Fisheries Innovation Scotland

# FIS037 A Review of Satellite Technology and Opportunities for Scottish Fisheries

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# FIS037
# A Review of Satellite Technology and Opportunities for Scottish Fisheries

**Partners: Space Intelligence Ltd and Fisheries Innovation Scotland**

**Final Report**
**7th June 2021**

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## Executive summary

The Space sector is gaining an increasing role in our lives, and taking a more prominent role in our economy, with an increasing number of applications and sectors becoming supported by space and satellite technology in some way. There are a number of trends driving this process. Historically, satellite launch and operation has been dominated by nation states due to the high costs of development, construction, launch and operations of satellites. However, as with other areas of technology, satellite technology is benefiting from miniaturisation, and increased flows of investment capital. This means that the space sector is increasingly being dominated by the private sector, with new companies emerging annually offering new sensors onboard new satellite constellations; and new companies offering data analysis services. Moreover, the speed with which new sensors and satellites are developed is increasing, with satellite missions being developed for specific use cases. This 'Agile Space' approach sees companies moving from mission concept to launch and operation in as little as 18 months. As such, there are an increasing number of applications derived from Space data, and increasingly it is being mainstreamed into our daily lives: each time you book an Uber taxi, or JustEat, you are relying on space-based location services.

With the proliferation of demand for space-based applications, and acceleration of supply of technological innovation, the Space sector is projected to grow rapidly, and be worth £400bn by 2030. The UK government aspires to capture 10% of this market, and the Scottish government 1% of this market. In the abstract, this huge potential is exciting. This report was commissioned in this context. The objective was to provide an overview of current satellite and satellite-enabled technology and understand how this could be deployed to support the Fisheries sector in Scotland, both now and in the future.

The commissioning of this report is timely: as we write, the UK is running a consultation on its national space strategy. Here in Scotland, more satellites are being produced than anywhere else outside California. Scotland has a growing expertise in 'Agile Space', with the big picture being that within the next couple of years, Scotland will have an end-to-end supply chain in space. This means that we will have the capacity to specify, launch, operate and analyse the data from small satellites in one country. This is not to be parochial - there are of course organisations across the UK (e.g. Satellite Applications Catapult, UK Space Agency) and Europe (e.g. European Space Agency) with whom FIS can engage - rather more this is to convey the dynamic and exciting Scottish context in which this text is written, hence we do retain a Scottish focus.

When it comes to data analytics, Edinburgh has set itself the ambition of becoming the Space Data Capital of Europe. Already, the capital is developing an aggregation of companies with expertise in the analysis of Space data, with a world-class research hub centred around the city's Universities. This provides exciting opportunities for the fisheries sector for long-term engagement in the development of new applications through research and development partnerships.

This growing ecosystem of university researchers and private companies offer a suite of services relevant to the fisheries sector, from design and manufacture of new small satellites, through to transformation of satellite data into useful information to support management decisions and regulation. We provide some of these connections explicitly in a summary 'outcomes' section at the beginning of the report. This provides a wrapper around a document rich with technical detail and applications, and transforms it into an actionable piece of work. Moreover, given the enthusiasm for technological innovation amongst fisheries stakeholders, the Space Intelligence team sees this report not as an end output, but rather the beginning of an engagement to help support the Scottish fisheries sector benefit from exciting new Space technologies.

Whilst the industry seems new, satellites have in fact been orbiting Earth since the last century, enabling global communications and earth observations. These satellites have helped us to map the planet, enabled new navigation tools, mass communication and more recently to document large-scale environmental change. In the marine realm, fisheries-specific tasks are enabled by two main classes of satellites: earth observation (EO) satellites and communications satellites. EO satellites can provide information about the marine environment (e.g., sea surface temperature and wind speed) and can also be used for vessel monitoring purposes. Communications satellites (most commonly, radio-frequency satellites) can be used to record the location of vessels and for transferring information via satellite link.

We are focussed in this report on novelty and horizon scanning for the fisheries sector; however, it is reassuring to note that many of the available data and technologies are already used by the fisheries sector around the world today; for example, through automatic identification systems (AIS) and vessel monitoring systems (VMS). However, there are some areas where technology does not appear to have been adopted so readily, or are seen only as desirable by some segments of the sector. In some cases, this is because even where Space technologies offer benefits to some stakeholders, deployment needs to be undertaken in an equitable and sensitive manner. For instance, efforts to roll out cameras across the fishing fleet offer the chance to improve catch verification, but has been resisted by fishers where this has not been applied to all vessels fishing in the same waters. We learned that despite plans by the Scottish Government to place tracking devices on the entire Scottish fleet, only 30% of one segment of the fleet have them fitted.

One of the main areas where satellite technology can help the Scottish fishing industry is through the creation of a spatially-explicit annual map of Scottish fishing activity. This was identified as a specific use-case through discussion with a Fisheries expert. It aligns with the Scottish Government's *Fisheries Management Strategy* for 2020-2030, which identifies the need for increased spatial understanding of fisheries distribution to support decision making around fish stocks and sustainable levels of fishing. Fishing activity distribution maps can also help to resolve gear conflicts and to reduce the loss of fishing areas to other marine stakeholders (e.g., offshore wind farms). This use-case is discussed in more detail in the 'outcomes' section below.

Satellite technology can also help the industry through improved monitoring of illegal, unreported and unregulated (IUU) fishing, an issue raised through meetings with various stakeholders. It is increasingly difficult to monitor IUU fishing, particularly in the high seas where land-based tracking data is unavailable and ship-based monitoring resources are expensive, time-consuming and otherwise limited. This report explores the uses of satellite technology alongside traditional AIS and VMS for vessel tracking and monitoring, including the use of small constellations of radio-frequency satellites as well as high-resolution imagery from satellites and UAVs. Artificial Intelligence (AI) and machine learning (ML) can be used to process large amounts of data, training models to identify fishing patterns and vessel properties, including the type of fishing gear used (e.g., trawling gear, longlines). Given this, we dedicate a high-level summary section of the report to AI and ML.

Satellite technology can also be used to improve the efficiency and sustainability of day-to-day fishing, for example by providing information to help fishers find optimal fishing grounds and reduce bycatch. Thinking to the future, maps of satellite-derived sea surface temperature and ocean currents could be used alongside local knowledge to identify optimal fishing grounds as the climate changes. This information can be used by fishers to decrease the length of time spent at sea searching for and catching their quota, reducing fuel use and costs, but also carbon emissions. Hotspots for protected and/or choke fish could be similarly identified, and can be avoided by fishers to significantly reduce bycatch, and improve sustainably.

As with most environmental-based datasets, the use of satellite data does present some challenges; for example, issues with cloud cover for optical satellites, the frequency of satellite passes for providing near-real time monitoring and the sometimes prohibitive costing of acquiring large volumes of commercial satellite data. This list is not exhaustive, and identified challenges are discussed throughout the report where appropriate.

In addition, as mentioned at the outset, the satellites which provide the information that we are describing are both privately and publicly owned. This means that some data can be acquired freely, whereas other datasets must be purchased or the systems hired as a bespoke service. Information can therefore be acquired as a product or service, integrating into existing and future management frameworks to support decision-making. The aim is to make things easier for the Scottish fishing industry to make more informed decisions.

For example, Space Intelligence undertakes the majority of its work mapping out land cover and forestry across the world. We provide information on how much land cover there is, of what type and where (e.g., there were 3000 ha of Native Woodland in Argyle in 2020). This is useful for mapping out what is called Natural Capital, which is a requirement of national government.

Recently we produced an interactive web-map providing this information for all stakeholders in Scotland (https://www.space-intelligence.com/scotland-landcover/). This project came about after winning the Can Do Innovation Challenge competition, and the maps of land cover produced for the project will be integrated into NatureScot's annual natural capital asset index (NCAI) assessment. This is just one example of how satellite data can be turned into actionable information and integrated into existing management systems used for making important, informed decisions.

For the Scottish fishing industry, a fully digitalised, integrated fisheries management system could provide information relevant to all industry stakeholders, with information and data shared via ship-to-shore and ship-to-satellite communication links. This could include near real-time updating of satellite-derived maps of sea surface temperature and phytoplankton concentration to help fishers increase efficiency, downloaded with a smartphone app or on a laptop. Fishers would be able to share information on fleet position and catch electronically, reducing the burden of paperwork and improving product traceability to increase buyer confidence. A virtual fish market could allow catches to be sold before landing, working towards a more balanced supply and demand. Setting up an integrated electronic system will require an immense amount of effort and cooperation from all parties along the seafood supply chain, and the different capabilities in terms of equipment and gear across all types of fisheries will need to be considered; however, once operational the system of this kind would significantly enhance fisheries management.

## Outcomes of the report

This report reviews satellite technology opportunities for the Scottish fishing industry, accounting for the needs of a range of industry stakeholders (e.g., fishers, policy makers, regulators, and markets/buyers). Satellite technology can be used to provide information about the marine environment, for example sea surface temperature and phytoplankton concentration, both key parameters for determining fisheries habitat. Satellites can also be used to provide information about vessel locations (including the monitoring of IUU fishing), which when combined with traditional vessel tracking methods using AIS and VMS signal data, can provide a powerful, comprehensive system for monitoring fishing activity at sea. Communications satellites play an important role in digitalising fisheries management, with ship-to-satellite electronic transfer of information on vessel position and catch to improve traceability just one component of a fully digitalised management system. Other potential components include near-real time information on marine environmental parameters and weather transferred to fishers via smartphone app (or website) and selling catch in a virtual market before landing.

The uses of satellite technology to address challenges within the Scottish fishing industry, as identified through stakeholder interactions, are reviewed in detail within the report. Table 1 below summarises these challenges, alongside the advantages and availability of using satellite technology now and in the future, and who can help advance and develop these technologies within the Scottish fisheries sector. Further details on each satellite technology and background information on techniques and datasets are provided throughout the report. More details on next steps and who can help implement satellite technology within the industry are provided in Section 8.

In addition, two specific use-cases for satellite technology were identified through further discussion with a Fisheries expert: (1) near-real time knowledge and mapping of vessel locations (particularly inshore vessels less than 12 m long) and (2) an improved general understanding of fishing effort distribution in Scottish waters. There is policy support for both types of fisheries distribution maps; for example, Outcome 5 of Marine Scotland's 2015 Scottish Inshore Fisheries Strategy details the need for baseline data "*to understand the fishing footprint and the interactions between sustainable fishing*." The Scottish Government's Scotland's Fisheries Management Strategy 2020-2030 also identifies the need for increased spatial understanding of fisheries distribution to support "*technical, spatial and operational decisions related to how and where people can fish*," including decisions around fish stocks and sustainable levels of fishing.

As well as providing marine planning and decision making support, the creation of fisheries distribution maps can help to resolve gear conflicts, as evidence can be provided that areas in conflict have traditionally been used for specific types of fishing activity. Distribution maps can also help reduce the loss of fishing areas to other marine stakeholders (e.g., offshore wind farms), by providing historical evidence of fishing within these areas.

The most up to date information on fishing intensity/pressure is from 2017, provided by OSPAR and based on collected VMS and logbook data for vessels over 12 m long, including beam trawlers, dredgers, demersal seines and otter trawlers. Satellite data provides an exciting opportunity to undertake updated fisheries distribution mapping through the use of machine learning with optical and radar imagery combined with available ship-based location data, as discussed in the following sections of this report. Creation of annual fisheries distribution maps would be a significant undertaking not without its challenges, for example lack of available historical catch data and cloud cover issues with optical satellite imagery, as well as the expenses associated with obtaining high resolution satellite imagery. However, these maps are certainly achievable and would go a long way in supporting marine planning in Scotland, ensuring that our shared marine spaces are managed effectively and sustainably.

***Table 1. Key challenges and specific uses cases in Scottish fishing industry with opportunities for satellite technology***

| Challenge / Use Case | Opportunity for satellite technology | Advantage of satellite technology over current practices | Off-the-shelf capability of satellite technology (and who can help now) | Future availability of satellite technology |
|---|---|---|---|---|
| Live (near-real time) mapping of inshore vessel locations, with applications to IUU fishing monitoring | Providing information on near-real time, widespread vessel locations for assisting in monitoring of IUU fishing and marine planning | Radio-frequency satellites and other nanosatellites can locate inshore vessels, even with AIS switched off; can combine radio-frequency and other satellite data with AIS data and AI to learn, identify and predict vessel behaviour | **Spire Global UK** Maritime Data Dr. Hina Khan (hina.khan@spire.com) **HawkEye 360** Mission Space Platform Craig Erikson (craig.erikson@he360.com) | Opportunity to launch constellation of nanosatellites for specific Scottish fishing industry uses; Earth-i full colour high resolution video from space |
| Improved general understanding of spatial distribution of fisheries in Scottish waters | Providing annual map of fisheries distribution for assisting in marine planning, gear conflict resolution and reduction of loss of fishing areas | Analysis at scale; inclusion of smaller vessels with no VMS; use of AI to learn and identify vessel behaviour | Limited off-the-shelf capability (partly due to lack of available training data) | **Space Intelligence** as Innovation Partner for RnD work into creation of annual fisheries distribution maps |
| Increasing fishing efficiency and reducing bycatch | Providing information for locations of optimal fishing ground and hotspots for protected and choke species (for avoidance) | Near-real time global coverage of environmental parameters (e.g., sea surface temperature, phytoplankton, salinity) | Existing commercial apps (e.g. CATSAT) DTU Aqua habitat forecasts | Ability to combine satellite, weather, historical catch and other data with AI to predict fisheries habitats |
| Tracking marine debris and vessel emissions | Providing measurements of air pollutants and identifying marine debris and different types of plastic from space | Analysis at scale; emissions from all vessel types (not just those with on-board sensors) | Limited off-the-shelf capability (technology still in development) | Upcoming launches of nanosatellites for measuring global methane and $CO_2$; hyperspectral satellites which can better resolve marine debris/plastics |
| Long-term blue-sky research into innovation | Harness the skills of academic researchers and create new innovative products/services to support fisheries over the coming three years | Continue an iterative process of technology development and adoption in the fisheries sector | Not applicable. | **Space Intelligence** alongside University of Edinburgh & Bayes Centre as an Innovation Hub for Space and Satellites |

# 1. Introduction

There are numerous stakeholders in the Scottish fishing sector, from fishers through to buyers, policy-makers and regulators (see Figure 1). This report sets out how satellite technology can support the diverse range of stakeholders with the challenges that they face, and add value to their work. Technologies and types of information which are useful for a range of these stakeholders are identified throughout this report, and are summarised at the end of the document. However, with such diversity in the sector, even amongst a single stakeholder group, there may be a range of different technologies that could be useful. For instance, amongst fishers, large pelagic trawlers are more able to deal with stormy conditions at sea than smaller coastal vessels working in-shore fisheries. This means that the large pelagic trawlers require less information on sea conditions than smaller in-shore fishing vessels, for whom severe weather conditions have a larger impact on daily operations.

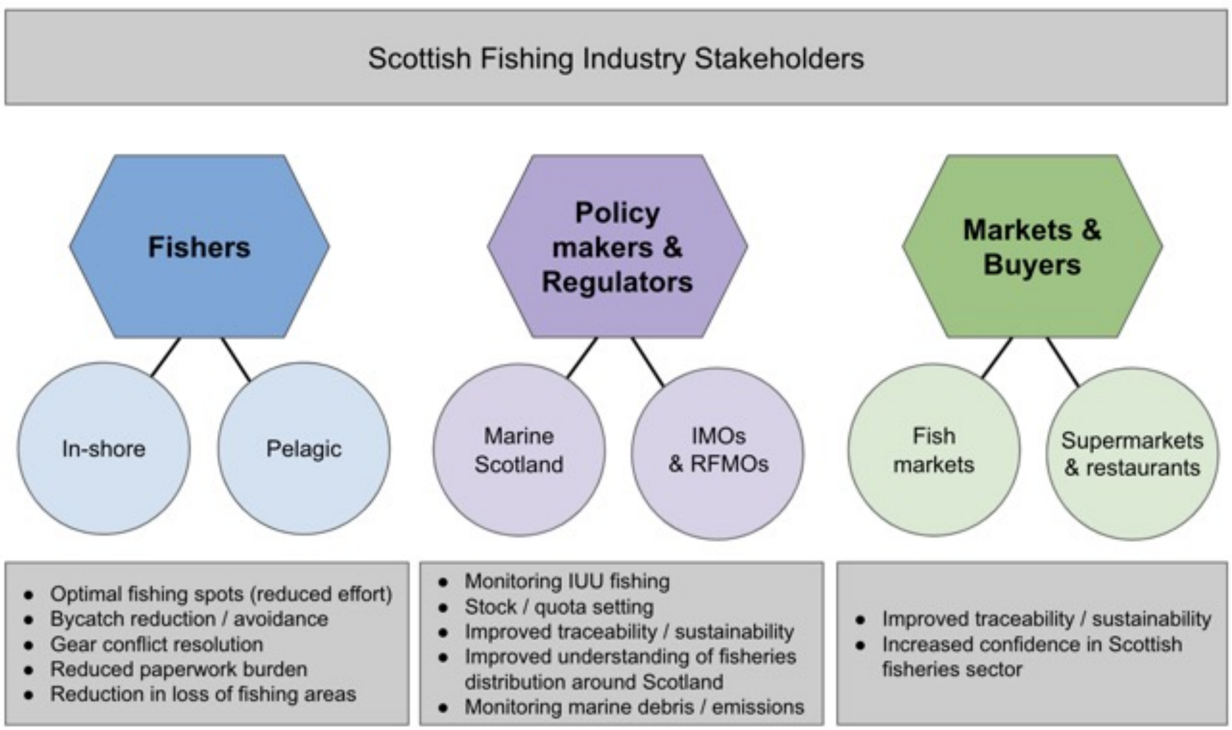



***Figure 1. Key stakeholders in Scottish fishing industry and associated requirements***

Whilst we were commissioned to make observations and recommendations for the Scottish fishing industry, one of our main observations is that in fact there are many satellite and other digital technologies and tools which are already being used by various stakeholders. For example, fishers often use weather forecasts and MarineTraffic data to plan the timing of fishing trips, particularly important when bringing fresh catch back to land. This positive message highlights how the sector is already employing satellite data in daily activity, even though it might not explicitly be described or thought of as being satellite-based, or satellite enabled technology.

Other key satellite technologies which are currently being used to support regulators and policy makers for fisheries globally include the use of automatic information system (AIS) and vessel monitoring system (VMS) location data, alongside ship and airplane-based observations. These data help to monitor illegal, unreported and unregulated (IUU) fishing activity and to enforce fishing regulations and restrictions around protected areas.

In some cases there appear to be gaps between available technology explicitly designed for fishers, and its uptake. For instance, based on the stakeholder engagement undertaken during this project, the most common method of finding optimal fishing spots in Scottish waters is word-of-mouth (spread by messaging apps such as WhatsApp) and local knowledge. However, there are also commercial apps available for locating preferred fish habitats and areas to avoid in order to reduce bycatch (e.g., the BATmap pilot application, CATSAT), which could be more widely used, and enhanced for the Scottish context.

The following sections of this report review satellites and other air-borne technologies and how they could be used within the Scottish fishing industry, either as independent information or in combination with existing systems (e.g., AIS, VMS). The report also reviews artificial intelligence (AI) and machine learning techniques that are currently being used within the global fishing industry, for example the use of AI to analyse AIS location data from billions of vessels worldwide, or to quickly analyse on-ship video camera footage of catches. Integrated systems for fisheries management and monitoring are discussed, including the role satellite technologies could play in these increasingly digitalised systems. Climate change, and how satellite data can be used alongside expert knowledge to predict future fisheries movement, is discussed briefly. The report ends by highlighting the different possible uses and users of satellite technologies within the Scottish fishing industry, providing potential next steps and contacts.

# 2. Remote sensing: Satellites and airborne sensor technologies

Remote sensing encompasses a range of technologies that collect environmental data at a distance. Here we focus upon satellites and airborne technologies useful to the fisheries sector. Air-borne sensors useful for fisheries monitoring and management include data collected from unmanned aerial vehicles (UAVs), small aircraft and high altitude pseudo-satellites (HAPS). Crucially, these technologies can obtain fisheries-relevant data *at scale*. Broadly, these data can relate to environmental conditions; or to the tracking of fishing vessels in Scottish waters. This review considers both the use of satellite data for environmental management, and for recording the activity of fishing vessels.

## 2.1. Overview of Satellite Sensors for environmental monitoring

There are numerous environmental parameters relevant for fisheries management that can be measured from space using a range of satellite and other air-borne sensors, including sea surface temperature and salinity; phytoplankton and chlorophyll levels; bathymetry; sea level change; air pollution and marine debris from fishing vessels, and wind and surface roughness.

There are two main types of satellite sensors that are typically used to collect environmental data: optical and radar sensors. Optical sensors use complex cameras onboard satellites, using only the “passive” reflection of sunlight off the Earth’s surface to capture information (Figure 2a). These camera sensors can view light in multiple wavelengths, including both the visual wavelengths we see as well as wavelengths beyond human vision, for example infrared or thermal radiation. These optical sensors are thus called ‘multispectral’ sensors. Multispectral sensors such as those onboard the Landsat-8 satellite capture information using between 3 and 10 different wavelength bands (e.g., red, green, blue, near-infrared). Beyond this, hyperspectral sensors (e.g., EnMap and the forthcoming HyspIRI) use hundreds of very narrow, near-overlapping bands. The benefits of this is increasingly detailed information about the Earth’s surface. However, hyperspectral data isn’t as readily available as multispectral data, and it is typically lower quality and resolution, as well as more complex to process and interpret. We expect the availability of hyperspectral data to improve in the next three to five years, with a number of private companies developing new constellations of satellites with hyperspectral sensors.

Radar (radio detection and ranging) is an “active” type of remote sensing. Active sensors emit a signal from the satellite itself, which is then scattered back from Earth’s surface and the return, effectively an echo, captured by the sensor. Radar sensors are a type of active sensor that emits microwave radiation and receive back the faint echoes of this signal, called backscatter (see Figure 2b). Information on roughness of the sea surface can be inferred from the backscatter signal. One of the main benefits of using radar data is the ability to “see through” clouds (as the microwave signal can penetrate the cloud cover) and during the night. This is especially relevant over the ocean, where clouds can prevent optical satellites from obtaining a useful image perhaps 95% of the times they pass overhead.

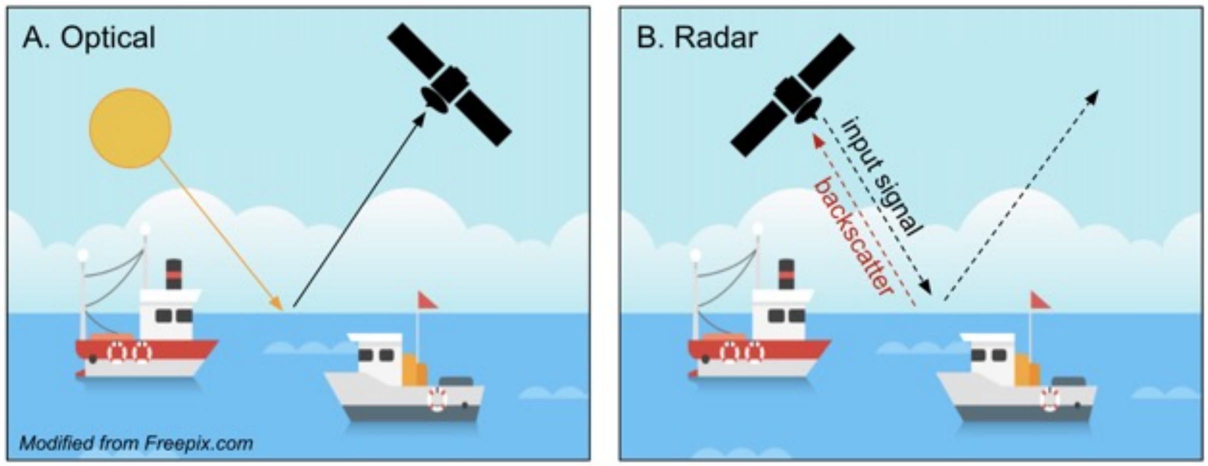



***Figure 2. Schematic of optical and radar satellite data acquisition. Optical is described as 'passive' since it simply relies on the use of sunlight reflected from the Earth's surface. Radar (SAR), on the other hand, is 'active' since it involves transmitting pulses of microwave energy directed at the Earth's surface, and recording the reflected signal back at the satellite receiver. LiDAR (Light detection and ranging) is another form of active sensing, that relies upon pulses of laser light, rather than microwave energy.***

Synthetic aperture radar (or SAR) is a form of radar data that emits successive radio pulses and in turn receives multiple backscatter signals from each point on Earth's surface, allowing for a higher spatial resolution than more traditional radar systems. SAR data can be used in many applications, including measuring sea surface roughness and wave characteristics.

**Spatial resolution** Satellite imagery (both optical and radar) are available at various spatial resolutions, from very high resolution commercial satellites offering 30 cm pixels (e.g., WorldView-3) to tens of kilometres from satellites with larger global imaging footprints. For mapping large scale environmental variables like sea surface temperature, lower spatial resolutions (larger pixel sizes) would provide the amount of detail required. However, for monitoring small fishing vessel activity (e.g., number of fishing lines, safety protocol), a much higher spatial resolution (smaller pixel size) would be required. Coarser resolution satellites can monitor more frequently, but the large pixel size makes them less useful for small scale monitoring.

**The power of satellites for understanding environmental processes and human activity**

The main benefit of using satellite data is the opportunity for regular, repeated observations at a global scale, or specific to a region of interest at a finer scale. However, some limitations include the necessity for some degree of ground-truthing of the data, required expert interpretation or processing of the data, the often very large file size of the data (which relates to computing costs and may be an issue for smaller organisations undertaking analysis with the freely available data discussed below) and the trade-off between spatial resolution and imagery cost.

Cloud cover is also an issue for obtaining useful optical imagery, particularly over Scotland where clouds prevent optical satellites from obtaining a useful image perhaps 90% of the time they pass overhead. Applications that require infrequent monitoring (e.g., on an annual basis) can use cloud-free composites of optical data, which merge cloud-free images collected over the course of a year. While it is possible to spatially interpolate across cloud-covered areas of optical imagery to fill data gaps for more frequent monitoring (see discussion of sea surface temperature in Section 2.3 below), any service or application requiring more frequent monitoring from satellite data over Scotland should rely on radar rather than optical data, which can penetrate through cloud cover.

A further disadvantage to satellite data is that users have very little control over which satellites are in orbit at any one time. Using aircraft or UAV sensors, it is possible to control what data is collected if budget is available. For satellites, the user mostly relies on what has already been launched and is still operational. Some satellites are part of operational constellations, with long-term plans to replace satellites and a good guarantee of data availability into the 2030s (e.g., Sentinel-1 and 2 from the EU-funded Copernicus programme); but others are often already operating beyond their design lifetime, and could fail at any moment (e.g., Worldview-3, WindSat).

However, the launch of clusters of small satellites for environmental monitoring and communications are increasing in popularity. These satellite clusters are significantly more affordable than launching a full-sized satellite mission, as they are much smaller (ranging in weight from 1 to 100 kg) and less complex, often focusing on one observation or measurement type[1]. By using clusters of small satellites, revisit time can greatly be reduced without a corresponding reduction in spatial resolution. Since 2013, over 1,500 nanosatellites have been launched successfully by organisations ranging from space, military and government agencies, to universities and commercial organisations[2]. This raises the possibility of the fisheries sector developing dedicated missions that address specific questions for the Scottish context.

## 2.2. UAVs, Aircraft and HAPS

Unmanned aerial vehicles (UAVs), small aircraft and high altitude pseudo satellites (HAPS) also provide potential opportunity for monitoring, control and surveillance of fisheries. For example, UAVs can be deployed from patrol ships to identify fishing vessels and observe if they are using the appropriate fishing gear for that specific area and type of catch. Environmental phenomena and parameters can also be observed from UAVs, aircraft and HAPS using a variety of sensors: these include algal blooms and pollution events that could impact fish mortality, or sea surface temperature and weather conditions[3]. In addition, UAVs have been used for fish stock and habitat assessments[4,5], providing a more cost-effective service than ocean-going vessels undertaking similar assessments.

**Classes of UAV** There are two main types of UAVs: fixed-wing and rotary-wing (see Figure 3a-b). Fixed-wing UAVs often allow for heavier monitoring equipment and larger-scale surveys (e.g., 1km$^2$), but are more difficult to use than rotary-wing UAVs, which allow vertical take-off and landing, hovering and recovery capability[6]. Table 2 compares the advantages and disadvantages of both systems.


***Figure 3. Example (a) fixed and (b) rotary-wing UAVs; (c) high altitude pseudo satellite (HAPS)***

**Airborne sensors** Depending on the size and type of UAV or aircraft, different sensors can be used for collecting information about the marine environment, from basic cameras for aerial photography and video acquisition to multispectral, thermal and hyperspectral imaging sensors. LiDAR (Light Detection and Ranging) sensors can also be flown using UAVs or aircraft to detect schools of fish[7]. A LiDAR sensor emits flashes of laser light tuned to a particular wavelength, and uses the time taken for the light to reflect back to infer properties about the surface below (see Figure 4); for example, when the return signal could indicate the presence of a school of fish as well as its depth below the surface[7], although LiDAR can typically only “see” beneath maximum water depths of ~25 to 30 m[8], depending on the water clarity. There may be some difficulty discriminating between schools of fish and surrounding phytoplankton, with different LiDAR settings most appropriate under different conditions (i.e., depending on fish species and aggregation structure, the intensity of phytoplankton blooms, water clarity and turbidity, time of day and area)[9].

One of the benefits of using UAVs is their low cost for continued monitoring, after initial costs for purchasing the equipment and training are undertaken. In addition, imagery collected from UAVs typically has much better spatial resolution than that collected from satellites, with the added benefit of user-determined revisit periods[5]. One of the challenges of using UAVs for monitoring is regulation which requires a visual line of sight of the aircraft at all times while flying[10], which can become problematic in certain environments, or if there is a desire to cover a larger area. Processing large amounts of UAV data can also be time consuming, but the application of artificial intelligence and machine learning (see Section 5) can be used to speed up processing time, depending on the application of the imagery.

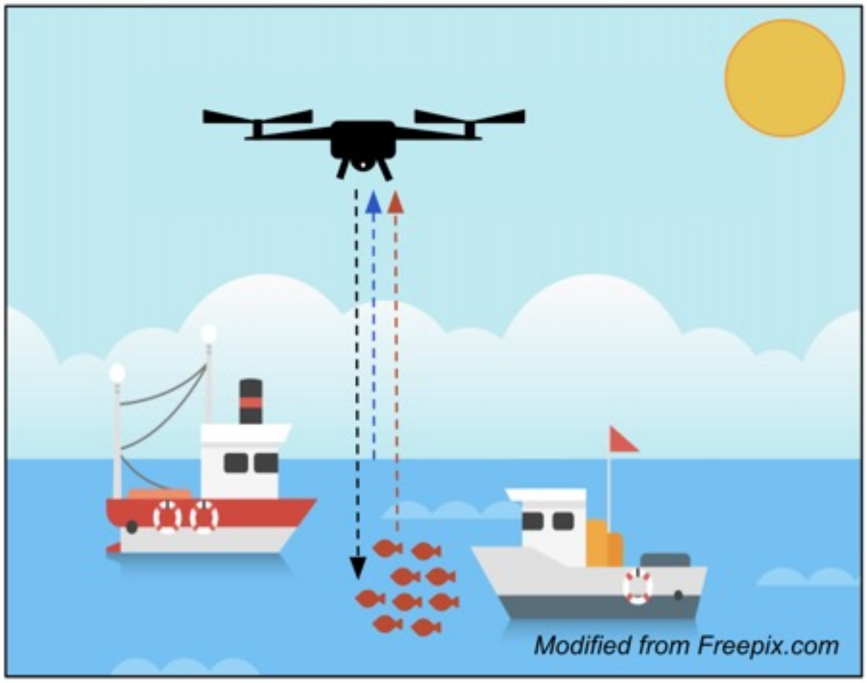



***Figure 4. LiDAR sensor deployed on UAV over school of fish***

**UAVs for marine surveillance** The European Maritime Safety Agency (EMSA) offers remotely piloted aircraft system (RPAS) services in support of surveillance work undertaken by Member States coast guards and other authorities. RPAS services include the use of UAVs for the detection of illegal fishing, maritime pollution and emission monitoring, among other surveillance operations[11]. RPAS is only one tool used within the surveillance system, which also includes satellite imagery, AIS and VMS data, and surveillance by manned patrol vessels and aircraft[11].

**HAPS for fisheries applications** High altitude pseudo satellites (HAPS) operate within the stratosphere, flying at an altitude of approximately 20 km[11] (see Figure 3c). While traditionally used for defence purposes, HAPS have started to be used for civilian purposes, with ESA's HAPS4ESA programmes in 2017 and 2019 and increased industry interest from Airbus, Boeing, Thales Alenia Space and others. HAPS have several advantages over satellite monitoring systems, including a higher manoeuvrability, the ability to return for maintenance or payload reconfiguration and a lower overall mission cost[11]. They also have longer mission times when compared to UAVs, flying or hovering for up to months at a time. Due to their flying altitude, HAPS are also able to collect imagery at much higher resolutions (10 cm or less) than geostationary satellites. Data collected from HAPS could be used to monitor marine resources, particularly surveillance of illegal fishing, pollution and piracy in high resolution over larger stretches of the ocean than would be possible using UAVs.

*Table 2. Advantages and disadvantages of different UAV types (Modified from Ref [6]).*

| Advantages | Disadvantages | Flight Time & Coverage |
|---|---|---|
| ***Fixed-wing UAVs*** | | |
| • Can cover large areas<br>• Higher speed/reduced flight time, as much lower battery use per unit area covered | • Experienced pilot and suitable open area needed for take-off/landing<br>• In UK context, hard to obtain permission to fly Beyond Visual Line of Site (BVLOS), minimising many advantages of fixed wings<br>• Harder to fly close to the ground, minimising ability to map small objects | • Up to hours of flying<br>• >20 $km^2$ coverage (altitude/permissions depending) |
| ***Rotary-wing UAVs*** | | |
| • Flexible and easy to use<br>• Low flight heights and speed<br>• Hovering capability<br>• Vertical take-off/landing | • Lower area coverage<br>• Wind can affect stability and flight time (in even moderate wind conditions data collection only possible with fixed wing systems) | • 10 - 40 mins of flying<br>• 5 - 50,000 $m^2$ coverage (altitude depending) |
| ***Hybrid UAVs*** | | |
| • Hovering capability<br>• Vertical take-off/landing<br>• Can cover large areas | • Mechanically complex systems<br>• Expensive | • Up to an hour of flying (less than fixed-wing)<br>• ~1 $km^2$ coverage |

## 2.3. Environmental Parameters Measurable from Space and Air-borne Sensors

### Sea Surface Temperature

Sea surface temperature is one of the main factors controlling where a particular fish species can reproduce and live, with each species having a preferred temperature range (see Figure 5). As water temperatures can fluctuate significantly over a relatively short period of time, previous hot spots for fishing may not lead to similar success in the future. Maps of sea surface temperature can also show the locations of and boundaries between distinct water masses, separated from the surrounding water by differences in density[12].

Satellite data can be used to map sea surface temperature globally twice a day with a lower spatial resolution of ~4 km, or every few days with a higher spatial resolution of between 250 to 300 m. Relevant satellite sensors currently in operation for mapping sea surface temperature are summarised in Table 3, with Figure 6 showing sample day and night-time maps of sea surface temperature around the UK. While these optical datasets may be freely available and provide good coverage, they rely on low cloud cover for useful imagery. Spatial interpolation of the imagery can be performed to fill in data small data gaps caused by cloud cover by using data from surrounding cloud-free areas within the same image, or by merging and interpolating data from multiple sensors. While used widely within the satellite data community to provide gap-free products, it is worth noting that image interpolation requires many assumptions about trends in the estimated variable(s) and introduces error and uncertainty to the final data product.

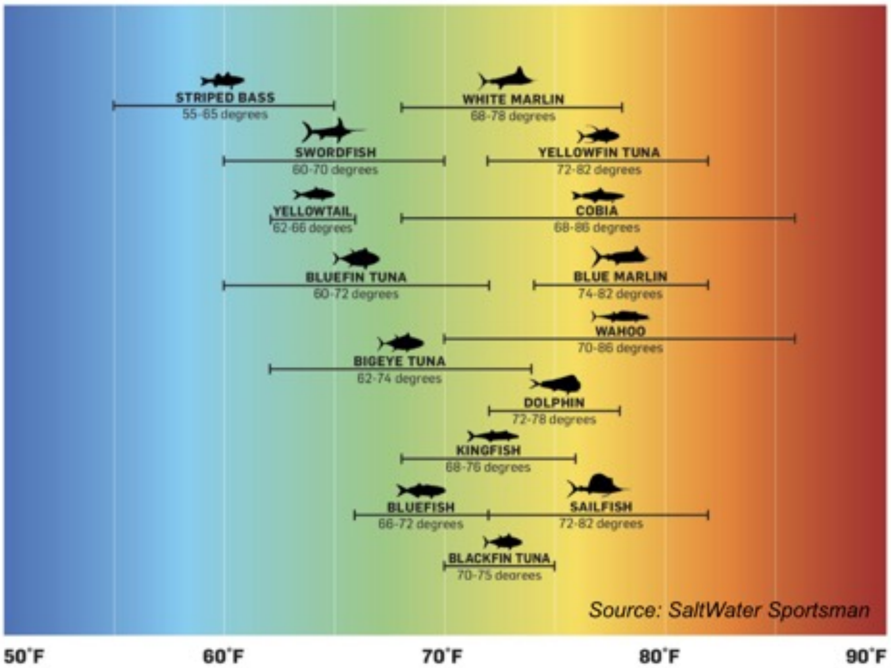



***Figure 5. Sea surface temperature preferred ranges for various fish species.***

***Table 3. Relevant satellites in operation for mapping sea surface temperature (SST)***

| Organisation | Dataset | Time period | Spatial / temporal resolution |
|---|---|---|---|
| NOAA[a] | AVHRR Pathfinder v5.3 (Level 3) | 1981-present | 4 km, twice daily |
| NOAA | Optimum Interpolation SST (OISST) v2.1 | 1981-present | 1/4°, daily |
| NASA[b] | MODIS SST<br>(Level 2 and Level 3) | 2002-present | L2: 1 km, every 2 days<br>L3: 4.6 km, twice daily |
| ESA[c] | Sentinel-3 SLSTR SST (Level 2) | 2016-present | 300 m, every ~2 days |
| JAXA[c] | GCOM-C/SGLI SST | 2017-present | 250 m, every 1-3 days |

[a] National Oceanic and Atmospheric Administration (United States)
[b] National Aeronautics and Space Administration (United States)
[c] European Space Agency
[d] Japan Aerospace Exploration Agency

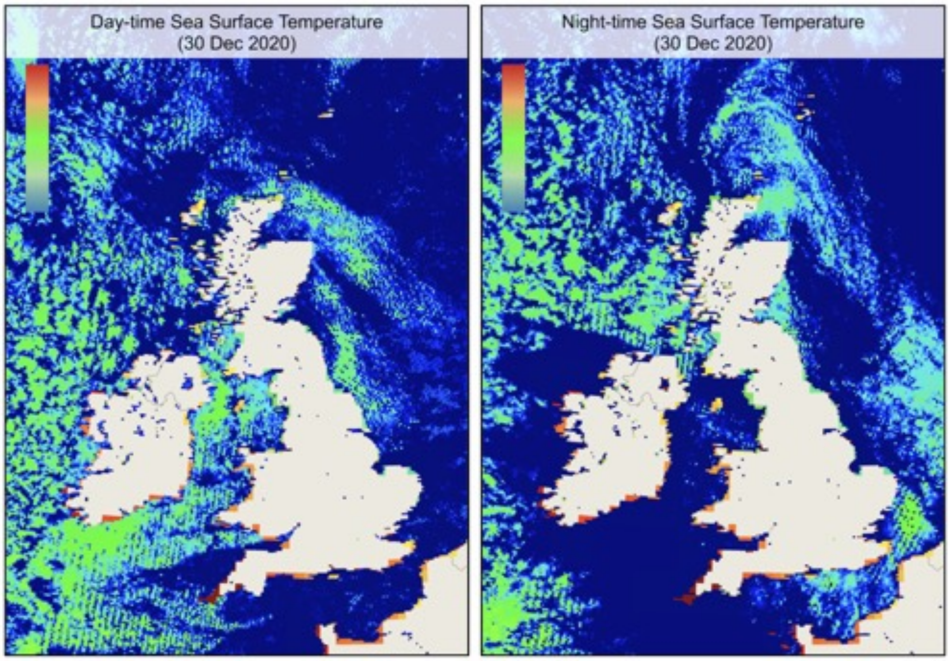



***Figure 6. Sample twice daily sea surface temperature maps from AVHRR Pathfinder v5.3 (L3 dataset), December 2020.***

## Phytoplankton and Chlorophyll-a Levels (Ocean Colour)

Phytoplankton blooms can be indicative of areas containing large amounts of small baitfish, which feed on phytoplankton. As larger pelagic species in turn feed on smaller baitfish, these areas can also indicate good fishing conditions. The area along the boundary between the green, murky water caused by a phytoplankton bloom and clearer, blue water just outside the bloom often represents ideal fishing conditions, as pelagic species generally prefer the clearer water and can usually be found along the edges of green blooms[13].

Phytoplankton blooms can be identified from optical satellite imagery by their distinct green colour, due to the chlorophyll contained inside the cells of the phytoplankton. Maps of ocean colour can also be used to identify incoming red times, or harmful algal blooms, which often result in widespread fish sickness and mortality. Relevant satellite sensors currently in operation for mapping chlorophyll concentrations and ocean colour are summarised in Table 4, with Figure 7 showing a sample chlorophyll concentration map around the UK.

As with optical satellite sensors used for estimating sea surface temperature, cloud-free or low-cloud conditions are required for the acquisition of useful imagery for estimating chlorophyll-a levels. However, gap-filling algorithms have been developed specifically for chlorophyll-a level maps, with the most commonly used algorithm (Data-Interpolating Empirical Orthogonal Functions, DINEOF) estimating gap values by interpolating a single or multiple correlated oceanographic variables[14]. Other approaches use statistical and machine learning algorithms (e.g., random forest models) to predict values for cloud-covered pixels based on valid chlorophyll-a values and other related variables recently observed nearby[14].

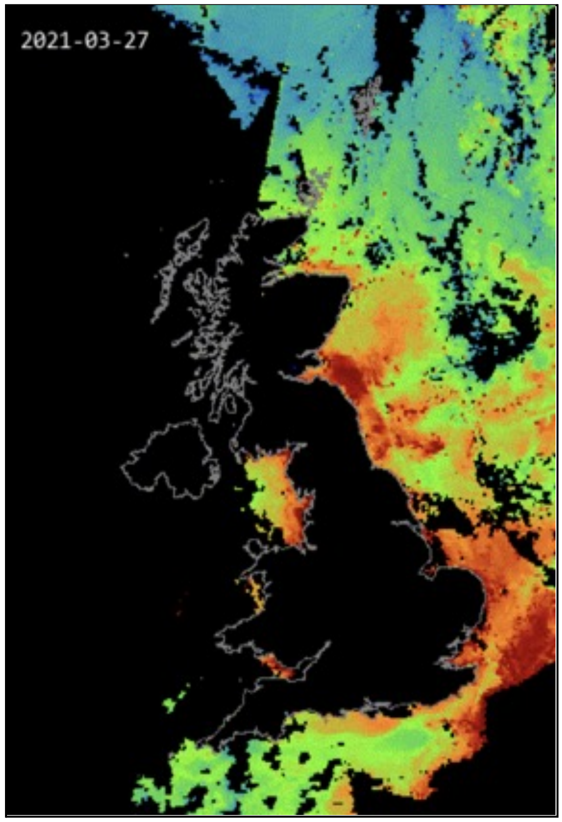



***Figure 7. Sample chlorophyll-a concentration map from GCOM-C***

***Table 4. Relevant satellites in operation for mapping chlorophyll concentration***

| Organisation | Dataset | Time period | Spatial / temporal resolution |
|---|---|---|---|
| NASA | MODIS Aqua Chlorophyll Concentration | 2002-present | 1 km, near daily |
| NOAA/NASA | Suomi NPP (VIIRS) Chlorophyll-a | 2012-present | 750 m (at nadir), every 16 days |
| ESA | Sentinel-3 OLCI Terrestrial Chlorophyll Index | 2012-present | 300 m, every ~2 days |
| JAXA | GCOM-C/SGLI Chlorophyll-a Concentration (Level 3) | 2017-present | 250 m, every 1-3 days |
| NASA/UNCW | SeaHawk Ocean Color | 2018-present | 120 m, every 9 days |
| Note: Other common satellites with optical sensors (e.g., Landsat-8, Sentinel-2) can also be used to derive a chlorophyll index | | | |

## Bathymetry

Bathymetric data are useful in identifying the location and movements of fish, with global bathymetry data freely available online (e.g., from the European Marine Observation and Data Network (EMODnet) or the International Hydrographic Organization Data Center for Digital Bathymetry). Figure 8 shows the available bathymetry data around the UK coastline from EMODnet, which combines satellite-derived bathymetry data products with other bathymetric survey data sets.

This open bathymetric data has a large spatial footprint, and while open ocean areas may be mapped to a sufficient level, the data is often inadequate in shallow (<40 m deep) coastal waters[15]. Regular, repeat mapping of ocean floor bathymetry would enable better sharing of coastal waters and marine planning, accounting for changes in bathymetry from processes such as sediment erosion and accumulation and channel dredging[15]. While coastal bathymetry data will not be as useful for pelagic fishers out in deeper waters, it would make a big difference for those fishers catching shellfish and other organisms in near shore areas where bathymetry may undergo short-term changes.

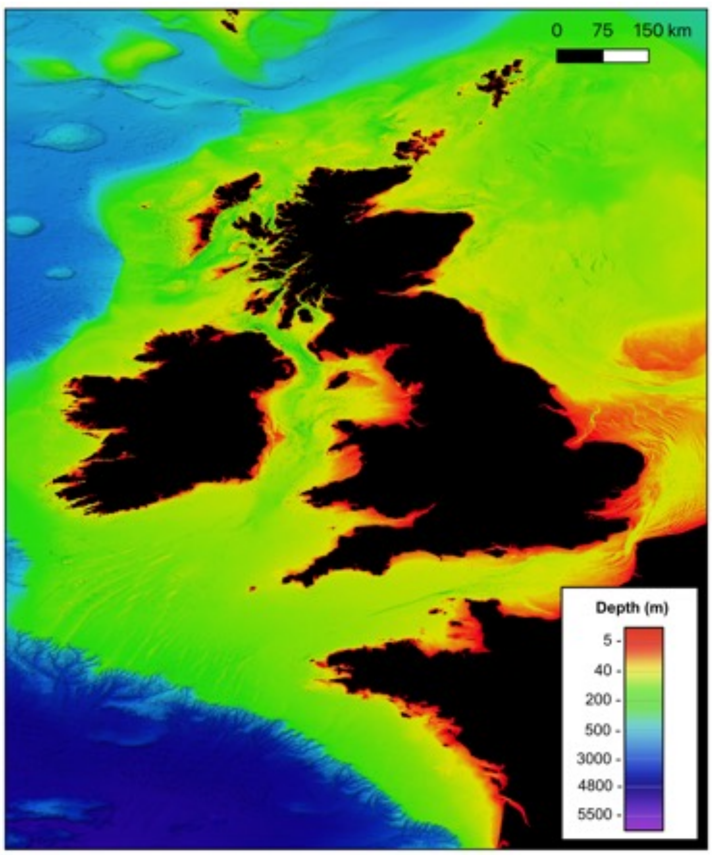



***Figure 8. Sample bathymetry around the UK coastline from EMODnet.***

Optical imagery from satellites has been used to derive bathymetry in shallow areas. For example, the blue and green bands of Landsat 8 imagery have been used with a ratio transform algorithm to derive bathymetry in clear water with depths >25 m[16], although this data would best be used in combination with hydrographic survey bathymetry data. While optical datasets such as Landsat 8 may be freely available and have high spatial resolution, they rely on low cloud cover for useful imagery. In addition, the method for deriving bathymetry assumes spatially homogeneous water quality and works best in clear water.

A combination of satellite-derived optical imagery and other spaceborne sources of bathymetry data have also been used to produce large-scale bathymetry maps. For example, a method for producing high spatial resolution satellite-derived bathymetry has been developed using the relationship between ICESat-2 LiDAR data points (which can show bathymetry at discreet locations) and Sentinel-2 optical imagery reflectance[15], which has much larger spatial coverage and a small ground footprint (10 m pixel size).

Satellite-derived bathymetry with machine learning algorithms has also made considerable progress as more relevant and high quality data become available from space with the use of cloud-computing platforms. Landsat 8 imagery has been used with machine learning to produce bathymetry maps, by training a random forest model using a large amount of reference bathymetry data[17].

Spaceborne radar data can also be used to derive bathymetry, relying on the relationship between sea floor topography and wave characteristics on the sea surface. For example, Sentinel-1A C-band SAR data has been used following a fast Fourier transform method to retrieve wavelength and wave direction, from which water depth was estimated[18].

Table 5 summarises a few example satellite datasets for deriving bathymetry. This is not an exhaustive list of available datasets or relevant sensors for measuring bathymetry; indeed, many other optical and radar satellite sensors could be used to derive bathymetry using similar methods.

***Table 5. Examples of relevant satellites in operation for sea floor bathymetry***

| Organisation | Dataset / Satellites | Time period | Spatial / temporal resolution | Maximum depth visible |
|---|---|---|---|---|
| NASA/ESA | Landsat or Sentinel-2 | 2013-present | 30 m, every 16 days | ~25 m |
| NASA/ESA | ICESat-2 LiDAR combined with Sentinel-2 (S2) optical data | 2018-present<br>2015-present | 10 m, every 5 days (S2) | 25 to 30 m |
| ESA | Sentinel-1A C-band SAR | 2015-present | 10 m, every 6 days | 15 to 30 m |

## Sea Surface Salinity

Salinity is another one of the main factors controlling where a particular fish species can survive. Most fish and crustaceans are either exclusively freshwater or exclusively saltwater species. Some species adapt to both environments depending on their stage of life; for example, anadromous species live in saltwater but spawn in freshwater, and catadromous species follow the opposite (spawn in saltwater but live in freshwater)[19]. Euryhaline species can survive in either saltwater or freshwater at any point in their life cycle[19]. Figure 9 shows some example salinity preferences for several fish and crustaceans.

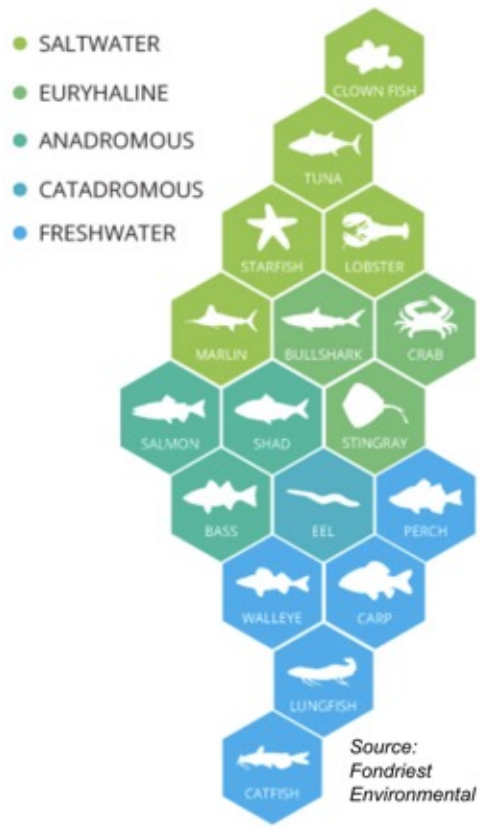



***Figure 9. Salinity preferences for select fish and crustaceans***

Sea surface salinity can also be measured from satellite sensors. Using a combination of data from three L-band satellite sensors (see Table 6), salinity can be mapped globally every 2 to 3 days since 2010, with a spatial resolution between 40-150 km. Figure 10 shows a map of global sea surface salinity, from the ESA Climate Change Initiative project. While these maps provide frequent global coverage, they are more uncertain in the cold waters found at higher latitudes, due to for example a loss of sensitivity, increased sea roughness, land and sea ice, and radio frequency interference[20]. They also have a large spatial footprint and are less accurate in coastal regions.

Recent advances in machine learning capabilities have led to new methods developed for estimating sea surface salinity from optical satellite imagery. For example, a deep neural network has been used to link Sentinel-2 optical data band information with a large network of in-situ data collected from various vessels, buoys and measurement platforms[21], resulting in high resolution (100 m x 100 m averaged squares) mapping of sea surface salinity. The use of optical imagery, however, presents issues with cloud cover and the presence of sea foam, vessels and algal blooms[21], which can all affect reflectance measured by the satellite.

***Table 6. Examples of relevant L-band satellites in operation for sea surface salinity***

| Organisation | Dataset / Satellites | Time period | Spatial / temporal resolution |
|---|---|---|---|
| ESA | Soil Moisture and Ocean Salinity (SMOS) L-band MIRAS | 2010-present | ~50 km, every 2-3 days |
| NASA | Aquarius L-band | 2011-2015 | 150 km, every ~7 days |
| NASA | Soil Moisture Active Passive (SMAP) L-band | 2015-present | ~40 km, every 2-3 days |

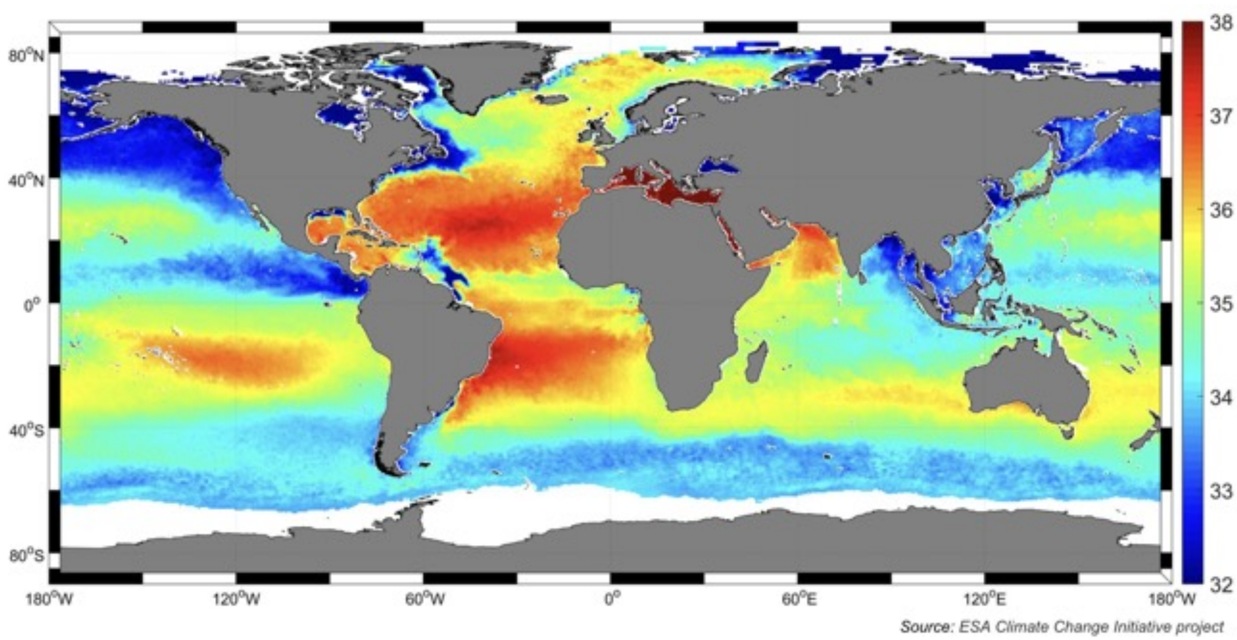



***Figure 10. Monthly average sea surface salinity for July 2015 from merged SMOS, Aquarius and SMAP data.***

## Wind and Surface Roughness

Weather conditions at sea have important implications for the fishing industry, controlling when and where vessels can operate. Stormy conditions, such as those seen in the winter of 2013/2014, can severely disrupt the industry by keeping vessels tied up at port for months[22]. Characteristics of storminess, such as sea surface roughness and surface wind can be measured from satellite sensors.

Sea surface roughness, which can provide information about surface currents and wave fronts, can be measured using SAR data or from radiometer-derived sunglints. For example, ESA's Sentinel-1 SAR and NASA's Multi-angle Imaging SpectroRadiometer (MISR) can both provide information about oceanic fronts (see Figure 11a-b), with Sentinel-1 also able to capture pure ocean waves (see Figure 11c). Sentinel-1 SAR data can also capture wind streaks on the sea surface, an imprint of enhanced wind perturbations near the surface that appear on the image as 2D roll-shaped patterns[23] (see Figure 11d). Areas of low wind activity are also visible on the SAR imagery, appearing as dark areas with no ocean wave signature on the image, where the radar backscatter from the sea surface is weak[23] (see Figure 11e).

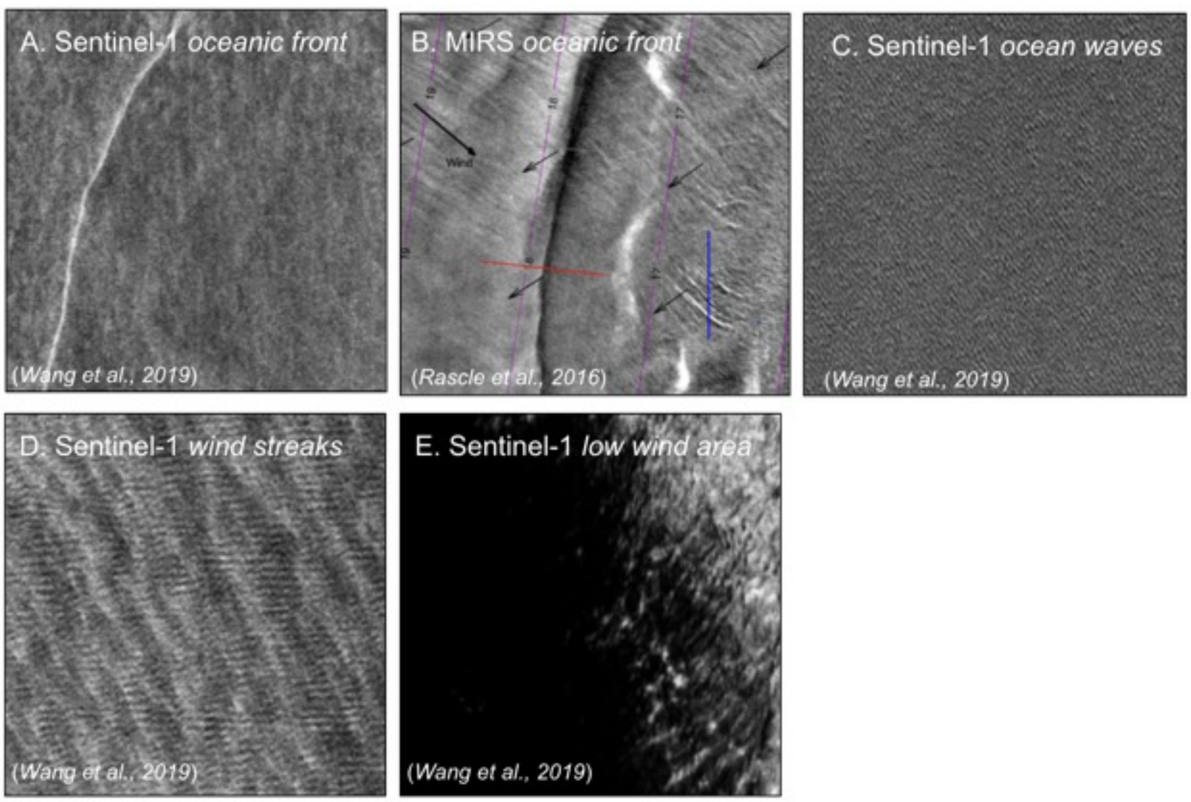



***Figure 11. Sample Sentinel-1 imagery[23] of (a) ocean waves, (b) an oceanic front, (d) wind streaks and (e) a low wind area, and a MISR image[25] of (c) an oceanic front. Note that images are not taken on the same date or over the same area.***

Near surface ocean wind speed and direction can also be measured using active scatterometers and passive radiometers; scatterometers can provide ocean wind speed and direction data, whereas radiometers can provide wind speed only[24]. Figure 12 shows example wind speed and direction maps over the Fiji islands from 14th February 2016 from three different satellite sensors, during the development of tropical cyclone Winston.

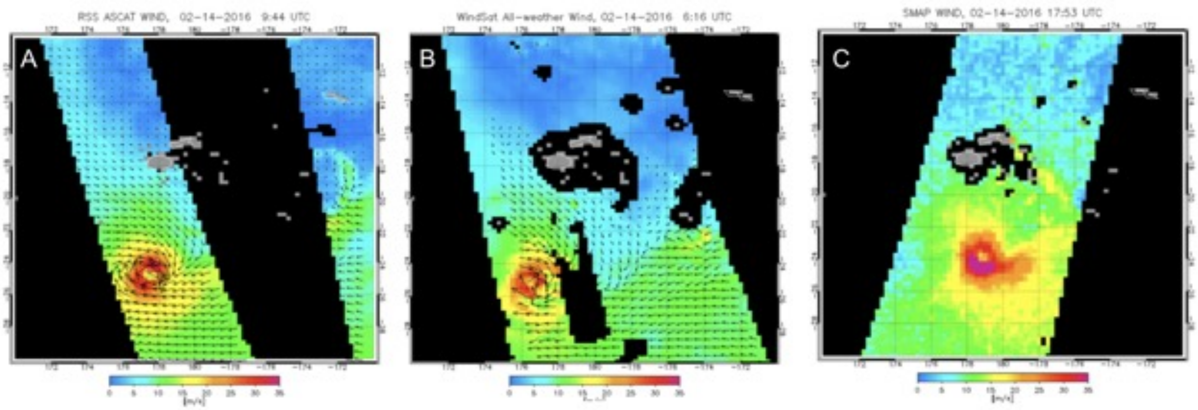



***Figure 12. Sample wind speed and direction maps from (a) ESA's ASCAT and (b) USAF STP WindSat and wind speed from (c) NASA's SMAP.*** *Source: Ref [26].*

Table 7 summarises a few example satellite datasets for deriving surface roughness and wind characteristics. This is not an exhaustive list of available datasets or relevant sensors for measuring these parameters, with other SAR and radiometer satellite sensors used to derive roughness and wind patterns using similar methods.

***Table 7. Examples of relevant satellites in operation for sea surface roughness and wind***

| Organisation | Dataset / Satellites | Time period | Spatial / temporal resolution |
|---|---|---|---|
| ***Sea surface roughness*** | | | |
| ESA | Sentinel-1A C-band SAR | 2015-present | 10 m, every 6 days |
| NASA | Multi-angle Imaging SpectroRadiometer (MISR) onboard TERRA | 2000-present | 275-1100 m, every 9 days |
| ***Wind properties*** | | | |
| USAF STP[a] | Coriolis WindSat | 2003-present | 25 km, every 8 days |
| ESA | Advanced Scatterometer (ASCAT) | 2006-present | 30-50 km, every ~1.5 days |
| ESA | SMOS MIRAS | 2010-present | ~50 km, every 2-3 days |
| NASA | SMAP | 2015-present | ~40 km, every 8 days |

| | | | |
|---|---|---|---|
| ESA | Sentinel-1 C-band SAR | 2015-present | 10 m, every 6 days |
| ISRO[b] | SCATSat-1 OSCAT-2 Ku-band | 2016-present | 12.5 km, every ~4 hrs |

[a] United States Air Force Space Test Program
[b] Indian Space Research Organisation

## Air Pollution from Fishing Vessels

All pollution from vessels at sea can have negative impacts on climate change, ambient air quality and human health[27]. For example, the emission of $CO_2$ and methane ($CH_4$) impacts Earth's greenhouse gas budget, leading to increased global warming. The release of air pollutants such as nitrogen dioxide ($NO_2$) and sulphur dioxide ($SO_2$) can lead to acid rain, and human health can be impacted by the release of hydrocarbons and fine particulate matter[27].

Air pollutants released from small fishing vessels are difficult to measure and monitor, with most past studies focusing on larger vessels and coastal transport ships, and emissions mostly measured using in-lab engine tests, on-ship sensors and plume tracking from aircraft[27]. However, recent advances in satellite technology have allowed for the measurement of some air pollutants from space (see Table 8), including $NO_2$ and $CO_2$. For example, ESA's Sentinel-5P Tropomi instrument is able to highlight trails of $NO_2$ left in the air from vessel movement (see Figure 13). The instrument is also able to measure carbon monoxide (CO), $CH_4$ and ozone ($O_3$).

Several satellites currently monitor $CO_2$, including NASA's Orbiting Carbon Observatory-2 (OCO-2), Japan's Greenhouse gases Observing Satellite (GOSAT) and China's TanSat. However, these satellites collect global measurements of $CO_2$ at coarse resolutions for characterizing global or regional scale carbon fluxes, and would not be suited for monitoring $CO_2$ emission from small fishing vessels. There are, however, future plans for monitoring $CO_2$ from space in higher resolution, including ESA's planned 2025 launch of Sentinel-7, also known as CO2M (Copernicus Anthropogenic Carbon Dioxide Monitoring). Sentinel-7 is dedicated to monitoring $CO_2$ emissions, with three orbiting satellites for pinpointing specific sources of emissions[28]. Current satellites (i.e., OCO-2, GOSAT and TanSAT) are only able to give an average reading of $CO_2$ concentration, not its specific source.

Constellations of smaller satellites are also being developed to track $CO_2$ and $CH_4$ emissions. A project called Space Carbon Observatory (SCARBO) is currently being undertaken to develop small instruments for measuring $CO_2$ emissions from individual cities and power plants[29]. The project has estimated that a constellation of 24 of the small satellites would be able to provide global weekly estimates of $CO_2$ concentration, and could be tasked to fly over a specific area on a daily basis[29]. In a similar vein, the Environmental Defense Fund (EDF) is working with researchers at Harvard University to develop small satellites for monitoring $CH_4$, called MethaneSAT. A constellation of the small satellites will be able to monitor methane concentration on a weekly basis, at a spatial resolution of 1 km[30]. MethaneSAT is currently planned for launch sometime after October 2022.

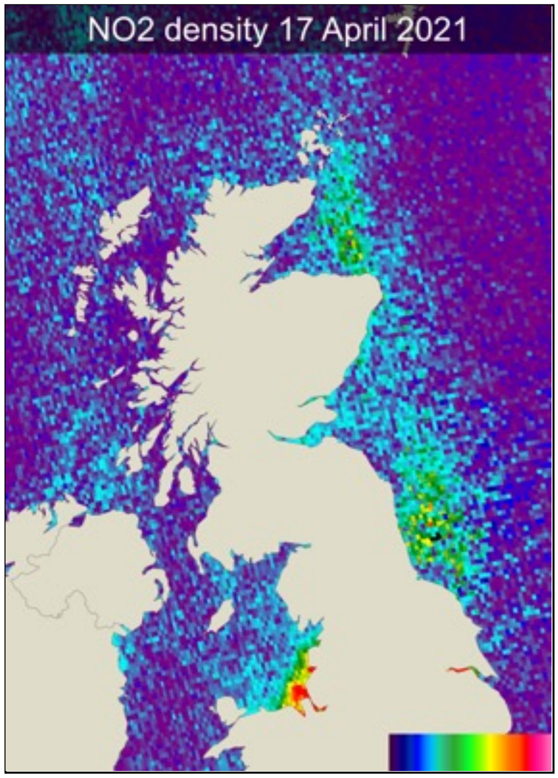



*Figure 13. Nitrogen dioxide concentration, 16 April 2021, Sentinel-5P TROPOMI*

*Table 8. Examples of relevant satellites in operation for monitoring air pollution*

| Organisation | Dataset / Satellites | Pollutants measured | Time period | Spatial / temporal resolution |
|---|---|---|---|---|
| ***Coarse resolution satellites (global or regional scale measurements)*** | | | | |
| JAXA | GOSAT-1/2 TANSO-FTS | $CO_2$, $CH_4$, $O_3$, $H_2O$, CO | 2009-present | ~10 km, every 3 days |
| NASA | OCO-2 | $CO_2$, $O_2$ | 2015-present | 1°, every 16 days |
| MOST[a] | TanSAT | $CO_2$ | 2017-present | ~2 km, every 16 days |
| ***Higher resolution satellites (suitable for vessel emissions tracking)*** | | | | |
| ESA | Sentinel-5P Tropomi | $NO_2$, CO, $CH_4$, $O_3$ | 2019-present | 7 km, every 16 days |
| EDF[b]/Harvard | MethaneSAT | $CH_4$ | 2022 launch | 1 km, every 7 days |
| ESA | Sentinel-7 (CO2M) | $CO_2$, $NO_2$ | 2025 launch | 2 km, every few days |

[a] Ministry of Science and Technology of China
[b] Environmental Defense Fund

## Marine Debris from Fisheries Activity

Increasing amounts of marine debris are ending up in the ocean, posing new threats to the ocean health and marine organisms. Marine debris from humans can travel large distances across the oceans, with a large amount of debris congregating in what is known as the Great Pacific Garbage Patch floating between Hawaii and California. Derelict fishing nets have been estimated to account for 46% of the marine debris found in the patch[31]. The majority of the rest of the 79,000 tons of debris is mostly other fishing gear, including ropes, crates and baskets, and other fishing traps (e.g., eel traps, lobster pots)[31]. These discarded fishing nets, called ghostnets, are hugely problematic for marine organisms, as they trap, kill or injure large marine mammals like whales, seals and turtles.

The prevention and reduction of marine pollution and debris by 2025 is the aim of the UN Sustainable Development Goal (SDG) Target 14.1, part of the Decade of Ocean Science for Sustainable Development (2021-2030)[32]. Due to limited and often inaccurate observations, it's difficult to monitor the source, distribution and transport pathways of marine debris[32, 33]. Debris is currently identified using land and ship-based observations as well as aircraft and imagery from UAVs.

The concept of an integrated marine debris observing system (IMDOS) was recently introduced, which aims to provide global coverage of marine debris and provide support for proposed mitigation strategies[32]. IMDOS would combine remote sensing data (e.g., SAR data, fluorescence data, high-resolution imagery, and multi- and hyperspectral data) with in-situ observations from ships, buoys, UAVs and aircraft to measure different types of marine debris[32]. Models would also be used to represent ocean dynamics, such as circulation patterns, and to track particles representing debris throughout the global ocean system.

Several satellite sensors are already being used to identify marine debris, including very high resolution optical sensors like PlanetScope, RapidEye and WorldView-3, as well as spectroradiometers and SAR sensors (see Table 9). Very high resolution imagery with a spatial footprint of 30 to 50 cm can be used to identify floating masses of debris (see Figure 14a); however, it cannot be used to identify individual objects smaller than a few meters wide. Aerial surveys taken from aircraft or UAVs can be used to identify smaller individual objects with masses of marine debris[34] (see Figure 14b); however, these methods cover a smaller spatial area compared to satellite imagery and may be reliant on weather conditions, battery life and other airspace regulations.

Spectroradiometers can be used to detect plastic materials based on unique spectral absorption features in the near-infrared (NIR) and short-weave infrared (SWIR) spectrum, as plastic debris has a higher reflectance signal compared to open ocean water[32]. However, in order to identify different types of plastic, huge libraries of spectral properties of different types of marine debris would need to be created, as well as libraries considering the spectral properties of inorganic substances that may also be nearby[32].

*Table 9. Examples of relevant satellites in operation for monitoring marine debris*

| Organisation | Dataset / Satellites | Time period | Spatial / temporal resolution |
|---|---|---|---|
| ***Optical sensors*** | | | |
| Planet Labs | PlanetScope & RapidEye[a] | 2009-present | 3-5 m, daily |
| DigitalGlobe | WorldView-3 | 2015-present | 0.30 m, as tasked |
| DLR[b] | EnMAP (hyperspectral) | 2021/22 launch | 30 m, every 4-24 days |
| NASA | HyspIRI (hyperspectral) | 2023 launch | 30 m, every 16 days |
| ***Radar sensors*** | | | |
| DLR | TerraSAR-X (X-band SAR)<br>TanDEM-X (X-band SAR) | 2007-present<br>2010-present | 1 m, every 11 days |
| ESA | Sentinel-1 (SAR) | 2016-present | 10 m, every 5 days |

[a] PlanetScope and RapidEye imagery is much less expensive than its commercial counterparts as it's automatically collected everywhere (whereas the others need to task it specially)
[b] German Aerospace Center

SAR and other radar sensors (e.g., altimeters and scatterometers) can be used to derive ocean surface currents, waves and velocity, which all play a large role in the movement of marine debris. SAR data can also be used to detect larger debri, such as derelict fishing gear, from the intensity of the backscattered signal; although, differences in size and composition of debris, as well its interaction with the surrounding ocean, make direct detection using SAR data challenging[33].

Identifying and monitoring marine debris using satellites is still a developing field, with the launch of two hyperspectral sensors in the next few years allowing for potential further differentiation between materials. In addition, the growing popularity of nanosatellites presents further opportunities for specialised sensors dedicated to the monitoring of marine debris.


***Figure 14. High resolution imagery of marine debris from (a) RapidEye** (modified from Ref [30]) **and (b) aerial surveys using a Cessna 206 plane** (Ref [32])*

## 3. Case Study from the Scottish Landcover Sector

This brief case study from the Scottish landcover sector highlights how satellite data can be turned into actionable information and integrated into existing management systems used for decision-making. NatureScot and the Scottish Government required landcover maps of Scotland in order to measure and value the nation's natural capital (i.e., assets and services provided by the natural environment). While landcover maps of Scotland exist, they were not available on the annual basis required to support the existing natural capital measurement system. Partnered with NatureScot and funded as part of the Can Do Innovation Challenge competition, Space Intelligence provided annual maps of landcover over Scotland for 2019 and 2020 (see Figure 15). We've also undertaken analysis to produce maps of landcover change between years. The maps are made using large amounts of satellite data and machine learning, and are available for viewing at https://www.space-intelligence.com/scotland-landcover/.

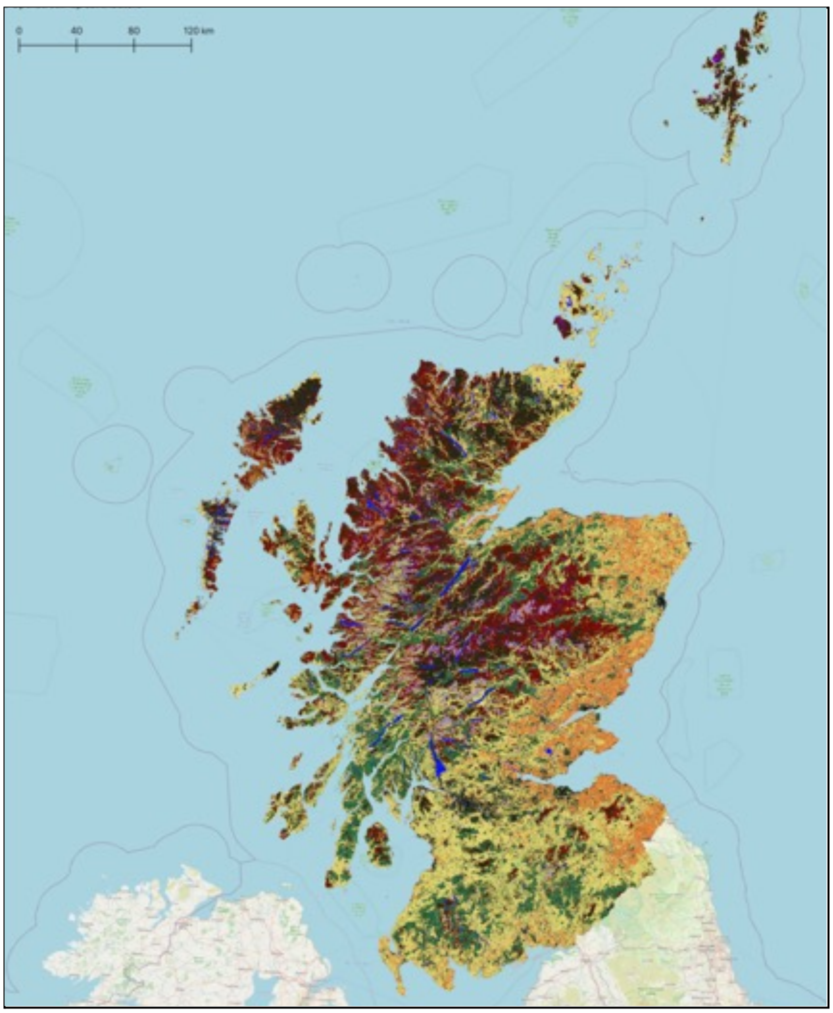


***Figure 15. Scottish landcover map for 2020*** *(Souce: Space Intelligence)*

# 4. AIS and VMS Technologies

Automatic identification system (AIS) and vessel monitoring system (VMS) technologies are already used by key stakeholders within the Scottish fishing industry for a variety of purposes. For example, fishers use AIS location data to avoid collisions at sea and to see where other vessels in the fleet are currently fishing. Regulators use AIS and VMS data to monitor IUU fishing, for example in Marine Protected Areas (MPAs). Both technologies are described below, with more detailed sample applications of AIS and VMS data discussed throughout the report.

## 4.1. Automatic Identification System (AIS)

AIS is a location-sharing system developed to avoid collisions, allowing vessels to transmit their position, identity, course and speed. The International Maritime Organization (IMO) mandates that AIS be used on large vessels (>300 gross tonnes) and on those that travel through international waters.

Traditionally received on land, AIS signals can also be received by satellite sensors, extending the range across which vessels can be monitored; this is referred to as Satellite AIS (S-AIS) - see Figure 16. A ship transmits an AIS signal, which is then picked up by S-AIS receivers and transmitted back to earth stations via radio and microwave frequency links. Data is then transferred in real time to processing centres and used to inform both local and overseas agencies like the IMO.

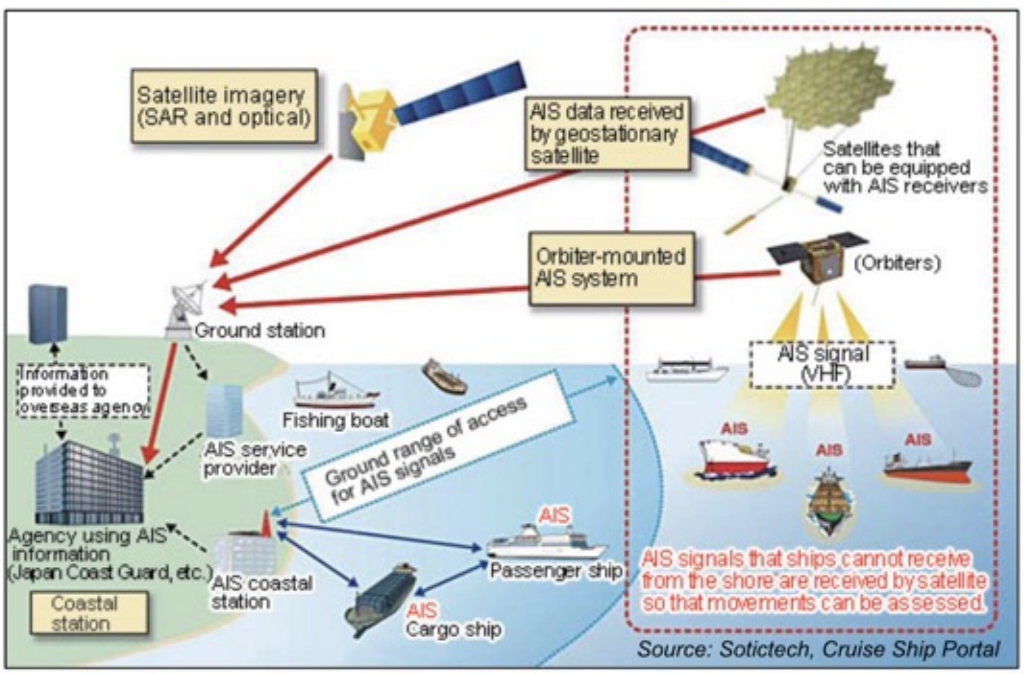



***Figure 16. Schematic illustration of AIS, including S-AIS.***

AIS data is openly available worldwide and can be accessed by anyone with an internet connection. MarineTraffic, a popular website (marinetraffic.com) and smartphone app, shows global near real-time vessel positions using a large network of land-based AIS receivers covering most of the world's major ports and shipping routes. Fishers use MarineTraffic (or other web-based maps and apps showing AIS signal locations) to avoid collisions at sea and to see where other vessels within the fleet are currently fishing. Regulators use AIS data to help monitor IUU fishing, for example vessel presence with an MPA.

Spire, a space-to-cloud data and analytics company, uses land-based and satellite-AIS data, alongside data from their constellation of nanosatellites, to provide near real-time data on vessel locations[35]. Spire has also developed a product called Dynamic AIS, which combines data collected from land-based and satellite-AIS with data from thousands of sensors located in busy shipping lanes worldwide. Predictive modelling using artificial intelligence provides information about future vessel activity, including calculated estimated time of arrival (ETA) and predicted 8-hour forecasts of vessel positions[35]. Forecasted vessel positions are based on knowledge of specific regions and vessel types, combined with forecasted weather data. Uses of artificial intelligence with AIS and VMS data are discussed further in Section 4.2.

## 4.2. Vessel Monitoring System (VMS)

VMS was developed in the 1990s specifically for vessel monitoring, control and surveillance, to help address national sovereignty issues within fishing territories, to combat illegal fishing and to monitor marine resources in a more sustainable way[36]. VMS works in a similar fashion to AIS, with an automatic location communicator installed permanently on a vessel to send out a signal (every 1 to 2 hours) with a unique identifier. However, unlike AIS, signals sent via VMS are encrypted, providing vessel location information only to the flag states responsible for registering and licensing the vessels, and to coastal states to monitor foreign vessels licensed to fish in Exclusive Economic Zones (EEZs)[37]. More recently, most regional fisheries management organisations require VMS on all licensed fishing vessels, and as of 2012, VMS units are mandatory for all EU vessels greater than 12 m long[38].

In addition to vessel tracking, VMS is now also capable of two-way reporting, facilitating near-real time electronic catch reporting and integrated documentation schemes[37], which can help hold fishers accountable for catch shares or quotas. VMS can also be used to send other useful information to vessels, including weather reports and storm alerts[36].

# 5. AI and Machine Learning

## 5.1. Introduction to AI and Machine Learning

Artificial Intelligence (AI) is the field of science concerned with the creation of machines and software that can undertake tasks that could be considered to require intelligence, such as recognising and understanding speech, perceiving surroundings, moving around in a changing environment and using understanding of a situation to predict the effect of an action and make decisions[39]. There are many different branches of AI which consider how specific tasks can be achieved. For example, computer vision deals with methods by which computers can gain an understanding of images and video, and perform tasks such as recognising where a particular object is or identifying specifically what is shown in an image.

Machine learning is a part of AI in which a model is trained to perform a specific task. In traditional programming, an input is given to a program that has been written to fulfil a task. The computer executes the program then outputs the results. Using machine learning, the computer is given the input and the corresponding expected results (training data), and then outputs a program which is based on a given model[40].

There are a number of different models which can be used in machine learning. One of these is called an artificial neural network (ANN) - see Figure 17. This model is based loosely on the human brain and is composed of multiple layers of nodes called artificial neurons. There is an input layer, some number of hidden layers and an output layer. Depending on the purpose of the ANN, the neurons in the input layer could represent, for example, pixels in an image or movements at different points in time. Each neuron is connected to all the neurons in the neighbouring layers and a weighting is associated with each connection, representing the relative importance of the signal sent through that connection. The neuron with the strongest signal in the output layer is the classification given by the ANN. Through the learning process, the computer finds the best values for these weightings for the ANN to correctly classify the training data[41].

There are a number of different types of neural networks, including convolutional neural networks (CNNs). CNNs are particularly good at computer vision tasks like object recognition and identification, as well as other tasks which involve processing data which can be represented in two dimensions, such as movement and sounds[42].

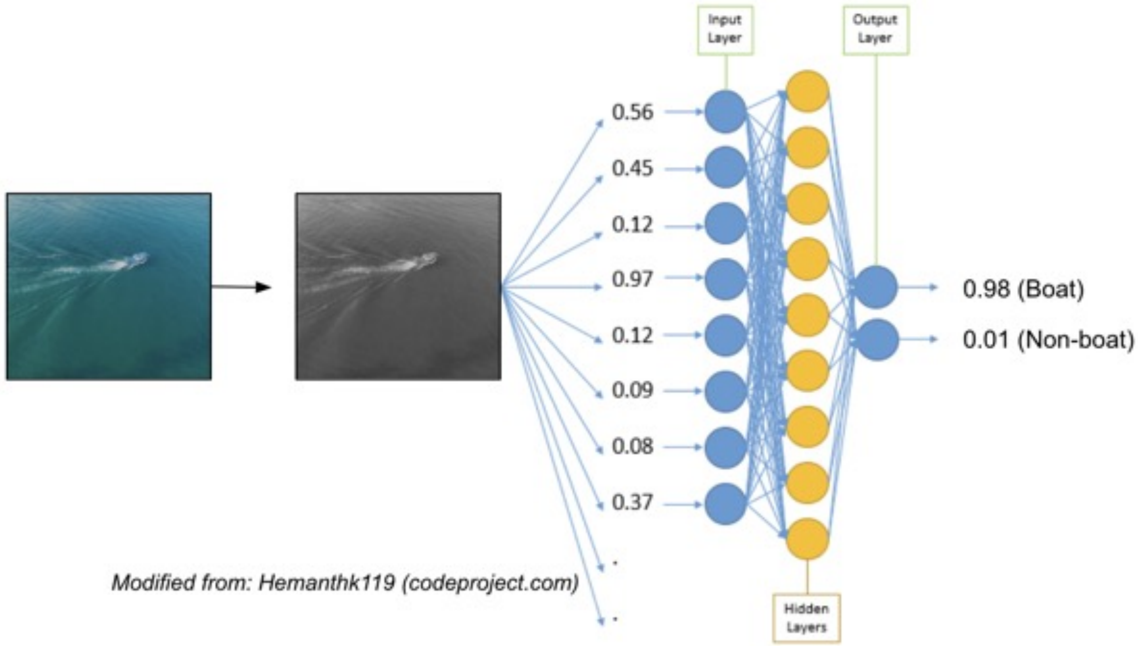



***Figure 17. Sample structure of ANN which classifies whether an image is of a boat. Each neuron in the input layer represents a pixel in the input image and the numbers represent the greyscale value of the pixel with 0 being black and 1 being white. The signal is processed in the hidden layers, then in the output the number represents the likelihood that the image is or isn't a boat.***

## 5.2. Uses of AI for Scottish Fisheries

Computers are good at carrying out simple and repetitive tasks and solving problems that can be expressed using mathematics and logic. AI is commonly applied to tasks involving classification, pattern recognition and modelling possibilities. It can be used to process vast amounts of data on much shorter timescales than humans and at a lower cost.

Machine learning is already being used in the fishing industry worldwide. For example, **Global Fishing Watch (GFW),** an independent, international non-profit organisation, uses broadcasted AIS data to identify and map possible commercial fishing vessels based on changes in speed and direction[43] (Figure 18). Vessel properties such as length, engine power and gross tonnage were identified with more than 90% accuracy using AI algorithms to process billions of AIS signals between 2012 and 2016[44].

As well as the type and size of each vessel, neural networks were able to determine what kind of fishing gear was being used (e.g., trawling gear, longlines, purse seines) and when and where fishing activity was taking place[43]. Thousands of vessel tracks were manually analysed and labeled in order to train the model in the identification of fishing patterns. The use of cloud computing helps to speed up analysis, splitting the processing over thousands of machines running in parallel[43]. This technology allows for increased traceability and verification of catch.

GFW aims to provide increased transparency of human activity at sea, for the effective governance of marine resources, and actively pursue partnerships with government and industry for data sharing and fisheries management; for example, Indonesia partnered with GFW in 2017, making all of their VMS data available to the organisation for inclusion in their map. The online map can also show historical data dating to 2012, and has the option for a user to upload their own datasets and save and share their work.

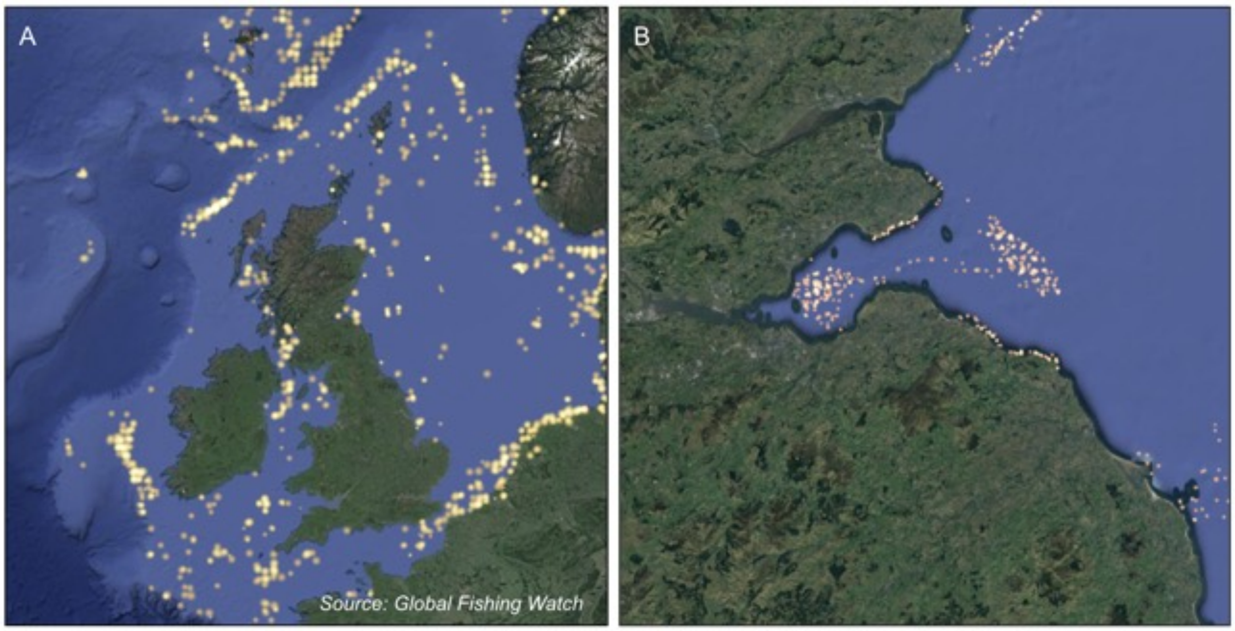



***Figure 18. Example from Global Fishing Watch online map, showing apparent fishing effort (a) around the UK between 15th and 22nd May 2021, with (b) showing more details along the south-eastern coast of Scotland.***

Machine learning can also be used to identify fish species caught and discarded at sea, aiding regulators in fisheries management. In a recent pilot programme, NOAA deployed cameras on board fishing vessels to replace humans as regulatory observers. Computer algorithms were used to analyse the camera footage and were trained to identify fish species and size and to count the number of fish per scene[45]. In one trial, an algorithm was able to identify fish species at 75% accuracy and fish count at nearly 100% accuracy[45]. Electronic monitoring of fisher's catch and discard would greatly improve the traceability of the catch, proving that the correct fish were legally caught in the right place and time and with the correct equipment. This would also give buyers greater confidence in the sustainability of Scottish fishing, leading to an increase in fisheries profit.

SMARTFISH H2020 is a project recently funded by the EU's Horizon 2020 research and innovation programme, led by the Scandinavian independent research organisation SINTEF Ocean and including Marine Scotland as a research partner. The project aims to use AI and machine learning to develop innovative high-tech systems for the EU fishing sector. A variety of on-board technologies are being developed and tested to assist fishers in making informed decisions, to improve catch efficiencies and reduce unintended fish mortality and fishing pressure within EU waters[46]. New technologies will also provide new data to improve stock assessments, and use automatic, electronic catch data collection to ensure legality and regulatory compliance[46].

Some of the SMARTFISH H2020 innovative tech developments are currently being trialed in the west of Scotland and the northern part of the North Sea, with the trial running from January 2019 to December 2021. One of the technologies trialled is called NephropsScan, which automatically detects and counts nephrops burrows[47]. Other technologies being tested in Scottish waters include CatchScanner and CatchSnap, which use 3D machine vision for catch analysis on on-board conveyor belts and for inspecting catch on smaller fishing vessels, respectively[47].

# 6. Monitoring Fishing Vessels from Space

It is possible to detect tracked and untracked fishing vessels from space in order to monitor vessel speed, territory covered, equipment used (e.g., number of fishing lines or lobster pots) and IUU fishing. Both AIS and VMS transmitters, traditionally used for vessel tracking and monitoring, can legally be turned off, for example, when in port or when the vessel is no longer in use. However, there are many instances of vessels turning off their AIS transmitters when fishing illegally in protected waters, or in waters where they are not licensed.

The monitoring of IUU fishing is currently undertaken using a combination of AIS and VMS data (when available), and in-person monitoring both at sea (e.g., Coast Guard) and via aircraft. This section reviews existing technologies for monitoring fishing vessels from space, including the use of high resolution radar and optical imagery and radio-frequency satellites.

## 6.1. Monitoring using High Resolution Radar and Optical Imagery

High resolution radar and optical imagery present several possibilities for monitoring and tracking fishing vessels at sea, even if AIS and VMS systems have been turned off. Satellite surveillance can be used for regulatory monitoring, for example to detect illegal fishing activity within Marine Protected Areas (MPAs). Very high resolution (sub-meter) optical satellite imagery could potentially be used to detect the number of fishing lines trailing behind a vessel or to check whether crew are using legally-required safety equipment.

The ability of SAR data to operate in all weather conditions and during both day and night makes it suitable for detecting vessels of various sizes, depending on the spatial resolution of the sensor. Sentinel-1 has a spatial resolution of 10 m, suitable for detecting vessels longer than 15 m (see Figure 19a), although small vessels can sometimes be hidden by waves, depending on wind speed and direction[48]. ICEYE and Capella data have spatial resolutions of 25 and 50 cm, respectively, allowing for easier detection of smaller vessels (see Figure 19b-c). SAR data can also capture classical ship wake patterns, including “V” and turbulent waves trailing behind a vessel (see Figure 19d).

SAR data was used as part of a larger satellite surveillance trial for monitoring fishing vessel activity in the Ascension Island EEZ and MPA[49]. By cross-correlating SAR detections against the AIS-derived positions of known vessels, a list of uncorrelated detections was compiled, leading to the identification of potential longline fishing vessels within the EEZ. Vessel activity was monitored by OceanMind, a technology program developed by the Pew Charitable Trusts and a UK company called Satellite Applications Catapult (SAC). SAC uses advanced machine learning to learn the movements of vessels performing fishing activities, which can then be applied to other vessels; for example, the movement patterns when a vessel off-loads catch onto another ship at sea to avoid coast guard[50]. While providing useful information on vessel location, SAR data alone cannot be used to determine whether a vessel is actively fishing or simply travelling through an area[49].

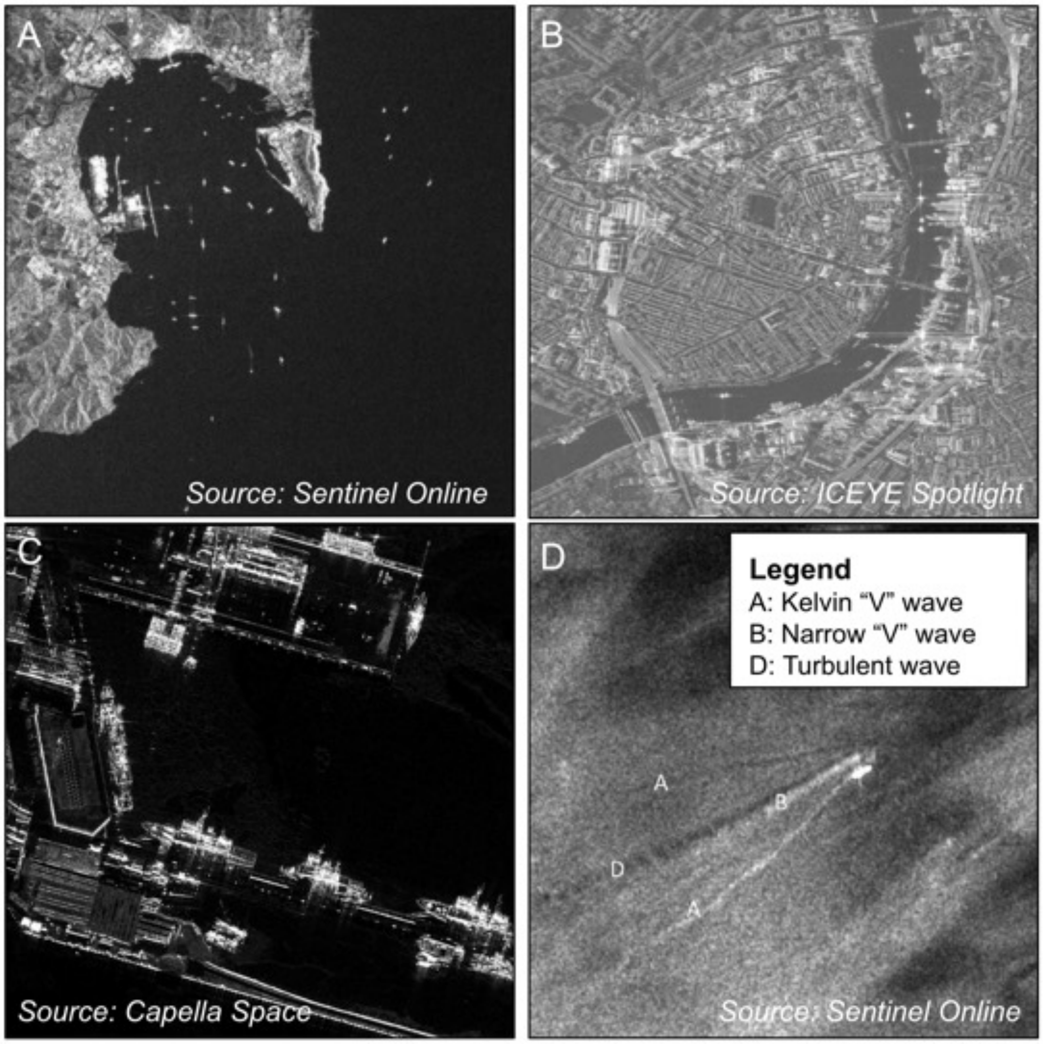



***Figure 19. Sample high resolution radar imagery: vessel detection in (a) Sentinel-1 imagery over Gibraltar (b) ICEYE imagery over the River Thames in London and (d) Capella Space SAR image; and (c) ship wake detection in Sentinel-1 imagery.***

High resolution optical imagery can also be utilized for vessel tracking and monitoring. Commercial satellite sensors such as WorldView-3, Pléiades and GeoEye-1 provide data with a spatial resolution of ~30 to 50 cm and can be tasked to fly over a specific area on an as frequent basis as needed, budget allowing. Planet Labs offers frequent global coverage with a spatial resolution between 3 to 5 m from its PlanetScope and RapidEye satellites; this imagery is automatically collected globally, so it is much less expensive than its commercial counterparts, which need to be tasked specifically over an area of interest. Sentinel-2 optical imagery is freely available and could also be used for vessel tracking and monitoring, although it has a lower spatial resolution (10 m). Figure 20 shows a few sample high resolution images with vessels from WorldView-3 and PlanetScope satellites.


***Figure 20. Sample high resolution optical imagery: WorldView-3 imagery showing vessels near (a) Auckland, New Zealand and (b) Lima, Peru; Planet Labs (c) PlanetScope imagery near San Francisco, USA and (d) SkySat imagery near Hainan Island, China.***

Whether a vessel is present in a high resolution optical image can be quite obvious; however, it's possible that a vessel has a perfectly legitimate reason for being in a particular location, depending on vessel type (e.g., a dredger may be undertaking illegal fishing, while longline fishing may be allowed in the area). It may be possible to differentiate between vessel types in sub-meter resolution imagery, depending on any gear visible on deck or trailing behind a vessel. This becomes increasingly difficult as resolution increases, with differentiation likely not possible using 3-5 m resolution imagery, even with vessels >15 m long.

Observed behaviours such as direction and speed can also help to determine vessel type or whether a vessel is just passing through an area or undertaking IUU fishing. For example, trawlers pulling nets behind them will typically move with a steady speed and direction, whereas non-trawling vessels like seiners will remain relatively stationary, or sometimes move in circles around a shoal of fish. Vessels just passing through an area would likely cruise at faster speeds than those trawling.

One way of deriving vessel direction and speed is by using the temporal offset between different bands taken during the acquisition of one multispectral optical image. For example, temporal offsets of up to 2.6 seconds are recorded for different bands of Sentinel-2 imagery. As such, a fast moving object like a boat or plane will be observed at slightly different positions in each band image, from which direction and speed can be determined. However, it is difficult to determine vessel velocity with high accuracy due to long wakes following behind the ships[51]. A study has been undertaken to estimate ship and aircraft velocity from Sentinel-2 temporal band differences with some success[51], although more research into the influence of vessel length, speed and wake reflections as well as surface winds on determining velocity is necessary before widespread use of this methodology.

A single image can also be used to determine vessel speed if Kelvin waves are observed behind the ship (e.g., in Figure 19d), as Kelvin wavelength is related to velocity[51]. Kelvin wavelength ($\lambda$) can be estimated by undertaking a Fourier analysis of the image, and velocity $(V)$estimated using a simple equation[51], where $g$ is the gravitational acceleration at Earth's surface (9.8 m/s$^2$):

$$\lambda = \frac{2\pi V^2}{g}$$

Vessel direction and speed can also be estimated using images from multiple sensors taken in quick succession with overlapping spatial footprints.This has previously been undertaken within the glaciology community to estimate iceberg velocity[52,53]; however, this method requires significant assumptions in object direction and speed (i.e., assumed linear movement through time), as any changes in speed or direction between any two images are unknown.

Optical satellite imagery can also be used to monitor vessel activity at sea during the night, due to the large contrast between the dark sea and bright lights from vessels at night. For example, lights at sea are visible in NASA's Visible Infrared Imaging Radiometer Suite (VIIRS) nighttime monthly composites (see Figure 21). While the spatial resolution of VIIRS is only ~450 m, approximate locations of night time activity at sea are still visible due to the high contrast between surface reflections.

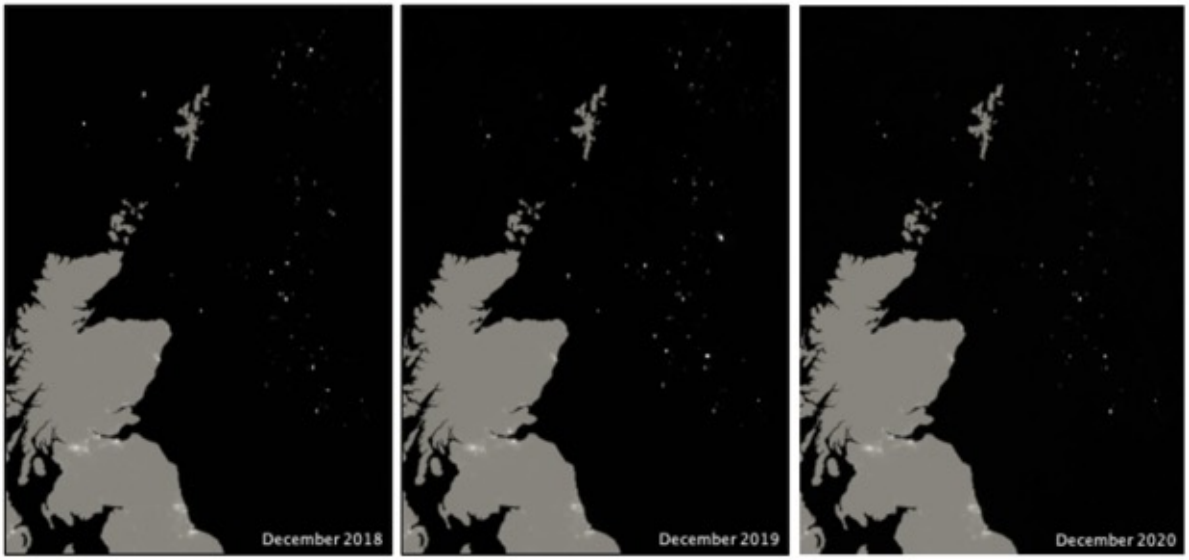



***Figure 21. Nighttime monthly composites east of Scotland from VIIRS, showing bright lights from cities, on land, and in the sea from vessels (including shipping) and oil/gas infrastructure.***

Table 10 below provides details of high resolution radar and optical satellites which could be used for vessel tracking and monitoring. There is of course a trade-off between spatial resolution, cost and temporal frequency when using satellite imagery for monitoring purposes. The lower end of the high resolution satellites like Sentinel-2, PlanetScope and RapidEye automatically collect global data and are thus more cost-effective for longer-term monitoring; however, sub-meter spatial resolution would be necessary for more detailed monitoring of fishing activities (e.g., number of lines, safety compliance). While sub-meter resolution commercial satellites can be tasked for a specific area of interest, this comes with a significant increase in cost and would be more suitable for infrequent spot checks rather than long-term monitoring programmes.

However, earth observation satellites provide wider coverage than monitoring IUU fishing from aircraft or ships, **allowing monitoring over a much larger area than previously possible**. In addition, as previously mentioned, satellite data can be used to monitor vessels which have turned off their AIS or VMS signaling and would otherwise be difficult to locate.

*Table 10. Examples of high resolution radar and optical satellites for use in vessel monitoring*

| Organisation | Dataset / Satellites | Time period | Spatial / temporal resolution |
|---|---|---|---|
| ***High resolution radar satellites*** | | | |
| ESA | Sentinel-1A SAR | 2015-present | 10 m, every 6 days |
| SSTL | NovaSAR-1 (Maritime Mode) | 2019-present | 30 m, every 14 days |
| ICEYE | ICEYE Spotlight<br>ICEYE Stripmap | 2018-present | 0.25 m, as tasked<br>3 m, as tasked |
| Capella Space | Capella Spotlight<br>Capella Sliding Spotlight<br>Capella Stripmap | 2019-present | 0.50 m, as tasked<br>0.80 m, as tasked<br>1.2 m, as tasked |
| ***High resolution optical satellites*** | | | |
| DigitalGlobe | GeoEye-1 panchromatic<br>GeoEye-1 multispectral | 2009-present | 0.50 m, as tasked<br>~2 m, as tasked |
| Planet Labs | PlanetScope & RapidEye[a]<br>Planet SkySat | 2009-present | 3-5 m, daily<br>0.50 m, as tasked |
| Spot Image | SPOT-6/7 | 2012-present | 1.5 m, as tasked |
| CNES[a] / Spot Image | Pléiades | 2013-present | 0.50 m, as tasked |
| DigitalGlobe | WorldView-3 | 2015-present | 0.30 m, as tasked |
| ESA | Sentinel-2 | 2016-present | 10 m, every 5 days |

[a] National Centre for Space Studies (French space agency)

## 6.2. Monitoring using Radio-Frequency Satellites

Recent advances have been made in the monitoring of fishing vessels from space using radio-frequency (RF) intelligence satellites. These RF satellites are small (about the size of a microwave) and fly in a cluster, passing the same spot on the Earth's surface several times a day[54]. The satellite receivers can pick up faint signals from radar devices, walkie-talkies and satellite phones[54]; as these are used for navigation purposes and collision-avoidance at sea they are unlikely to be switched off to avoid detection, which is traditionally done through disabling vessel AIS or VMS.

RF intelligence satellites are able to pinpoint a vessel's location with an accuracy between 200 to 3000 m by using a technique called trilateration, the Doppler effect or a combination of the two[54]. Trilateration uses the distance of the received radar signal to each satellite in the cluster to create a ground radius in which the radar source (e.g., vessel) could be located, as the location of each satellite is precisely known[55]. The areas where all perceived signal ground radii overlap or intersect shows the location of the received signal (see Figure 22a).

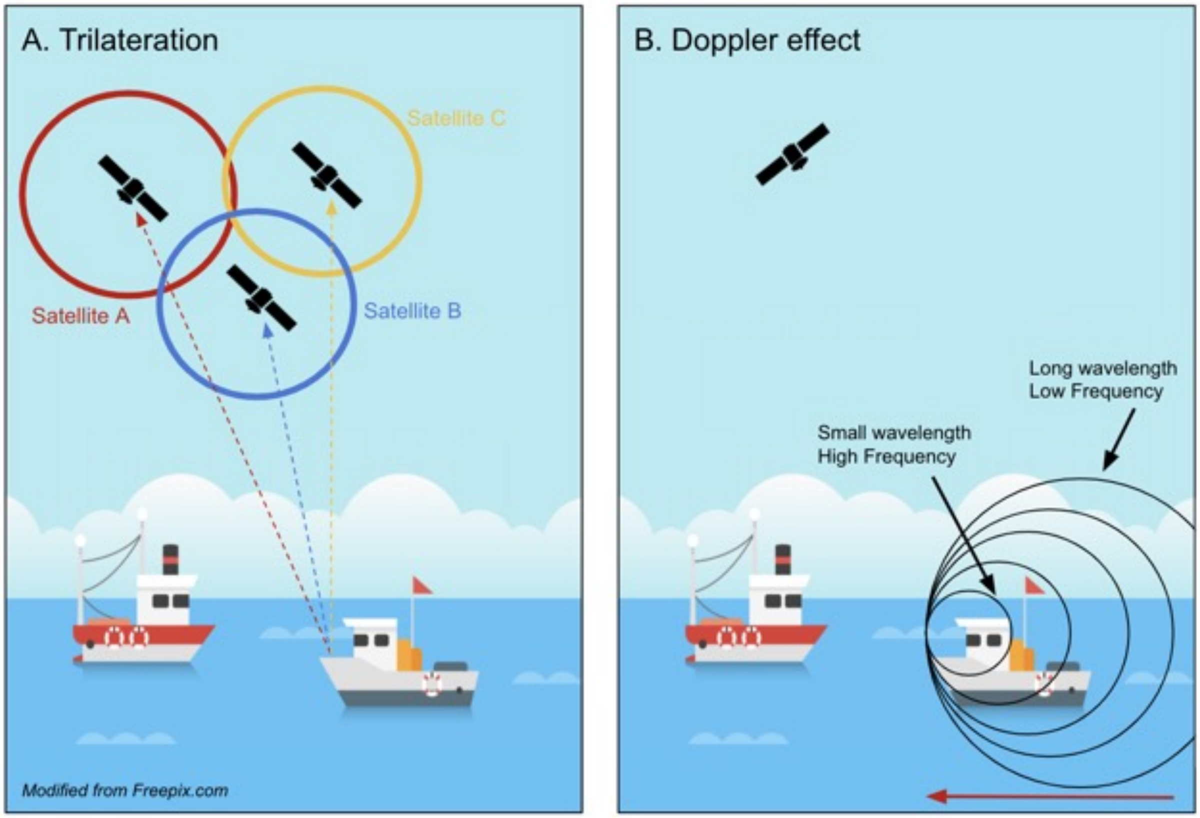



***Figure 22. Schematic of (a) trilateration and (b) the Doppler effect used to pinpoint a location.***

The Doppler effect is used to locate moving vessels, relying on the observed shift in the received radar signal's frequency with movement relative to the satellite receivers[54]. The closer the vessel is to the satellite receiver, the smaller the received wavelengths and the higher the frequency - see Figure 22b. An RF intelligence satellite operator based in the United States called HawkEye 360 uses both trilateration and the Doppler effect to locate a vessel within 500 m of its true location[54]. Further advances have been made to decluster RF intelligence satellites, meaning that a vessel could be located using only one satellite instead of a cluster of three. However, this technology, currently used by UnseenLabs in France, is only able to pinpoint a vessel's location within 5000 m and is currently protected by the French state[54].

HawkEye 360 has also recently released an online commercial platform for the analysis of RF geospatial intelligence data, called Mission Space (see Figure 23). The platform uses AI algorithms to automatically identify specific vessel behaviour from the RF data, and merges other information including vessel identification, history and past sanction violations[56]. The platform also offers a subscription service, where a user can specify an area of interest or vessel behaviour pattern, receiving automatic notifications when RF activity appears within the area of interest. Other companies offering RF satellite surveillance of vessels include Kleos Space, based in Luxembourg, and Airbus Defence and Space.

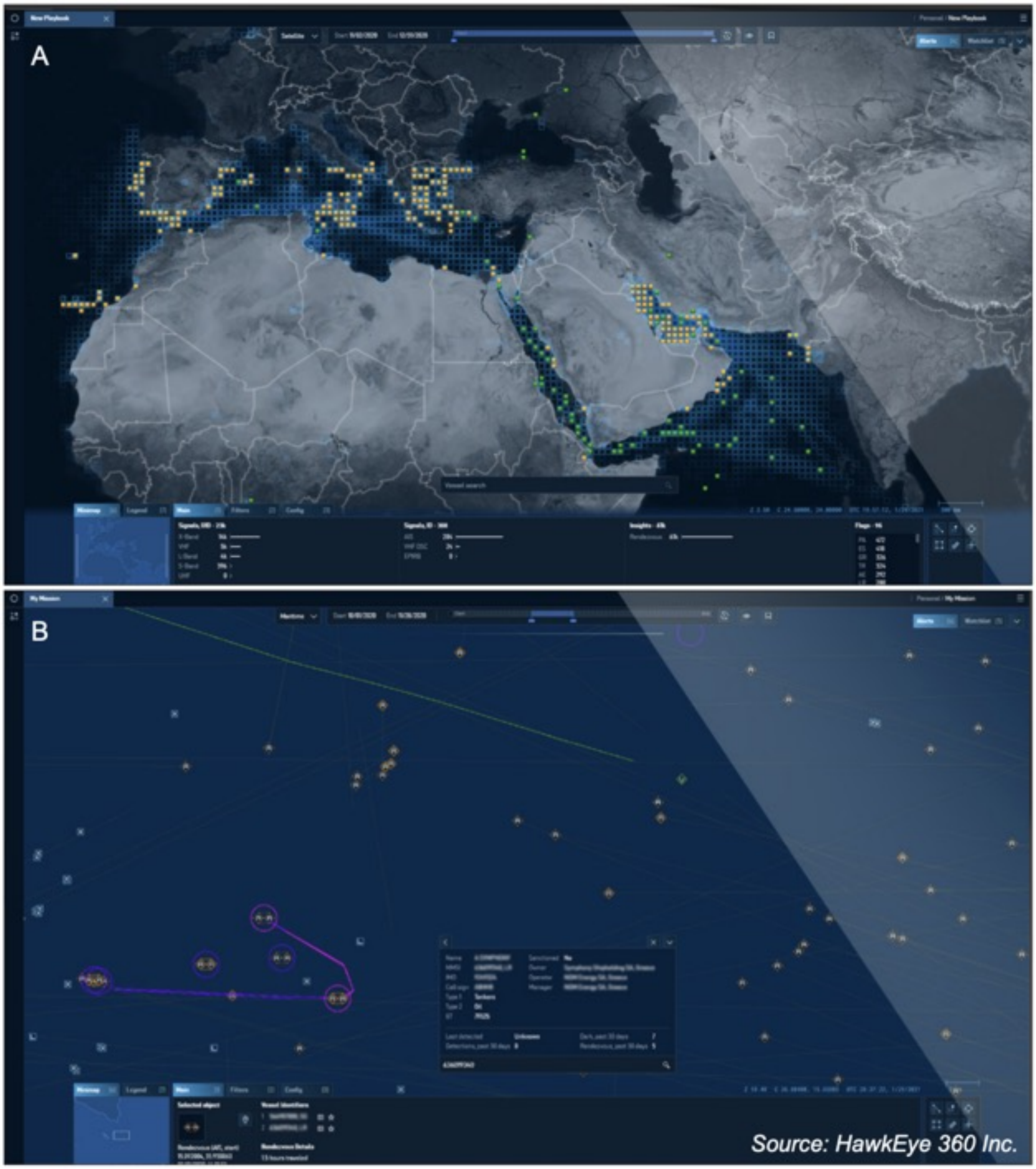



***Figure 23. Example of Mission Space platform (a) heat map and (b) vessel tracking history.***

# 7. Integrated Fisheries Systems

## 7.1. Fisheries Monitoring, Control and Surveillance (MCS) Systems

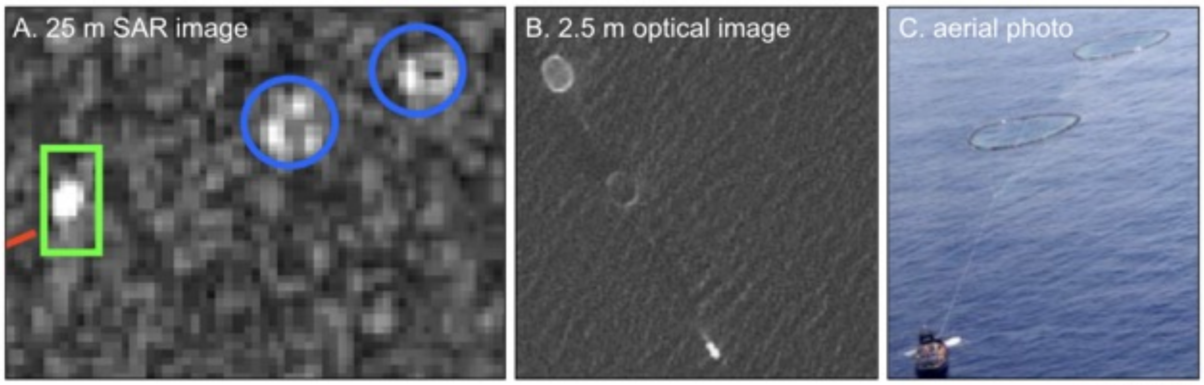
Monitoring, control and surveillance (MCS) systems aim to facilitate compliance with fisheries management measures by monitoring fishery activity to aid in management development and surveillance to ensure compliance[11]. Any MCS system has a variety of components and methods for monitoring and surveillance of fisheries activity, with many combining more traditional monitoring systems like AIS and VMS with satellite-derived data to create a more comprehensive vessel monitoring system. Data from patrol UAVs, aircraft and surface vessels can also be integrated, as can data from floating buoys and unmanned underwater vehicles.

For example, a potential workflow for detecting dark vessels could start by using lower resolution SAR or optical data to identify vessels in an area of interest, which could then be compared against S-AIS and VMS data to investigate whether any vessels in the image are unknown; after which, very high resolution optical imagery could be used to identify the unknown vessel. However, there would likely be a time delay between identifying an unknown vessel and retrieving higher resolution optical imagery to confirm vessel identify and activity, as most commercial high resolution optical satellites need to be tasked to fly over an area; in this time, an unknown vessel could move a great distance or change its activity[57]. Alternatively, an aircraft or unmanned aerial vehicle (UAV) flyover could be performed instead of using very high resolution optical data, which may be a faster approach.

The European Commission's Joint Research Centre (JRC) has developed a conceptual Vessel Detection System along these lines. Within the proposed system, vessels would automatically be detected using SAR imagery and then cross-checked with AIS and VMS positioning data, as well as visual inspection sightings[58]. Any mismatched signals would then be reported to the appropriate authorities for investigation. JRC estimated that it would take between 15 and 90 minutes to report an unknown vessel, which includes the satellite image delivery and processing time, as well as analysis and correlation time[58].

The detection system was successfully used in a campaign to monitor bluefin tuna fisheries in the Mediterranean in 2007 and 2008, identifying interesting activities such as vessels towing tuna cages, the possible transfer of tuna from vessels into sea farm cages and group vessel fishing activity in near-real time[58]. Figure 24 shows example SAR and optical imagery from the campaign.

Fisheries and Ocean Canada have developed a Salmon Ocean Surveillance Information System (SALOSIS), which uses satellite data and historical knowledge to define ocean salmon habitat in order to target monitoring in areas where illegal salmon fishing is likely to occur[59]. The system helps to identify Pacific salmon distribution in relation to ocean conditions at and below the surface, relying mostly on the relationship between latitude, sea surface and mixed layer temperature[59]. Suggested future work would also include information on fisheries abundance in addition to the location information, allowing for maximum benefits from surveillance efforts.




Source: JRC

***Figure 24. Sample imagery from JRC vessel detection campaign: (a) vessel with towed tuna cages identified in SAR image, and vessel confirmed in (b) optical image and (c) aerial photo.***

## 7.2. Integrated Fisheries Management Systems

### ESA Feasibility Studies: i-Fish North Sea and FISHSAT

ESA spearheaded two feasibility studies for integrated fisheries management systems between 2011 and 2013: i-Fish North Sea and FISHSAT. Completed in May 2013, i-Fish North Sea aimed to develop a system for providing integrated solutions and associated services to enhance sustainability of fisheries resources[60]. The project targeted various stakeholders and potential system end-users, including: fishing authorities and compliance agencies (e.g., Marine Scotland); fishery organisations; fishers; auction houses and fish markets; food processors; and wholesalers and restaurants.

The overall concept of i-Fish North Sea was based on a central message hub that could be accessed by all relevant stakeholders, for the sharing of information and data via ship-to-shore or ship-to-satellite communication links (e.g., S-AIS and VMS),[60] see Figure 25. For example, fishers could sell their catch before arriving at port via a virtual fish market; or near-real time updating of fleet position and catch could be used for product traceability and management, and catch analysis support[60]. In this way, processes across the value chain can be optimised, leading to reduced waste and environmental impact, as well as cost reduction and a more balanced supply and demand[60].

FISHSAT aimed to provide an integrated satellite service for fishing support and safety, developing a system that would use satellite-derived data (e.g., meteorological information, sea surface parameters) and communication links to improve the collaboration between fishers, markets and regulatory authorities[61]. The project targeted two main stakeholders: fisheries and the sea authorities who enforce regulations (e.g., the National Federation of Fishermen's

Organisations), with intended benefits of increasing fishing efficiency, fair competition and reliable stock estimation and quota setting for fishers; traceability and strengthening enforcement were identified benefits for regulatory authorities.

The inclusion of satellite-derived environmental and biological parameters with the system, such as sea surface temperature and phytoplankton concentrations, could be used by fishers to predict the likelihood of fish presence, with more productive zones identified to reduce fishing effort[61]. Location-based information can be used for product traceability, providing accountability for the sustainability of each catch, as well as for the identification of illegal fishing practices. The FISHSAT system would be designed to automatically alert regulatory authorities when a vessel entered a forbidden fishing area, allowing for the rapid launching of an investigation from coast guard vessels[61].

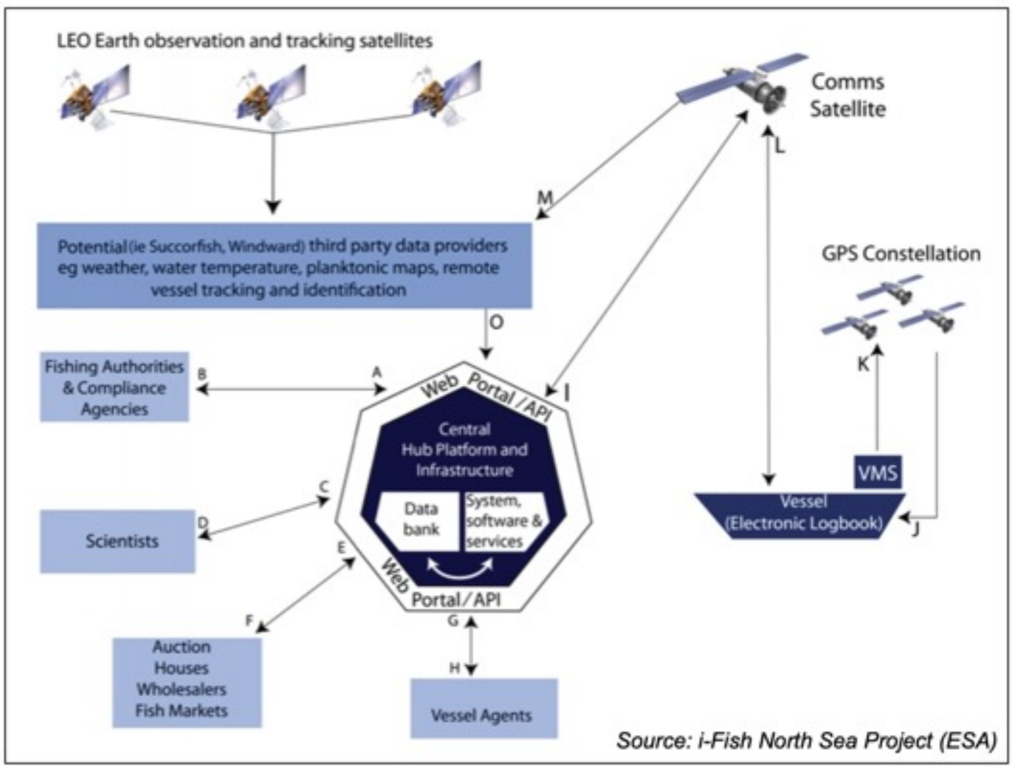



***Figure 25. Conceptual diagram of i-Fish North Sea central hub system***

## Electronic Catch Documentation and Traceability (eCDT) System

Catch documentation and traceability are important parts of fisheries management, allowing catch to be verified and traced as it moves through the supply chain from point-of-catch to export[62]. Traditionally, fishers report at-sea capture information via a paper logbook, which is turned into a catch certificate at port and passed along to the buyer, shipper and processor by batch ID and a final certificate of origin[62]. An electronic catch documentation and traceability (eCDT) system could instead use mobile devices to record at-sea capture information, transmitting information via cell or satellite communication, after which data could be stored on the cloud and accessed by various users along the supply chain[62], providing increased transparency and traceability.

Figure 26 provides an example eCDT system infrastructure, developed by the Oceans and Fisheries Partnership between USAID and SEAFDEC (Southeast Asian Fisheries Development Center) to help regulate illegal, unreported and unregulated fishing. An eCDT system would allow regulators and consumers to ensure a catch has been legally caught and properly labelled, as well as complying with international regulations[62]. Setting up an eCDT system requires an immense amount of effort and cooperation from all parties along the seafood supply chain; however, once operational, the system would enhance fisheries management and provide benefit to many.

| Seafood Supply Chain | At-sea capture | Port | Buyer/Broker | Shipper (domestic) | Processor | Shipper (non-domestic) |
|---|---|---|---|---|---|---|
| Current data capture method (not integrated across supply chain) | None or paper | Paper or electronic | Paper or electronic | Paper | Paper and electronic | Paper and electronic |
| Who | Captain | Company and Port Authority | Company or agent | Shipper (company) | Processor (company) | Shipper and Export Authority |
| Data Type | Logbook and Captain's certificate | Catch certificate / document | Purchase order | Manifest or delivery order | Raw material, batch ID, finished good ID | Certificate of Origin, packing list, health certificate, Bill of Landing |
| Future data capture method (integrated across supply chain) | Mobile data collection, pushed to Data Exchange Server (DES) | Mobile data collection, pushed to DES | Data submission to DES, cloud storage | Data submission to DES, cloud storage | Data submission to DES, cloud storage | Data submission to DES, cloud storage |
| eCDT data submission system | Cell or satellite | Cell or WiFi | Internet | Internet | Internet | Internet |

***Figure 26. Conceptual eCDT system infrastructure*** *(Modified from Ref [11]).*

## Digitalised Fisheries Management Case Study: Iceland

Iceland's fishing industry has become increasingly digitalised, with a shared digital information system that provides real-time information for all stakeholders - including fishers, scientists, management authorities (i.e., regulators) and interested buyers[63]. Collaboration between fishers and scientists at the Marine Research Institute allows for reliable, updated fish stock assessments, with species data collected year-long to determine if fishing quota should be maintained, reduced or increased. Monitoring is performed on-board as well as upon landing, where catch is weighed and recorded in a central database[64]. Information is updated online on a daily basis (i.e., all catches from all vessels and quota status, updated the day after they are landed), and is freely available online for viewing by anyone on the Directorate of Fisheries webpage (http://www.fiskistofa.is/english/quotas-and-catches/).

## 7.3. Predicted Fisheries Habitat Maps

The locations of prime habitat for particular fish are most commonly predicted using sea surface temperature and chlorophyll-a concentration[65], which can both be used to help explain fish presence and abundance. Predicted fish habitat can be used by fishers for various purposes, for example to find better fishing areas for reduced catch effort and increased efficiency. On the other hand, predicted fish areas can also be used to avoid habitats of protected or choke species in an effort to reduce bycatch.

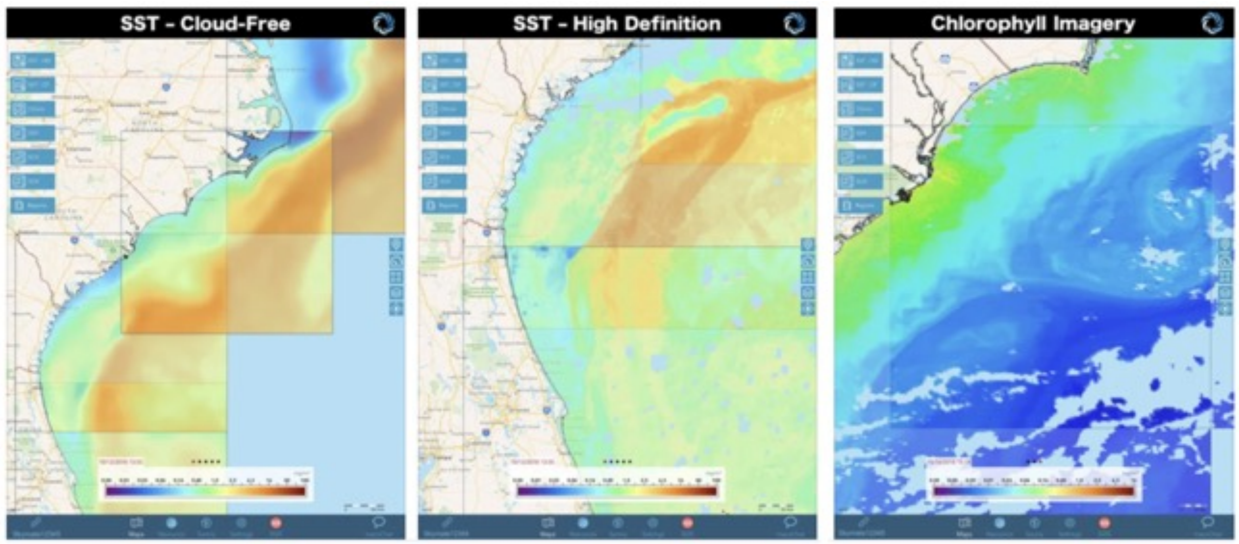
### Systems for Reducing Catch Effort & Increased Efficiency

There are several existing commercial systems which can be used to predict fish presence, including CATSAT and the Mazu SportFishing app. CATSAT is a commercial system with European headquarters based in France (catsat.com). The CATSAT system aims to provide fishers with accurate, near real-time oceanographic data and marine weather information to support smarter, safer and faster fishing[66]. The system integrates satellite-derived data on surface currents, observed sea surface and modelled subsurface temperatures, salinity, ocean colour, marine meteorology data and more, all of which can be accessed directly from a fishing vessel. By identifying favourable areas, fishing trips can be more efficient, saving time and money as well as reducing the carbon footprint of each trip.

The Mazu SportFishing iPad (or iPhone) app (https://www.mazu-marine.com/sportfishing/) provides quick downloads and overlay maps of various satellite-derived datasets, including twice daily maps of sea surface temperature in either 30 or 60 nautical mile sections, daily chlorophyll-a concentration charts and altimetry data[13]. Weather information is also available, as well as a chat system and the ability to share your vessel position with friends. The app aims to help fishers locate optimal fishing zones, to save them time, money and fuel on each fishing trip. Figure 27 shows a few sample screenshots of information provided by the app along the southeast coast of the United States.

While these commercial apps are certainly useful for fishers, subscriptions are often expensive and many only provide mapping over specific coastal regions. It's possible that a less expensive system for displaying daily sea surface temperature could be made available to Scottish fisherman, either through FIS or various government subsidies.

SusTunTech, another project recently funded by the EU's Horizon 2020 research and innovation programme, aims to reduce tuna fishing vessel emissions and fuel consumption by 25%[67]. The project uses satellite data and machine learning, along with advanced vessel monitoring to improve the detection of tuna fisheries, reducing vessel time at sea to save fuel and reduce emissions[67]. In return, two tuna fishing vessels will be collecting valuable validation data for the Copernicus satellite programme. One of the expected project results will be a commercial system called MarineView, which will allow all types of fishing vessels (and potentially the shipping industry) to improve operations and fuel efficiency. Figure 28 shows a flow chart of the project and expected outcomes.




Source: Mazu SportFishing

***Figure 27. Screenshots from Mazu SportFishing app showing sea surface temperature and chlorophyll concentration along the southeast coast of the United States.***


***Figure 28. SusTunTech project and expected outcomes.***

Fisheries and Oceans Canada has developed operational salmon migration timing forecasts, using satellite-derived data in combination with an ocean circulation model[59]. Specifically, the system uses maps of sea surface temperature along with ocean current modelling within the Gulf of Alaska to forecast when various stocks of Fraser River sockeye salmon will arrive in the Pacific Ocean, as well as to forecast the percentage of salmon that will migrate along the east and west coasts of Vancouver Island[59]. A similar forecasting system could be developed for fisheries specific to Scotland, for example, forecasting the migratory route of mackerel.

### Tools for Reducing Bycatch

As well as being useful for targeted, more efficient fishing, predicted habitat maps can also be used to avoid fishing within the preferred habitats of protected or choke species, effectively reducing bycatch. TurtleWatch is a great example of a bycatch reduction tool, developed by the Pacific Islands Fisheries Science Center in Hawaii. TurtleWatch was developed to help reduce the number of loggerhead sea turtles inadvertently caught by longline fishing vessels around Hawaii[68]. Daily maps of loggerhead turtle thermal habitat are published via NOAA, based on satellite-derived sea surface temperature, historical fisheries data (e.g., recorded information on turtle and vessel interactions in the past) and turtle tracking data. In order to avoid catching loggerhead turtles, fishers are advised to check these daily maps before heading out to sea, and to plan their fishing routes outside of the identified habitat areas. A similar tool could be developed for Scottish fisheries in order to avoid protected fish species and to reduce bycatch.

A pilot tool called BATmap (By-catch Avoidance Tool, https://info.batmap.co.uk/) has recently been trialed with one fleet on the west coast of Scotland to help fishers avoid high catches of protected or choke species. BATmap relies on fishers sharing real-time location information for hotspots of these species (e.g., cod, whiting and spurdog) with other nearby fishers via an online app[69]. Through the app, fishers receive alerts on a map showing the time and location of bycatch from other fisher's reported hauls, so that they can avoid these areas.

While BATmap relies solely on word of mouth for identifying hotspots of protected species, this information could be used alongside satellite data to predict hotspots before they're reported by fishers. As with the TurtleWatch tool, predicted hotspots would be based on a derived relationship between ocean properties and preferred species habitat, as well as using historical and current catch records from within the Scottish fishing industry and expert knowledge. Machine learning could be applied to historical catch data, alongside weather data and maps of oceanic parameters from the same time periods, to produce maps of species habitat. These habitat maps could be used to avoid protected species, or to undertake more efficient fishing for allocated commercial species. However, such data likely does not exist for Scottish fishing vessels in Scottish waters. There are data available on the location of vessels through time, which would show where fishing takes place, but we were not able to discover any good datasets on where particular species were caught. Potentially therefore to develop such a tool, a new data collection drive involving the willing participation of fishers in Scotland would be necessary.

# 8. Impact of Climate Change

Climate change is considered likely to have a significant impact on marine biodiversity and fisheries productivity through changes in ocean conditions, such as sea temperature, ocean circulation and coastal upwelling[70]. These changes will impact levels of primary productivity, which has a large influence on species distribution and productivity, with fish and other marine organisms shifting their distributions accordingly.

Impacts already observed in UK fishing waters due to climate change include distributional shifts in commercial fish species like the Atlantic bluefin tuna, cod, mackerel and herring[71]. While there are of course several underlying factors (e.g., fishing pressure, habitat modification), warmer sea surface temperatures are considered to be one of the main drivers of changes in fisheries distribution[70,71] (see Table 11). Smaller body sizes of commercial fish species in the North Sea have also been observed, most likely due to warmer sea surface temperatures, which decreases aerobic capacity and leads to the risk of oxygen deprivation[72]. In addition, changes in fish species spawning and migratory patterns have also been attributed to warmer sea surface temperatures, for example the observed earlier peak of the Atlantic cod spawning in the North and Irish Seas[73].

Satellite data can be combined with complex numerical ocean models and expert ecological knowledge to help predict the effects of climate change on marine biodiversity and future fisheries catch potential. For example, a project from the University of British Columbia called Sea Around Us projected changes in global catch potential for over 1000 species of exploited marine fish, using IPCC climate change scenarios from 2005 to 2055[70]. Results from the study show a large-scale redistribution of global catch potential, including an average decrease in catch potential of up to 40% in the tropics alongside an increase between 30-70% in high-latitude regions[70]. Studies like the Sea Around Us project can be used to help implement adaptive fisheries management plans that are responsive to these predicted changes in spatial distribution and fisheries productivity.

Short-term forecasts for fish spawning distributions and feeding habitats around the UK have previously been issued for blue whiting and bluefin tuna, respectively. Figure 29 shows the blue whiting spawning habitat forecast for March 2021, issued in January 2021 by the Danish Institute of Aquatic Resources (DTU Aqua). The forecast is based on an ecological niche model of blue whiting larvae distributions, and requires input datasets of oceanographic profiles, bathymetry and salinity, the latter of which has a large control over the spawning distribution[74]. Both in-situ and remote sensing observations of salinity were used within the model.

***Table 11. Example UK fisheries impacted by climate change and potential drivers of change***

| Fish species | Observed change | Potential driver |
|---|---|---|
| Atlantic mackerel | Change in distribution (shift westward and north-westward since mid-2000s); changes in fish quota allocation | Warmer sea surface temperatures; changes in food availability; density-dependent expansion of stock |
| Atlantic bluefin tuna | Change in distribution (increased frequency in UK fishing waters) | Warmer sea surface temperatures; response to expansion of mackerel (prey) |
| Atlantic cod and sole | Changes in timing of spawning and migration (spawning in North Sea and Irish Sea earlier in the year); changes in stock recruitment | Warmer sea surface temperatures; changes in ocean salinity; changes in distribution of phyto- and zooplankton |
| Plaice (flat fish) and herring | Changes in stock recruitment; smaller body size | Warmer sea surface temperatures; changes in ocean salinity; changes in distribution of phyto- and zooplankton |
| Haddock, whiting, Norway pout, sole and sprat | Smaller body size | Warmer sea surface temperatures (leading to lack of oxygen) |
| Cephalopods (squid, cuttlefish and octopus) | Change in distribution (increased frequency in UK waters) | Warmer sea surface temperatures |

At present, most fisheries quotas are based on historical fishing patterns and allocations[75]. However, as many fisheries have experienced changes in spawning and migratory patterns, these historical patterns and allocations are often no longer accurate or valid. Monitoring and forecasting shifts in fisheries distribution due to climate change and other factors is therefore crucial for adaptive management purposes, allowing governmental and regulatory bodies to set flexible quotas based on the most up-to-date information on the current and anticipated future distribution.

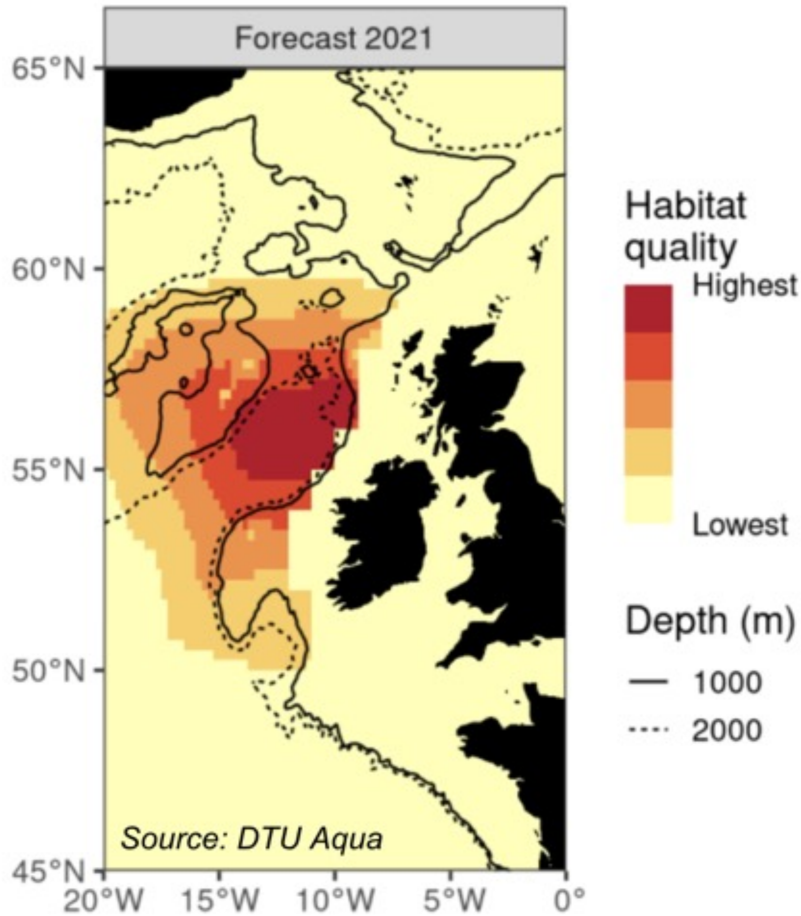



***Figure 29. Blue whiting spawning habitat forecast for March 2021***

# 9. Summary and Recommendations

This report provides an overview of satellite technology opportunities for the Scottish fishing industry, considering technologies which would be useful for a range of industry stakeholders, including fishers, policy makers and regulators, and markets and buyers.

Both earth observation and communications satellites are explored, with the former providing near-real time information about the marine environment such as sea surface temperature, salinity, phytoplankton concentration, bathymetry and wind and surface roughness. Many of these environmental parameters influence where a particular fish species can reproduce and live, with sea surface temperature, phytoplankton concentration and salinity particularly important factors for predicting fisheries habitat. These parameters are measured from space on a daily or near-daily basis globally with spatial resolutions ranging from 300 m to 40 km. Finer spatial resolution data is also available, with revisit time reduced to between 3 to 16 days.

Information on environmental parameters would be of interest to fishers for locating optimal fishing grounds to reduce catch effort and increase efficiency, or for avoiding bycatch. Several commercial products for predicting fish presence are already available, for example the CATSAT system and Mazu SportFishing app. These products use near-real time satellite-derived oceanographic data and marine weather information to support smarter, safer and faster fishing. Information on fish habitat is also used to avoid areas with protected or choke species, effectively reducing bycatch. Existing apps (e.g., the BATmap pilot application) use word of mouth for identifying hotspots of these species; to further advance this system, satellite data could be used alongside local knowledge to predict hotspots before they're reported by other fishers.

Advances in satellite technology have also progressed towards measuring air pollution from fishing vessels, previously measured using in-lab engine tests, on-ship sensors and plume tracking from aircraft. Marine debris from fishing activity (e.g., ghostnets and other discarded fishing gear) can also be seen from space, with floating masses of debris visible in very high resolution satellite imagery with a ground footprint between 30 to 50 cm. Measuring and monitoring air pollution and marine debris using satellites would likely be of interest to policy makers and regulators.

High resolution earth observation satellites can also be used to monitor IUU fishing, currently undertaken using a combination of AIS and VMS data and in-person monitoring both at sea and via aircraft. Both optical and radar satellite data can be used to identify fishing vessels at sea, even if the vessels have turned off AIS and/or VMS signaling. Very high resolution imagery (i.e., between 0.3 to 5 m) can clearly identify small and large vessels, with moderately high resolution imagery with a ground footprint of ~10 m picking up vessels longer than 15 m. The sub-meter resolution imagery is commercially available and can be tasked for a specific area of interest; however this comes with a significant increase in cost and would be more suitable for infrequent spot checks rather than long-term monitoring programmes.

The main benefit of using earth observation satellite data is the opportunity for regular, repeated observations at a global scale or specific area of interest at a finer scale. Limitations of satellite data include the potential for required expert interpretation and/or processing, the limitations introduced by cloud cover for optical imagery, and the trade-off between spatial resolution and cost, with higher resolution imagery increasingly more expensive. In addition, users typically have little control over which satellites are in orbit at any time; however, the increasing popularity of small satellite clusters for environmental monitoring and communications has made small satellite systems more affordable, providing the option to launch a Scottish fishery specific satellite.

Communications satellites, most commonly radio-frequency satellites, can also be used to monitor IUU fishing, picking up faint radar signals from devices used on-ship for navigation and collision-avoidance. A cluster of radio-frequency satellites can pinpoint a vessel's location with an accuracy between 200 to 3000 m. HawkEye 360, an American geospatial analytics company, has recently released an online platform called Mission Space, which uses AI algorithms to identify vessel behaviour from radio-frequency data.

AI and machine learning can also be used alongside traditional fisheries monitoring systems like AIS and VMS. Machine learning algorithms are already being used by organisations like Global Fishing Watch to automatically identify and map possible commercial fishing vessels based on changes in vessel speed and direction derived from AIS data. AI is also used to analyse AIS and VMS data to identify vessel properties like length and engine power, as well as the type of fishing gear being used. In addition, on-ship camera footage can be assessed using machine learning much more rapidly than using humans for inspection, by training algorithms to identify fish species, size and count along conveyor belts on-board larger fishing vessels. The use of on-board cameras to electronically monitor a fisher's catch and discard would greatly improve the traceability of the catch, providing evidence that the correct fish were legally caught in the right place and time using the correct equipment. It would also give buyers greater confidence in the sustainability of Scottish fishing, leading to an increase in fisheries profit.

Satellite-derived data and more traditional fisheries monitoring systems like AIS and VMS can be combined alongside data from patrolling vessels and aircraft into an integrated fisheries monitoring, control and surveillance (MCS) system, most useful for fisheries regulators. A potential workflow for such a system could start by using satellite data to identify vessels in a region of interest, comparing this against AIS and VMS data to identify any unknown vessels and using AI to determine if any of the vessels are demonstrating fishing behaviours. If nearby, very high resolution satellites can then be tasked to fly over the area to confirm IUU fishing activity, or an aircraft or UAV flyover could be performed instead.

Moving towards a fully digitalised, integrated fisheries management system would be beneficial for all fishing industry stakeholders. Near-real time information on environmental parameters communicated to fishers via a smartphone app or laptop can help increase catch efficiency and reduce fuel consumption. Using ship-to-shore and ship-to-satellite communication links, fishers can share information on position and catch electronically, reducing the current burden of paperwork and improving product traceability, which will increase buyer confidence. Using a digitalised system, catch could be sold in a virtual market before reaching port. Although setting up it will require a large amount of effort and cooperation from all industry stakeholders, once operational, a fully digitalised system would significantly enhance fisheries management in Scotland.

As identified through discussion with a Fisheries expert, one specific use-case for satellite technology within the Scottish fishing sector is through the creation of spatially-explicit annual maps of Scottish fishing activity. This aligns with the Scottish Government's *Fisheries Management Strategy* for 2020-2030, which identifies the need for increased spatial understanding of fisheries distribution to support decision making around fish stocks and sustainable levels of fishing. Fishing activity distribution maps can also help to resolve gear conflicts and to reduce the loss of fishing areas to other marine stakeholders (e.g., offshore wind farms).

The most up to date information on fishing intensity/pressure is from 2017, provided by OSPAR and based on collected VMS and logbook data for vessels over 12 m long. Satellite data provides an exciting opportunity to undertake updated fisheries distribution mapping through the use of machine learning with optical and radar imagery combined with available ship-based location data. Creation of annual fisheries distribution maps would be a significant undertaking not without its challenges, for example lack of available historical catch data and cloud cover issues with optical satellite imagery, as well as the expenses associated with obtaining high resolution satellite imagery. However, these maps are certainly achievable and would go a long way in supporting marine planning in Scotland, ensuring that our shared marine spaces are managed effectively and sustainably.

Table 12 summarises all of the satellite technology applications discussed above, detailing each application's importance to the industry and assumed applicability to stakeholders. A comparison is made between what is currently used by the industry and why satellite or remotely sensed data provides an improved option. Tentative next steps are also suggested, including contact information where relevant. In addition, contact information and links for various projects and platforms discussed throughout the report can be found in Appendix A.

*Table 12. Summary of satellite technology applications for Scottish fishing industry and next steps*

| Satellite technology use (*and importance*) | Interested stakeholder(s) | Current solution | Why satellites / remote sensing provides improved solution | Next steps |
|---|---|---|---|---|
| **Improved general understanding of spatial distribution of fisheries in Scottish waters** (*assisting in marine planning, gear conflict resolution and reduction/avoidance of loss of fishing grounds to other marine stakeholders)* | Fishers, policy makers and regulators | Fishing intensity/pressure data from 2017, provided by OSPAR and based on collected VMS and logbook data for vessels over 12m long, including beam trawlers, dredgers, demersal seines and otter trawlers. | Satellites can be used to create annual maps of the spatial distribution of Scottish fisheries, using a combination of satellite and non-satellite data with AI and machine learning. | **Space Intelligence** as Innovation Partner for RnD work into creation of annual fisheries distribution maps |
| **Locating optimal fishing grounds for commercial species and hotspots for protected/chock species** (*reduces catch effort, fuel, $CO_2$ emissions, time spent at sea and bycatch*) | Fishers - *small, in-shore fisheries and large pelagic trawlers* | Fishers currently use apps like MarineTraffic, WhatsApp (word of mouth and local knowledge) and BATmap to find good fishing places and avoid bycatch. | Satellites can provide near-real time widespread coverage of environmental parameters (e.g., phytoplankton, sea surface temp) to help fishers locate areas for fishing and avoidance; this can be combined with local knowledge to predict hotspots before they are reported by other fishers. | Commercial apps already exist for this purpose, including BATmap which was trialled with one fleet in Scottish waters.<br><br>Further patterns could be identified using machine learning. |
| **Live (near-real time) mapping of inshore vessel locations** (*prevent and police illegal fishing; protection of MPAs and EEZs*) | Policy makers and regulators | Regulators currently use AIS and VMS technology alongside ship and aircraft-based monitoring. | Radio-frequency (RF) satellites and other nanosatellites can locate inshore vessels, even with AIS switched off; can combine RF and other satellite data with AIS data and AI to learn, identify and predict vessel behaviour | **Spire Global UK Ltd** (Glasgow-based) provides vessel tracking services using AIS data as well as their own constellation of nanosatellites;<br>Dr. Hina Khan is a key contact (hina.khan@spire.com)<br><br>**HawkEye 360**<br>Mission Space Platform<br>Craig Erikson<br>(craig.erikson@he360.com) |

| | | | | |
|---|---|---|---|---|
| **Tracking air pollution from fishing vessels** (*quantify, mitigate and reduce air pollution from Scottish fishing industry*) | Policy makers and regulators | Air pollution from marine vessels is currently measured using in-lab engine tests, on-ship sensors and plume tracking from aircraft. | Satellites provide wider coverage and can measure pollutants from all vessels, not just those with on-ship sensors; high resolution nanosatellites are in development for measuring specific pollutants. | This technology is in development; current satellites measuring air pollutants (e.g., $CO_2$, $NO_x$) are not able to resolve emissions from individual vessels or fleets. |
| **Tracking marine debris** (*understand origin / distribution, remove current debris and prevent future debris*) | Policy makers and regulators | Marine debris is currently identified from land- and ship-based observations, or from aircraft and UAVs. | Satellites can measure spectral absorbance of debris, identifying different plastics by their unique spectral signatures. They also provide wider spatial coverage. | This technology is in development; there is no satellite specifically tasked for high resolution monitoring of marine debris. Upcoming launches of hyperspectral satellites are promising advances. |
| **Improved catch traceability and sustainability** (*ensure legality of catch - correct time, place and gear; increase buyer confidence of legality and sustainability)* | Fishers, policy makers, regulators and markets/buyers | Paper logbooks and Captain's and catch certificates are currently used for tracing purposes. | Satellites can be used as part of an electronic catch documentation and traceability (eCDT) system, reducing burden of paperwork for fishers; AI can be used to analyse on-ship camera footage of catch, reducing human effort. | USAID and SEAFDEC have developed an eCDT system for Asia-Pacific nations; a similar system could be adopted for Scotland.<br><br>Technology contacts include:<br>**Pointrek** (*at-sea capture*) Nirwan Harahap (nirwan@sisfo.net)<br><br>**Altermyth** (*landing*)<br>Dien Wong<br>(dienw@altermyth.com)<br><br>**MDPI** (*processing*)<br>Stephani Mangunsong<br>(stephani@mdpi.or.id) |

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# Appendix A

*Table A1. Links to projects discussed in main report with contact information (where available)*

| Project | Brief description | Relevant link(s) | Contact information (where available) |
|---|---|---|---|
| European Maritime Safety Agency (EMSA) remotely piloted aircraft system | Remotely piloted aircraft services in support of surveillance work by Member States | http://www.emsa.europa.eu/operational-scenarios.html | |
| HAPS4ESA | ESA programmes in 2017/2019 for using high altitude pseudo satellites (HAPS) for civilian purposes | https://business.esa.int/projects/haps4esa | **Airbus Defence & Space (UK)**<br>uasmarketing@airbus.com<br>mktg-space-systems@airbus.com |
| MethaneSAT | Development of small satellites to monitor methane concentration on weekly basis at 1km resolution | https://www.methanesat.org/ | |
| Spire Maritime service | Provides near-real time data on vessel location, including predictive modelling using AI for calculating vessel ETA and forecasted positions | https://spire.com/maritime/ | Dr. Hina Khan<br>*Project Coordinator*<br>hina.khan@spire.com |
| Global Fishing Watch online map | Mapping of vessels using AIS and VMS data to identity commercial fishing vessels based on changes in speed and direction | https://globalfishingwatch.org/map/ | Technical support<br>support@globalfishingwatch.org<br>Research program<br>research@globalfishingwatch.org |
| SMARTFISH H2020 | Uses AI and machine learning to develop high-tech systems for EU fishing sector (to improve catch efficiency and stock assessment) | http://smartfishh2020.eu/ | Bent Herrmann<br>*Project Coordinator*<br>bent.herrmann@sintef.no<br>+45 29617964 |
| HawkEye 360 Mission Space | Commercial platform for analysis of radio-frequency data to identify specific vessel behaviour | https://www.he360.com/products/mission-space-commercial-rf-analysis-platform/ | Craig Erikson<br>*Director of Commercial Sales*<br>craig.erikson@he360.com |

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|---|---|---|---|
| European Commission Joint Research Centre (JRC) Vessel Detection System | System using SAR data to identify presence of vessels, which is then cross-checked with AIS and AMS positioning data | https://github.com/ec-europa/sumo<br>https://ec.europa.eu/jrc/en/news/jrc-makes-its-ship-detection-software-open-source | Harm Greidanus (JRC-ISPRA)<br>harm.greidanus@ec.europa.eu |
| i-Fish North Sea | Feasibility study completed in 2013 for system providing integrated solutions and services to enhance sustainability of fisheries resources | https://business.esa.int/projects/ifish-north-sea | **Avanti Communications**<br>contact@avantiplc.com<br>**OLSPS Marine**<br>https://marine.olsps.com/contact/ |
| FISHSAT | Feasibility study for integrated satellite service for fishing support and safety; system that would use satellite-derived data and communication links to improve collaboration between fishers, markets and regulators | https://business.esa.int/projects/i-fishsat | **Avanti Communications**<br>contact@avantiplc.com<br>**SATOC**<br>info@satoc.eu<br>+44 (0)1663 747970<br>**flyby**<br>info@flyby.it |
| USAID SEAFDEC eCDT system | Electronic catch documentation and traceability system that uses mobile devices to record at-sea capture information and transmit data to cloud storage for use by various users along supply chain | https://www.seafdec-oceanspartnership.org/catch-documentation-and-traceability/ | **Pointrek** (*at-sea capture*)<br>Nirwan Harahap<br>(nirwan@sisfo.net)<br>**Altermyth** (*landing*)<br>Dien Wong<br>(dienw@altermyth.com)<br>**MDPI** (*processing*)<br>Stephani Mangunsong<br>(stephani@mdpi.or.id) |
| CATSAT | Commercial system providing fishers with accurate, near-real time oceanographic data and marine weather information | https://www.catsat.com/ | Headquarters<br>info@catsat.com<br>Fisheries Experts<br>oceanographer@catsat.com |

| | | | |
|---|---|---|---|
| Mazu SportFishing | Smartphone app providing maps of satellite-derived data (e.g., sea surface temperature, chlorophyll-a charts and altimetry data) | https://www.mazu-marine.com/sportfishing | |
| SusTunTech | Feasibility study aiming to reduce tuna fishing vessel emissions and fuel consumption by 25%; uses satellite data and AI to improve detection of tuna fisheries | https://www.sustuntech.eu/ | https://www.sustuntech.eu/contact/ |
| BATmap (By-catch Avoidance Tool) - currently in trial with one Scottish fleet | App to help fishers avoid high catches of protected or choke species, relying on fishers sharing real-time location information | https://info.batmap.co.uk/ | batmap@scottishfishermen.co.uk |
| DTU Aqua habitat forecasts | Short-term forecasts for fish spawning distributions and feeding habitats for blue whiting and bluefin tuna | https://fishforecasts.dtu.dk/ | Mark R Payne<br>mpay@aqua.dtu.dk<br>+45 35 88 34 22 |

Fisheries Innovation Scotland

FIS is a unique public-private collaboration between seafood industry experts, government and scientists to champion innovation in the Scottish fishing industry. Our Member Organisations include:

- marine scotland
- Scottish Natural Heritage / Dualchas Nàdair na h-Alba / nature.scot
- The Scottish Government / Riaghaltas na h-Alba
- Sainsbury's
- Young's Seafood Limited
- seafish
- M&S EST. 1884
- SFF Services Limited

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