, weight, and weather conditions have a strong influence on the battery life of UAVs: the flight time of a UAV is of paramount importance, along with cost and price. Large UAVs can fly for hours, while smaller UAVs have a limited flight time of 20-30 minutes. Flight time is also affected by the autopilot system and GPS (Global Positioning System).

Landing and take-off

This is a very important aspect to consider, especially if a survey is to be carried out in impervious areas where there are no flat areas or runways where drones with horizontal take-off could fly. This type of drone also has limited use in the open sea, as it cannot be launched from a ship or other offshore structure.

Hovering

Helicopters have a major advantage over fixed-wing aircraft in that they can hover over a target area, descend for closer inspection, and change altitude to provide imagery for mapping at preferred spatial resolutions (*Klemas, 2015*). This is also a distinct advantage for inspections in confined areas.

Payload

Payload refers to the lifting capacity of a UAV to carry any load. The payload can vary from a few grams to hundreds of kilograms. A larger payload can carry more accessories at the cost of short flight time, high battery consumption and larger size. Common payloads are sensors and video cameras used for surveillance, reconnaissance or commercial applications. UAVs can also carry cellular user equipment, including mobile phones or tablets weighing less than 1 kg. Heavy payloads are expected to reduce the endurance of UAVs. However, if a UAV has more surface area and carries more engines, it can store more energy, which ultimately increases flight time. Thus, the quality of the payload can contribute to a longer flight for the same accuracy and resolution (*Watts, 2010*).

Range and altitude

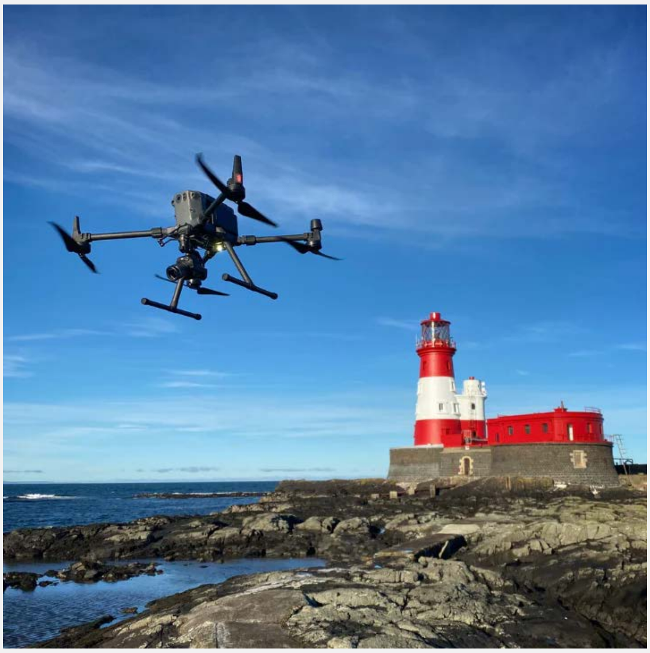
The range of a UAV refers to the distance from which it can be remotely controlled. Range varies from a few meters for small drones to hundreds of kilometers for larger drones. Altitude, on the other hand, refers to the height at which a drone can fly.

Table 2-3. Characteristics of different small UAVs

Characteristics	Fixed-wing	Rotary-wing		Hybrid
		Quad-copter	Exa/octo-copter	
Energy efficiency	High	Low	Low	High
Flight system	Complicated	Simple	Simple	Complicated
Length	< 2 m	< 80 cm	< 80 cm	< 2 m
Fly time	< 60 min	30-40 min	30-40 min	< 60 min
Range	< 10 km	< 3 km	< 3 km	< 7 km
Landing	Horizontal	Vertical	Vertical	Vertical
Deploying from ship	No	Yes	Yes	Yes
Hovering	No	Yes	Yes	Yes
Payload	3-5 kg	1-2 kg	3-5 Kg	3-5 kg
Costs	Medium/high	Medium	High	High
Scenarios	• Detection/ tracking pollution • Survey danger environment • Shoreline monitoring	• Detection/tracking pollution • Guidance recovery pollutants • Survey confined areas • Shoreline monitoring • Inspection of remote areas • Wildlife monitoring	• Detection/tracking pollution • Guidance recovery pollutants • Survey confined areas • Shoreline monitoring • Inspection of remote areas • Wildlife monitoring • HNS gas identification	• Detection/tracking pollution • Guidance recovery pollutants • Survey danger environment • Shoreline monitoring • Inspection of remote areas • Wildlife monitoring • HNS gas identification

2.2.1 Drone sheets

This section contains sheets related to the characteristics of the main small drones, selected on the basis of their airframe a landing mechanism.

Brand and Model	**DJI MATRICE 300**
	 https://www.dji.com/it/matrice-300
Type of drone	Multi-rotor
Technical characteristics	General description: The Matrix 300 RTK is inspired by advanced aviation systems. The system is equipped with advanced artificial intelligence capabilities, 6 sensing and positioning sensors. The Matrix 300 RTK sets a new standard in intelligence and reliability combined with advanced performance. The OcuSync Enterprise system enables image transmission up to 15 km and supports 1080p video over the frequency channel. Automatic selection between 2.4 GHz and 5.8 GHz enables more reliable flight in high-interference environments, and AES-256 encryption ensures secure data transmission. M300 RTK is equipped with a Primary Navigation Display (PFD) that combines flight data, navigation and obstacle information to enhance the pilot's awareness of the airspace in which he is moving. RTK positioning: GPS+Galileo+BeiDou+GLONASS Payload: The M300 RTK UAS can meet different operational needs. It can carry up to three payloads simultaneously, with a maximum weight of 2.7 kg. The Matrix 300 can accommodate the following solutions: • integrated LiDAR + survey-grade RBG for true-colour point clouds • 45 MP full-frame sensor with 3 lens options for photogrammetric flight missions • hybrid sensor with LRF, zoom and wide-angle camera • hybrid sensor with LRF, zoom, wide-angle and thermal camera • sensor consisting of two zoom cameras and a laser distance detector

Brand and Model	**DJI MATRICE 300**
	• third party payloads Flight autonomy: Enhanced flight performance 55 min flight autonomy - 15 m/s Wind resistance - 7 m/s Maximum descent speed - 23 m/s Maximum speed. Flight planning software: DJI Pilot is the flight planning software. With enhancements designed specifically for the M300 RTK series, DJI Pilot optimises flight functionality to ensure flawless performance when planning and managing flight operations. DJI FlightHub 2 is a flight operations management solution designed to organise and simplify complex operational tasks. Compatible with M300 RTK drones, FlightHub 2 can be integrated directly into the drone fleet to unleash its potential in all types of operations.

Brand and Model	**DJI MATRICE 30**
	 https://www.dji.com/it/matrice-30
Type of drone	Multi-rotor
Technical characteristics	General Description: The DJI Matrice 30 integrates multiple high-performance sensors into a single payload. Its size makes it easy for manual transport and quick setup. The M30 series is available in two versions, the M30 and the M30T. The M30 integrates a camera with a CMOS sensor. The M30T has an additional radiometric thermal camera. The Matrix 30 is compatible with the DJI Dock autonomous take-off, landing and charging station, which enables programmed and fully automated flights with the DJI M30 series (dock version). Once set up, the fully charged M30 drone can take off from the DJI Dock using FlightHub 2 programmed automated missions anywhere within a 7km radius. 4 built-in antennas support OcuSync 3 Enterprise, which enables triple-channel 1080p video transmission and easy swapping of input feeds, even in complex environments. Supports connection to DJI Cellular Module 4, which provides stable video transmission even in complex or remote operating environments. RTK positioning: GPS+Galileo+BeiDou+GLONASS Payload: 30 Series Matrix integrates wide-angle, zoom and thermal (M30T only) cameras with a laser rangefinder.

Brand and Model	DJI MATRICE 30
	<table><tr><td>Wide-angle camera</td><td>Equivalent focal length: 24 mm, DFOV: 84° 12 MP 1/2'' CMOS sensor Video resolution: 4K/30fp</td></tr><tr><td>Zoom camera</td><td>48 MP 1/2'' CMOS sensor 5x-16x optical zoom 200x Max. hybrid zoom Photo resolution: 8K Video resolution: 4K/30fps</td></tr><tr><td>Thermal imaging camera</td><td>Equivalent focal length: 40mm Resolution: 640×512 Frame rate: 30 fps Measurement accuracy: ±2°C or ±2%[5]</td></tr><tr><td>Laser distance detector</td><td>Radius: 3 m - 1200 m Accuracy: ±(0.2 m + D × 0.15%)[6]</td></tr></table> Flight autonomy: Enhanced flight performance 41 min Flight autonomy - 15 m/s Wind resistance - 23 m/s Maximum speed. Flight planning software: DJI Pilot is the flight planning software. With enhancements designed specifically for the M30 RTK series, DJI Pilot optimises flight functionality to ensure good performance when planning and managing flight operations. DJI FlightHub 2 is a flight operations management solution designed to organise and simplify complex operational tasks. Compatible with M30 RTK drones, FlightHub 2 can be integrated directly into the drone fleet to unleash its potential in all types of operations.

Brand and Model	DJI MAVIC 3 ENTERPRISE
	 https://www.dji.com/it/mavic-3-enterprise
Type of drone	Multi-rotor
Technical characteristics	General description: The DJI Mavic 3 has a maximum range of 15 km. DJI O3 Enterprise Transmission allows Mavic 3 Enterprise drones to fly farther and transmits signals with good stabilisation. DJI RC Pro Enterprise is a professional RC with a 1,000

Brand and Model	**DJI MAVIC 3 ENTERPRISE**
	nits high-brightness screen for clear visibility in direct sunlight and a built-in microphone for clear communication. The Mavic 3 Series UAS are equipped with an RTK module that provides pinpoint accuracy with support for network RTK, custom network RTK services and the D-RTK 2 mobile station. Three models are available: • The DJI Mavic 3E enables highly efficient mapping and surveying missions without the need for ground control points • The DJI Mavic 3T is designed to meet the specific needs of aerial firefighting, search and rescue, inspection and night missions • The DJI Mavic 3M is equipped with an RGB camera coupled with a multi-spectral camera with 4 lenses (Green (G), Red (R), Red Edge (RE), Near InfraRed (NIR)) RTK positioning: GPS+Galileo+BeiDou+GLONASS Payload: 30 Series Matrix integrates wide-angle, zoom and thermal (M30T only) cameras with a laser rangefinder.

	DJI Mavic 3E	DJI Mavic 3T	DJI Mavic 3M
Wide-angle camera	4/3 CMOS, effective pixels: 20 MP	1/2" CMOS, effective pixels: 48 MP	4/3 CMOS, effective pixels: 20 MP
Telephoto lens	100-6400	100 – 25600	/
Thermal imaging camera	/	≤50 mk a F1.1	/
Multi-spectral camera	/	/	1/2.8" CMOS, effective pixels: 5 MP 4 bands

	Flight autonomy: Enhanced flight performance 45 min Flight autonomy - 15 m/s Wind resistance - 12 m/s Maximum speed. Flight planning software: DJI Pilot is the flight planning software with enhancements specifically designed for the Mavic 3 Enterprise. DJI FlightHub 2 is the complete flight management solution, designed to organise and simplify complex operational tasks. Compatible with Mavic 3 Enterprise drones, FlightHub 2 can be integrated directly into the drone fleet. DJI Terra is a PC application software based on 2D orthophotos and 3D model reconstruction, with features such as 2D multi-spectral reconstruction, LiDAR point cloud processing and detailed inspection missions.

<table>
<tr><td>Brand and Model</td><td>AGEAGLE AERIAL SYSTEMS INC. XBEE X</td></tr>
<tr><td></td><td>
https://ageagle.com/drones/ebee-x/</td></tr>
<tr><td>Type of drone</td><td>Fixed-wing</td></tr>
<tr><td>Technical characteristics</td><td>General description: The eBee X is an advanced fixed-wing drone designed to meet all surveying and mapping needs, from small areas to large areas. The eBee X can collect data without Ground Control Points (GCPs) while maintaining a GSD of up to 1.5 cm/0.6 inches and can cover an area of up to 500 ha / 1. 235 ac. The eBee X fixed-wing photogrammetric drone weighs approximately 1.6 kg and meets the highest standards of various industries. The eBee X drone features the FAA-approved integrated remote ID system and European Union Class C2 identification label. The eBee X is the first drone to receive M2 mitigation design verification for the SORA process from the European Union Aviation Safety Agency (EASA), which is required to obtain SORA authorisation for Beyond Visual Line-of-Sight (BVLOS) and Operations Over People (OOP) missions in Europe.
RTK/PPK positioning: 1.5 cm / 0.6 inch absolute accuracy
Payload: The eBee system is compatible with 3D, RGB, multi-spectral and thermal cameras.
<table>
<tr><th>Sensor</th><th>Characteristics</th></tr>
<tr><td>S.O.D.A. 3D camera</td><td>Photogrammetric sensor optimized for 3D mapping applications</td></tr>
<tr><td>Aeria X</td><td>High-resolution camera for precision mapping</td></tr>
<tr><td>S.O.D.A.</td><td>Photogrammetry sensor optimized for drone applications</td></tr>
<tr><td>Corridor</td><td>Portrait-oriented camera for optimized linear mapping</td></tr>
<tr><td>Duet T</td><td>Dual-purpose thermal and mapping camera</td></tr>
<tr><td>Duet M</td><td>Dual-purpose RGB and multi-spectral camera</td></tr>
</table>

Fly autonomy: 90 minutes flight time.
Flight planning software: The eBee drone comes with flight planning software called eMotion 3, thatcan manage multiple drones simultaneously. The entire workflow results in automated data acquisition:</td></tr>
</table>

Brand and Model	AGEAGLE AERIAL SYSTEMS INC. XBEE X
	• Flight plan creation • Autonomous acquisition of georeferenced data • Postflight process (PPK) • Post-processing and analysis

Brand and Model	WINGTRA - WINGTRAONE GEN II
	 https://wingtra.com/mapping-drone-wingtraone/
Type of drone	Fixed-wing VTOL
Technical characteristics	The WingtraOne GEN II is a fixed-wing drone designed for centimeter-precision mapping and surveying. It uses a combination of state-of-the-art technologies, including PPK technology, to capture highly detailed information about structures and the surrounding terrain. The VTOL drone can fly at speeds of up to 60km/h and has an endurance of approximately 59 minutes. It has a wide flight range, with a maximum area of 400 ha per flight. It can collect data without GCPs, while maintaining a GSD of up to 0.7 cm/px (0.3 in/px). It also incorporates an automatic landing system, making it easy-to-use even in confined or hard-to-reach areas. One of the unique features of the WingtraOne GEN II is its interchangeable lens camera, which allows users to choose the camera that best suits their specific sensing needs. In addition, the drone's integrated software simplifies the process of flight planning, data acquisition and subsequent processing.
Payload	The Remotely Piloted Aircraft Systemis compatible with oblique, RGB, and Multi-spectral cameras.

Brand and Model	WINGTRA - WINGTRAONE GEN II
	Sony RX1R II: For high-accuracy surveys, Sony's 42 MP full-frame sensor guarantees superior image resolution for a drone camera, while the low distortion lens ensures the best reconstruction results. Sony a6100: The a6100 camera from Sony offers the best combination of accuracy and coverage for an affordable price. Oblique Sony a6100: Optimized to map vertical structures, the Oblique Sony α6100 allows you to generate high-resolution 3D meshes with centimeter-level accuracy. MicaSense RedEdge-P: The MicaSense RedEdge Panchromatic (RE-P) is a premium multi-spectral camera, which combines a panchromatic sensor with five narrow bands to produce high-resolution multi-spectral and RGB from one flight for advanced analytics.
WingtraPilot flight planning software	• Automatic Terrain following • Flight planning software capable of planning multiple separate surveying areas at once • Flight planning software capable of importing custom terrain models (DEM) for up-to-date terrain following
Hardware characteristics	• Weight below 4.5kg • Wingspan 1.25 m for easy portability • Wings non-detachable for robustness and reliability • Glass-fibre body for superior aerodynamics and more stable flight
Performance characteristics	• Cruise speed 60 km/h+ • Horizontal Absolute Accuracy below 2cm when using PPK • Fully autonomous flight incl. take-off and landing • Flight distance in 1 flight 50km+ • Telemetry range 6km+

2.3 Flight planning software

Flight planning is a very important aspect of conducting a proper survey with a UAV. Therefore, flight planning consists of the process of determining the area to be flown, defining the relevant tracks to be followed, and the actions to be performed by the UAV (taking timed photographs) in a given period of time (*Gandor et al., 2015*). Specifically, one of the first steps in the planning workflow of a survey is to define the flight area (study area), the flight time, speed, maximum height and distance from the ground, the type of sensor to be used (in terms of resolution and focal length), the orientation of the camera and the positioning of the images to be acquired (*Table 2-4*).

The planning of a photogrammetric mission is determined by the type of survey to be carried out: for example, conventional aerial photogrammetry uses aircraft or helicopters capable of covering long distances, while close-up photogrammetry uses UAVs for distances of less than 300 m. Depending on the purpose of the survey and the image processing methods and algorithms (e.g.

Structure from Motion), there are numerous aspects to consider when planning the mission. The parameters of flight altitude, UAV cruising speed, % forward and transverse overlap determine the timing of photogrammetric surveys (*Gómez-López et al., 2020*).

Table 2-4. Main features of mission planning applications in relation to the most commonly used platforms. VIM: Vector Integrated Map; OIM: Orthoimages Integrated Map; 3DV: 3D Visualisation; RBP: Block Flight Planning (defined by a rectangle); PBP: Block Flight Planning (defined by a polygon); DEM: Digital Elevation Model; CFP: Corridor Flight Planning; CCFP: Circular-Cylindrical Flight Planning. (modified from Gómez López et al., 2020).

Application	VIM	OIM	3DV	RBP	PBP	DEM	CFP	CCFP	Website
DJI GS Pro	✓	✓		✓				✓	https:// www.dji.com/it/ground station-pro
DJI Pilot	✓	✓		✓	✓	✓		✓	https:// www.dji.com/it/downloads/djiapp/dji-pilot
DJI FlightHub 2	✓	✓		✓	✓	✓		✓	https://www.dji.com/it/flighthub-2
UgCS	✓	✓	✓	✓	✓	✓	***	✓	https://www.ugcs.com/
Litchi	✓	✓	✓	✓	✓	✓	***	✓	https://flylitchi.com/Lit
Pix4D Capture	✓	✓		✓	✓			✓	https://www.pix4d.com/product/pix4dcapture/
Dronelink	✓	✓		✓	✓	✓	***	✓	https://www.dronelink.com/
DroneDeploy		✓		✓	✓				https://www.dronedeploy.com/
Skyebrowse	✓	✓		✓	✓	✓	***	✓	https://www.skyebrowse.com/
OpenDroneMap	✓	✓		✓	✓	✓	***	✓	https://www.opendronemap.org/webodm/
eMotion X		✓	✓	✓	✓	✓	***	✓	https://ageagle.com/drone-software/emotion/
MikroKopter Tool		✓		✓			***	✓	https://wiki.mikrokopter.de/en/MikroKopterTool
Mission Planner	✓	✓		✓	✓	**	***	✓	https://ardupilot.org/planner/
AscTec Navigator	✓	*		✓	✓		✓	✓	https://asctec-navigator.software.informer.com/1.0/

The general trend in photogrammetric surveys with UAVs is to use high overlaps (both longitudinal and lateral) due to the advantages in photogrammetric processing. Therefore, UAV photogrammetric mission plans have a high forward overlap (80%) and side overlap (60-80%) to compensate for the instability of the UAV. Examples of UAV photogrammetric mission planning software are shown in *Figure 2-7*.

Specifically, all UAV manufacturers provide proprietary software for photogrammetric flight planning operations. In the work of Gómez-López (*Gómez-López et al., 2020*), eight categories are described that can differentiate flight planning software based on specific functional and operational characteristics of the management of the mission planning.

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Figure 2-7. Examples of photogrammetric mission planning software: (a) Astec Navigator using OpenStreetMap; (b) Mission Planner displaying Bing Aerial Image; (c) UgCS planning module using a block flight determined by a polygon limit using a DEM; (d) image footprints in Astec Navigator block flight; (e) image footprints in Astec Navigator corridor flight; and (f) circular flight planning in DJI GS Pro. (From Gómez López et al., 2020).

In an emergency context, UAS flight planning is a very important aspect, especially depending on the different possible operational scenarios and the flight restrictions imposed by local factors, such as the presence of airports, urban areas, industrial sites, etc. The more flexible the UAV flight planning software, the greater the chances of operating efficiently in an emergency scenario environment. In this respect, the greater the flexibility of the UAV flight planning software, the greater the chances of being able to operate efficiently in an emergency scenario environment. Therefore, the more flight plans available, the easier it will be to deal with operational difficulties in the field. Advanced multiple remote management and control of all UAV operations, including real-time data transfer, is the new technological frontier of UAV flight mission management to date.

An example of this is DJI's FlightHub" software, which provides a cloud service that enables real-time visualisation and control of all flight operations of enabled drones during data collection operations (*Figure 2-8*). This software can be seen as a tool to ensure remote control of all operations.

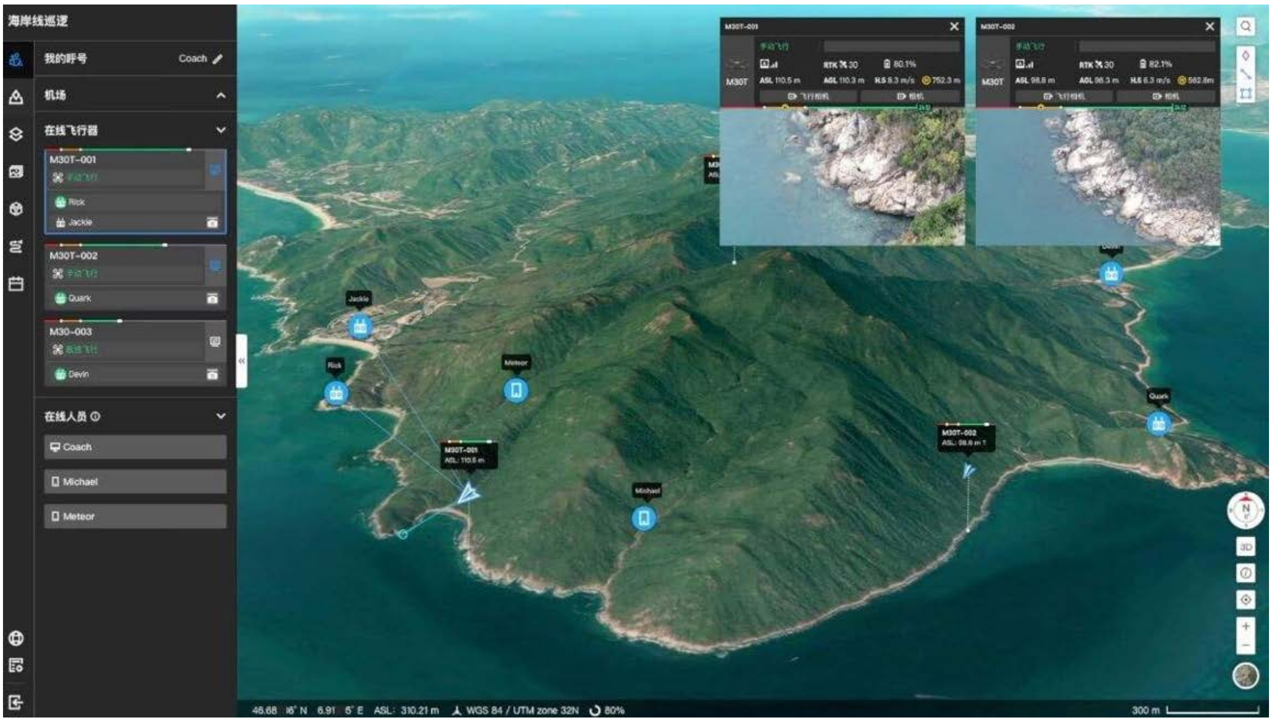

Figure 2-8. Example of the FlightHub 2 cloud-based UAV operations management platform.

DJI's "FlightHub" software features two different operating modes:

Map View

This is a mode in which all authorised users receive telemetry data in real-time, with a view based on the base map, allowing the coordination of remote missions to be carried out by operating in an operational group of pilots deployed in the field. Specifically, this mode allows pilots to have information on the exact location of the drones of the entire team deployed in the field by displaying the names of the pilots, the type of aircraft being used, as well as real-time positioning information such as altitude, speed, direction and exact location of the UAV.

Live View

This is a mode in which multiple team members can view real-time video feeds from cameras and sensors mounted on the UAVs, for up to 4 aircraft simultaneously. This feature allows the Decision Operations Centre to quickly manage all operations based on the information captured, especially in emergency scenarios where decision-making choices must be coordinated and correlated with information received from operational scenarios. The information collected by the software, in terms of data collected, statistics and flight telemetry, is stored in the cloud. Three levels of software are currently available, as follows:

- Base: this level allows the management of a maximum of 5 UAVs and access to full fleet and team management, as well as automatic synchronisation of locations and flights. All telemetry information is based on real-time maps.

- Advanced: this level allows the management of a larger fleet of drones, up to 10 UAVs, and has the same features as the Basic level, but with the addition of real-time "live" camera and sensor views of the aircraft.
- Enterprise: this level allows the management of more than 10 UAVs and includes all the features of the Advanced system, with the addition of cloud storage of all the data acquired by the UAS.

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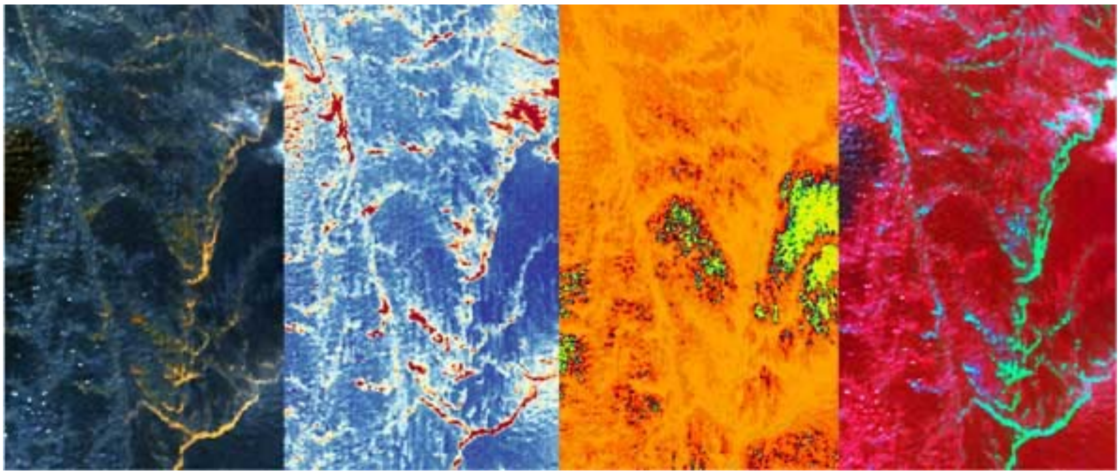
3 Sensors for drones in marine pollution emergencies



Hyperspectral imagery can be used to pull out multiple aspects of the environment, and even classifying the oil signature as opposed to the background water (from l3harrisgeospatial.com)

A prompt and effective response to an acute marine pollution incident requires a rapid assessment of the extent of the spill and monitoring of its behaviour and fate in the marine and coastal environment.

The collection of data on substances released into the sea is crucial for assessing the best response techniques and strategies to be implemented. In the case of a mystery spill, it is essential to provide data and information as quickly as possible. This could be done using drones equipped with specific, appropriate and selected sensors.

Drone technology lies at the intersection of conventional airborne/spaceborne remote sensing and portable, hand-held sensors/detectors. Accordingly, there is a surprising number of commercial sensors specifically tailored for drones, ranging from high-resolution photography and thermal infrared (IR) cameras to hyperspectral imaging systems, Radio/Light Detection and Ranging (RADAR/LiDAR), and gas detectors (sniffers/imagers). In recent years, miniaturised sensors have been developed/adapted for UAV payloads (*Klemas, 2015*). A multispectral image is shown in the figure is shown in *Figure 3-1*.

It should be stressed that the choice of a particular sensor is determined by several factors, including the target composition (oil, gas, HNS), its quantity/concentration range, its spatial extent, the background medium (soil vs. water), the working time (day vs. night), the operating environment (weather, temperature, wind, sea conditions, etc.), the measurement scenario (point vs. area) and, above all, the specificity of the given vehicle, in particular its payload capability. In practice, however, more than one sensor should be used to meet all the requirements of a survey (*Asadzadeh et al., 2022*).

While satellite sensors are used for preliminary oil spill assessment, and aerial imagery acquisition can be time consuming due to the need to obtain the right permissions to fly to the desired location, sensors mounted on UAVs offer greater simplicity and appropriate flexibility for detailed, operational and effective oil spill analysis. The following sections describe the operating principles of different types of sensors that can be mounted on UAVs to measure, identify and characterise oil and HNS spills.

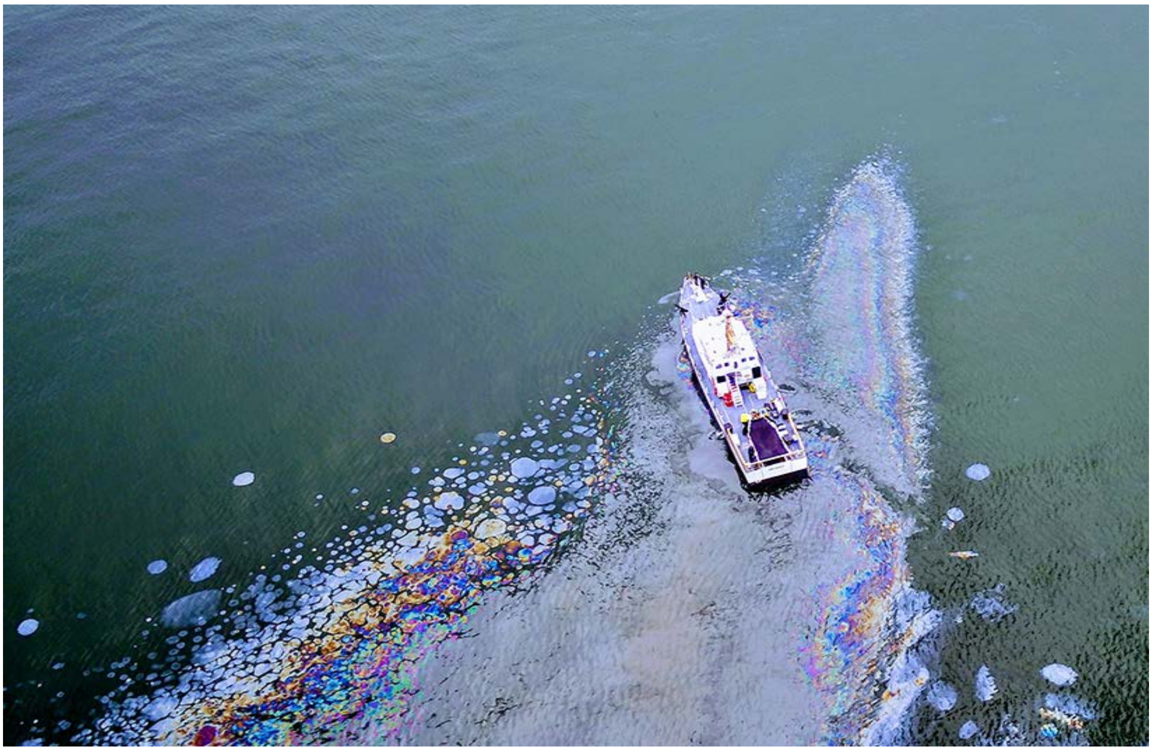


Figure 3-1 Remote sensing with multispectral sensors reveals physical properties of the floating oil that allow scientists to characterize thickness, weathering, and emulsification processes. (from www.eos.org; credit: Oscar Pineda-Garcia

3.1 Properties and characteristics of oils and HNS detected by drone-mounted sensors

Marine accidents can potentially involve many different substances, both petroleum products and HNS, as shown below.

In general, HNS spills are more difficult to deal with than oil spills. Due to the large number of different types of chemicals with different properties, characteristics and hazards, HNS marine casualties are more difficult to assess than oil spills. In 2016, the IMO estimated that more than 2,000 different types of HNS were transported by ship (*IMO, 2016*) or treated in coastal facilities that could potentially spill into the sea. They can be transported both as bulk cargoes (solid, liquid, liquefied gas) and as packaged goods.

In contrast, the types of oil products are less numerous and better known than HNS, and their risks and impacts are generally well understood.

The first assessments to be made in the event of an acute marine pollution incident relate to the behaviour of the product immediately after spillage, which is closely linked to its physico-chemical properties.

The specific characteristics of each type of substance (i.e., optical properties) and their interaction in the marine environment (e.g., formation of a surface film, cloud, plume, etc.) are "captured" by sensors. Their detection or measurement must always consider the environment in which they are released (i.e., optical properties of the medium, sea weather conditions, etc.).

When spilled into the sea, oils tend to float and form surface slicks before weathering processes begin. The assessment of an oil spill is based on a number of parameters such as °API, cinematic viscosity and pour point. These data are used to predict the behaviour and fate of oils, considering environmental conditions and weathering processes (*Fingas, 2021*) (*Table 3-1*).

Oils have optical properties that are determined by their molecular composition (i.e., aromatics, paraffins, naphthenes). When spilled into the sea, they are immediately subjected to weathering processes that alter their properties, including their optical properties. Therefore, the oil slicks or the oil/water content of the emulsions will have a light-attenuating effect. Consequently, the proper design and selection of sensors must consider the changes in the spilled oils as they undergo a wide range of dynamic weathering processes at sea. These changes become more pronounced the longer the oils remain in the environment. The optical properties of seawater must also be considered.

Table 3-1 Oils classification according to American Petroleum Institute. Consideration for the behaviour of oil products when spilled at sea (rif. Pavlov et at., 2022; Michel and Rutherford, 2013, Fingas, 2021a)

API group #	°API (oil density kg/m^3)	Examples		Behaviour & fate
		Crude oils	Refined oils	
1	API > 45 ($\rho \leq 800$)	**NA**	**Gasoline products** Complex mixture C1-C5 HCs	Very high volatility and flammability Quick evaporation and dissolution (in a few hours) Low viscosity; spreads rapidly No persistent
2	35<API < 45 ($800<\rho < 850$)	**Light crude oils** Brent, Arabian Super Light, Iranian Light Arabian Extra Light, Nigerian Light	**Diesel-like products** Kerosene, Naphta, Jet Fuel,	Moderate volatility and solubility Not residues from refined products evaporation Crude oil evaporation residues Low to medium viscosity; fast spreading into thin slicks; formation of stable emulsions is unlikely. Longer persistence than Group #1

API group #	°API (oil density kg/m^3)	Examples		Behaviour & fate
		Crude oils	Refined oils	
3	17.5 ≥ API ≤ 10 (850 < ρ ≤ 950)	**Medium crude oil** Arabian Medium, Arabian Heavy, Iranian Heavy, Nigerian Medium	**Intermediate Products** oil (IFO 180), Marine Gas oil (MGO)	Moderate volatility 1/3 of the crude oil is evaporated in 24 hours. Moderate to high viscosity; spreading in thick slicks. Stable emulsion formations are possible.
4	10 ≥ API ≤ 17.5 (950 < ρ ≤ 1000)	**Heavy crude oils** Nile Blend, Bachaquero	**Residual Products** Intermediate Fuel oil (IFO 380), lubricant oils	Very low evaporation and dissolution product losses High viscosity / solid form (oils may need to be heated to transport) Stable and even more viscous emulsions can be formed. Tar balls formations High persistence
5	API < 10 (ρ > 1000)	**Sinking oil** Orinoco heavy oil	**Sinking refined product** Heavy fuel oils (HFO380), Bitumen, asphalt, paraffin, waxes	Very low evaporation and dissolution product losses High viscosity / solid form; during transport, oils may be heated or blended with light HC which evaporate if spilled. High persistence

As Fingas explained (*Fingas, 2021*), "the optical properties of an oil can be described by the attenuation specific cross-section and the absorption specific cross-section, which depend on the optical characteristics of the oil and the seawater, on the size distribution of oil slick, oil droplets and on their concentration". *Figure 3-2* shows the interaction between a thin oil slick and the sunlight.

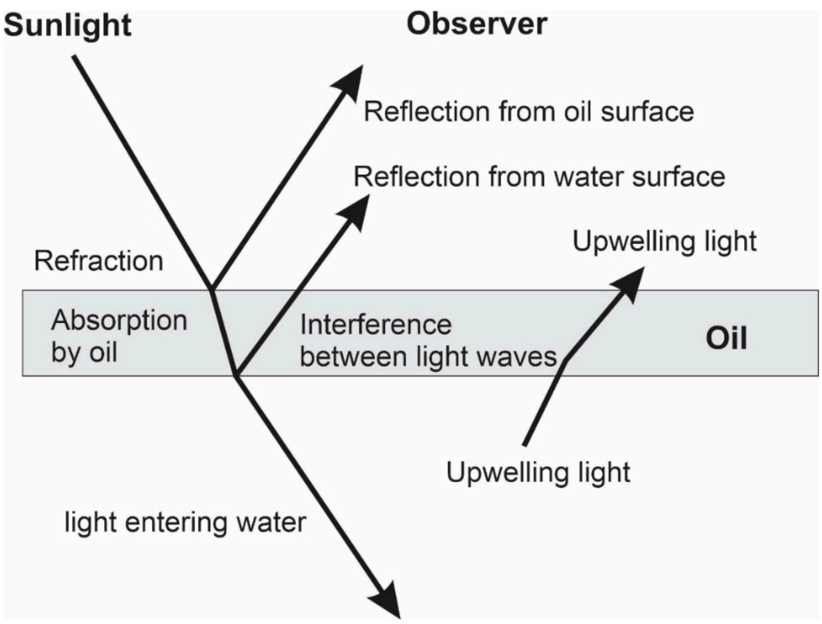


Figure 3-2 Diagram on the basic optical phenomena involved in the appearance (colouration) of thin oil slicks (Fingas, 2021)

The general principles mentioned above in relation to oil spills will also apply in the event of a release of HNS at sea but considering the specificities of HNS marine accident.

The Standard European Behaviour Classification (SEBC) categorises 12 different types of of HNS behaviour at sea based on their solubility, density, and vapour pressure. Then, according to their own physico-chemical properties, HNS could float on the surface, sink, dissolve, evaporate (*Figure 3-3*). Some HNS do not have a single behaviour, but rather multiple behaviours due to their nature, which can also be influenced by environmental conditions (*Alcaro et al., 2021*).

In any case, reactivity and possible reaction products must also be taken into account for a proper assessment.

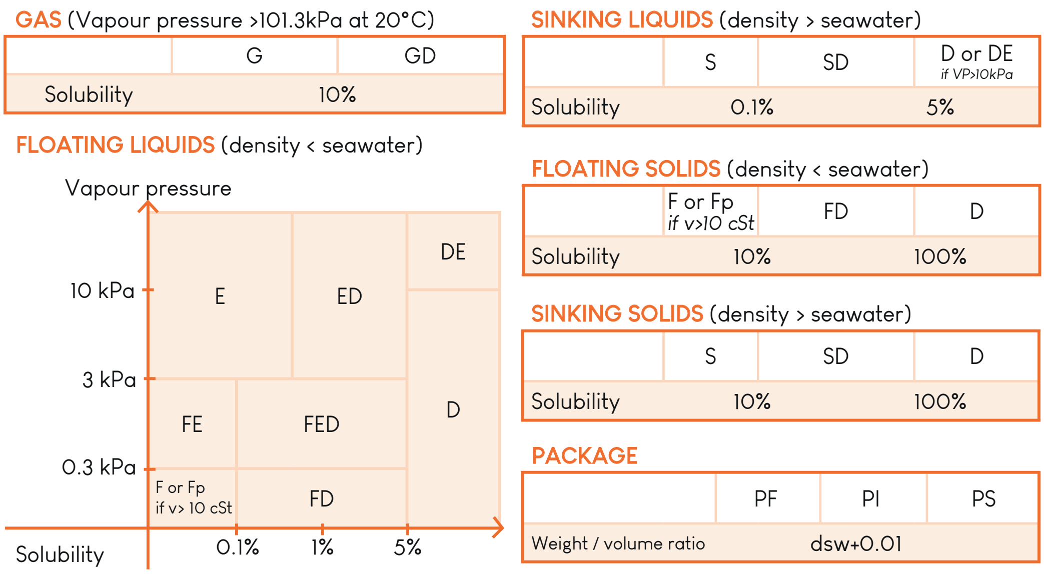


Figure 3-3 HNS behaviour classification under SEBC Code (from Alcaro et al., 2021)

For packaged goods, the specific gravity data (*Table 3-2*) are crucial in assessing the situation; the type of packaging (e.g. containers, drums, etc.), the shape and the water tightness are other relevant factors to be considered. The floatability of a drum or a container is also affected by weather condition and depends on whether or not they were damaged (*Figure 3-4*).

Table 3-2 Packaged group - behaviour classification under SEBC Code (from Alcaro et al., 2021)

	SEBC package groups		Behaviour	Relevant environmental conditions
1	PF	W/V < dsw-0.01	Floater	Sea and wind conditions; surface sea currents,
2	PI	W/V = dsw-0.01	Immersed	Sea and wind conditions; surface sea currents,
3	PS	W/V > dsw-0.01	Sinker	Sub-surface and bottom sea currents, bottom morphology
W= gross weight of packaged goods (kg) V= gross volume of packages (l) dsw= seawater density				

It is also important to note that all classification methods and subsequent considerations for substances and packaged goods are based on measurements under controlled conditions (i.e., @20°C with no wind). This Code is therefore a useful tool for quickly predicting the short-term HNS behaviour at sea, in calm conditions. However, to properly assess the situation in the medium and long term, the real environmental conditions must also be taken into account (Legrand et al., 2017).

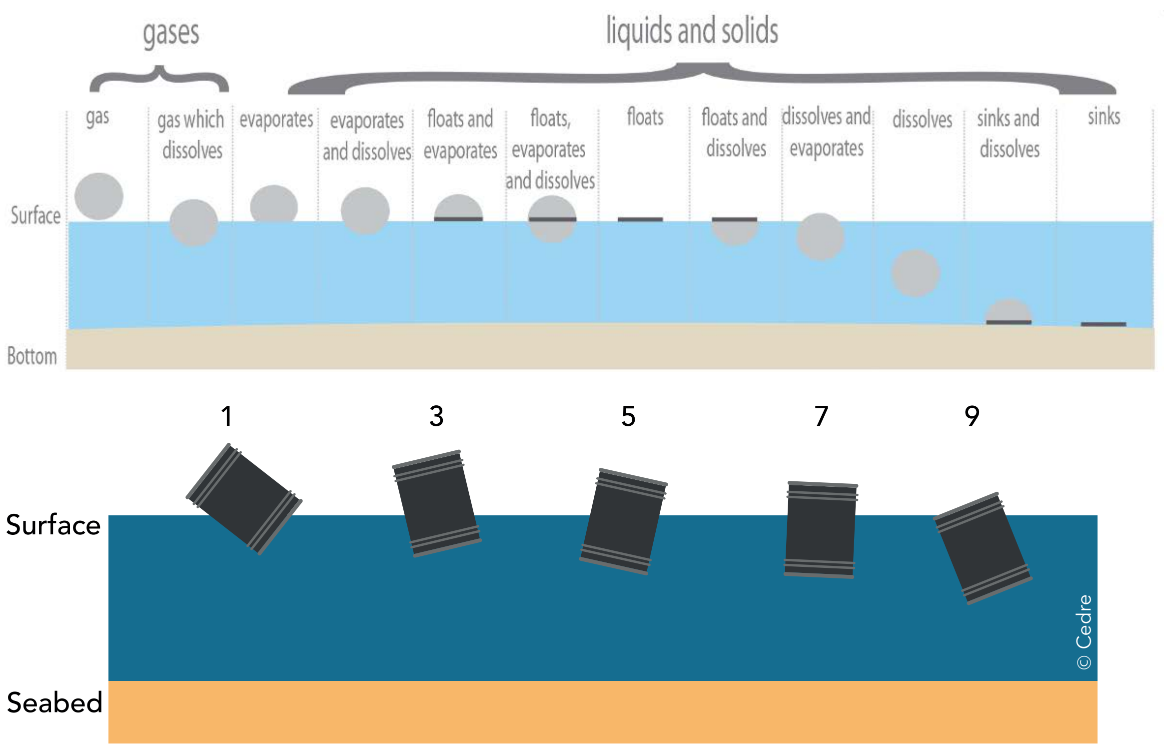


Figure 3-4 Top: Different possible behaviours of the HNS according to the SEBC Code (from https://www.hns-ms.eu/what-are-hns). Bottom: change in buoyancy of packages lost at sea from 1 (fully floating on the surface) to 9 (submerged below the surface and sinking) (from Alcaro et al, 2021).

For the purposes of using drone technology, we focus on pollutants floating on the sea surface or, in some circumstances, in the upper layers of the water column. We also include floating materials (i.e., barrels and containers at sea before they sink). However, the detection of HNS by drone-mounted sensors is less developed than for oil spills. This is due to the greater variability in the type of HNS and therefore its optical properties. However, as the maritime transport of HNS continues to increase, many studies are being carried out and drone sensor technology is also being developed and deployed for chemical spills.

In summary, a rapid and effective response to an oil spill at sea requires an assessment of the extent of the oil slick and its quantity (i.e., thickness) distribution. Thickness reference parameters based on the appearance of the oil film are commonly included in oil spill response training manuals around the world (*Bonn Agreement, 2022*). Nevertheless, visual estimation of oil film thickness distribution is highly subjective, affected by varying light and background colour conditions (e.g., comprehensive visual assessment is impossible at night), and tends to be inaccurate unless performed by specially trained and experienced personnel (*Svejkovsky et al., 2016*, *Fingas, 2021b*). Thus, there is a need to use sensors to objectively quantify the distribution and quantity of oil slicks.

The spatial distribution of oil spills and HNS can be mapped using remote sensing imagery. At present, no single remotely sensed sensor can provide all the information required for oil and HNS spill contingency planning. Therefore, combinations of sensors are currently used for oil spill monitoring (*Jha et al., 2008*). Finally, the detection of HNS sensors is not as well developed as that of oil spills. However, promising studies and research have been carried out in recent years.

3.2 Type of sensors in oil/HNS spill response

There are a number of sensors that can be attached to UAS to perform inspection, monitoring and surveillance tasks. Remote sensing sensors can be divided into two categories: passive and active. Passive sensors measure the natural radiation reflected or emitted by target materials. Active sensors are those that have their own source of light or illumination. This means that active sensors have two main components: an emitter and a detector. Due to the large power source and additional hardware required to emit radiation onto the target, the typical weight of active sensor systems is greater than that of passive sensor systems. Therefore, active sensors are less versatile for use in UAS than passive sensors (*Wanasinghe et al., 2020*).

Table 3-3 Characteristics of remote sensing sensors.

Sensor Type	Detection method	Imaging	Radiometric interval	Wavelength
Passive	Reflectance	Multi-spectral/ Hyperspectral	UV	0.25 - 0.4 µm
			VIS	0.4 - 0.7 µm
			NIR	0.7 - 1.0 µm
			SWIR	1.0 - 2.5 µm
		Spectral/ Multi-spectral	MWIR LWIR	3 - 5 µm 8 - 14 µm
Active	Laser Backscatter	LiDAR	UV (Fluorescence)	0.25 - 0.4 µm
			VIS / NIR	0.4 - 1.0 µm
Active	Radar Backscatter	SAR	Microwaves	2.4 - 100 cm

3.2.1 Passive optical sensors

Remote sensing imagery can be acquired using passive optical multi-spectral and hyperspectral sensors that measure sunlight reflected from the water surface (i.e., surface reflectance) at different radiometric intervals of the electromagnetic spectrum such as Ultra Violet (UV), VISible (VIS), Near InfraRed (NIR), Short Wave InfraRed (SWIR).

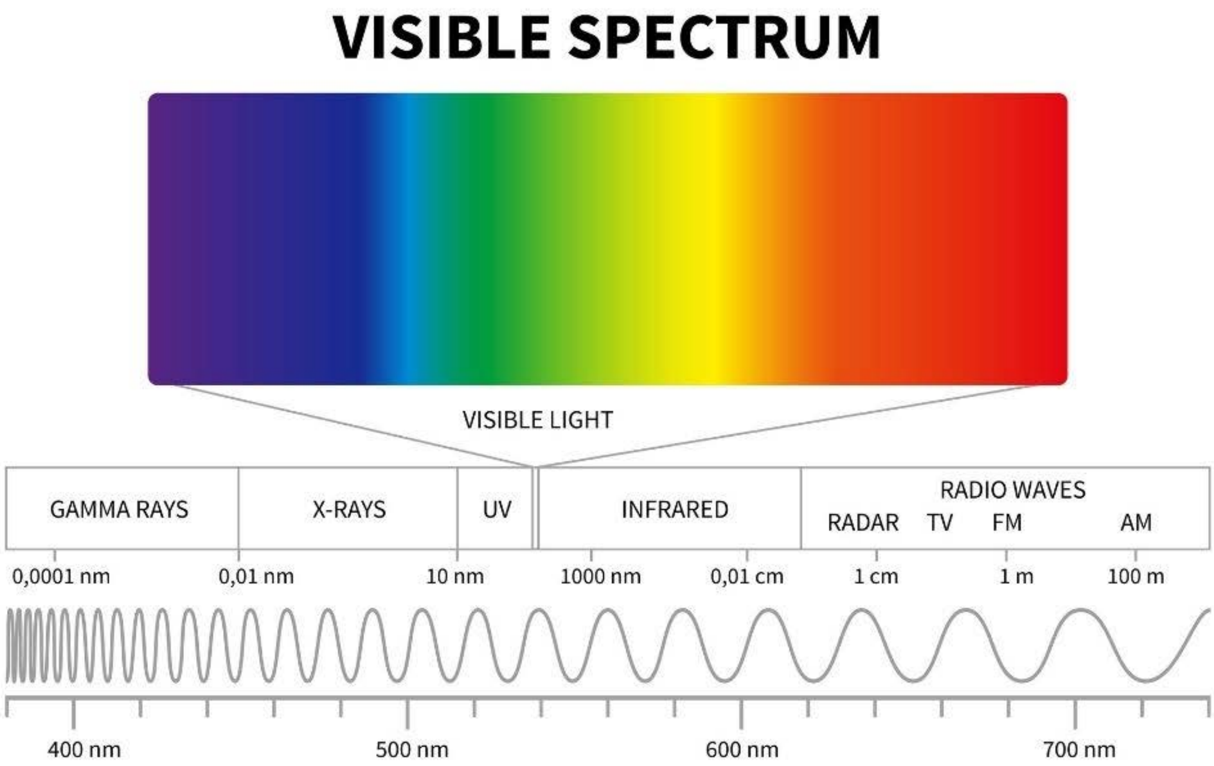


Figure 3-5 Light electromagnetic spectrum, with a zoom on visible range mage (Credit: MicroOne/Shutterstock.com)

Digital cameras operate in the visible part of the electromagnetic spectrum (VIS) and are by far the most widely used passive sensors on board UAVs. In fact, VIS sensors and video cameras are widely available, less expensive, and easy-to-use, and are therefore often used to provide baseline data in coastal areas (*Brown and Fingas, 1997*; *Goodman, 1994*). Depending on their capabilities, visible sensors can be divided into several classes, including high-resolution still cameras, video cameras and stereo cameras. While a single optical sensor cannot provide depth information, this limitation can be mitigated by using a stereo camera system. The operating principle of extracting depth information from the stereo camera is similar to that of the human visual system (*Wanasinghe et al., 2020*).

Surveying requires a high spatial resolution camera with a large sensor size and a fast shutter speed (global shutter). The sensor size determines the spatial resolution of the camera, and in general larger sensors provide a wider imaging swath and larger area coverage in a single pass. UAV-mounted cameras typically have a resolution of 10+ megapixels (Mp) and capture the VIS radiometric interval in three spectral bands (namely true-colour RGB) or four spectral bands, including the NIR. Most of these cameras could be used to capture still or video images during the day. In general, true-colour images acquired by conventional cameras, although widely used, are not the perfect option for oil spill detection because the wide radiometric resolution does not allow the diagnostic absorption feature within the visible (0.4-0.7 µm) or NIR (0.7-1.0 µm) part of the spectrum to be accurately detected. The effect of some environmental conditions such as sun glare and wind sheen would lead to misinterpretation by creating a similarity to oil sheen, which is considered a limitation of such sensors. Visual sensors cannot operate at night because they use sunlight reflection to operate. They also require cloudless and clear weather conditions. Given the limitations of visual sensors for oil spill detection, and their inability to provide thickness information or oil classification, these sensors are not used alone for oil spill monitoring. Rather, optical sensors are used to document the spill and provide a frame of reference for other sensors (*Hammoud and When, 2022*).

Small digital cameras with multi-spectral sensors that collect information in the VIS and NIR are commonly used on UAVs. These sensors use multiple spectral wavelengths simultaneously, measuring light in a small number (typically 3 to 15) of spectral bands. Compared to RGB cameras, they allow radiometric calibration of the captured images and therefore the use of oil spill detection algorithms based on spectral characteristics. Like visible sensors, multi-spectral sensors can be used in daylight conditions and are affected by atmospheric effects such as clouds, haze or smoke.

Hyperspectral sensors collect data in narrow, usually contiguous spectral bands containing hundreds of spectral components. Typically, the resolution and number of bands are customisable, providing a high degree of flexibility in configuring the sensor for different applications. Because of their hyperspectral capability, these sensors can be used to identify materials and substances.

Hyperspectral cameras that can be mounted on UAVs typically acquire in the VIS and NIR radiometric intervals. A hyperspectral camera can also extend the radiometric interval into the SWIR (1.0-2.5 µm), a region of the spectrum where oil slicks are best detected because they retain diagnostic absorption features centred at ~1.7 and ~2.3 µm wavelengths. The power consumption of this type of sensor is comparatively low. SWIR is not visible to the human eye but can be detected using indium-gallium-arsenide (InGaAs) sensors. The limited production of InGaAs may pose some challenges for the manufacture of SWIR-based sensors (*Wanasinghe et al., 2020*). *Figure 3-6* shows an example of spectral signatures from hyperspectral sensors.

Hyperspectral cameras can also detect in the LWIR - long wave infrared (8-14 µm) and occasionally in the MWIR - medium wave infrared (3-5 µm) wavelengths. Heavy camera weight may limit use on UAVs.

Hyperspectral data allows radiometric calibration and identification of oil diagnostic absorption characteristics from specific radiometric bands. Hyperspectral imaging data have the unique ability to detect and map oil with a high degree of certainty, classify oil type based on API gravity (American Petroleum Index), and determine oil slick thickness (*Asadzadeh and Souza Filho, 2017*; *Angelliaume et al., 2017*; *Clark* et al.*, 2010*; *Lammoglia and Souza Filho, 2011, 2012*; *Leifer* et al.*, 2012*).

Oil slicks floating on the sea surface have a higher surface reflectance compared to water in the VIS region (0.48-0.57 µm) of the electromagnetic spectrum (*Plaza* et al., *2005*). Correlation analysis between oil spill reflectance values and oil spill thickness showed that reflectance increases with increasing oil spill thickness (*Karathanassi, 2014*). Oil is more reflective than water in the ultraviolet (UV) spectral region (0.25-0.35 µm), even for very thin slicks (less than 0.1 µm). However, passive UV sensors cannot detect oil thicknesses greater than 10 µm and false detections can occur due to wind sheen, sun glare and seaweed (*Jha* et al., *2008*).

Information such as the oil/water emulsion ratio can be derived from oil absorption features in the NIR and SWIR (0.7-2.5 µm) (*Leifer* et al., *2012*). A strong relationship between oil thickness and spectral values of crude oil emulsions has also been observed in the NIR spectral region 0.75-1.4 µm (*Clark* et al., *2010*). In the 0.72-1.0 µm region, oil reflectance was found to be higher than water (1%-2%) for all thicknesses except thin slicks of crude oil (a few micrometers) and thin slicks of light oils (less than 300 µm) (*Karathanassi, 2014*), as also reported for oil/water emulsions (*Clark et al, 2010*). Thick oil (e.g., crude oil and water in oil emulsions) is characterised in the NIR by multiple peaks in reflectance from 1.0 to 1.5 µm and diagnostic organic C-H absorptions at 1.2, 1.7 and 2.3 µm, which can be used to determine oil/water ratios and minimum oil and oil emulsion thicknesses (*Clark* et al., *2010*). The reflectance ratios of the continua were also used to constrain the spectral characteristics of thick oil patches using absorption features at 0.93 µm due to liquid water, at 1.2 and 1.7 µm due to organics, for low oil-to-water mixtures with less than 2% oil. For thicker oil, the features at 1.2, 1.7 and 2.3 µm were used together with the peak reflections near 1.3 µm and the observed downward trend in the spectra from about 1.3 to 2.2 µm. For the highest abundance oil (thick oil with low water content, less than a few percent water), the 2.3 µm C-H absorption becomes too saturated and the 1.2 and 1.7 µm feature shape and shoulderness are used to distinguish those spectra from oil with higher water content (*Clark* et al. *2010*).

As the signal in the VIS and NIR spectral domains is strongly influenced by the underlying water, the use of spectral bands in the SWIR domain has been successfully tested for establishing the relationship with oil thickness (*Caillault* et al., *2021*) by calculating the Hydrocarbon Index (HI), which takes advantage of the unique and prominent absorption feature of hydrocarbon-bearing materials at 1.73 µm (*Kühn et al., 2004*). Like the HI, the Hydrocarbon Detection Index (HDI) uses an absorption feature around 2.31 (*Lenz* et al. *2015*).

The main C-H absorption bands and optimal intervals for discriminating between oil types were identified in all VIS, NIR and SWIR spectral regions by examining specific spectral regions where crude oil absorption feature bands are strongest or show more variability (e.g., 1.345-1.45 µm, 1.66-1.79 µm, 3.3-3.7 µm) (*Pabón* et al., *2019*).

Experimental activities have shown that reflectance values increase from light to heavy oil (specifically in the order: Kerosene; Heating oil; Crude oil; Heavy fuel; Marine fuel oil) in the spectral range of 0.308-0.367 µm for simulated oil spills with thicknesses above 50 µm (*Lammoglia et al., 2011*; *Karathanassi, 2014*). Such evidence has been preserved for measurements over a period of five days and suggests that the oil-to-water reflectance ratio at the spectral wavelength of 0.344 µm can be used to estimate oil type. Experimental activities showed that spectral bands at 0.675 and 0.699 µm are effective for oil spill detection, although their detection capability is limited for very thin oil slicks (thickness less than 5 µm), while the use of spectral index Normalised Difference Oil Spill Index (NDOSI) performed best for medium thickness oil slicks (*Guangbo et al., 2019*). When the oil-to-water ratio is greater than 90 percent oil, the oil is optically thick at a thickness of 500 µm, and this oil could also be much thicker (*Clark* et al*. 2010*).

Oil thickness can be estimated using the best-fit function for the specific oil type in the corresponding spectral region (*Karathanassi, 2014*). The absorption properties of oil slicks have been used in experimental research campaigns in pools to calibrate an oil thickness estimation model from remotely sensed optical hyperspectral data, which was later used to estimate oil slick volumes (*Laure et al., 2019*). The oil thickness estimation algorithm needs to account for fundamental optical differences in oil types (i.e., light-medium crudes vs. heavy crudes and fuel oils), different background water colour conditions, and ambient light conditions (i.e., sunny vs. cloudy skies) (*Svejkovsky* et al*., 2006*). Since the spectral signatures of oil with low thickness (up to 200 µm) are affected by reflectance from the underlying water and background (*Karathanassi, 2014*), it is not possible to estimate oil thickness on shallow water based on oil spectral signatures. At film thicknesses greater than approximately 200 µm for light and medium crudes and 100-150 µm for heavy crudes, the background water reflectance signal is no longer a significant factor, as all detected reflectance comes from within the oil film itself (*Svejkovsky* et al*., 2006*).

Oil film thicknesses in the range from sheen to approximately 500 µm (depending on the oil type and viscosity) can be measured over open water using a multi-channel UV-VIS airborne sensor; at greater thicknesses, the reflectance characteristics of the oil film do not change significantly as sunlight no longer penetrates the entire film. Experiments have shown that under real-world conditions, the largest reflectance changes due to thickness variations in different oil types occur in the spectral ranges between 0.4-0.48 µm and 0.62-0.68 µm (*Taravat* et al*., 2012*; *Srivastava* et al*., 2010*). However, there is no specific or unique reflectance/absorbance peak at any wavelength that changes significantly with oil thickness (*Svejkovsky* et al*., 2006*). NIR wavelengths help to determine the weathering state of the floating oil. In fact, the weathering process significantly alters the reflectance characteristics of oil in the NIR, causing it to become highly reflective in this spectral region (*Svejkovsky* et al*., 2006*), resulting in a strong correlation between oil spill reflectance values and oil spill age in the 0.576 - 0.919 µm radiometric interval (*Andreou* et al*., 2011*). In general, emulsification of oil with water and weathering complicate monitoring by optical sensors.

Based on diffuse reflectance spectroscopy (covering UV, VIS, NIR and SWIR radiometric ranges) and equivalent wavelet spectra, Principal Component Analysis (PCA) allowed three major groups of crude oils with different densities to be distinguished. Partial Least Squares Regression Analysis (PLS) was later used to obtain sixteen predictive models tailored to estimate oil density (i.e., °API gravity) based on their spectral signatures, providing a viable and rapid alternative method to characterise crude oils (*Pabón et al., 2019*).

Passive optical sensors can distinguish surface oil from the surrounding seawater due to oil-induced wave attenuation resulting in higher surface reflectance, where sheen occurs when sunlight is reflected directly from the water surface to the satellite sensor, creating enough optical contrast to distinguish the bright oil slick from the water surface (*Schaeffer* et al.*, 2022*). Therefore, solar and wind sheen can create an impression similar to that of an oil sheen, and such artefacts should be considered when analysing remotely sensed data. In addition, passive optical multi-spectral sensors that measure reflected light in the UV, VIS, NIR and SWIR radiometric intervals cannot normally operate at night because they are based on the reflectance of sunlight. Look-alikes, such as surface biomass, are a major limiting factor for automated monitoring, even with the recent development of neural networks (*Blondeau-Patissier* et al.*, 2020*).

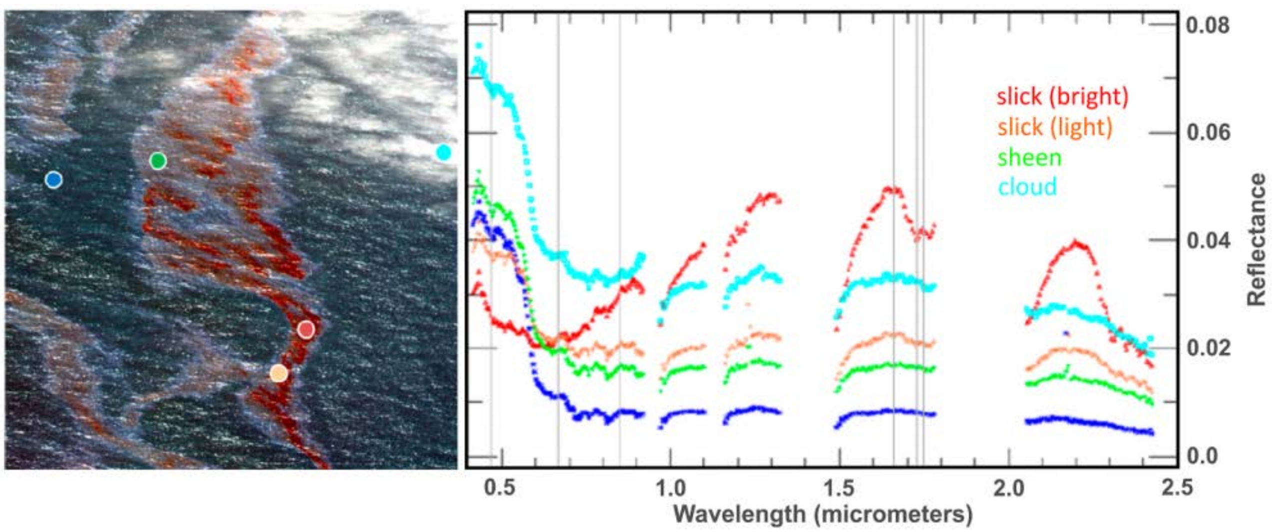
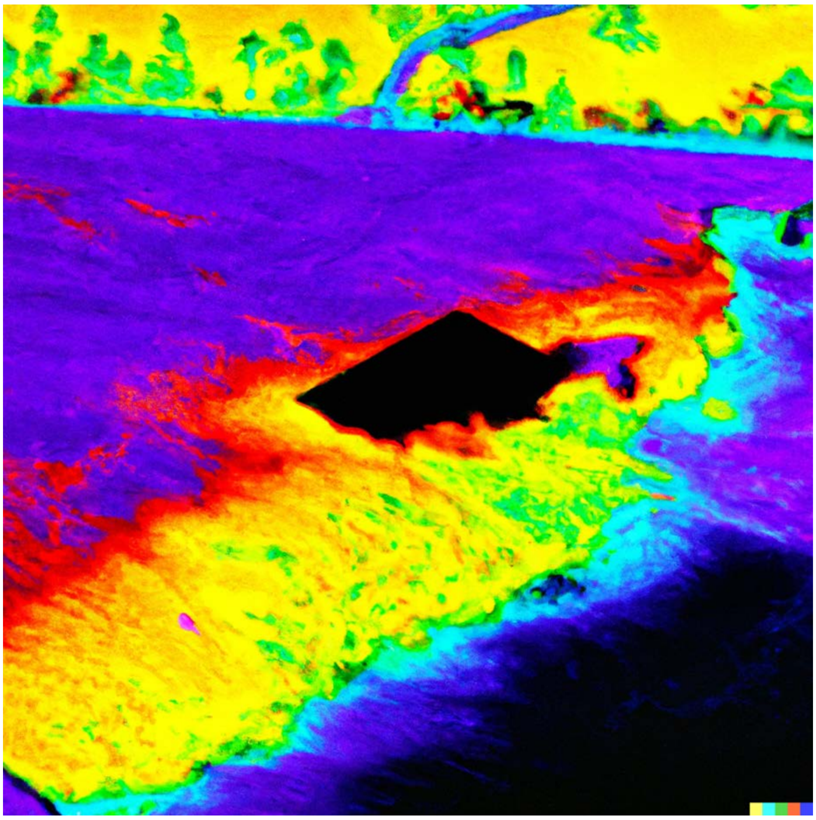


Figure 3-6. Spectral signatures in the radiometric interval 0.4 - 2.5 m of bright oil slick (red), light oil slick (orange), sheen (green), cloud (cyan) and seawater (blues) corresponding to the circles on the left image (Angelliaume et al., 2017).

3.2.2 Thermal sensors



Simulation of image acquisition by passive IR sensor (Floating container at sea)

Passive infrared sensors are relatively cheap remote sensing technologies that can be used to detect oil spills (*Hammoud and When, 2022*). These sensors detect temperature changes and typical applications include leak detection, leak monitoring and infrastructure monitoring. The sensor can operate day and night and its operation is not affected by atmospheric effects such as clouds, haze and smoke. In almost all cases, a reference dataset is required to interpret the thermal images (*Wanasinghe* et al*., 2020*).

Thick oil absorbs greater amounts of radiation and therefore appears hot in the LWIR, a spectral interval between 8 and 14 µm (*Jha* et al*, 2008*). The MWIR is a spectral interval between 3 and 5 µm, and it can detect thermal emission from hot bodies. Both MWIR and LWIR are commonly referred to as Thermal InfraRed (TIR). Oil of intermediate thickness appears cool in the thermal region, but thin sheens cannot be detected in the LWIR. The thickness of the minimum detectable layer is between 20 and 70 µm. The change from hot to cold layer occurs between a thickness in the range 50 - 150 µm (*Fingas* et al*., 1997*). At night, the opposite behaviour is observed: heat loss in oil is faster than in water and therefore thick oil appears cooler than water (*Samberg, 2005*). The addition of a LWIR channel to the imaging system could extend the thickness measurement range, which is limited to 500 µm using the VIS radiometric interval, where sunlight no longer penetrates the entire film, as thermal radiance characteristics have been shown to be related to thickness (*Svejkovsky et al., 2006*). MWIR can measure oil slick thickness from 50 µm to a few millimeters, but suffers from coarse spatial resolution (*Jha* et al*., 2008*).

Another group of specialized thermal IR sensors measures a very narrow spectral band corresponding to diagnostic absorption features of a gas compound, thereby enabling trace gas imaging (Gas IR camera). Absorption coefficient of various natural gases calculated shows spectral features in the thermal radiometric interval, with specific absorption in 3.1-3.6 µm spectral interval (*Ayerden* et al*., 2015*). Drone-based gas leak detection thermographic cameras, sensing in the MWIR spectral range (3-5 µm), are quite capable of detecting lightweight hydrocarbons (C_1-C_8), VOCs, ethylene, ethanol, methanol, and other trace gases in very low concentrations (*Asadzadeh et al., 2022*), evaporating from oil spills. Optical gas imaging is based on infrared absorption characteristics, determining a lack of energy, it is very sensitive from a leak detection standpoint, but not leads for true speciation or quantification. Although they can operate at night, the performance of the sensor is highly dependent on winds.

Small, light and low-price thermal sensor (8 - 14 µm) has been successfully tested onboard UAV during experimental campaign (*Al-Shammari* et al*., 2018*). The thermal IR cameras record The LWIR and turn them into calibrated temperature image/video footage. Within the image, the gas leaks/plumes are visualized by changes in the intensity of the detected radiation. Several thermal sensors have been integrated along with a visual sensor into one entity. Such a configuration can facilitate data collection and allow for integration of temperature data with visible imagery for follow-up interpretations. The so-called 'thermal drones' have a built-in thermal camera and are sold as a package. In the collected thermal data, thick oils tend to appear hot, intermediate thicknesses of oil appear cool, and thin oils or sheens go undetected (*Fingas and Brown, 2014*).

A promising solution for improved oil spill detection could be offered by the LWIR polarimetric sensor by taking advantage of the polarimetric differences between oil and water (*Chenault et al., 2016*). The idea of polarimetric imaging could be extended to other wavelength ranges including visible light for the aim of oil spill detection (*Iler and Hamilton, 2015*).

3.2.3 Laser-based systems

Laser fluorosensor is the most reliable and useful instrument that detects hydrocarbon against various backgrounds such as water, soil and snow. The main application of the laser fluorosensor is to detect and monitor hydrocarbon leaks and spills. Although this sensor group can work during day and night, it requires specialized processing and requires a clear atmosphere. Laser fluorosensors use the phenomenon that oil aromatic compounds interact with UV light (between 0.308 and 0.355 µm) becoming electronically excited, absorb the light energy, and release the extra energy as visible light. The excitation is released through fluorescence emission by the compound mainly in the visible region. Various types of oil have distinct fluorescent intensities and spectral properties, resulting in the ability to differentiate different oil classes. Inelastic hyperspectral Scheimpflug LiDAR (Light Detection and Ranging) system with blue Laser Diodes (LD) at 0.446 µm has been used to induce fluorescence and distinguish seven kinds of typical oil samples, measurements were clustered using PCA and Linear Discriminant Analysis (LDA) methods (*Gao et al., 2017*). By measuring both the spectra and the decay rate of the fluorescence, the system not only can detect the presence of oil but also can identify the type of targeted oil (i.e., light, heavy, medium) (*Fingas and Brown, 2014 and 2018*). For example, crude oil fluoresces from 0.4 to 0.65 µm with an excimer laser (UV radiometric interval) excitation.

Laser fluorosensor can be used for day and night operations, and it was found to successfully detect water-in-oil emulsions (*Brown et al., 2004*). Research studies demonstrated that oil detection was possible as far as 2 m and easily at 1 m below a water surface, using a gated fluorosensor that measured signal returns under the target sea surface (*Brown, 2017*). Laser fluorosensors are limited in their ability to measure oil slick thickness: oil slick of thicknesses greater than 10-20 µm cannot be measured (*Jha et al., 2008*).

The laser fluorosensor is the most useful and reliable instrument to detect oil on various backgrounds including water, soil, weeds, ice and snow. A drawback is that the atmosphere should be reasonably clear for the operational use of laser fluorosensors (*Jha et al., 2008*). Scanning fluorosensors have been successfully employed in aerial image acquisition. A drone-based system for monitoring laser-induced fluorescence from the aquatic environment has been designed, it integrates a continuous-wave diode laser at 0.412 µm and a portable spectrometer, for a total weight of about 1.5 kg (*Duan et al., 2019*). Acquisition allows to measure information on linear transects, thus it cannot be considered an imaging sensor (generating georeferenced 2D images).

Currently, there are only a small number of commercial airborne laser fluorosensors in routine operation outfitted to drones. The power limitations of the laser and the sensor payload are amongst the biggest obstacles to fit these systems into UAVs (*Sassi et al., 2018*).

Information on the geomorphology of coastal areas can instead be obtained mounting a (Laser imaging detection and ranging) on a drone to measure ranges (variable distances) to a target by illuminating a pulsed laser and analyzing the reflection time. The time differences in combination with other data recorded by the platform are then used to calculate three-dimensional information about the shape of the landscape below the vehicle.

Despite optical passive infrared imaging sensors can detect gas plumes, they do not offer quantitative measurement. Differently, gas sniffers are laser-based systems that provide a quantitative analysis, because the laser beam is not affected by the background context, and can be tuned to sense CO, CO_2, NO_2, SO_2, and VOCs among several other gases, by scanning the characteristics of gas absorption feature at a given wavelength (*Asadzadeh et al., 2022*). In fact, plumes of NH_3, H_2S, NO_2, and SO_2 emitters are successfully detected within the LWIR wavelengths (*Hulley et al., 2016*). If the gas corresponding to the emitted wavelength is present, it will absorb the part of the emitted radiation, and the sensor will measure the backscattered radiation after the absorption. Differential absorption laser gas detector uses pulses of two different wavelengths to detect the presence of specific gases. One wavelength of the light pulse serves as a reference while the second wavelength is absorbed by the gas (if present) (*Wanasinghe et al., 2020*). Several parameters regulate the sensitivity and effectiveness of these systems: target composition; wind speed; imaging distance; imaging backdrop (*Asadzadeh et al., 2022*). Gas plumes have been easier to detect against the sky or low-emissivity backgrounds (*Ravikumar et al., 2017*). Nevertheless, these systems retain limited range (and frequency) and cannot detect emissions at long distances, with optimal flying distance for these detectors reported to be between 4 and 15 m (*Iwaszenko* et al., *2021*). Moreover, the laser beam profiling techniques suffer from an inherent small sampling capacity, and it becomes possible to interpolate the data points into concentration maps to approximate the shape of the corresponding plumes only when the density of the measurements is high enough (*Asadzadeh et al., 2022*). In the case of methane, the laser beam is tuned to scan the characteristics of methane absorption feature at 1.653 µm (*Asadzadeh et al., 2022*). Gas concentrations by laser detectors are usually reported as ppm-m (column density), which is the concentration in ppm over the air column between the platform and the target point in meter. Depending on the sensor technology, the detection limit of the existing sensors varies from 1 ppm-m down to a few ppb-m (*Asadzadeh et al., 2022*). The hyperspectral imaging systems onboard airplanes are shown to detect methane plumes at the level of 4-5 kg/h in the LWIR, and of 2-5 kg/h in the SWIR spectral range (*Asadzadeh et al., 2017*). Spectral imaging technology was able to detect methane fluxes varying from 3.6 to 180 kg/h at a distance of 100 m from the release point (*Xavier et al., 2016*). In similar settings, aliphatic compounds have been detected at lower levels than aromatics (*Bénassy et al., 2008*), or wet gas (methane in addition to ethane, butane, etc.) has been detected at 3-4 times lower levels compared to dry gas. An independent methane release experiment indicated that while the drone-mounted laser detectors are capable of measuring methane concentrations at 0.5-3.0 ppm levels from distances higher than 15m, they are not successful in mapping the shape of the plume nor the methane concentrations within mixed plumes (*Tannant et al., 2017*).

Considering gas sniffers limitations, including high power consumption and their imprecision estimates under windy conditions (*Wanasinghe et al., 2020*), combination of optical passive thermographic imaging sensors and laser-based systems onboard drones represent a solution for gas emission detection and quantification (*Al-Walaie et al., 2021*).

3.2.4 Synthetic Aperture Radar (SAR)

With the absence of oil slicks, a bright image is obtained by radar sensors for clean seawater. Once the oil is spilled into seawater, the ocean capillary waves are reduced, and radar reflections are decreasing. Dark spots are obtained in radar imaging. This allows for oil spill detection. Synthetic Aperture Radar (SAR) and Side-Looking Airborne Radar (SLAR) are the two most common types of radar, which are used for oil spill remote sensing. SAR is highly prone to false targets, however, and is limited to a narrow range of wind speeds when small ocean waves do not yield a difference between the oiled area and the sea (*Hammoud and When, 2022*).

Sea capillary waves reflect microwave (radar) signals, yielding an illuminated image called clutter (*Fingas et al., 2018*). As said before, oil on the sea attenuates capillary waves, and the sea clutter from radar imagery, resulting as a dark areas of sea clutter absence (*Marzialetti et al., 2016*), with reduce the Normalized Radar Cross Section (NRCS) compared to the surrounding area (*Alpers et al., 2017*). The radar backscattering from clean sea surfaces as well as from surfaces covered with mineral oil and biogenic surface films can be described by the 2-scale Bragg scattering theory (*Valenzuela, 1978*). This theory applies for radar backscattering for incidence angles between 23° and at least 50° and for low to moderate wind speeds (*Alpers et al., 2017*). The sea state limits in fact radar ability to image oil. Specifically, minimum wind speeds of 1.5 m/s are required for oil spill detectability, producing a contrast with the oil that has damped sea clutter, and a maximum wind speed of 6–10 m/s will hamper radar detection (*Leifer* et al.*, 2012*), since the surface film disappears from the sea surface because of entrainment into the underlying water by wave breaking (*Alpers* et al.*, 2004*).

The reduction of the radar backscattering from mineral oil films varies considerably depending on: the type of oil; time after spillage (during which oil changes temperature and its composition due to weathering); distribution of the oil within the oil patch; wind speed and direction. Typical values for the reduction of the NRCS by mineral oil films are 5 to 12 dB (*Alpers* et al.*, 2017*).

Studies on large oil spill sensing indicate that X-band provides better data than L-band or C-band radar (*Marzialetti* et al.*, 2016*). Dealing with SAR polarization, research activities showed the suitability of the VV polarization for detecting oil spills as well as the reduced utility of the VH polarization (*Nezhad* et al.*, 2018*; *Melillos* et al.*, 2021*). Among the six HNS tested during experimental activities at sea, three have been detected without any ambiguity using X-band and L-band SAR imagery (i.e. rapeseed oil, FAME, xylene), while the non-detectability of the other three substances (i.e. methanol, heptane, toluene) can be caused either by a high volatility of tested products or by an impact into the water column that physically does not affect the backscattered signal at microwave frequency (*Angelliaume et al., 2017*). Normalized Polarization Difference (NPD) of SAR L-band resulted in wide range of values within the spill, probably due to less L-band sensitivity to oil slicks. Such variation is related to the impact of the product on the ocean surface and can be used for detection and quantification of HNS impact on the ocean surface (*Angelliaume* et al., *2017*).

There are many slick look-alikes, such as freshwater slicks, calm areas, behind structures or topographical features, shallow seaweed beds, biogenic oils, and seawave shadows behind structures or topographical features, shallow seaweed beds, biogenic oils, and life sperm (*Fingas* et al., *2014*). In certain areas, slick look-alikes could number in the hundreds. A key challenge in oil spill detection by radar is the discrimination between oil films and biogenic or monomolecular slicks. Polarimetric parameters derived from fully-polarimetric SAR data, like entropy, anisotropy, and mean scattering angle, do not have the potential to significantly improve oil spill detection, particularly the separation of mineral oil from natural biogenic films (*Alpers et al., 2017*).

Nowadays UAV-SAR systems exist (*Koo et al., 2012*; *Luebeck* et al., *2020*). However, they are typically too heavy to be supported by small UAVs. Furthermore, the use on small UAVs requires embedded INS and GPS, which are used to provide integrated flight information for geometry correction, since irregular motion of the aircraft due to atmospheric turbulence seriously affects the image quality (*Koo et al., 2012*). A comprehensive list of the proposed, or under development SAR systems for class 1 b/1c drones (see

Table 3-3) is provided by Pajares (*2015*). The application of UAV-SAR to oil spill detection is yet to be demonstrated in real-world studies (*Hammoud and When, 2022*).

A comparison of oil spill seen from different remote sensing sensors is given in *Figure 3-7*.

Figure 3-7. Oil spill as seen from: a) VIS sensor; b) thermal sensor; c) SAR sensor (Chanault et al., 2016).

3.3 Features of sensors for good maritime survey

There are several characteristics to be taken into consideration during selection of best sensors:

- *spatial resolution*: it is an important characteristic of the sensor that affects the accuracy in mapping oil slicks with accurate thickness measurements;
- *quick response*: oil spill surveillance requires an acceptable time frame for collecting and processing the data, which stresses the need for real-time data availability ;

- *day-time conditions*: the operation of the sensor at any time during the day and night is essential for an effective surveillance system;
- *weather conditions*: it is important to limit the effects of weather conditions including rain, fog and sky conditions;
- *large-scale view*: the sensor that captures a synoptic view of the area allows monitoring over a large spill spread;
- *cost and size*: the acceptable size and cost of the sensor are critical to decreasing the overall cost of the system.

Table 3-4 Comparing the most widely used drones used in marine environmental emergencies (Adapted from Jha et al., 2008)

		PASSIVE SENSORS					ACTIVE SENSORS		
		Multi-spectral/Hyperspectral				Spectral/ Multi-spectral	Laser		SAR
		UV	VIS	NIR	SWIR	MWIR/LWIR	VIS/NIR	Laser Fluorescence	Microwave Radiometer
Applicability	At sea	Sea Surface	• Sea Surface • Sea Subsurface	Sea Surface	Sea Surface	Sea Surface	Sea Surface	• Sea Surface • Sub surface (< 2m depth)	Sea Surface max B = 2
	On shore	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Operational features	24-hour operation*	No	No	No	No	Yes	Yes	Yes	Yes
	Power consumption	low	low	low	low	low	high	high	high
	Weight	Low	Low	Low	Low/Medium	Low/Medium	Medium	Medium	Hight
	Ideal Sky Conditions	Clear-sky conditions	Clear-sky conditions	Clear-sky conditions	Clear-sky conditions	Any sky conditions (interferences by vapors)	Clear-sky conditions	Clear-sky conditions	All weather except heavy rain
Further considerations	Cost	Low	Very low	Low	High	Medium	Medium	Medium	High
	Advantage	Low power consumption	• Easy to use • Low-cost sensor • Low power consumption • Useful to monitoring oil spills response operations	• Easy to use • Low power consumption • Useful to monitoring oil spills response operations	• Can identify specific oil spectral (absorption) features • Can penetrate smoke	Can be used at nighttime and with cloud sky conditions	Can be used at nighttime and with cloud sky conditions	• Effective in various backgrounds • Can detect water-in-oil emulsions	Can be used at nighttime and with cloud sky conditions
	Drawback / limitation factors		Can not identify specific oil spectral features	Can not identify specific oil spectral features	• Heavy for small UAVs • Limited number of sensors available	Possible interferences by vapors	Heavy for small UAVs	• Requires specialized processing • High, line profile	• Requires specialized processing • Heavy for small UAVs

* ”No” refers to the use limited on daylight hours

Table 3-5 Application of drone-mounted sensors for marine oil /HNS spill detection and monitoring

		UV	VIS	NIR	SWIR	MWIR/LWIR	Laser VIS/NIR	Laser UV-Fluorescence	Microwave Radiometer SAR*
Oil spill detection	Detectable slick thickness	1 μm	> 5 μm	slicks > 300 μm		minimum range: 20 - 70 μm	> 5 μm	> 10-20 μm	> 50 μm
	Oil Thickness estimation	< 10 μm	< 500 μm	< 500 μm	Yes	50 μm - few mm	medium thickness	< 10-20 μm	50 μm - few mm
	Weathered floating oils detectability			oil-to-water emulsion ratios oil emulsion thicknesses thick oil patches	oil-to-water emulsion ratios			water-in-oil emulsions	
	Oil Classification	Yes	Yes	Yes	Yes	No	Yes	Yes	No
HNS detection§ **			Potential radiometric anomaly detection from LAOS**, F and Fp HNS; coloured dissolved HNS plumes, floating packaged goods			VOC		Aromatic substances	Rapeseed oil, FAME, xylene*
False detection		LAOS**	LAOS, darker shoreline	LAOS, shoreline	LAOS	LAOS	LAOS	LAOS	LAOS low wind areas
Notes			Main use: to provide a frame of reference for other sensors	Yes (Weathering alters reflectance in NIR spectral interval)	Detection and mapping	Leak detecting, leak monitoring, and infrastructure monitoring At night, the reverse behaviour is observed Also combined in Thermal drones		Leaks and spills Can identify oil on any background	HNS: **NO**: gas/VOC, methanol, heptane, toluene

§ HNS detection with drone-mounted sensors is not yet fully implemented. The table shows experimental results that are not yet fully validated.*LAOS= look-alike oil slicks –e.g. see weed, jellyfish blooms, life sperm and allowed discharges by ship (e.g., margarine, and others vegetable oil, according to international laws - Marpol Annex II and IBC Code). False positives can also include wind sheen, sun glint, sediments, coastline and oceanic fronts. **Non-exhaustive list

References Cap. 3

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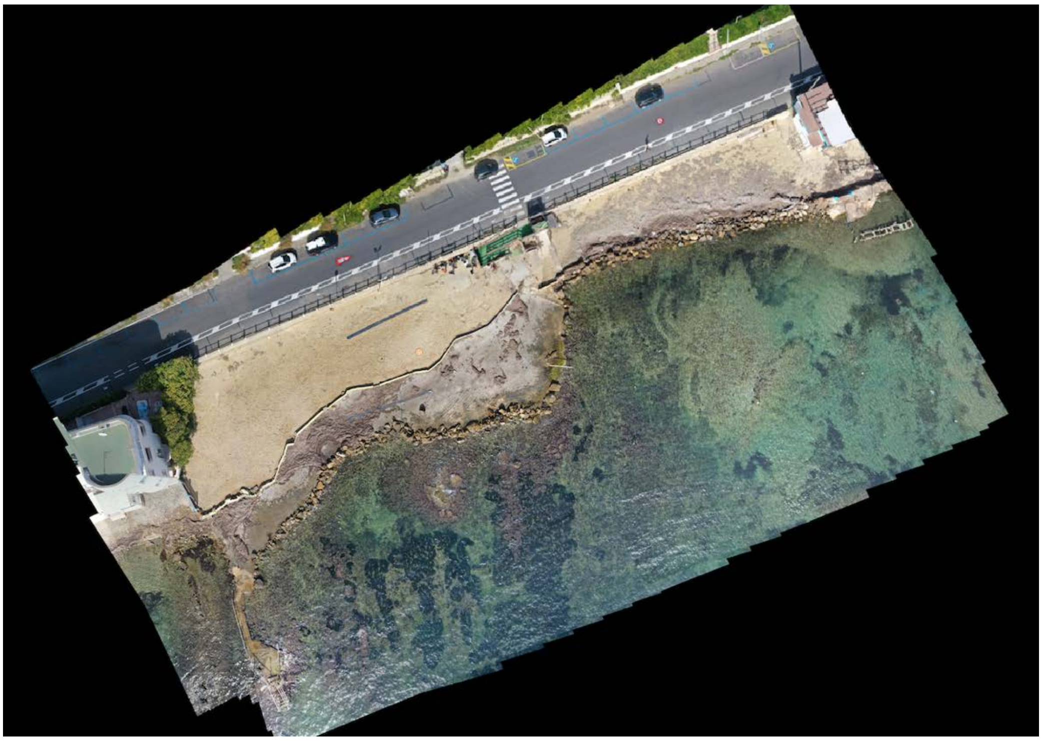
4 Data processing procedure



Example of a photomosaic of a coastline - Santa Marinella, Italy (ISPRA)

The proliferation of low-cost, commercially available drones has made it easier to carry out certain environmental monitoring activities. Once the UAV data has been collected, there are a number of Structure from Motion (SfM) photogrammetry software packages available for pre-processing, point clouds, orthomosaics and Digital Elevation Models (DEMs). However, not all software packages are the same, nor are the outputs. The most common outputs from an workflow are a point cloud, a DEM and an orthomosaic. Orthomosaics are created by stitching together a series of individual orthorectified aerial images and overlaying them to create a single continuous image/map (*Xin et al., 2007*). DEMs are spatial data sets that describe the features of the surface terrain and are divided into two categories: Digital Terrain Models (DTM) and Digital Surface Models (DSM) (*Berra et al., 2020*). Both proprietary and open source software options are available to perform photogrammetry. Open source photogrammetry software can be more flexible and allow customisation of many workflow steps. In contrast, proprietary software often provides a simplified workflow to facilitate photogrammetric processing.

There are many studies that have attempted to compare the results of different photogrammetry software. These studies have been conducted exclusively in terrestrial environments, focusing on forests (Brach et al., 2019; Gross et al., 2016), quarries (Casella et al., 2020), agriculture (*Jiang et al., 2020*; *Chen et al., 2020*) or urban environments (*Jiang et al., 2020*). An overview of the performance of different software packages using (urban and agricultural) data is provided in the study by Jiang (*Jiang et al. 2020*). The study by Pell (*Pell et al. 2020*) compares the different software packages in terms of processing times, output file characteristics, colour representation of orthomosaics, geographic displacement, visual artefacts and digital surface model (DSM) elevation values.

Aerial triangulation (AT) requires knowledge of the initial values of the centres of capture. With the SfM, all unknown parameters of camera positions and 3D points can be retrieved automatically and simultaneously from overlaid images (*Jiang et al., 2020*). Unlike conventional AT methods, SfM does not require priors of camera poses and 3D points. Therefore, SfM has been widely used for UAV image orientation (*Jiang et al., 2020*). As in classical SfM, the image orientation procedure consists of three main steps: (1) feature extraction for individual images, (2) feature matching for image pairs, and (3) resolution of the unknown parameters as part of the iterative execution of the bundle adjustment (BA). For the first step, the time consumption is linear in the number of images involved, and many attempts have been made to increase the efficiency of feature extraction, e.g. optimised feature detectors (*Jiang et al., 2020*), and especially hardware acceleration using GPUs (*Chang et al., 2020*). However, as the volume of data increases, so does the time required to perform the last two steps, which are at least quadratic in the number of images. In order to process large numbers of images in short processing times, the computing powers of computers need to be carefully evaluated.

Specifically, data processing is the manipulation of digital data to produce meaningful information. Data processing for UAV-acquired data can be divided into two phases:

- pre-processing: includes photogrammetric processing steps such as radiometric calibration, geometric calibration, georeferencing and mosaicking;
- post-processing: includes methods and algorithms for analysis, identification, classification and characterisation of the pre-processed data.

4.1 Pre-processing

4.1.1 Passive sensor pre-processing

Drone image processing and analysis software allows users to perform photogrammetry on aerial data (visual RGB cameras, infrared thermal imaging, multi-spectral imaging, LiDAR and SAR data) collected by unmanned aerial vehicles. Image analysis software is widely used to process drone data to produce detailed and accurate maps, capable of outputting 2D and 3D models and maps.

Drone image processing and analysis software can include a variety of advanced features such as intelligent feature identification and extraction algorithms and on-the-fly editing tools. It may provide scalable distributed processing across networks and multiple hardware platforms, or the ability to upload images to the cloud for processing, taking advantage of powerful servers rather than limited desktop computers. Some software suites enable rapid mapping of UAV imagery for emergency response and public safety by reducing processing time.

4.1.2 Photogrammetry and image processing software sheets

This section contains a selection of photogrammetry software for processing UAV imagery with technical specifications. The software list should not be considered exhaustive. The following is a description of each of the pre-processing software packages.

Software name	**RECAP PRO** (commercial)
Manufacturer	Autodesk https://www.autodesk.com/products/recap
Software specifications	General Description: is used to capture 3D reality via photogrammetry, converting photographs into accurate 3D models. The software can be used for both aerial and terrestrial photogrammetry. It is widely considered to be one of the best point cloud software available. It quickly and easily simplifies all scans into multiple point clouds, and there are a variety of settings that can be applied before the project is indexed and finalised into the unified point cloud. ReCap has many high-quality analysis tools, advanced editing tools and collaborative tools. You can measure and edit cloud point data and easily output a point cloud or mesh for use with other software. RGB image processing: Yes Multi-spectral image processing: Yes Thermal image processing:? LiDAR: Yes Video: no? Advantages: Speed; Quality; user Friendly; highly accurate Disadvantages: Price
Main employment scenarios	Survey, Mapping, Plan, construct
Multi-platform	Windows; macOS

Software name	**AGISOFT METASHAPE** (commercial)
Manufacturer	Agisoft https://www.agisoft.com/
Software specifications	General Description: is a professional photogrammetry software often used for Geographic Information System applications. The software can be used for both aerial and terrestrial photogrammetry. It includes some great tools for editing the point cloud before generating a 3D mesh, automatic classification of point clouds to customise the geometry reconstruction and extensive measurement tools for measuring distances, areas and volumes. Agisoft Metashape is capable of processing over 50,000 photos on a local cluster

Software name	AGISOFT METASHAPE (commercial)
	thanks to its distributed processing capabilities. Alternatively, the project can easily be sent to the cloud to minimise hardware investment. RGB image processing: Yes Multi-spectral image processing: Yes Thermal image processing: Yes LiDAR: Yes Video: YES Advantages: Speed; Quality; highly accurate; Python Module Disadvantages: Price
Multi-platform	Windows; macOS; Linux
Main employment scenarios	Survey, Mapping, Plan, construct

Software name	PIX4D MAPPER (commercial)
Manufacturer	Pix4D https://www.pix4d.com/product/pix4dmapper-photogrammetry-software/
Software specifications	General Description: is a professional photogrammetry and drone mapping software that provides an end-to-end photogrammetry solution, meaning that in addition to generating point clouds, elevation maps and 3D meshes from imagery, it's processed in Pix4D software, where you can generate point clouds, elevation models, index maps and orthomosaics. The software can run on your desktop or in the cloud. Is the software for professional photogrammetric drone mapping. You can share annotations, maps and models via URLs, making it easy to involve team members in a single project. You can use standard templates to automatically process your projects or create your own with custom settings for full control over data and quality. PIX4Dmatic, the next generation of photogrammetry software, is designed to work with the latest generation of drones, turning large volumes of images into accurate point clouds, DSMs and orthomosaics over 40% faster than ever before. RGB image processing:Yes Multi-spectral image processing: Yes Thermal image processing: Yes LiDAR: NO (Pix4Dmatic can combine the point clouds form both LiDAR and RGB images) Video: YES Advantages: Speed; Quality; highly accurate; user friendly Disadvantages: Price
Multi-platform	Windows; macOS beta version;
Main employment scenarios	Survey, Mapping, Plan, construct

Software name	**3DF ZEPHYR** (commercial)
Manufacturer	3Dflow https://www.3dflow.net/it/
Software specifications	General Description: is a software solution from 3DFlow that has been designed to be as user-friendly as possible. There are easy-to-use wizards that explain the processes and help you choose the right settings to generate 3D scans, so it's a great software for beginners. That doesn't mean it's not suitable for more experienced users, however, as you can make extensive adjustments to optimise the final result. This professional photogrammetry software can align photogrammetric data with laser scans, you can retain texture maps and increase the accuracy of your model. Users can also benefit from a wide range of export options in many file formats. The process can be done automatically or manually. It can be easily customised to suit the user's needs. 3DF Zephyr can automatically perform 3D reconstructions using images and video data captured by any sensor and acquisition technique. You can use different focal lengths, lenses and cameras during the same survey or scanning session. Get the most out of aerial and ground photogrammetry with a single software platform that processes video, spherical photos and thermal + RGB imagery. RGB image processing:Yes Multi-spectral image processing: Yes Thermal image processing: Yes LiDAR :Yes Video: Yes Advantages: Quality; Speed; user friendly; Python scripting Disadvantages:
Multi-platform	Windows;
Main employment scenarios	Survey, Mapping, Plan, Construct

Software name	**MESHROOM** (FREE)
Manufacturer	Alice Vision https://alicevision.org/
Software specifications	General Description: is free, open source 3D reconstruction software developed by AliceVision, a photogrammetric computer vision framework. One of the best things about this free photogrammetry software is that you can view your 3D photogrammetric model in real-time as you make edits and add images to the dataset, so you can see how additional data fills in incomplete parts of the model over time. The nodular interface is somewhat obscure and takes a while to master. Instead of a linear pipeline, several SfM modules can be run in parallel and later combined to create a more robust mesh. This offers the advantage of additional control over the final mesh quality. While professional users get

Software name	**MESHROOM** (FREE)
	the full under-the-hood view, novices benefit from simply hitting the start button after uploading photos and letting the computer do the rest. All in all, Meshroom is one of the best Free and Open Source Software (FOSS) solutions for photogrammetry and generally produces good quality meshes. It offers no mesh editing tools, so the user has to rely on third party products. It also tends to reject a significant percentage of camera positions, so it is important to adhere to proper photography guidelines. RGB image processing: Yes Multi-spectral image processing: Yes? Thermal image processing: Yes? LiDAR :Yes? Video: YES? Advantages: Quality; free; Disadvantages: Not user friendly; no editing tools;
Multi-platform	Windows; Linux
Main employment scenarios	Survey, Mapping, Plan, Construct

Software name	**WEBODM** (free and open source)
Manufacturer	OpenDroneMap https://opendronemap.org/webodm/
Software specifications	LiDAR
Multi-platform	Windows; Linux; MacOC
Main employment scenarios	Survey, Mapping, Plan
References	https://peterfalkingham.com/2020/05/11/photogrammetry-testing-opendronemap/

Software name	**REGARD3D** (free and open source)
Manufacturer	The source code of Regard3D is released under the MIT license: Copyright (c) 2015-2018 Roman Hiestand https://www.regard3d.org/ hiestandroman@gmail.com
Software specifications	General Description: is a free, open source 3D reconstruction software. It's a really nice GUI around some well-established and powerful algorithms. They don't work particularly well on this dataset, and it's not GPU-accelerated, so it's not super-fast. On the other hand, the lack of GPU requirements means that this will run on anything with a half-decent CPU and a good amount of RAM.RGB image processing: Yes Multi-spectral image processing: ?

Software name	**REGARD3D** (free and open source)
	Thermal image processing: ? LiDAR :? Video: ? Advantages: free; high-performing algorithms Disadvantages: Not user friendly;
Multi-platform	Windows; Linux; MacOC
Main employment scenarios	Survey, Mapping, Plan

Software name	**PhotoModeler premium** (commercial)
Manufacturer	PhotoModeler Technologies https://www.photomodeler.com/products/premium/photomodeler-standard-vs-premium/hiestandroman@gmail.com
Software specifications	General Description: This affordable software creates accurate measurements and models from photographs taken with ordinary cameras. It provides an easy and inexpensive way to use a camera to create measurements and drawings that can then be used to manufacture, fit, retrofit and modify products. RGB image processing: Yes Multi-spectral image processing: ? Thermal image processing: ? LiDAR :YES Video: ? Advantages: precision; Disadvantages:
Multi-platform	Windows;
Main employment scenarios	Forensics; Manufacturing; Engineering / Surveying

Software name	**Trimble INPHO** (commercial)
Manufacturer	Trimble Geospatial https://geospatial.trimble.com/products-and-solutions/trimble-inpho
Software specifications	General Description: Digital photogrammetry software. Transform aerial imagery into accurate point clouds, surface models or orthophoto mosaics. The software is aimed at a wide range of applications including national mapping, forestry, agriculture, mining, utilities and energy, urban development, defence and disaster relief. Inpho can also process airborne LiDAR scans for third party software such as automated city modelling software.

Software name	**Trimble INPHO** (commercial)
	RGB image processing:Yes Multi-spectral image processing: YES Thermal image processing: ? LiDAR :YES Video: Advantages: precision; Quality Disadvantages:Price
Multi-platform	Windows;
Main employment scenarios	Map; Engineering/Surveying

4.1.3 Synthetic Aperture Radar pre-processing

A standard pre-processing workflow for SAR data applies a set of standard corrections, namely to apply the precise orbit (or flight line) of acquisition, remove thermal and image boundary noise, perform radiometric calibration to sigma null, apply despeckle filters, apply ellipsoid correction, and mask land pixels (Filipponi, 2019). Optionally, ship detection and masking can be applied to remove similarities related to differences between ships that appear bright in the SAR image on the darker sea surface.

The irregular motion of UAVs due to atmospheric turbulence will seriously affect the SAR image quality. Special processing of the UAV-embedded INS and GPS may be required to provide integrated flight information (*Koo et al., 2012*).

4.2 Post-processing

It should be noted that the density and frequency of data collection is rapidly increasing with the use of UAS for wide area monitoring. It is therefore challenging to manually review and analyse this large amount of data to detect anomalies over a wide area. Therefore, automation of data interpretation using specialised computer software tools supported by artificial intelligence is required to gain maximum benefit from the collected data (*Wanasinghe et al., 2020*).

During a single day of operation, a UAS can produce terabytes (TB) of data (high-resolution still images and video). Manual review of this large amount of data is time consuming and may require simultaneous review of different parts of the survey or inspection data, increasing the cost of data interpretation. These limitations can be addressed by deploying Artificial Intelligence (AI) enabled systems to analyse the collected data, and by using cloud-based processing techniques to process the data. (*Wen et al., 2019*).

Oil spill identification methods from remotely sensed pre-processed datasets are based on:

- spectral properties;
- spatial patterns;
- a combination of spectral properties, spatial patterns, temporal characteristics of the data.

4.2.1 Identification from spectral properties

Methodological approaches that have attempted to identify oil spills from remote sensing data acquired by optical sensors use the spectral information and include band ratio (*Taravat et al., 2012*; *Srivastava et al., 2010*), Spectral Angle Mapper (SAM) (*Salem, 1998*), maximum likelihood method (*Sanchez et al., 2003*), Minimum Noise Fraction (MNF) method for dimensionality reduction of hyperspectral data (*Liu et al., 2016*).

Among the band ratio approaches, the Fluorescence Index (FI), which measures the slope between the blue and red parts of the spectrum, has been successfully applied to optical multi-spectral data acquired by the Compact Airborne Spectrographic Imager sensor (CASI) to discriminate surface oil slicks from marine clutter (*Lennon et al., 2003*). Other band combination approaches include the use of the Hydrocarbon Index (HI) (*Kühn et al., 2004*) and the Hydrocarbon Detection Index (HDI) (*Lenz et al., 2015*).

Hyperspectral information can be used to distinguish between different types of oil (i.e. crude or light oil) (*Salem et al., 2004*). A method to derive oil thickness and oil-to-water ratio has been introduced (*Clark et al., 2010*) using remotely sensed hyperspectral absorption features. Spectral unmixing and partial spectral unmixing analysis techniques have been successfully applied to oil spill detection from remotely sensed hyperspectral data. Linear spectral unmixing analysis was tested on the full set of spectral bands acquired by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) hyperspectral sensor without prior dimensionality reduction, using end member selection refined by a three-stage approach and based on dilation and erosion spatial filtering (*Plaza et al., 2005*). A partial unmixing technique based on Constrained Energy Minimisation (CEM) has been shown to provide excellent results for surface oil spill detection (*Sidike et al., 2012*). A hyperspectral imaging-based method for detection and identification of oil and oil-derived substances at surface and subsurface levels has also been proposed, using Support Vector Machine (*Cortes et al., 1995*) algorithm for oil spill detection and Beer-Lambert law for estimating the depth at which the oil or oil-derived substance is present in the remote sensing images (*Alam et al., 2012a*). A comparison of five widely used oil spill detection techniques (namely: SID, ACE, CEM, SFJTC, RX-UTD) was applied to AVIRIS hyperspectral datasets (*Alam et al., 2012b*).

Identification of oil films by the position or shape of dark areas in the SAR image is the most feasible method (*Alpers et al., 2017*). Edge detection algorithms can be used to define discontinuities in the intensity function or very steep gradients in the image, even with a single radar polarisation (*Arslan, 2018*). Oil spill detection from SAR images requires a threshold shift in dB units to be defined within a background window, the size of which should also be defined. Finally, spatial filtering can be applied to remove small pixel clusters (*Melillos et al., 2021*).

4.2.2 Identification from spatial patterns

Spatial patterns in remotely sensed imagery, such as shape, texture and homogeneity, can be used to identify oil spills, also benefiting from high spatial resolution. Oil spill detection techniques include Morphological Attribute Profile (MAP) (*Dalla Mura et al., 2010*), a spatial analysis approach that exploits various structural and shape descriptive attributes (e.g., grey mean, standard deviation, elongation, shape complexity, solidity, and orientation) based on the geometric properties of the oil spill region (*Bhangale et al., 2017*).

Super-pixel segmentation (*Sun et al., 2022*) and DCNN machine learning algorithms were applied to satellite optical multi-spectral data in the VIS-NIR spectral regions to demonstrate that sun glint can be used to classify surface oil slicks, whose surface reflectance is higher than the surrounding water and can also appear as an elongated silvery sheen (*Schaeffer et al., 2022*).

4.2.3 Combination of spectral properties, spatial patterns, temporal characteristics

The combination of mathematical morphology operators with spatial and spectral information can be used to improve oil spill detection (*Plaza et al., 2005*). Classification from satellite time series optical multi-spectral data (VIS, NIR and SWIR) based on object-oriented image analysis approach using fuzzy rules applied to spectral indices (*Kolokoussis et al., 2018*) has been proposed to obtain robust response and avoid false alarms.

Machine learning methods allow the combination of multiple information. A one-dimensional convolutional neural network (CNN) based on hyperspectral features resulted in higher accuracy compared to other machine learning algorithms such as Support Vector Machine (SVM) and random forests (RF) (*Liu et al., 2019*). A Spectral-Spatial Feature Integrated Network (SSFIN), which calibrates a 1-D and 2-D CNN model to extract the spectral and spatial features, was tested for use with hyperspectral data (*Wang et al., 2021*). A weakness of the use of machine learning approaches is the need for high computational resources, which may limit the availability of near real-time analysis results.

Oil from oil seeps, oil platforms and oil terminals can often be detected using time series of SAR images, as the oil films manifest as recurring features at the same location (*Suresh et al., 2015*).

Methods proposed to discriminate between mineral oil films and biogenic (monomolecular) surface films are based on differences in the statistical properties of radar backscatter using single or dual polarisation SAR data (*Alpers et al., 2017*). A comparison between decision tree models and Neural

Networks (NN) showed that machine learning techniques are the most appropriate choice to discriminate oil spills and look-alikes (*Magrì et al., 2021*). An appropriate selection of relevant features, based on spatial and spectral properties, can significantly improve the characterisation of an oil spill and thus the discriminative ability between oil spills and look-alikes (*Chehresa et al., 2016*).

4.3 Web server for data collection and user's management

Acquiring data from different types of sensors and processing it to create models or maps of the environment, such as LiDAR. The data can be processed to produce digital terrain models, 2D and 3D maps, vegetation analysis and other applications. Processing can be done locally or remotely using software tools designed specifically for data analysis.

Hosting refers to the process of storing data or applications on a remote server and accessing them via the Internet. For example, LiDAR data hosting refers to storing raw point cloud data collected from sensors on a remote server and accessing it from there. This approach can be useful when the data are too large to store locally and when multiple users need to access the same data at the same time, as could happen during an emergency.

If we were to conduct several flights throughout the day and then over the next few days and weeks, the sheer volume of raw data could be a problem both in terms of processing and storing such a large amount of data.

The combination of hosting and model processing can be useful if the models need to be processed and analysed by multiple users in different locations. By hosting the raw data on a remote server, users can access the data and perform their own analysis without having to download or transfer large files. This approach can save time and reduce the need for local storage and processing power; this type of approach could be advantageous in emergency situations where the survey of affected areas can be shared very quickly due to the large computing power this type of service offers. The return of an instantly searchable model reduces intervention time and improves response.

This type of service is now being offered by many companies who, at various stages, also offer fleets of drones configured with the necessary sensors, including satellite data and even the drone pilot and flight plans if required.

Even some drone manufacturers have moved in this direction. DJI, for example, has launched DJI FlightHub2, a service that allows all information to be managed remotely, from flight plans to the management and processing of the data collected; in particular, it also offers the possibility of drone charging stations, where the drone can return to recharge its batteries or because flight conditions are no longer safe, and resume the observation from where it left off without having to revise flight plans or create new ones.

Unlike the DJI FlightHub2, which only supports the Matrice series (DJI M300 and M30), FlytNow is compatible with a wide range of drones and operates hybrid fleets of drones and docking stations, whether it's a DJI Mavic, Matrice, Mini-series or custom built on PX4/Ardupilot. FlytNow allows users to remotely control the drone via the cloud using a keyboard, external joystick or on-screen joypad while standing miles away from the base station. This allows real-time decisions to be made in complete safety for operators flying in hazardous environments.

A useful tool for improving the effectiveness of emergency response is provided by smart device applications that allow access to all the information generated following a spill of oil or other hazardous and noxious substances, including spatially explicit maps generated from UAS-acquired imagery. To enable a wide range of practitioners to make the most of the data acquired by UAV systems, the application should include access to a web mapping or online mapping service that allows the maps to be visualised and used. Once spatially explicit information has been generated using local or cloud computing resources, it can be stored on a web server and distributed through a Web Geographic Information System (WebGIS). WebGIS provides visualisation of the UAV-processed georeferenced thematic maps consisting of RGB or greyscale spectral band representation, oil spill polygon extent and thickness estimates (if any), and other ancillary thematic maps. Supplementary information related to the spill and response (*Table 4-1*and *Table 4-2*) *can* be stored on a web server and accessed from smart devices for visualisation and editing purposes. and provide tentative lists of useful incident and intervention related information.

Table 4-1 List of data and information about the incident at sea.

INCIDENT data gathering	
ID incident	Distribution
Date	Water temperature
Location	Surface current
Geographic coordinates	Gallery
Effective amount of pollutant	Maps
Estimated amount of pollutant	Team Information
Source	Note
Spill type	Weather conditions (wind, sky condition, air temperature)

Table 4-2 List of data and information about the response operations.

INTERVENTION data gathering	
Intervention area	Thickness

Intervention ID	Appearance (Sheen, Rainbow, Metallic, Discontinous True Oil Colour, Continous True Oil Colour)
Date and start time	Water depth
Note	Quantity
Coordinates	Breakdown (Barriers, Curtain, Intertidal, Fireproof)
Weather Conditions	Anti-pollution configuration (U, V, J, W, Single)
Material type (tables for different substance groups)	Skimmer (Wicked, Aspirant, Skizzo, Brush, Rape mob, Tape, Trained wicked, Submerged wing, Lift)

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5 Current most common use of drones in oil/HNS spill response

5.1 Use of drones in past case of oil/HNS spill: advantages and challenges

Domaille and Campion (ITOPF) discuss considerations for the use of UAVs in future oil spill incidents, based on their experience with other parties who have used the technology in the field over a three-year period from November 2014 to November 2017 (*Domaille and Campion, 2018*). In almost all cases, the UAVs were of rotary-wing configuration, with visible imaging capabilities, and had been used in a number of offshore oil spill incidents.

The technique was found to be particularly successful in validating oil spill trajectory maps, and in examining the condition and efficiency of oil response equipment. The technique was also found to be highly versatile along a variety of coastline types.

Domaille and Campion list the advantages and disadvantages of the use of drones from the analysis of past maritime emergencies; the advantages and challenges are listed below and summarised in a table, considering all the publications consulted.

The benefits associated with UAV operations:

- government agencies could post UAV footage of an accident and associated oil spill on their websites to inform, notify and reassure the public of a response;
- allow shoreline monitoring and assessment to be carried out quickly with photographic and video evidence;
- reduce costs and time. Significant cost and time savings can be achieved with UAS-based inspection and monitoring activities. UAS-based asset inspection is carried out by a two-person team, which is significantly smaller than a conventional inspection team, reducing the operational cost of the inspection;
- frequent inspections. Due to the low-cost and no additional infrastructure requirements, UAS-based inspections can be performed on demand and frequently;
- flexibility and availability. UAS come in a variety of sizes, payload capacities and endurance;
- UAVs have proven to be highly versatile along a variety of coastlines, including hard-to-reach areas, to provide timely preliminary assessments and recurrent monitoring;
- UAVs could be used to assess the condition and effectiveness of oil response equipment;
- trajectory maps were validated using UAV imagery. With more accurate and frequent input of the position and weathering of a slick, trajectory maps can be made more accurate to aid response planning;
- improve worker safety and minimise HSE risks. UAVs have been used in areas where there are significant health and safety risks. In a dangerous environment where human health would be at risk, for example monitoring from a helicopter or boat in high fumes environment, a UAV has overcome the safety concerns and allowed continued monitoring of the incident;
- better information. UAS-based inspections can easily and quickly access almost any location within onshore/offshore facilities and pipelines to capture high-resolution still images, video, thermal imagery, spectral imagery and point clouds.

The use of UAVs can be detrimental, particularly if the equipment is not operated responsibly or with clear coordination. Despite the wide range of applications and numerous benefits, there are a number of constraints that need to be overcome before UAS can be adopted on an industrial scale. These challenges can be divided into two groups: regulatory challenges and technological challenges. Limited sensor payload and shorter battery life (flight time) dominate the technological challenges.

Main challenges are:

- The limitations of the optics typically mounted on UAVs have prevented surveillance at night or in areas with minimal lighting. The UAVs commonly used at spill sites have only captured visible images, rather than using other sensors;

- The reflection of sunlight off the sea surface has also made oil identification difficult, and care must be taken to optimise the angle of incidence to improve pollutant visibility;
- Regulatory constraints. Legislation requires operators of UAVs to be commercially licensed, which includes approvals from communications and aviation authorities. In some cases, national restrictions may also prevent the use of UAVs;
- Interference with aviation. Care had to be taken to ensure that different platforms (drones, helicopters, aircraft) did not interfere with each other's airspace. Synchronous use of both UAVs and aerial surveillance is an unnecessary and inappropriate duplication of effort and a potential increase in risk;
- Many UAVs are unable to operate in bad weather, particularly high winds or rain, which may not otherwise prevent helicopter or boat operations. If a UAS is operating in high winds, the local controllers for the UAS may not be able to stabilise the robot. In addition, high winds may require more power to the propellers to overcome wind resistance, increasing battery consumption. In certain regions, direct sunlight creates high ambient temperatures, which can cause the UAS equipment to overheat and deviate from its nominal operating conditions;
- Lighting conditions and shadows. Regardless of the type of sensor (HD camera, thermal camera, laser and other sensors), the pilot must maintain a visual line-of-sight with the UAS at all times when conducting any inspection or monitoring. This can only be achieved if there is sufficient light;
- Limited sensor payload, particularly for nano, micro and mini UAS, which are widely used in maritime emergencies. Unfortunately, the sensor payload of these UAS is limited (often less than 1 kg);
- Short battery life. The flight time of most commercially available nano, micro and mini UAS varies between 5 and 30 minutes. This can be further reduced depending on the power consumption of the sensor payload;
- Big data challenge. In a single day of operation, a UAS can produce terabytes (TB) of data (high-resolution still images and video). These limitations can be overcome by using AI enabled systems to analyse the collected data and by using a cloud-based processing technique to process the data;
- Radio frequency and magnetic interference. Current regulations require all UAS used for civil applications to be remotely piloted systems, rather than fully autonomous systems. The pilot maintains visual contact with the aircraft and controls it via an RF link. The RF interference generated within a facility (such as an offshore structure or a ship) can cause the communication link between the UAV and the pilot's control unit to break down.

Table 5-1. Summarising benefits and challenges in the use of drones in oil/HNS spill response

Benefits	Challenges
Reassure the public on development of a response	Limitations of the optical equipment usually utilised
Enable shoreline monitoring	Reflection of sunlight on the sea surface
Reduced costs and time	Regulatory constraints
Frequent inspections	Aviation interference
Flexibility and availability	Bad weather limitations
High versatility along different shoreline types	Light conditions and shadows
Examine oil response equipment condition and efficiency	Limited sensor payload
Trajectory maps validation	Short battery life
Improved safety for workers, minimizing HSE risks	Big data management
Better informations of damaged manmade structures	Radio Frequence and magnetic interference

5.2 Previous projects

The following lines report on the main results obtained through the implementation of projects related to the use of drones in the response to oil and other spills at sea.

In particular, the results of the following projects are summarised:

- HazRunof - Integration of sensing and modelling technologies for early detection and follow-up of hazmat and flood hazards in transitional and coastal waters
- IPoMaC - Intervention sur Pollution Marine par produits Chimques

5.2.1 HazRunoff Project

HazRunoff - Integration of sensing and modelling technologies for early detection and follow-up of hazmat and flood hazards in transitional and coastal waters. WP1 action 1.3 “Integration of Unmanned Aerial Vehicles”

As part of the Hazrunoff project, Cedre, in collaboration with the French authorities and the Port of Nantes-Saint-Nazaire, organised trials of oil recovery equipment specifically designed for operations in fast-flowing waters. The equipment trials took place in October 2018 and provided an opportunity to assess the benefits of using drones as aerial support (surveillance, data transmission, asset positioning, etc.) for response operations on water.

Indeed, the authors emphasise that the drone could be useful for a number of purposes during an oil spill in an estuary (but also at sea):

- detection and tracking of slicks on the water

- guide recovery boats to slicks to facilitate efficient recovery of pollutants
- facilitate information to authorities and command centres with rapid image transmission

The first UAV trial organised in the pilot area of the Loire estuary, as part of the HazRunoff project, made it possible to assess the operational constraints of using a UAV on water in an industrial estuary (regulations, rules, limitations and efficiency of the UAV). The drone used was a Phantom4 pro.

Operational constraints to be tested:

- timeframe to obtain permission from civil aviation authorities, port authorities and industry owners to fly over and photograph facilities (e.g. restrictions for sensitive industries);
- compatibility of operating the drone on the desk of a boat whilst operating oil recovery equipment (space to take off and land the drone) and potential inconvenience to the boat operating team and boom deployment. In the estuary, it is impossible to plan the safety 'return home' function. This return point must be defined on the boat, which was moving during the trials;
- organising the take-off and landing on the boat, with the risk of interfering with the metal structure of the boat, which could affect the drone's GPS.

On the water, the UAV appeared to be potentially useful in the event of a spill, offering great flexibility in survey planning and flying at lower altitudes to detect and track visible/floating contamination and to guide recovery boats in operation. The oblique photographs taken during the first UAV trial provided a good understanding of the situation (slick and operation) and could be exported to Google Earth for geolocation in the estuary. Downloading and transmitting these images is immediate and easy, even on board a response boat, and in this sense they can be useful to authorities and people involved in the response.

Figure 5-1 and Figure 5-2.. Use of the drone to guide the recovery boat (source Altiview)

A further trial was carried out with the aim of producing an example of a photomosaic to be integrated into the HazRunoff operational systems to facilitate rapid delineation of estuarine contamination.

High-resolution imagery was acquired at low altitude, at 110 m and 70 m. Different levels of image overlap were also tested. Six trials were carried out to compare the suitability of the mapping results for assessing oil pollution (resolution and distortion of the images), the time taken to process the images to obtain the map and the size of the map, which must remain easy and quick to transmit.

This type of photomosaic would be useful in a real pollution situation to assess the extent of the pollution, the type of habitat affected and the initial impact. The results showed that a flight altitude of 110m or 70m gave both very good results for this type of assessment, and the option of a 50% degree of overlap of the images seems sufficient and allows to obtain a smaller size of image easier to transmit. Based on the trials, it is estimated that the drone would need to operate for approximately 1.5 to 2 days to obtain an image of the oil contamination spread over the entire estuary, as was the case during the 2008 oil spill.

Figure 5-3. Photomosaic (scenario 1, flight altitude 110 m, pictures overlap ratio 70%)

5.2.2 IPoMaC project

IPoMaC - *Intervention sur Pollution Marine par produits Chimques*

The main objective of the tests carried out as part of the IPoMac (*Intervention sur Pollution Marine par produits Chimiques*) project, led by the French Navy's CEPPOL (Centre d'Expertises Pratiques de lutte antipollution), was to evaluate the ability of remote sensing sensors to visualise the presence of chemical spills at sea in a controlled manner.

The sea trial took place in the Atlantic Ocean off the island of Sein from 17 to 19 May 2021. The primary objective is to confirm the presence of a chemical slick on the water surface or to detect the presence of a gas cloud. In order to provide a representative overview of the sensors' detection capabilities, six chemicals have been selected on the basis of various criteria, including their behaviour according to the SEBC classification, the risks they pose and their frequency of transport by sea. The spilled chemicals are butyl acetate, acetone, heptane, methanol, toluene and a mixture of xylene isomers.

Preference was given to products with a short-term fate of **F** (floating), **E** (evaporating) and chemicals with more than one behaviour according to the SEBC classification, as shown below:

- Butyl acetate - **F**loater, **E**vaporator and **D**issolver
- Acetone - **D**issolver and **E**vaporator
- Hepane - **E**vaporator
- Methanol - **D**issolver and **E**vaporator
- Toluene - **E**valorator
- Xylenes - **F**loaterers and **E**vaporators

The sensors tested include:

1. FLIR E75 42° portable camera deployed by Cedre from the ship bridge
2. FLIR DUO PRO XT2 thermal camera mounted on a quadricopter drone (DJI Matrice M210) from the company Drone Réponse
3. SIMAGAZ infrared multi-spectral camera implemented by ONERA and fixed above the bridge of the building. It is dedicated to the detection of gases and should allow the visualisation of volatile chemicals following accidental liquid and gas spills at sea. It is also capable of measuring the concentration of chemical compounds within the gas cloud.

All sensors for which results are available demonstrate the ability to detect chemical spills. As a preliminary conclusion, several sensors could be used simultaneously to analyse the risks in an emergency situation as efficiently as possible before sending an assessment and response team to an accident.

All the infrared sensors used were able to observe the chemical spill. However, the evaporation of the products into the atmosphere was only detected by the FLIR E75 42° (Cedre) and SIMAGAZ (ONERA) portable cameras.

The chemical spill is responsible for two changes in the thermal environment of a scene that can be observed in infrared remote sensing: 1) at the surface, caused by the presence of a slick or cloud of the product in the water above the surface; 2) in the atmosphere, with the presence of a gaseous cloud. The product in its liquid state can be identified by the formation of a "smooth" surface layer due to the attenuation of capillary waves with an apparent temperature different from that of water. For miscible products, this smoothness is not always visible.

On the other hand, products in the form of gases are no longer opaque and will have a very pronounced spectral behaviour in relation to the position of the absorption lines (a priori known spectroscopic databases). For most gases, this local signature is diluted when averaged over the entire spectral band, making it invisible to a broadband instrument. The SIMAGAZ camera, which separates the infrared information for different spectral regions, is therefore needed to detect, identify or quantify these emissions.

A FLIR DUO PRO XT2 thermal camera mounted on a quadricopter drone was used for observation tests of the pollutant slicks on the surface were carried out at a height of 10 and 80 m for all spilled products. All slicks in all tests were observed using thermal imaging. For some products, such as toluene, the slick was also visible in the daylight. On the other hand, gas detection was unsuccessful.

The slick area of each product can be calculated by overlaying the orthophotos taken by the drone. Estimating the slick area can be very useful for modellers and should be considered for future sea trials.

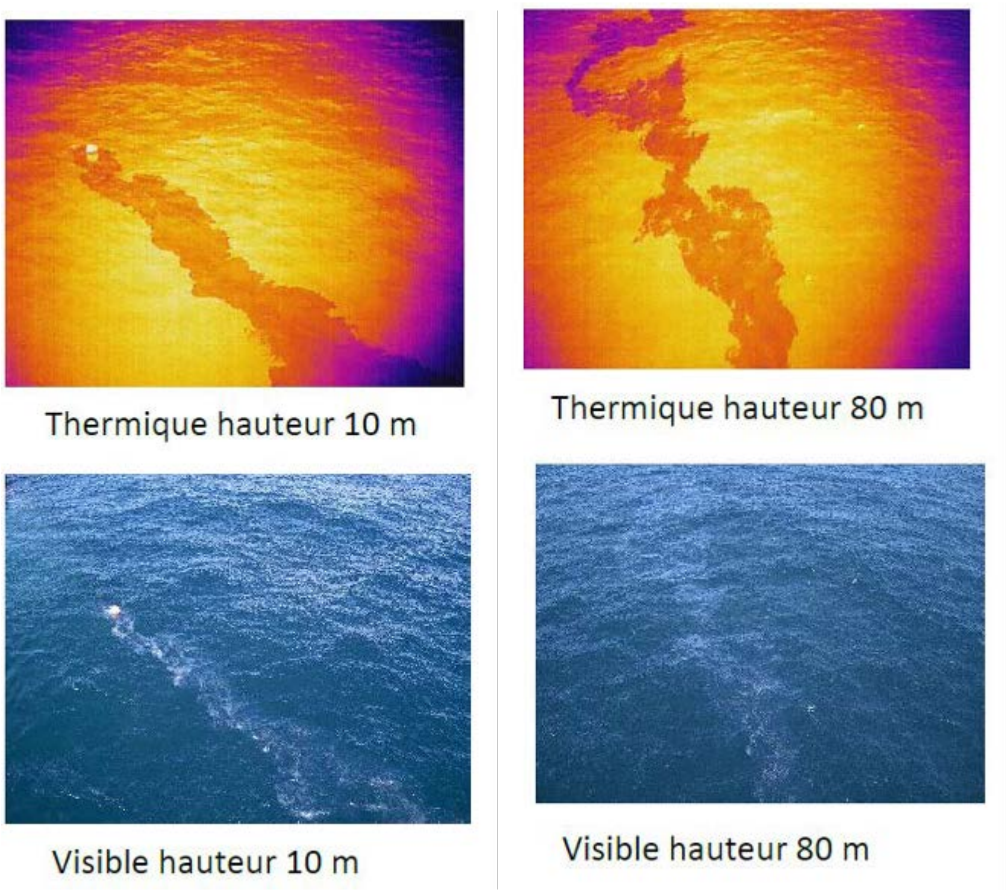

Figure 5-4. Thermal and visible views of the toluene slick via the FLIR DUO PRO XT2 camera mounted on the UAV at 10 and 80 m height.

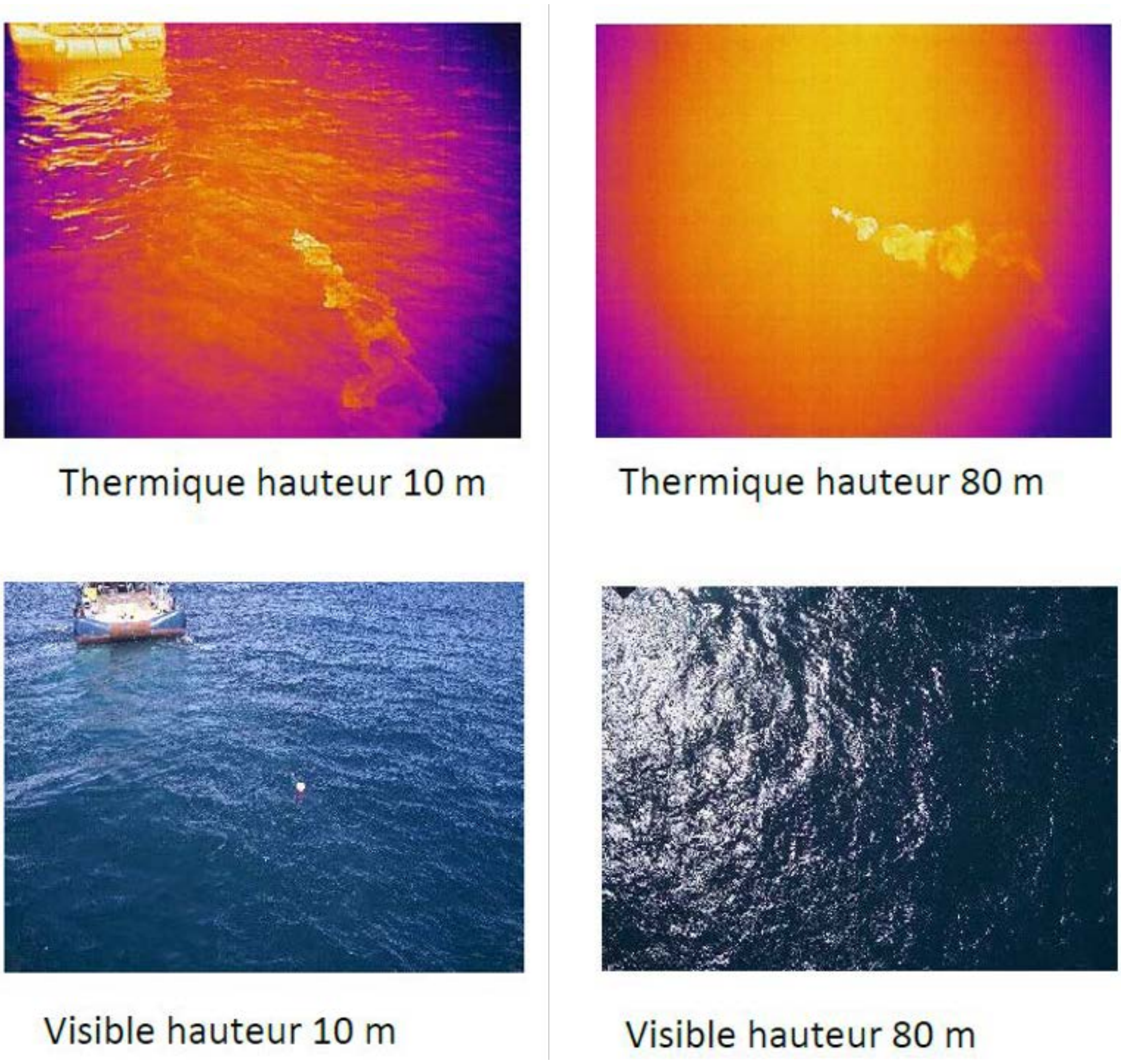

Figure 5-5. Thermal and visible views of the methanol slick via the FLIR DUO PRO XT2 camera mounted on the UAV at 10 and 80 m height

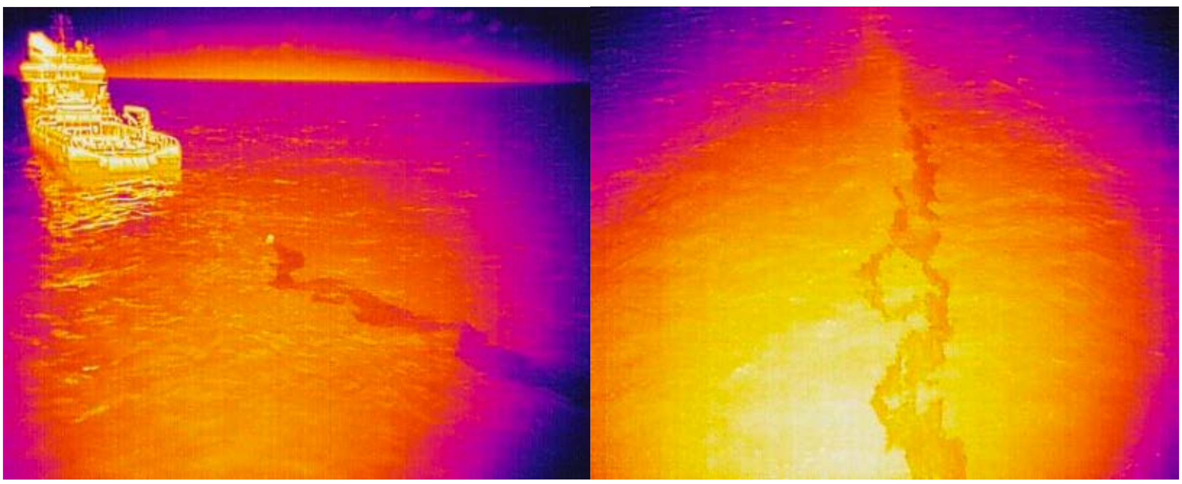

Figure 5-6. Thermal and visible views of the Butyl acetate slick via the FLIR DUO PRO XT2 camera mounted on the UAV at 10 and 80 m height

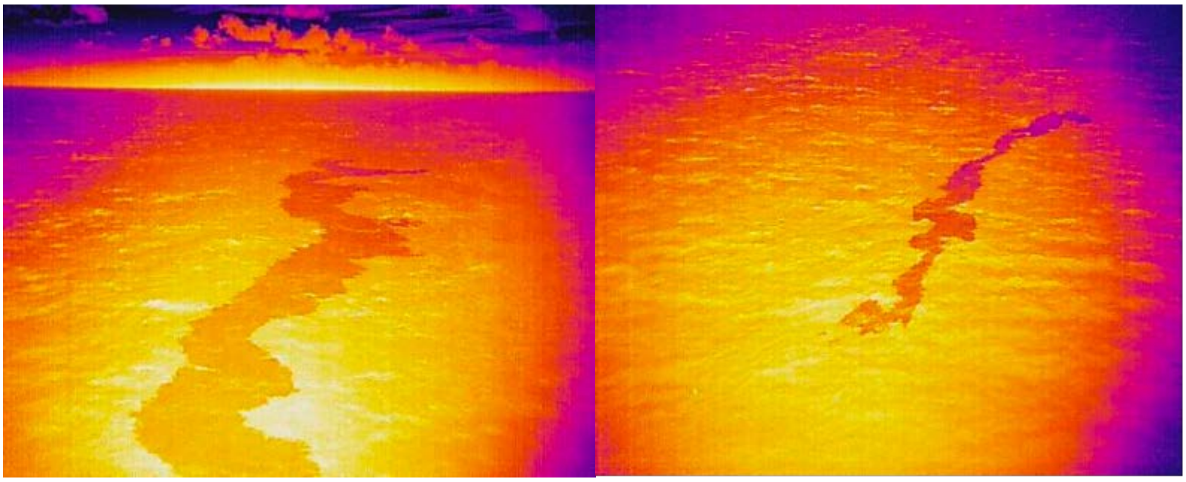

Figure 5-7. Thermal and visible views of the Xilene slick via the FLIR DUO PRO XT2 camera mounted on the UAV at 10 and 80 m height

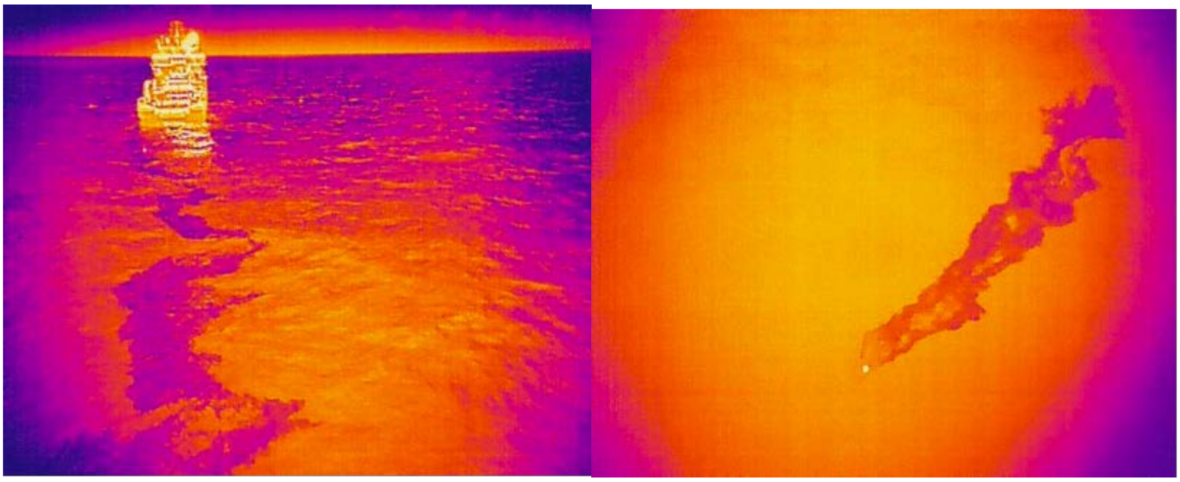

Figure 5-8. Thermal and visible views of the Heptane slick via the FLIR DUO PRO XT2 camera mounted on the UAV at 10 and 80 m height

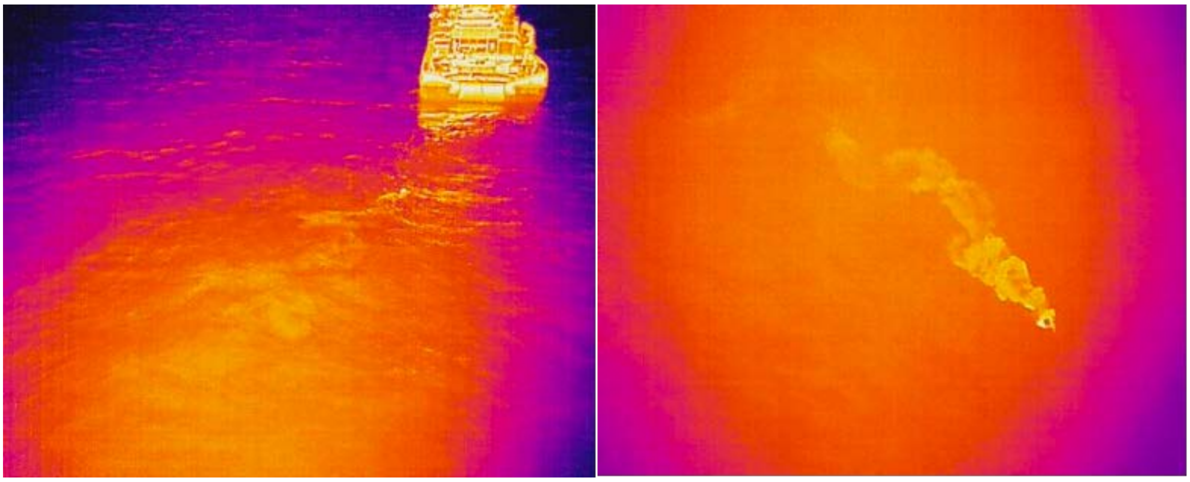

Figure 5-9. Thermal and visible views of the Acetone slick via the FLIR DUO PRO XT2 camera mounted on the UAV at 10 and 80 m height

Importantly, the UAV was found to be able to detect HNS slicks in the sea and associated oil spills. This indicates that this technology is a promising tool for the near future. On the other hand, the tests carried out do not allow to conclude that the UAV can be used to detect gas clouds and thus provide an immediate assessment of the situation before sending personnel to an incident.

5.3 EMSA Remotely Piloted Aircraft Systems Service (RPAS)

Remotely Piloted Aircraft System (RPAS) services are offered free of charge to all EU Member States by EMSA (European Maritime Safety Agency link).

They have been developed to support maritime surveillance operations and the monitoring of ship emissions, and can operate in all the seas surrounding the European Union. RPAS services can support traditional coastguard functions, including search and rescue and pollution prevention and response.

The services are offered to Member States individually and as part of EMSA's regional RPAS strategy, which allows multiple coastguard functions in several EU Member States to be supported by one or more RPAS services.

The EMSA RPAS services have been developed to assist in maritime surveillance operations in support of the authorities involved in the coast guard functions carried out by the Member States. The RPAS service could be used as a complementary tool in the overall surveillance chain, which includes satellite imagery, vessel positioning information and surveillance by manned maritime patrol aircraft and vessels, thus enhancing the maritime situational awareness with additional data sources.

Who can benefit and how?

The RPAS services are provided by EMSA free of charge to EU Member States, Candidate Countries and EFTA Member States. The area of operation can be any sea area surrounding the European Union with an EU or EFTA country as the starting point of the service.

The request for RPAS services can be made by the maritime authorities of the Member States of the European Union, Candidate and EFTA countries, or by other Member State authorities through the European agencies FRONTEX and EFCA.

What type of drones?

The aircrafts currently available have an endurance ranging from 6 to 8 hours, and weight from 25kg to more than 150kg. The type of lift-off can be from a runway, a catapult or vertical take-off (in case of a helicopter).

To address the different operational requirements, three types of RPAS are available:

1. Medium size aircraft with "Long Endurance and long or medium-range"
2. Medium size VTOL aircraft
3. Lightweight VTOL aircraft (i.e. quadcopter)

The specific characteristics of the drones can be found in Chapter 4 and on the EMSA website.

Remotely Piloted Aircraft Systems (RPAS) can be used as aerial platforms for sensors such as:

1. Optical cameras in the visible and infrared (IR) spectral range for night and day maritime surveillance
2. IR sensors for oil slick detection and analysis
3. Radar for maritime surveillance, and oil spill detection
4. Gas sensors ("sniffers") to measure the amount of SOx in a plume emitted by a ship to be able to calculate the percentage of sulphur used in the fuel burned by the ship

In addition, all RPAS are equipped with AIS sensors to provide a complete picture of vessel movements and distress sensors to respond in an emergency. Details of the sensor characteristics are given in *Chapter 3*.

The payload of each aircraft is adapted to the maritime surveillance activities required by the user. Depending on the type of mission, RPAS operate closer to shore, i.e. within Radio Line-of-Sight (RLOS), or further offshore, i.e. Beyond Radio Line-of-Sight (BRLOS), which requires special onboard equipment to communicate via satellite. All communication and control of the aircraft is handled by a Local Ground Control Station, a mobile unit set up in the area of operation.

The data and video recordings collected during all RPAS missions are made available to the responsible authority via the RPAS Data Centre.

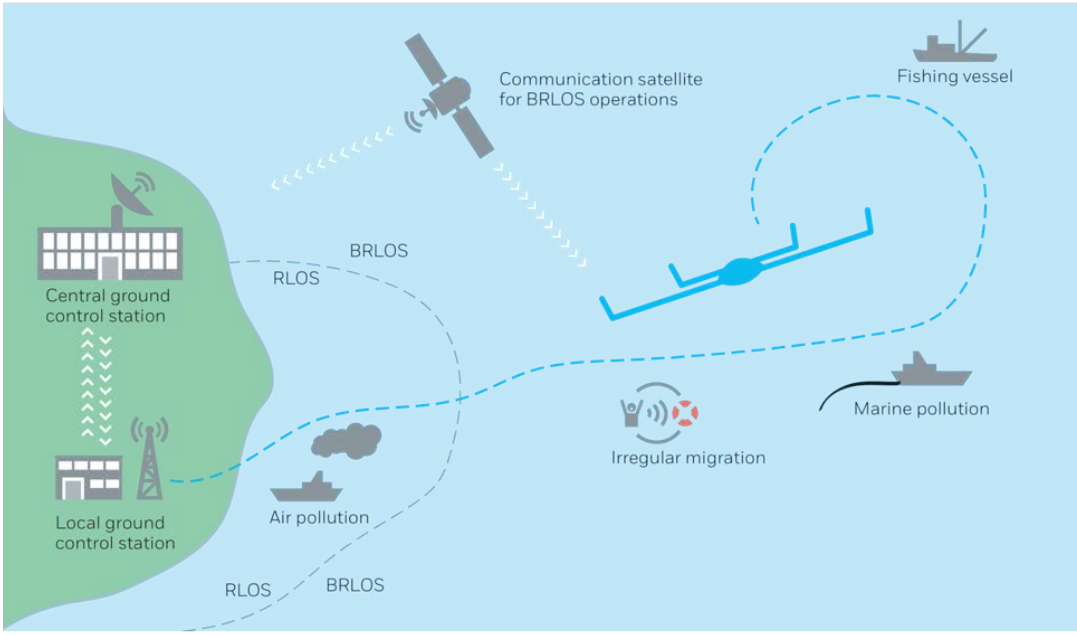

Figure 5-.5-10. Remotely Piloted Aircraft System concept (www.emsa.europa.eu)

RPAS Data collection and integration: the RPAS Data Centre

The RPAS Data Centre (RPAS DC) service provides different users with access to video and data archived or collected in real-time. The information is delivered and combined with other EMSA maritime systems through the same web interface. The RPAS DC service has become a key tool for remote monitoring of RPAS operations and real-time decision-making. The main features include: the possibility to view live or past flights, the use of the common chat and the possibility to define new tasks or new points of interest on the map.

For certain types of operations, such as those targeting a vessel to gather evidence of illegal activity, or those that require the RPAS to react as the situation at sea evolves, users will be able to control the actions of the RPAS in real-time, in collaboration with the pilot and sensor operator during the flight.

The main obstacle identified for the use of RPAS in the maritime domain is the current lack of a mature pan-European legal framework regarding the regulatory aspects of obtaining flight authorisation for RPAS and operating RPAS in non-segregated airspace. However, it is important to note that the EU's objective of establishing a regulatory structure to allow RPAS to operate safely in European airspace is progressing. Updates on regulations and communication are available at EASA website.

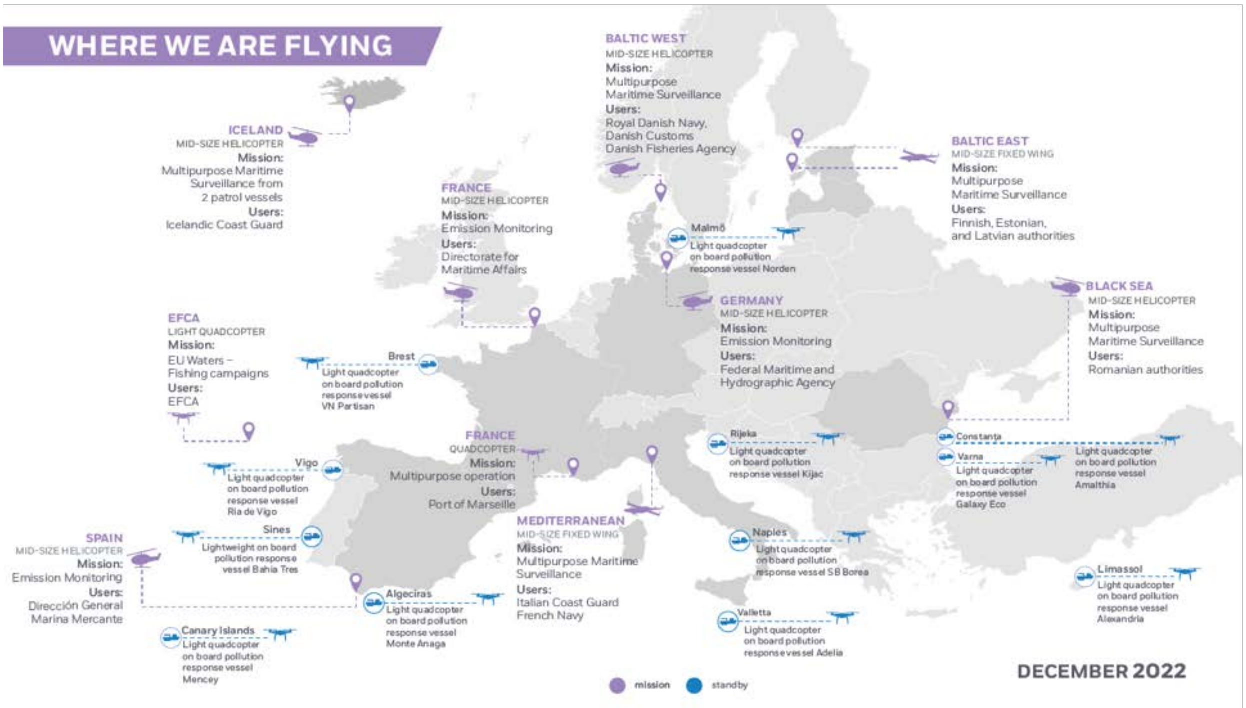

Figure 5-.5-11. Localisation of EMSA RPASs in European area (from www.emsa.europa.eu)

Operational scenarios for RPAS use

Hereinafter are the main scenarios for which drones are made available by EMSA:

- maritime patrol and general surveillance. The RPAS uses its radar, optical and IR sensors to detect vessels and objects at sea. After the information from the vessel is transmitted to EMSA, possible suspect vessels are identified through data analysis and immediately transmitted to EMSA/user. Potential oil spills can be detected by manual analysis or by automated algorithms on board the RPAS;
- marine pollution (monitoring and response support). Long-endurance RPAS with Line of Sight LOS and Beyond Line Of Sight propagation BLOS capabilities for marine pollution situations requiring day and night operations. This service is characterised by automatic observation pattern navigation for target tracking and identification of potential polluters, and for oil spill characterisation (size, thickness, etc.) using the appropriate sensors. The integration of RPAS services enriches the established pollution response network made available to the requesting Member State. The RPAS on board the stand-by oil response vessels have a wide range of operational capabilities depending on the weather conditions and the type of pollution;
- monitoring illegal fishing, anti-drug trafficking or other illegal activities;
- emissions monitoring. The RPAS can carry SOx sensors to measure the sulphur content of the plume emitted by the ship and thus estimate the sulphur content of the fuel burned by the ship. Based on the percentage of sulphur detected, Member States may be able to target inspections to see if further follow-up is required;
- monitoring port activities. The RPAS can be used to support day-to-day monitoring of port operations and rapid response to pollution incidents in the large port area. Several scenarios can be defined, such as: estimating the size of oil spills and assisting with clean-up operations;
- search and rescue. With LOS and BLOS capabilities, the aircraft operates towards the detection of a ship, life raft or boat, hence the need for search pattern navigation (with automatic target tracking and trajectory adjustment to maintain sight of the target).

A focus on marine pollution monitoring and detection by RPAS

While satellite data can detect oil pollution on a very large-scale, Remotely Piloted Aircraft Systems (RPAS) have the enhanced capability to detect and analyse an oil spill at any time of the day and can remain on site during the response operations. A number of tools are currently available to EMSA with different operational advantages.

Remotely Piloted Aircraft Systems (RPAS) can provide operational information on the size and shape of a slick. This complements the data collected by CleanSeaNet, EMSA's satellite-based oil spill monitoring and detection service. The RPAS can also assist in the identification of the source of the slick, e.g. using SAR and IR sensors for slick detection and volume estimation, and optical/IR cameras to identify potential polluters.

In supporting the response at sea, RPAS can identify 'hot spot' areas and provide real-time feedback on the effectiveness of clean-up operations. The data streams generated by the service will be provided free of charge to any requesting authority from EU Member States, Iceland, Norway and the European Commission, i.e. there will be no contractual cost to the user.

Each mission will last for a minimum of two months and the RPAS will be under the command (operational direction) of the relevant Member State authority or agency. The actual flight control/management will be performed by qualified pilots of the service provider. In order to facilitate operational efficiency and effectiveness, the relevant Member State authority should provide an appropriate take-off/landing area, on-site facilities (e.g. internet, water, etc.), as well as assistance in obtaining the RPAS flight permit from the national aviation authority for the deployment in question.

Advantages of using RPAS include:

- wide range, long endurance, and rapid flight activation, e.g. applicable for regular monitoring of a maritime zone for an extended period or targeting a specific area or as triggered by a CleanSeaNet alert;
- capability to stay on site to support response operations;
- designed to operate during day and night and in a broad range of environmental conditions, i.e. variable temperature, high humidity, rain and (as there is no human pilot onboard) potentially dangerous environments;
- invisible to vessels;
- aircraft-to-aircraft notification by transponder to increase aviation safety.

The sensor payload provides:

- maritime radar for initial long-range detection of vessels and oil slicks;
- electro-optical cameras to characterize the spill according to the “Bonn Agreement Oil Appearance Code” to classify oil spills and to record the maritime scene, e.g. photographic evidence linking spill to vessel and/or general observing of vessel activities;
- thermal infrared cameras for slick thickness detection, vessel identification, fire analysis, locating people in distress, general observation of vessel activities at night or in poor visibility conditions;

- distress signal transponder to determine the location of the person/object in distress;
- AIS transponder to identify vessels and determine their position.

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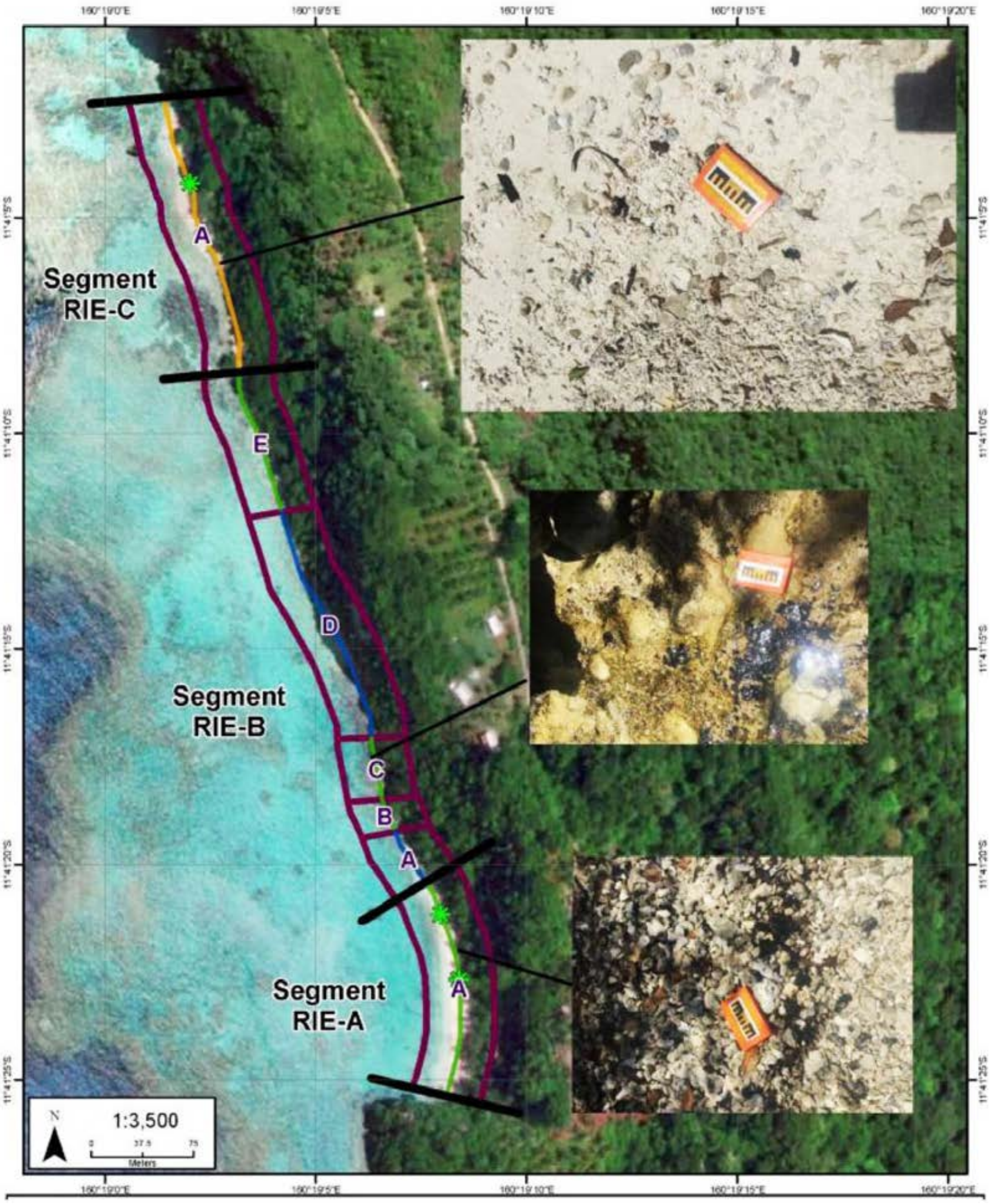
6 The integrated response to pollution accidents: the use of drones in maritime Contingency Plans



An example of a SCAT map with high resolution imagery as the basemap. Each section of the map provides details to cleanup crews and appropriate stakeholders. (source: wingtra.com)

The use of drones in marine environmental emergencies is an activity that cannot be organised at the beginning of an emergency, but must be planned by including it in a NCP. Indeed, the use of drones implies the involvement of various institutions and the mobilisation of personnel and equipment that must be available in the shortest possible time.

The use of drones should also be considered, particularly in the survey and monitoring phase, as a complement to the use of satellite data and data from 'conventional' aircraft. As mentioned above *(paragraph 1.3 Drones vs airborne manned systems and satellites*), the use of one platform does not exclude the others; each has strengths and weaknesses to be considered. Small drones (weighing less than 20 kg) are generally considered for surveys and monitoring in coastal areas, mainly due to their limited range. The NCP could also take into account the RPAS offered by EMSA, which is more concerned with observation and detection in the open sea with the assistance (see *paragraph 5.3 EMSA Remotely Piloted Aircraft Systems Service (RPAS)*.

With regard to the use of drones, the NCP must therefore contain:

- objectives and use of the data obtained;
- possible scenarios;
- institutions involved;
- type of drones and sensors to be used;
- their location;
- the procedures to be followed and the time required for the operation.

The objectives should be those already stated in *paragraph 1.1 Objectives* of this document and In general terms, the aim is to improve the response capacity in order to: facilitate the inspection of remote areas; develop synergies and the exchange of information between authorities; inform and reassure the public about the development of an emergency response.

It is therefore necessary to define the possible scenarios in which the drones/sensors/software systems can operate, indicating for each of them the best assets to use. This aspect is detailed in the *paragraph 6.1 Use of drones in different scenarios*.

The NCP must clearly identify the authority responsible for monitoring and coordinating the use of drones. In this context, it is necessary to specify that there are two possible approaches to the management of the drone fleet:

1. The competent authority establishes a branch (UAS service) with the task of acquiring a fleet of drones, with appropriate sensors and software, training personnel and distributing the equipment throughout the territory.
2. The management of the fleet of drones is entrusted to one or more private companies, which are activated in the event of an environmental emergency.

Both options have their advantages and disadvantages. It must be taken into account that the technology related to drones and sensors is constantly evolving and therefore their purchase and maintenance can be very expensive, depending on how often the use of drones is planned. It must also be taken into account that the type of drones and sensors needed may not always be the same, depending on the scenario. For this reason, it is often advisable to activate private entities with whom activation agreements have been concluded, entrusting them with the technological and logistical aspects, while the competent authority manages the strategic aspects.

Finally, the NCP must consider the procedures to be followed so that the drones can be effectively deployed in the shortest possible time once an environmental emergency has started. Basically, 7 steps can be defined schematically:

Step 1 - Define the scope of the intervention.

Step 2 - Asses the field conditions.

Step 3 - Estimate the flight distance or area and distance from land.

Step 4 - Review international and national regulation.

Step 5 - Select the platform and sensor payload.

Step 6 - Select data processing tools.

Step 7 - Apply for permission to operate.

Prior to commencing any UAS-based activity in the region of interest, it is essential to identify the licensing and certification requirements, restricted airspace, restricted UAS, restricted sensor systems, maximum take-off weight limitation, maximum lateral clearance for people, structures, commercial airspace, airports, etc., and maximum and minimum altitudes (Step 4). This allows the UAS operator to select the right UAS, sensor payload (Step 5) and mission plan to comply with all regulations applicable to the region of interest.

Depending on the scope of the project and the sensor payload, the most useful data processing software tools must be selected (Step 6). The difficulties in handling the data obtained (in terms of size and interchangeability) and the time required for processing must be taken into account when selecting the most appropriate processing software.

Depending on the region of operation, the UAS service provider may need to apply to the local regulatory authority for permission to use UAS for inspection, monitoring or surveillance tasks (step 7).

6.1 Use of drones in different scenarios

This section considers the possible arrangements that could be used depending on the different scenarios that could arise during an environmental emergency at sea, described in *paragraph 1.2* Scenarios. The following possible scenarios have been identified:

A. Pollutant detection and tracking;
B. Guide the recovery boats to the slicks;

C. Identification and mapping of atmospheric plumes of pollutants;
D. Survey of azardous environment;
E. Inspection of remote areas;
F. Shoreline Clean-up and Assessment Technique (SCAT);
G. Wildlife population Monitoring

As mentioned several times, this document is mainly concerned with so-called "small drones", i.e. those weighing less than 20 kg. These drones have objective difficulties in operating in the open sea, mainly for two reasons: they have a reduced energy autonomy; there are difficulties in operating take-off and landing from a boat.

Each UAS has to interrupt its survey activities and land at a home position to recharge. To reduce the time required for recharging, the survey team typically carries several fully charged spare batteries. When the UAS lands at the home position, the survey team swaps the batteries and may connect the discharged battery to a charging port. Once the battery change is complete, the UAS resumes its inspection activities.

There are objective difficulties in getting a UAV to take off and land from a ship due to three types of problems:

- limited space to launch and land the drone;
- difficulty in planning the safety 'return home' function for the boat, which moves during operations;
- interferance with the metal structure of the boat, which could affect the drone's GPS.

For these reasons, if you are planning a mission involving take-off and landing from a boat, it is advisable to consider using a multicopter or at least a VTOL drone.

Each individual drone requires a minimum "survey team" consisting of:

- a pilot who is fully focused on flying the UAS;
- a navigator, who directs the flight of the drone to achieve the mission objectives (detection and tracking of pollutants, inspection of remote areas, etc.).

Based on the real-time data, the navigator can ask the pilot to fly and orient the UAS in a specific pose to collect more data from the area of interest.

There is a wide range of plug-and-play sensors available for UAS. Therefore, the survey team has more flexibility (choice) in selecting a UAS and sensor payload depending on the requirements of the situation, the location of the inspection, the pollutant to be detected, etc.

In any case, it is necessary to consider the use of a web server for data collection and user management (*paragraph 4.1*), which is useful for the sharing and transmission of the data.

6.1.1 Scenario A: Detection and tracking of pollutant

The objective is to detect, track and classify the pollutant. With particular reference to oil/HNS spills, rapid and efficient intervention requires (1) detection of pollutant slicks, (2) thickness estimation, (3) pollutant classification and (4) pollutant tracking, as described in the *paragraph 3.1 Properties and characteristics of oils and HNS detected by drone-mounted sensors.*

Pollutant spill detection

The most important part of an oil spill is the detection of oil/HNS slicks. It is important to locate them and determine the extent of their spread. This necessary information allows oil/HNS spill mapping for both tactical and strategic countermeasures.

Pollutant thickness estimation

The thickness distribution of the spilled contaminant is another critical piece of information for spill containment. Knowing the thickness of the spill allows an estimate to be made of the total volume spilled so that the appropriate tools can be used in the clean-up operation.

Pollutant classification

Classification of the oil/HNS type is also important for spill containment. On the basis of this information, the authorities estimate the environmental damage in the short and long term in order to take appropriate response measures.

Pollutant tracking

As the spill can spread rapidly within a few hours, an effective contingency plan requires the ability to track the spill over time. Tracking provides timely and valuable information to anticipate possible damage scenarios, predict the trajectory with additional input from weather forecasts, and assist in clean-up operations.

Wherever possible, it is preferable to use fixed-wing drones, which can cover greater distances. If the starting point is a boat, it is preferable to use a VTOL.

It is suggested that the flight be planned at a sufficient altitude to cover as large an area as possible, but still be able to detect and characterise the pollutant. The altitude will therefore depend on the characteristics of the contaminant.

Orthophotos should be taken to help assess the extent of the identified patches and, if thicknesses are known, volumes.

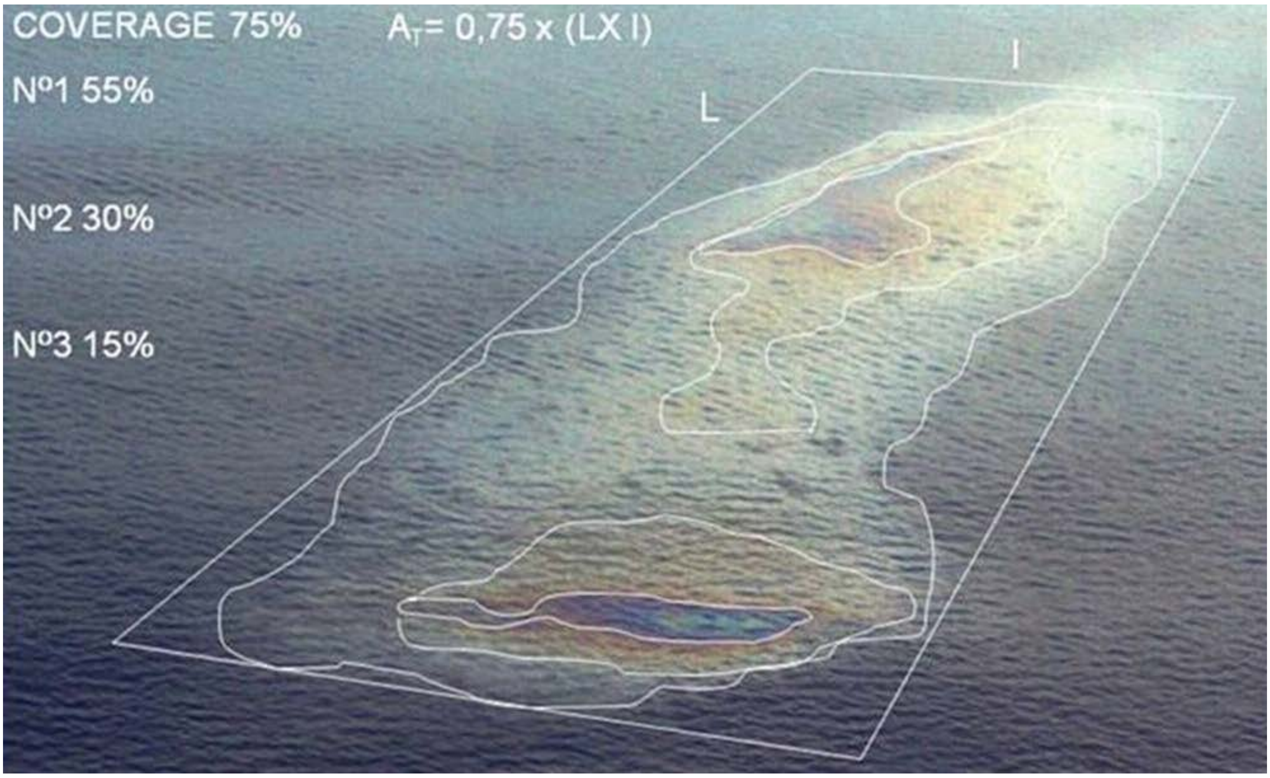


Figure 6-.1. An example of measure of area extention. Knowing the thickness distribution , it is possible estimate volumes involved

Regarding the sensors to be used, please refer to *chapter 3 Sensor of Drones*, to select the most appropriate sensors depending on the pollutant, the weather conditions, the type of drone available and the time of day (presence or absence of sunlight).

6.1.2 Scenario B: Guidance of the recovery boats toward the slicks

Drones can be an excellent tool for optimising and directing containment and recovery operations. Moreover, by observing the containment and recovery operations in real time, it is possible to check and verify the effectiveness of the anti-pollution means, which also depends on the environmental conditions and the characteristics of the pollutant.

In this case, it is preferable to use a VTOL capable of taking off from a boat and remaining in a fixed position to make observations.

In the case of an oil spill, the pollution response usually takes place during the day; it may be sufficient to mount a high-resolution video camera as a sensor.

The drone teams need to be in constant contact with the captains of the vessels and with the incident commander on the ground in order to position the vessels in the best possible way.

Figure 6.2. Drone could be a guidance for recovery boat (Callao oil spill, Perù 2022) (source: Fanny Chever – CEDRE)

6.1.3 Scenario C and D: Identification and mapping atmospheric plumes of pollutants and survey a dangerous environment

In these scenarios, the main objective is to detect and track the spread of a floating and/or evaporating chemical in order to minimise the risk to those who have to intervene.

Often it is necessary to verify whether the release of HNS is real or potential; therefore it may be necessary to carefully inspect the hypothetical source (chemical ship, chemical plant on land, container dispersed at sea, etc.). It is therefore advisable to use multirotor drones to enable stationary observation and inspection of confined spaces (e.g. tanks).

Regarding the choice of the most suitable sensors, these could vary from specific thermal cameras (e.g. FLIR for floating substances) to hyperspectral sensors or so-called "laser gas sniffers", which are also useful for volatile substances (*paragraph 3.2 Type of sensors in oil/HNS spill response*). In these cases, it is necessary to assess the payload of these instruments, which will clearly determine the type of drone to be used.

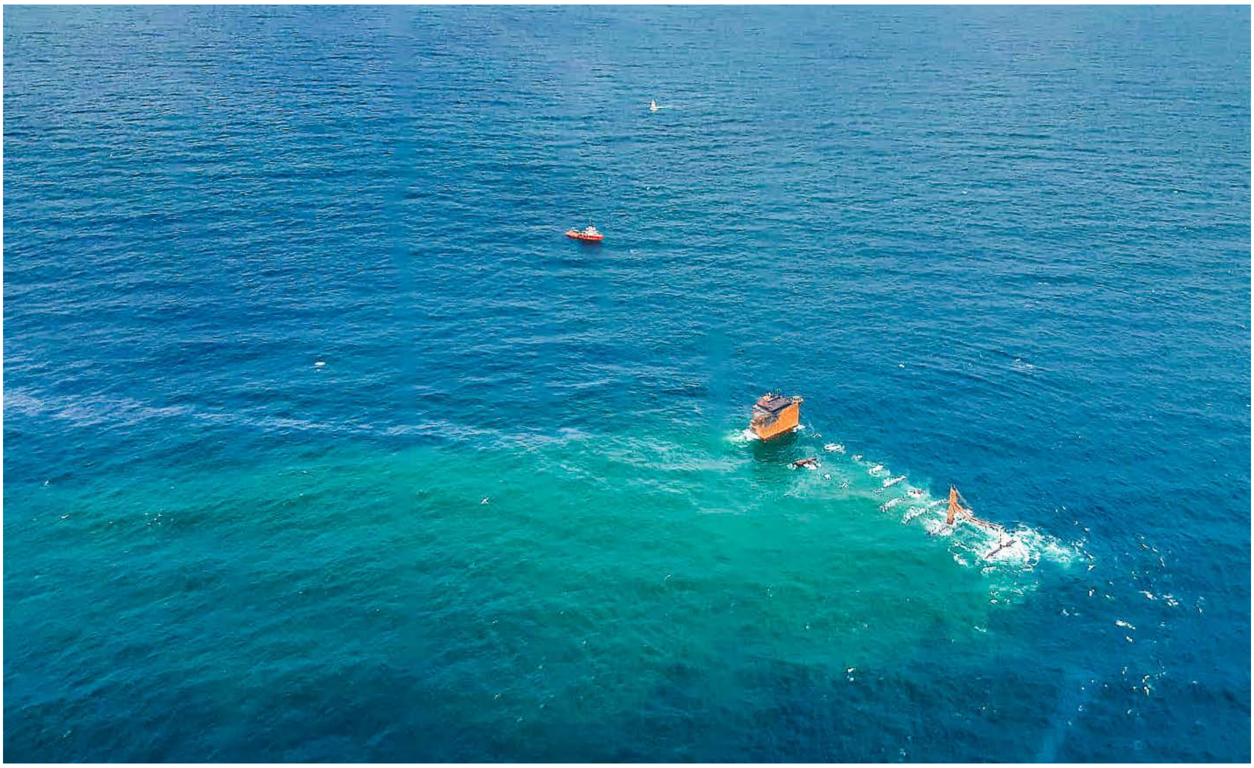


Figure 6.3.Inspection with drones of potential source of HNS spill reduce healty risks for interventors. Containers ship X-Press Pearl wreck, Sri-Lanka, 2021 (source: Luigi Alcaro - ISPRA)

6.1.4 Scenario E and F: Inspection of remote areas and Shoreline Clean-up Assessment Technique (SCAT)

The inspection of coastal areas affected by oil and HNS spills can be carried out quickly with the use of drones. The aim of the inspection is therefore to assess the state of pollution by carrying out what is known as the Shoreline Clean-up Assessment Technique (SCAT).

This technique can also be carried out by a team of operators walking through the area to be inspected. In this case, however, the time taken to deliver the results of the inspection can be very long, which is incompatible with the tight timeframe of the emergency. In addition, remote areas such as inaccessible cliffs or islets cannot be inspected with the necessary precision. SCAT shoreline inspection is an internationally standardised technique that allows coded data output. (*IMO/UNEP, 2009; ITOPF, 2011; IPIECA, 2016; POSOW Project, 2013*).

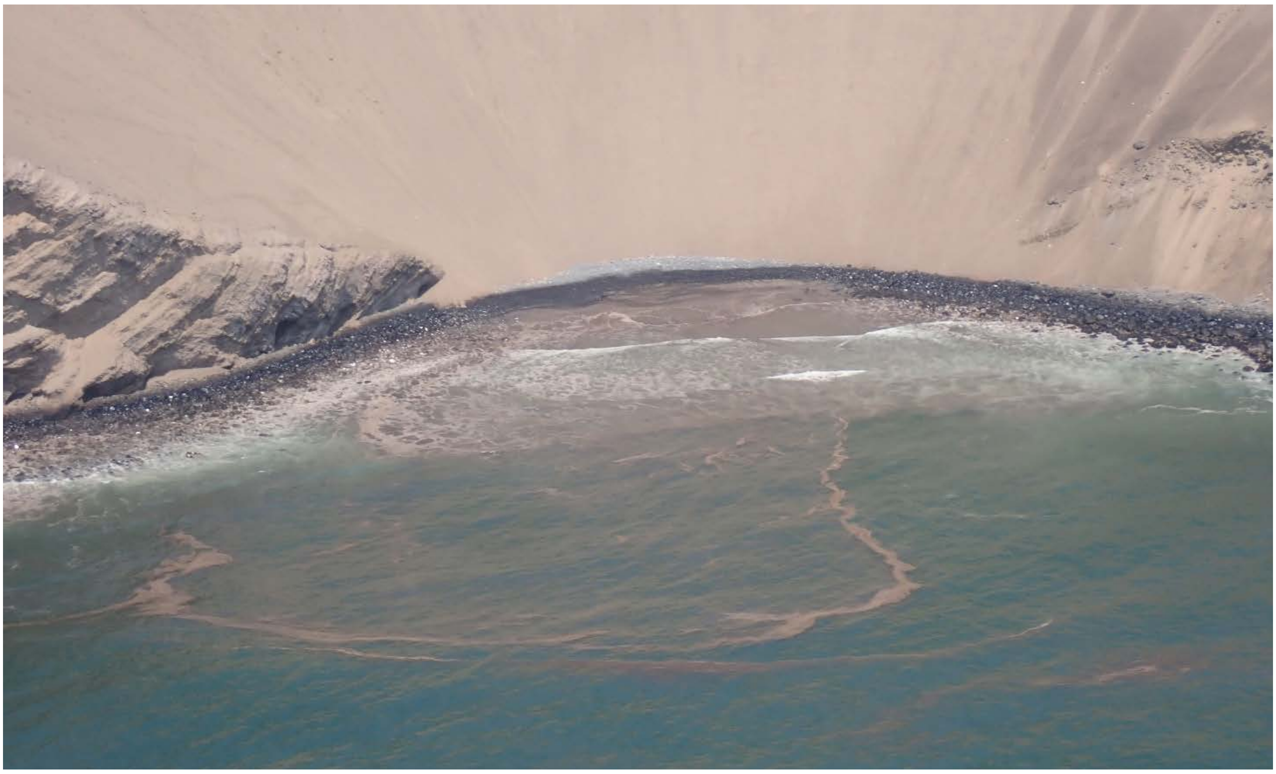


Figure 6.3. Drones could be excellent tools to inspect inacessible areas. Callao oil spill, Perù 2022 (source: Stig Nordaas – Norwegian Coastal Authority)

The information required by SCAT (usually contained in a sheet) can also be obtained by overflying the area with drones. Furthermore, the main product of the overflight will be a map of the area highlighting all the characteristics required for the SCAT inspection, such as: presence of the pollutant, distribution and position of the pollutant, shoreline characteristics, accessibility, use, etc.

The cartography of the area can be obtained by setting up the flight plan to carry out photogrammetry of the area, which, as explained in *paragraph 4.1.2 Photogrammetry and image processing software sheets*, consists in the creation of a photomosaic, the detail of which essentially depends on the flight altitude.

Where possible, it is recommended that a fixed-wing drone is used for the overflight, as it can cover greater distances in the same amount of time. After this initial overflight, a multi-rotor drone can be used to inspect the area, using its stationary flight capability to observe details that may have been missed during the initial survey.

The production of thematic maps is an extremely important tool which, if shared with all the authorities involved in the emergency, can be one of the factors in strengthening cooperation between the authorities on land and at sea.

6.1.5 Scenario G: Monitoring of wildlife populations

As is well known, wildlife can be seriously affected by a marime spill of pollutants. Seabird populations in particular come to mind, but other classes of organisms may also suffer: reptile (sea turtles), marine mammals (Cetaceans, like wahales and dolphins, Pinnipeds, like otaries and seals), Fishes.

The damage that can be observed may concern the entire ecosystem, the population of a single species, or individuals, and may include: alteration of the relationships between different species in an ecosystem; alteration of the structure of a population; the death of individuals; contamination of organisms on a chronic or acute level.

Drones could be used to evaluate some alterations through following strategies:

- counting the flock sizes of populations of wildlife, potentially injured by a oil/HNS spill;
- observing behaviour of individuals;
- observing sign of individuals contamination.

Unmanned aerial systems (UAS) have the potential to collect high-resolution photographs of wildlife for life-history studies without disturbing the species being studied. The use of a multicopter is preferable to a fixed-wing drone because it is often necessary to carry out precise observations (such as the behaviour of individuals) and therefore a stationary flight is required. If the UAS is operated under a beyond-line-of-sight (BLOS) permit, it could be used to search for wildlife.

The responsible study of wildlife using a drone should only be carried out by persons experienced in the biology and behaviour of the target animals. *Marcowski, 2021* use drones to investigate the flock sizes of 33 species of waterbirds during the breeding and non-breeding periods. The automatic counting of birds was best done with ImageJ/Fiji microbiology software. Machine learning using neural network algorithms proved to be an effective and quick way of counting birds (around 100 birds in 7 s). However, the preparation of images and machine learning time is time-consuming, so this method is recommended only for large data sets and large bird assemblages.

Figure 6.4. Automatic counting, using dedicated software, is recommended only for large wildlife populations. Callao oil spill, Perù 2022, Islas Grupo de Pescadores (source: Luigi Alcaro – ISPRA)

Koski et al., 2015 carried out a pilot study near Igloolik (Canada) in early July 2013 to collect identification-quality photographs of bowhead whales and record the responses of the whales to overflights by an UAS. They successfully collected high quality photographs of bowhead whales and none of the whales overflown responded to the overflights in an observable manner.

Similarly, *Adame et al. 2017* used drones to carry out a population study of the California sea lion (*Zalophus californianus*) in the Gulf of California. The work was particularly useful to estimate pup numbers, that reflect colony fitness. The use of drones was preferred to the classic counting carried out from boats, while circumnavigating rookeries and haul-out sites. This second method has several shortcomings, such as observers missing some animals lying between others or behind rocks. Land-based counts may partially overcome these problems, but not all sites are suitable for such technique. Nevertheless, land-based counts can be disruptive to the animals and can even result in pup mortality.

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