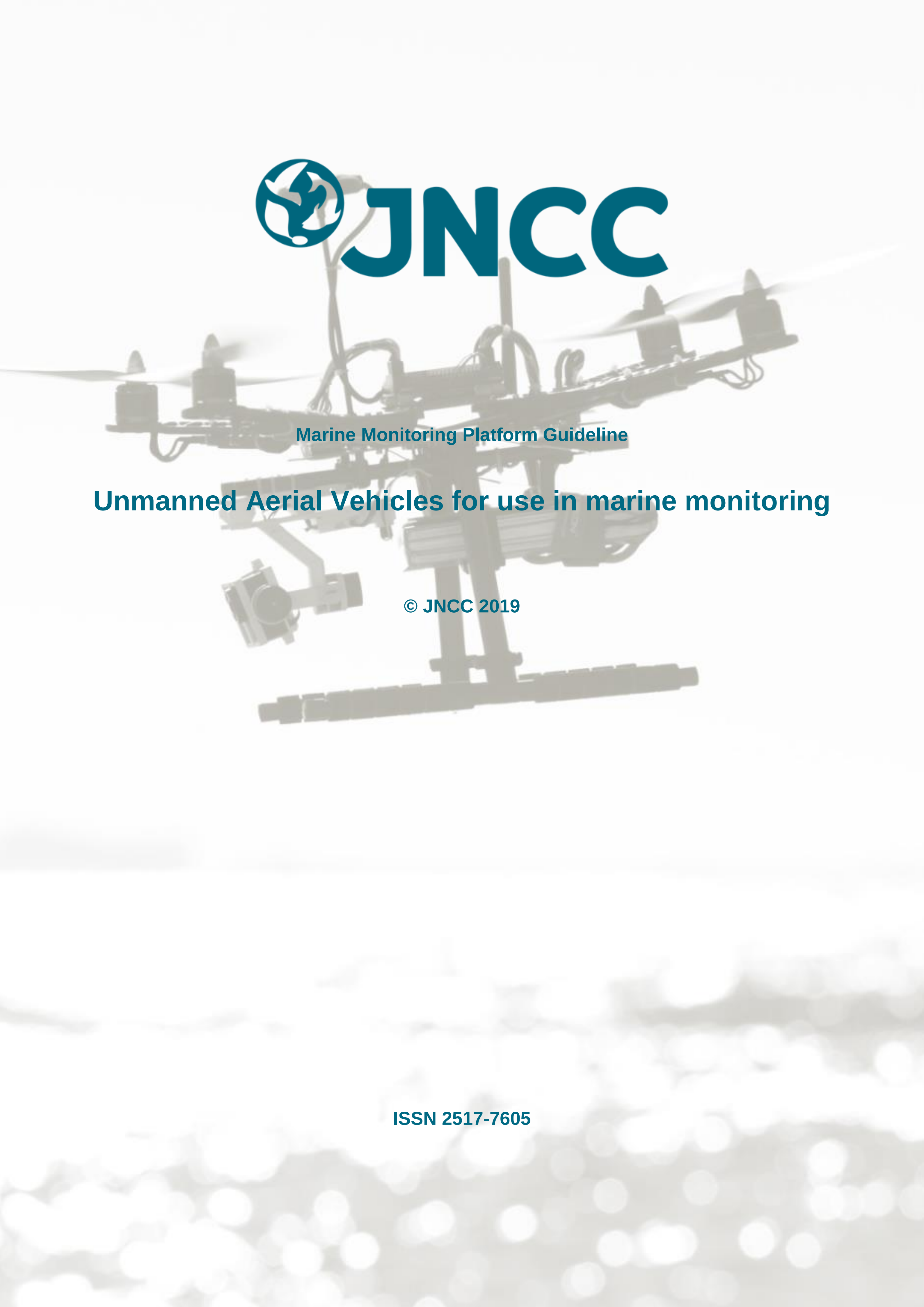

Marine Monitoring Platform Guideline

Unmanned Aerial Vehicles for use in marine monitoring

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Contents

Abbreviations

ANO	Air Navigation Order
AoS	Area of Search
ATC	Air Traffic Control
BVLoS	Beyond Visual Line of Sight
CAA	Civil Air Authority
CMOS	Complementary Metal-Oxide Semiconductor
DAC	Data Archive Centre
DEM	Digital Elevation Model
dGPS	Differential Global Positioning System
DSM	Digital Surface Model
DSLR	Digital Single-lens Reflex
DTM	Digital Terrain Model
EMODnet	European Marine Observation and Data Network
EUNIS	European University Information Systems
EVLoS	Extended Visual Line of Sight
GCP	Ground Control Point
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSD	Ground Sample Distance
HD	High Definition
IMU	Inertial Measurement Unit

IR	Infra-Red
LiDAR	Light Detection and Ranging
LoS	Line of Sight
MEDIN	Marine Environmental Data and Information Network
MTOM	Maximum Take-Off Mass
NMBAQC	North East Atlantic Marine Biological Analytical Quality Control
NOTAM	Notice to Airmen
NQE	National Qualified Entity
OS	Ordnance Survey
OSC	Operational Safety Case
PfCO	Permission for Commercial Operations
PPK	Post Processed Kinematic
RGB	Red, Green and Blue
RTK	Real Time Kinematic
SNCB	Statutory Nature Conservation Body
SfM	Structure from Motion
SUA	Small Unmanned Aircraft
TLS	Terrestrial Laser Scanner
UAV	Unmanned Aerial Vehicle
UHD	Ultra-High Definition
VRS	Virtual Reference Station
VTOL	Vertical Take Off and Landing

Overview

The term Unmanned Aerial Vehicle (UAV) can be used to describe a diverse range of aircraft that are piloted from the ground. The aim of this document is to detail UAVs that are used routinely for marine benthic monitoring, less than 20kg in mass, and termed Small Unmanned Aircraft (SUA). In this context, they can be characterised as small, battery-powered aircraft, typically capable of flying for a short period of less than an hour under the control of a pilot within line of sight of the aircraft. The UAV is a versatile platform that can be fitted with a wide range of sensors to capture data at known locations during survey flights. For example, fitting of imaging sensors (cameras) allows the system to acquire geo-referenced photographs and videos. These data can then be downloaded and processed by the end-user to create a range of outputs in order to meet survey objectives.

The use of UAVs for marine monitoring is still in its infancy but the potential applications are significant and include monitoring physical processes such as erosion and accretion, mapping and detecting change in habitat extent, distribution and condition, and producing species population counts. UAVs offer a rapid, repeatable method of capturing imagery (red, green and blue (RGB), multispectral, hyperspectral, thermal, *etc*.) at high spatial resolution over a range of coastal environments including cliffs, sand dunes, saltmarshes, rocky shores and seagrass beds. The use of UAVs can overcome some of the challenges presented by these habitats, which are often highly dynamic, spatially complex and difficult or dangerous to access on foot. Survey flights can be planned to take advantage of low spring tides or deployed rapidly in response to events such as mass strandings or pollution incidents. Flight paths can be pre-programmed and repeated to generate multi-temporal datasets for change detection analysis, although radiometric correction must be applied to optical data to enable comparison between dates. UAVs can also be used to map and monitor benthic habitats in shallow coastal waters, but this requires clear, calm water with minimal sun glint and is therefore more suited to tropical than temperate habitats.

The purpose of these procedural guidelines is to provide general guidance on the use of UAV systems for marine monitoring, with a focus on habitats. It is intended primarily for survey managers who are considering the use of UAVs to meet their survey objectives. Included in this guideline is information on equipment, survey planning and estimated costs (see Table 1 for an overview, and Annex 2 for more details), applicable at the time of writing. It should be noted that the use of UAVs is an exponentially growing field. Methods, techniques and legislation will rapidly change, and so it is recommended that users read this document in conjunction with contemporary research to capture any future requirements within the field. Organisations such as the Remote Sensing and Photogrammetry Society (RSPSoc), the Defra Earth Observation Centre of Excellence, the UK Earth Observation Framework (UKEoF) and Shared Agency Regulatory Evidence Programme (ShARE) are leading in UAV knowledge and application and can provide further information for users who intend to pursue UAVs as a viable monitoring option.

Table 1. Overview of two broad classes of UAV, multi-rotor UAVs and fixed-wing UAVs (L-R; image of the DJI Phantom 4 Pro V2.0, and the senseFly eBee Real-Time Kinematic / Post-Processed Kinematic (RTK/PPK), obtained from the respective manufacturers' websites). The capabilities presented are those applicable at the time of writing and these are likely to be surpassed as the technologies described are developed.

	Multi-rotor UAVs	**Fixed-wing UAVs**
	 Image: Copyright free for commercial use, no attribution required	 Image: Copyright 2019, Carcinus Ltd
Sampling platform	Multi-rotor UAVs are rotorcraft with more than two rotors.	Fixed-wing UAVs resemble a more traditional piloted aircraft.
Scale of operation	Small (~0.25km^2) to broad (<2km^2).	Broad (>0.25km^2) to large (<5km^2) – typically greater than multi-rotor.
Habitat-type	All intertidal and coastal habitats.	
Substratum-type	Any, including hard (bedrock, boulder), mobile (cobble, pebble, gravel, sand, mud) and biogenic reef.	
Target community	Broad benthic habitat, geomorphological change, localised population studies, population counts and behaviour of pelagic fauna (seabirds to whales) and of basking fauna (e.g. pinnipeds), where in an intertidal or coastal setting.	Broad benthic habitat, population counts of basking fauna (e.g. pinnipeds), and geomorphological change. Behavioural monitoring and monitoring of pelagic fauna not normally possible unless in a nearshore coastal environment due to take-off and landing requirements and lack of video capability.
Samples produced	Still RGB images and video, still multispectral imagery, hyperspectral imagery, Light Detection and Ranging (LiDAR), and thermal imagery.	Still RGB images, still multispectral imagery, and thermal imagery.
Data products	Georeferenced orthomosaic, point cloud, mesh surface and 3D model, Digital Surface, Elevation and Terrain Models (DSM/DEM/DTM), and reflectance maps (see Table 4 for more details).	
Cost per day	c.£500	c.£1000
Advantages	• Ability to survey areas that may be difficult to access, unsafe to survey using other methods or sensitive to disturbance (e.g. trampling under foot); • Surveys often more cost effective than other methodologies; • A high degree of repeatability, provided that radiometric correction is applied to optical imagery to ensure consistency between surveys; • Multiple data products can be produced from a single survey; and • Potentially reduced number of personnel required.	
Limitations	• Weather conditions may restrict usage, particularly during periods of high winds and precipitation (most UAVs are not waterproof);	

	• Usage for commercial purposes (including by charities, government agencies and clubs) strictly controlled under various UK legislation; • Compliance with Civil Aviation Authority (CAA) Air Navigation Order (ANO) required at all times, as such Company and pilot(s) must hold Permission for Commercial Operations (PfCO) from CAA - requiring training, continued upkeep of competency and insurance; • Airspace restrictions and considerations at many locations - need for consultation with Air Traffic Control (ATC); • Congested areas (traffic, buildings and persons outside of your control) - need for specific Operational Safety Case (OSC) to be agreed with CAA; • Data protection regulations - need for consideration of privacy of members of public who may be captured within imagery; • Potential for risk to / endangerment of third parties and property; • Take-off and landing areas must be permitted for use and segregated from public access; • Visual Line of Sight (VLoS) between pilot and UAV required at all times without additional permissions in place (Extended Visual Line of Sight (EVLoS) or Beyond Visual Line of Sight (BVLoS)); • Restrictions through local bylaws (examples include, The National Trust and New Forest Council) and policies of Statutory Nature Conservation Bodies (SNCBs); • Difficulty in terms of data processing if surveying visually homogeneous areas, or large volumes of high-resolution data; • Can cause disturbance to and changes in behaviour of wildlife; and • Ground-truthing of data still often required.

Logistics

A. Survey Planning

A detailed account of all survey requirements is listed in Annex 1. Included below are the key points to consider when planning a UAV survey.

Legal requirements

It is critical that Annex 1 is read and understood before contemplating a UAV survey due to the strict legal requirements in the UK. UAVs are more heavily regulated in the UK than other forms of marine monitoring platform.

Those wishing to conduct UAV surveys must adhere to the best and most up-to-date professional practice and legislative guidance. As part of the legal requirements for conducting UAV surveys for commercial reasons, the company or individual pilot (if trading as an individual) must develop and agree an Operations Manual with the CAA; all operations must be conducted in accordance with their Operations Manual. Training required for commercial UAV operations is undertaken at a National Qualified Entity (NQE) approved by the CAA, which undertakes the assessment of pilots on their behalf. As part of the training, the NQE typically advises the organisation or individual who wishes to conduct commercial UAV operations with the development of their in-house Operations Manual. An Operations Manual is specific to each organisation (or trading individual), covering the types of UAVs the Operator intends to fly, the type of flight operations and procedures that will be followed. The Operations Manual is a key document submitted to the CAA which in turn informs the conditions of the Permission for Commercial Operations (PfCO), which also must be adhered to for all operations[1].

The methodologies described within these Guidelines should be seen as generic and precedence should always be given to the terms of the Operator's Operations Manual, PfCO and current legislation.

Survey preparation and permissions

The specifics of pre-flight preparation should be detailed within each Operator's Operations Manual. A pre-flight desk study must be conducted prior to the flight. Additional permissions may need to be sought, such as a separate Operating Safety Case from the CAA or permissions from the relevant ATC, land owners and SNCBs. There is a legal requirement for land owner permission for take-off and landing. Failure to consider relevant legal and operational safety considerations will render any flight plan illegal, and the survey may not be undertaken unless it is approved.

Access and Privacy

Due care and consideration must be made in regard to third parties that may be encountered during the survey. It is normal best practice in areas where the public have general access that appropriate signage is placed and that landing and take-off areas are cordoned off to prevent risk to members of the public. The pilot must not be distracted from the safe operation of the aircraft throughout the survey, as such it is advisable that additional personnel are present to act as look outs and to handle any unexpected incursions into the survey area.

The issue of disturbance

Care must be exercised when flying and/or entering a study area particularly if that area is known for nesting, roosting or loafing birds or basking wildlife – whether they be the focus of the data collection or not. Whilst there is concern regarding the disturbance of wildlife by recreational UAV operations (Rebolo-Ifrán *et al*. 2019), a number of recent studies into scientific drone use have

[1] Further details on these requirements can be found at: https://www.caa.co.uk/Commercial-industry/Aircraft/Unmanned-aircraft/Small-drones/Permissions-and-exemptions-for-commercial-work-involving-small-drones/

indicated that disturbance and behavioural change in many animals is relatively minimal. The results of these studies range from animals becoming habituated to the presence of UAVs (Chabot *et al*. 2015) to disturbances only being caused by UAVs operating at relatively low altitudes (Vas *et al*. 2015; Raith *et al*. 2018; Rush *et al*. 2018), while in some cases UAV surveillance produces less disturbance than climbing or inspecting sites by more traditional means (Weissensteiner *et al*. 2015; Borrelle & Fletcher 2017). Nonetheless, it should be acknowledged that each site, and each species, might be different and advice should be sought from the relevant SNCBs. UAV operators must also understand that their very presence on or nearby a site might create disturbance, regardless of UAV use or not.

Survey flight design and operation

The mission plan decided upon by the Operator will depend upon the subject of the survey and the type and specification of UAV platform that is being used. Clearly the different types of platform perform in markedly different ways, such that they can only be used under certain circumstances or for producing certain data products.

Part of the planning will involve deciding between automated or manual flight. Almost all UAVs can be manually piloted, as this is often a failsafe requirement of the CAA. Manual control is normally used for observational surveys that do not aim to create joined up images with consistent overlap or support more complex data outputs. This method is less suited to fixed-wing UAVs, which need to keep forward motion to stay airborne, and have more limited flexibility in terms of sensor payload. Most UAVs also have the option for automatic flight, for the purposes of ensuring accurate and repeatable surveys flown to a set flight plan. Automated flight plans are best designed in flight planning software, coded to work in conjunction with the specific UAV on-board flight controller, and are uploaded prior to flight. In most cases, flight plans are designed based on the required Ground Sample Distance (GSD) and overlap of images, endurance of the aircraft and environmental conditions on site. The GSD is a measure of the distance between pixel centres measured on the ground. The GSD will be higher or lower dependent on the chosen resolution and focal length of imaging sensors and the flight height of the platform.

Constraints to consider

There are many constraints to consider during UAV surveys. Specific consideration should be given to the constraints of the chosen payload, in particular, the intended GSD and how to obtain it. Platform constraints must be considered from a safety and data quality perspective. Environmental conditions also need to be considered when planning the logistics of the survey. Weather conditions may affect the feasibility of conducting the survey; notably, most UAVs are not waterproof and cannot be safely operated during periods of precipitation. Furthermore, high winds may limit safe flight and flight duration. Terrain needs to be more carefully considered in regard to take-off and landing sites for fixed-wing UAVs. In addition, the effects of environmental factors on data quality need to be considered.

It should be noted that any new survey method can produce spurious changes in the measured variable, e.g. habitat extent or population size, *etc*. This issue is not just specific to UAVs but needs to be taken into consideration and weighed against any advantages or limitations to the accuracy and precision of the survey requirements and subsequent outputs.

B. Equipment

UAV Platforms and Classes

Under UK legislation, the CAA currently split UAVs into separate categories according to their weight (or mass) as follows:

- **<20kg - Small Unmanned Aircraft** - this class covers all types of UAV that are typically used for ecological monitoring and include traditional remotely controlled model aeroplanes, helicopters or gliders, fixed-wing drones and multi-rotor drones. These UAVs vary in design and each have their own benefits and limitations (see Tables 1 and 2 for more details);

- Fixed-wing systems begin at <1m wingspan and can extend to a few metres. Propulsion is provided by a single or multiple fixed or variable pitch propellers and lift is generated from airflow over the wing;
- Multi-rotor systems vary widely in overall size and mass; however, most have an upper size limit of about <1.5m in Pitch Circle Diameter (PCD). Multi-rotor UAVs normally use fixed-pitch propellers, with the control of vehicle motion achieved by varying the relative speed of each motor.

- **>20kg to 150kg - Light Unmanned Aircraft** - covering the larger and potentially more complex types of unmanned aircraft and large model aircraft. The CAA states that they are subject to all aspects of UK aviation law, although it is accepted that they will be exempt from many of the requirements. Approval to operate a UAV of this class is normally subject to the submission and approval of a Safety Case to the CAA.

- **>150kg** - unmanned aircraft within this class are normally subject to the same level of regulatory approval requirement as would be used for traditional manned aircraft.

For the purposes of this procedural guidance document, focus is placed exclusively on the <20kg class of UAVs as defined by the CAA. This document does not aim to provide guidance for UAVs >20kg.

UAVs of <20kg are considered to be the most feasible (cost-wise) and practical class for marine ecological monitoring and represents the type of UAV that is most commonly used for conducting scientific surveys within marine and coastal environments (Anderson and Gaston, 2013). Within this class, differing rules apply to UAVs under 7kg and those above 7kg; these are outlined within the ANO (2016), and are dependent upon the airspace designation, such that specific permission may be required by ATC.

Table 2. Further detail on the two primary designs of UAV, mode of operation and advantages / limitations of each design. Images copyright of Carcinus Ltd.

UAV type	Multi-rotor UAVs	Fixed-wing UAVs
Sampling platform	 Image: Copyright 2019, Carcinus Ltd Multi-rotor UAVs are available in a range of configurations[2] with a single or sometime multiple rotos per arm, including: • Bicopter (rarely used); • Tricopter; • Quadcopter; • Pentacopter (rarely used); • Hexacopter; and • Octocopter.	 Image: Copyright 2019, Carcinus Ltd Fixed-wing UAVs are available in a range of configurations[3], including: • Swept / delta wing; • Monoplane; • Biplane; and • Fixed-wing Vertical Take Off and Landing (VTOL).

[2] Image - Example of a hexacopter multi-rotor UAV.
[3] Image - Example of a swept / delta type fixed-wing UAV.

Definition and capability	**Small, <7kg – MTOM**	Intended for short <30mins surveys, carrying a wide variety of small payloads and offering manual manoeuvrability and payload operation (e.g. orientation and shutter control).	Almost all fixed-wing UAVs suitable for marine ecological monitoring fall into this size class. Suitable for longer flight time ~1 hour and larger survey areas, where payload orientation control is not required.
	Medium, 7 to 20kg MTOM	Intended for short <30mins surveys, carrying heavier payloads (such as large frame digital single-lens reflex (DSLR) cameras or LiDAR) and offering greater manoeuvrability and manual payload operation.	These are generally used for longer flights, with greater range, and so are governed by EVLoS or BVLoS protocols. At the time of writing, commercially available UAVs in this category are limited.
	Large, >20kg MTOM	Not typically used for ecological monitoring as described within these Procedural Guidelines due to cost and additional regulatory requirements, see https://www.caa.co.uk/Commercial-industry/Aircraft/Unmanned-aircraft/Large-unmanned-aircraft/ for further information.	
Legal requirements		All UAV pilots and their organisation to hold appropriate training and PfCO granted by the CAA, as well as appropriate insurances. Restrictions apply as defined within the ANO, with specific attention to be placed on: • Article 241 - endangering safety of any person or property; • Article 94 - small unmanned aircraft requirements; • Article 94A – small unmanned aircraft; height restrictions on flights; • Article 94B – small unmanned aircraft: restrictions on flights over or near aerodromes; and • Article 95 - small unmanned surveillance aircraft.	
Deployment method		VTOL	Manual launch by hand / throw or bungee propulsion (e.g. catapult system) and in some cases, VTOL.
Examples**		• DJI - Phantom (3, 4 and 4 RTK), Inspire 2, Matrice 600 & 210, Mavic 2 • Yuneec – H520 • SwellPro – V3 Auto and Splashdrone	• Sensefly – eBee • QuestUAV – Datahawk • Wingtra – WingtraOne • Mavinci Sirius Pro • Trimble UX5
Advantages		• VTOL means less restriction on take-off and landing area; • Less expensive than fixed-wing; • More flexibility to use a range of payloads; • Airframes often fold for compact storage and easier transport; • Ability to hover and rotate to acquire observations at one location over time; • Greater manoeuvrability, i.e. can fly in any direction and rapidly adjust altitude;	• Longer flight times compared to multi-rotor, typically up to 1 hour; • Multiple sensor options; • Faster data capture for orthomosaics than multi-rotor; • Airframes typically lightweight; • Most can glide safely to ground in case of motor / system failure, decreasing risk; • Quiet operation, minimal noise; and • Lower pilot skill required for simple surveys / platforms.

	• More easily controlled manually; • Multiple motor failure redundancy on some configurations; and • Three axis camera / sensor gimbal for stabilisation and targeting.	
Limitations	• Short flight times, typically <30mins; • No glide ratio, direct descent in event of catastrophic motor or system failure; • Heavier airframe than comparable fixed-wing; • Generally, greater pilot skill required compared to fixed-wing; and • Generally noisier than fixed-wing.	• Commercial options are generally more expensive relative to multi-rotor; • Most need clear area for launch and landing, although VTOL capability now available in some models; • Usually limited payload, as sensors often designed to fit airframe; • Not very useful for single targeted image acquisition; • Typically, cumbersome to carry; • Sensors typically only stabilised in 2 axes (or none); • Camera / sensor orientation normally limited to nadir (straight down) or near-nadir configuration; and • Typically, limited in ability to fly in manual mode.

** The platforms above are examples only. The authors do not recommend or have affiliation to any manufacturer; the intention being to guide the surveyor into making the correct choice of platform not specific models.

UAV accessories and other equipment

Many UAVs offer the ability to carry a range of payloads and the ability to swap as required by the surveyor. The most commonly used payload in an environmental monitoring UAV survey is an imaging sensor or camera. Several options exist for camera selection: it can come as standard with the UAV, be selected by the user from the UAV manufacturer's list or be provided by the user. Choosing a UAV without a camera system may allow for greater flexibility, however integrated systems ensure compatibility between equipment and software components and typically come with dedicated support services. A brief overview of the camera and other payload options for different types and models of UAV are provided in Table 3 along with information about integration and control. It is important that the requirements of the payload system are considered when selecting a UAV for marine monitoring purposes.

Equally important is consideration of how the payload integrates with the airframe, specifically how it can be controlled and orientated as required during flight operations. For some survey operations it will be important to maintain the direction of payload irrespective of airframe movement; this is achieved by mounting the payload on a gimbal. Gimbals can stabilise the payload against movements in one, two or three axes. Payload stabilisation typically differs between multi-rotor and fixed-wing UAVs, with the former offering a greater range of options and 3-axis stabilisation.

Table 3. Brief outline of example payloads with different UAV systems.

UAV type	Multi-rotor	Fixed-wing
Imaging / Video	Wide range of imaging payloads, including: • Video (HD and UHD); • RGB cameras; • Multi-spectral sensors; and • Hyper-spectral sensors. With a wide range of resolutions, lens configurations and sensor sizes.	Wide range of imaging payloads, including: • RGB cameras; and • Multi-spectral sensors. With a wide range of resolutions, lens configurations and sensor sizes.
Other (non-exhaustive list)	• Thermal / Infra-Red (IR) sensors; • LiDAR; • Chemical; • Radiation; • Magnetometer; and • Sample collector e.g. robotic arm and water sampler.	• Thermal / IR sensors.
Payload integration	Depending upon model, offers both manufacturers integrated and flexible (user chosen) payloads.	Tend to be limited to integrated payloads from manufacturers selection.
Payload stabilisation (maintenance of the direction of payload irrespective of airframe movement)	Full range: • Fixed, nadir only; • Single-axis gimbal (rarely used); • Two-axis gimbal (roll and pitch); and • Three-axis gimbal (roll, pitch and yaw).	Normally more limited than multi-rotor, with: • Fixed nadir only; • Single-axis gimbal (roll or pitch); and • Two-axis gimbal (roll and pitch) Three-axis gimbals are not normally available for fixed-wing UAVs in the <20kg MTOM class.

C. Navigation and positioning

Most UAVs have an on-board Global Navigation Satellite System (GNSS) capability. The on-board GNSS system(s) is used for both navigation of the aircraft and in most cases geotagging of images acquired during the survey. Further details of on-board navigation and positioning systems are provided in Annex 1.

Positional Accuracy

To further enhance the positional accuracy of UAV generated data products, and to serve as a robust measure of survey accuracy, Ground Control Points (GCPs) are often required. GCPs are typically large marked targets spaced strategically throughout the Area of Search (AoS), that can be easily identifiable within UAV images / data. GCPs should be surveyed in to accurately record the position at the centre of the target; it is normal to use survey grade RTK or PPK GNSS systems to achieve this. When used correctly, GCPs significantly improve the absolute accuracy by helping to ensure that images and data products are accurately georeferenced to actual coordinates within the required datum. By absolute accuracy we mean the extent to which a point on the orthomosiac or in the point cloud corresponds to a point in the real world in a fixed co-ordinate system. This is important when precision mapping and measurements are required. There is an ongoing debate about the numbers of GCP to be used in a project. These range from Pix4D (a photogrammetric software provider) suggesting a rule of thumb of ‘more than three, but between 5 or 6 is good’, to studies that vary from 1 GCP per $200m^2$ (Oniga *et al*. 2018) to >3 GCP for every 100 pictures taken (Sanz-Ablanedo *et al*. 2018).

The complexity of a landscape, and the relative textural homogeneity of the surface should determine the numbers of GCP used in each project. GCP should be distributed evenly throughout the survey area and represent the range of ground elevations present. It is also suggested that some consideration be given to placing GCP towards the edges of survey areas where camera distortion (sometimes called 'doming') may be exacerbated (Hackney & Clayton 2015). The position of each GCP is used during data processing to assist with georeferencing images and in further processing such as photogrammetry and structure from motion (SfM) and can be used to check the accuracy of outputs against conventional ground-based survey methods. In projects where only relative accuracy is required, GCP are less crucial. By relative accuracy we mean the extent to which a point on the orthomosiac or point cloud is accurate relative to all other points on the same map, or in the same point cloud.

The accuracy required for a given survey will depend on the nature of the survey, aims and objectives and anticipated end products. The potential need to augment positional accuracy with GCPs must be factored into the survey design and cost; surveying-in GCPs can be expensive, time consuming and operationally difficult in inaccessible areas, and they can be subject to tampering by animals and members of the public. However, it should be noted that where an UAV survey is conducted to high accuracy standards, multiple data products can be derived, often at a later date, where the initial need was not identified at the outset. Accuracy of data products can rarely be enhanced retrospectively. Relative accuracy is usually quoted in terms of a multiple of the Ground Sample Distance (GSD) of a project. Most systems suggest accuracies of 2 GSD in the horizontal, and 3 GSD in the vertical. Absolute accuracy is dependent upon using GCPs or PPK/in flight RTK correction or not. Here accuracies can be obtained that are in the order of centimetres in the horizontal and vertical (with GCP/RTK/PPK) and metres when not using them.

Like GCPs, Check Points (CPs) can also be surveyed by ground based RTK/PPK GNSS prior to flights. Checkpoints (CPs) can then be used to assess and quantify the absolute accuracy of derived data products as well as for Quality Assurance (QA) purposes to identify potential errors in data collection or processing.

D. Personnel Requirements

An Accountable Manager is required within any organisation holding a PfCO, even if they happen to be the same person as the UAV Operator. The Accountable Manager is the designated person who has overall responsibility to the Regulatory Authority (in the UK, the CAA) in terms of the safe and legal operations of the UAV on their organisation's behalf. They are responsible for maintaining and enforcing an effective management system, which ensures that all activities are carried out in accordance with the applicable regulations. They are directly accountable for UAV safety in their organisation.

All UAV pilots must be trained and recommended by an NQE and hold a PfCO from the CAA either through the organisation they work for or personally, if the work is of a commercial nature. The PfCO is reapplied for on a yearly basis. As from November 2019, there will also be a yearly competency requirement per pilot, as well as registration of the UAV. It is the pilot's responsibility that all survey operations are conducted in accordance with their Operations Manual, legislation and the advice of their Accountable Manager and that they are planned and executed in a safe manner.

It is normal best practice that the pilot is accompanied during field surveys by additional personnel to act as a lookout for hazards, to assist the pilot by preventing distraction through the approach of members of the public and to respond in the case of emergencies such as incapacitation of the pilot. Personnel undertaking this role may require training. An Operator's Operations Manual should detail the contexts when single or multi-person surveys are appropriate. Additional staff may also be required when the use of GCPs is required.

E. Risk assessments and health and safety requirements

All UAV survey operations must be subject to robust risk assessment processes and follow all health and safety requirements outlined within the Operations Manual and any current legislation. A full risk assessment must be carried out prior to each and every flight, in accordance with the Operations Manual and Health and Safety at Work guidance. Such processes should not only focus on the Operator's personnel but also any other airspace uses, third party persons, vehicles and infrastructure. It is beyond the scope of this document to advise further on these matters.

Operational guidelines

A. Preparation

The Operations Manual should have been developed in accordance with the best and most up-to-date professional practice and legislative guidance with regards to UAV surveys. It is imperative that the UAV survey team is familiar with the requirements of the survey set out in the Operations Manual and PfCO. The Operator / pilot must be fully aware of the modes of failsafe for the UAV in question and consider how they will affect safety during the planned mission, further details on UAV failsafes are provided in Annex 1.

B. Deployment

One of the defining differences between multi-rotor and fixed-wing UAV (excluding VTOL capable models) platforms is the way in which they launch and land. Consideration of the space required by each platform, the legal issues and the safety issues that arise from these needs must be carried out as part of the risk assessment process. For all platforms, the separation requirements between operations and third-party persons, vehicles and infrastructure specified within the Operator's PfCO (or approved OSC) must be adhered to.

Multi-rotor
Multi-rotor UAVs have VTOL. In this case, the space required for safe operations at these crucial stages of a mission can be notably less than with fixed-wing systems which often need a clear runway. The Operator will need to ensure a clear vertical space above the UAV in which to take off safely.

Fixed-wing
Fixed-wing systems require more space to take off and land, with the exception of specific UAVs such as the Wingtra, which has VTOL. Different fixed-wing systems have differing strategies for take-off. Some launch from the hand (e.g. the Sensefly eBee), whilst some launch via a catapult mechanism (e.g. the Trimble UX5). In both cases space is required in front of the Operator so that the UAV may gradually pick up speed and ascend to the appropriate height above ground level.

C. Sampling Operation

The mission plan decided upon by the Operator will depend upon the subject of the survey and the type of platform that is being used (see Logistics (Survey Planning)).

It must be decided during the pre-planning phase whether the flight will be conducted manually or through an automatic flight plan. If the latter option has been chosen, at the start of the mission, the UAV can be programmed to follow the pre-set flight plan and progress can normally be monitored from a ground control station.

Under UK regulations, the pilot must maintain direct communications with the UAV at all times and be in a position to take manual control for whatever reason, i.e. true autonomous flight is not currently allowed within the UK. Observational surveys, which just rely on the capturing of single or multiple but not necessarily joined images, may fly a slightly different pattern. Here manual control is more common and so the flight lines may just extend out to the AoS. Such flights are not suited to the use of fixed-wing systems.

D. Recovery (Landing and Post-Flight)

Landing is also dependent upon the type of platform being used. With both multi-rotor and fixed-wing platforms, the general procedure is that UAVs will return to a home point which is fixed before launch, and from which they can begin a landing sequence. With multi-rotor systems this is usually a case of flying above the home point and then slowly descending to the ground vertically. For fixed-wing systems landing can take place as a glide, so that the UAV flies out away from the Operator or home waypoint and then gradually descends towards the landing area defined within the flight control software. As such, the space required for safely landing a fixed-wing UAV is greater. Some systems (e.g. Quest Datahawk) can deploy a parachute. It is best industry practice to ensure that an alternative safe landing area is identified during flight planning in case the primary landing area becomes compromised e.g. through the approach of third parties.

Post flight checks are undertaken in the field, and then imagery is downloaded either in the field or back at base. In the case of photogrammetric work, the images are usually georeferenced within the flight control software. Where permissions from ATC (and other authorities) have been required, it is normally a requirement to notify them of the completion of operations.

Seagrass image collection, mosaicing and analysis

Duffy *et al.* (2018) used a small (i.e. <7kg) 3D Robotics Solo multi-rotor drone custom-mounted with a consumer grade camera (Ricoh GR II) to capture detailed imagery data of intertidal seagrass (*Zostera noltii*) meadows at two sites in Pembrokeshire, Wales. At each site an area of ~2500m^2 was surveyed using the 'lawnmower' method (running parallel lines along the length of the survey area in alternating directions). The use of an autopilot system, open-source firmware and flight planning software allowed for complete control of the flight to ensure optimal data outputs. Flights were conducted at 15m altitude and a speed of 2m/s, resulting in a GSD of 4.31mm. Images were captured at set intervals, as calculated using the flight planning software, to ensure optimal image overlap (~70% front and side overlap) for high quality orthomosiacs.

The survey successfully captured total of ~200 usable images at each site, during flights of <11 minutes. The most accurate estimates of seagrass coverage were 1110m^2 and 555m^2 for the two bays. Other features such as macroalgae, shells and mounds were identifiable and enumerable using the survey method, but also using a coarser GSD. Duffy *et al*. (2017) present a thorough comparison of three methods of image classification and their relative accuracy when ground-truthed against traditional methods, though this is beyond the scope of these guidelines.

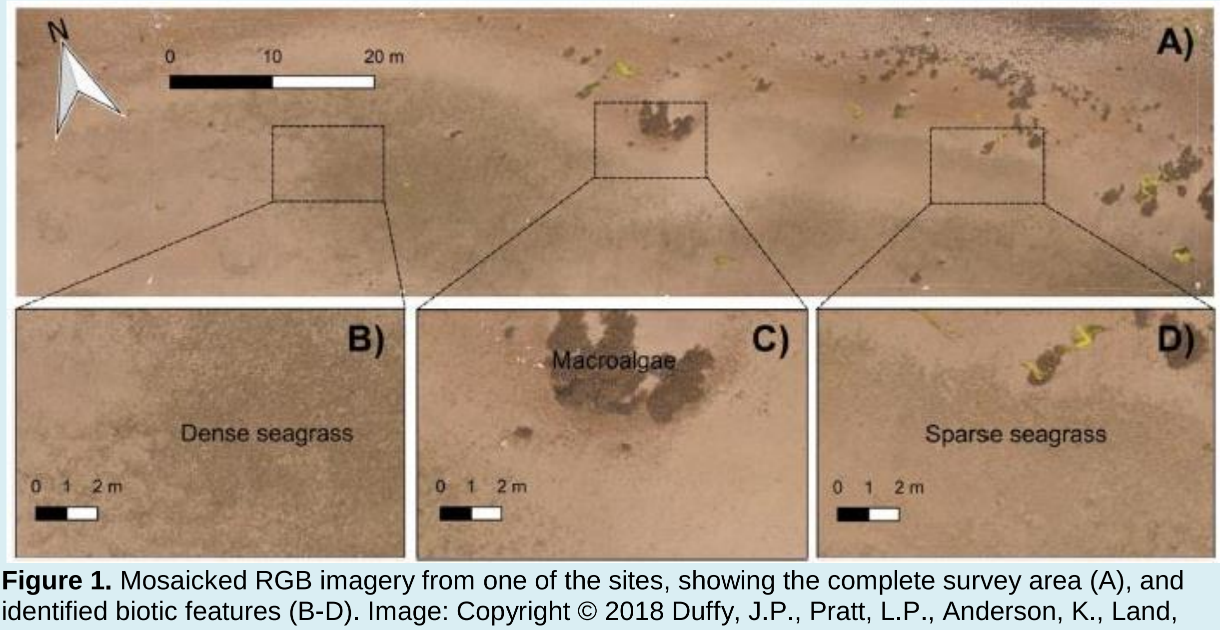

Figure 1. Mosaicked RGB imagery from one of the sites, showing the complete survey area (A), and identified biotic features (B-D). Image: Copyright © 2018 Duffy, J.P., Pratt, L.P., Anderson, K., Land, P.E. and Shutler, J.D. Published in Estuarine, Coastal and Shelf Science, under CC BY 4.0 licence.

E. Stowage

The transportation and stowage requirements differ between platforms and manufacturers. Some UAVs can be disassembled into smaller component parts for storage and transportation, whilst others cannot. Particular attention should be paid to batteries; most UAVs operate on lithium polymer batteries, which have specified storage, handling and operational requirements. The transportation, storage and maintenance requirements should be detailed in the Operations Manual and adhere to manufacturers recommendations.

Data products

A UAV can be fitted with a range of payloads to collect data for the purposes of marine monitoring (see Table 3). The different types of data products which can be produced using these systems and equipment are outlined below in Table 4. Various commercial and free software packages and websites exist which enable users to generate these products from their UAV imagery. These generally offer an easy-to-use graphic interface, but some offer extremely limited levels of user control, while others enable users to define processing parameters such as levels of compression of source imagery and removal of outlier points.

Table 4. Typical data products from UAV surveys

Data Product	Description
Orthomosaic	Individual images are reconstructed into a larger integrated image and then orthorectified (i.e. perspective is taken out of the resulting image). This eliminates measurement error from optical aberrations. Colour balancing is applied to create a seamless product.
Reflectance map	Radiometric corrections are applied to correct for factors including sun angle, solar irradiance and camera parameters to produce an image in which the value of each pixel faithfully indicates the reflectance of the object. No colour balancing is applied.
Point Cloud	A 3D surface of points that comes from SfM algorithms sometimes coloured in accordance with spectral data from the images. Useful for identifying variations in height and structure.
Mesh Surface and 3D model	A solid surface based upon triangulation between the points in the point cloud. Often textured with information from the images taken. Useful for presentation purposes, as well as obtaining volume calculations and a sense of elevation change and vertical structure.
Digital Surface Model (DSM) / Digital Terrain Model (DTM) / Digital Elevation Model (DEM)	DSM are the 2D representation of 3D models, which are useful for inputting into GIS analysis. DTM are enhancements of the DSM, using a range of algorithms to measure a given elevation (DEM) or removing surface features to obtain a ‘bare earth’ model (DTM). These are useful for understanding underlying surface features, sometimes hidden by vegetation. Note, however, that the ONLY true data captured by UAV is DSM data, DEM and DTM are inferred through computation. Non-LiDAR sensors cannot measure true distance to ground through vegetation.
Reflectance images	Depending upon wavelengths of light measured, different reflectance images can be generated and interrogated.
Thermal images or video	Non-radiometric cameras capture an RGB image that uses relative temperature differences to highlight hotspots or coldspots. Radiometric cameras capture a value for every pixel that can be

	converted to a temperature. Overlapping radiometric images can be combined to create an orthomosaic.
Other products	Non-imagery sensors (e.g. radiometers) can also be fitted in order to collect other environmental data. This can be used to build up a spatial picture of these other variables, and so include these in analyses to investigate any spatial relationships with the data from the imagery alone (Anderson *et al.* 2015).

Data management

Post processing, biological, environmental and acoustic data records should be appropriately archived. In the UK, the Marine Environmental Data and Information Network (MEDIN) promotes sharing of and improved access to marine data. To that end, MEDIN coordinates a network of Data Archive Centres (DACs) to secure long-term management of data, improve access through a central metadata portal and provide common standards[4] (Figure 2). The MEDIN helpdesk can provide advice to data managers pre-and post-survey on metadata, as well as which DAC(s) are the most appropriate to use. The MEDIN helpdesk will also triage data to assess quality, ease of processing and ingestion. Appropriate data archived to MEDIN is shared among other relevant DACs. It is also automatically uploaded to a variety of other databases, including the European Marine Observation and Data Network (EMODnet).

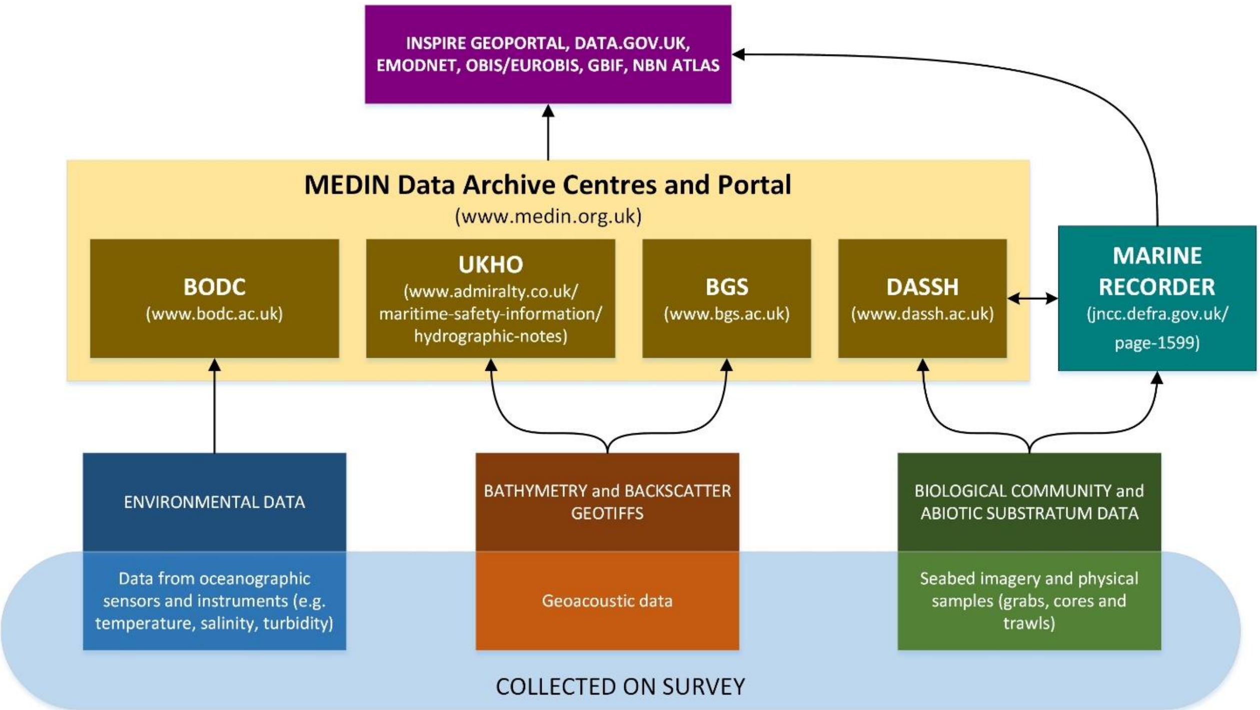

Figure 2. Diagram showing a simplified flow for marine data in the UK, from collection on survey to storage in MEDIN data archive centres, Marine Recorder and other databases as indicated.
MEDIN = Marine Environmental Data and Information Network; BODC = British Oceanographic Data Centre; UKHO = United Kingdom Hydrographic Office; BGS = British Geological Survey; DASSH = Data Archive for Species and Seabed Habitats; EMODNET = European Marine Observation and Data Network; OBIS = Ocean Biogeographic Information System; EUROBIS = European Node of the international Ocean Biogeographic Information System; GBIF = Global Biodiversity Information Facility; NBN Atlas = National Biodiversity Network Atlas.

[4] MEDIN data guidelines: http://www.oceannet.org/marine_data_standards/medin_data_guidelines.html

Interpretation guidelines

A key advantage of UAV surveys over more traditional walkover surveys for habitat monitoring is that they can cost-effectively cover a larger AoS, showing whole features at a time, compared to transects or point-sampling (Medcalf *et al.* 2014). This enables delineation of habitat boundaries and consideration of detailed changes in the extent and distribution of features of interest.

Coastal habitat mapping using a small UAV

Ventura, D., Bonifazi, A., Gravina, M.F. and Ardizzone, G.D., 2017. Unmanned Aerial Systems (UASs) for Environmental Monitoring: A Review with Applications in Coastal Habitats. In Aerial Robots-Aerodynamics, Control and Applications. InTechOpen.

A small quadcoptor (Quanum Nova CX-20) was used to map coastal habitats along the temperate Mediterranean coast in two case studies by Ventura *et al.* (2017). In these studies, the authors used easily available methods, including an inexpensive drone, commercial camera (GoPro Hero 3), handheld Global Positioning System (GPS), autopilot system developed by the online community, open-source mission planner, and easy-to-use non-specialist photogrammetric software.

Figure 3. Image: Copyright © 2017 Ventura, D., Bonifazi, A., Gravina, M.F. and Ardizzone, G.D. Published in Aerial Robots-Aerodynamics, Contol and Applications, InTechOpen, under CC BY 3.0 licence. Available from: http://dx.doi.org/10.5772/intechopen.69598

The first study compared use of imagery data from UAV and satellites for mapping the upper limit of seagrass *Posidonia oceanica* meadows. They found that, by using fine-scale UAV images, a more accurate assessment of dead ‘matte’ seagrass was possible than with satellite imagery. Their UAV survey of a 2ha bay took 6 minutes, during which 184 images were collected. A desirable 75% image overlap was obtained using a photo interval of 2s, medium field of view, and flight speed of 5 to 7ms^{-1}. The flight altitude was 30m, achieving a GSD of 2.5cm.

The second study mapped the distribution of juvenile white seabream *Diplodus sargus* using underwater visual census (UVC) and then characterised the relative substrate types in high density (i.e. nursery) areas from images taken during two UAV flights (of similar flight parameters to the case study above). Image analysis was undertaken using Maximum Likelihood Classification algorithms and manual editing. The habitat did not allow for GCPs, so the on-board GPS was used, in addition to geo-registration of the final orthomosaics.

Where orthomosaics and other photogrammetrically derived data products are required, images will ideally be collected with a sufficient overlap, as determined during the flight planning stage. These overlapping images can then be processed using relevant software to form an orthomosaic derived from images that cover the AoS. Ideally, data are georeferenced and calibrated against known GCPs positioned and surveyed in within the AoS prior to the UAV survey to enhance absolute accuracy.

There are no specific UK guidelines currently available for the interpretation of imagery collected with UAVs (see 'Quality assurance measures' section for more details). However, there are other relevant guidelines for interpretation of aerial imagery and for the classification of the habitats that UAVs are most likely to be surveying. For example, the Marine Monitoring Method Finder[5] collates a wide range of monitoring guidelines and procedures, some of which cover aspects of data interpretation relevant to imagery collected by UAVs. Medcalf *et al*. (2014) contains a relevant example of UAV use for the surveillance of terrestrial and freshwater habitats of conservation importance.

Guisado-Pintado E, Jackson D, Rogers D (2018). 3D mapping efficacy of a drone and terrestrial laser scanner over a temperate beach-dune zone. Geomorphology, 6612.

Coastal environments are subject to significant alteration and generation of landforms over relatively short periods. Guisado-Pintado *et al*. (2018) developed a means of measuring beach-dune morphology quickly and over large areas using two techniques – Structure from Motion (SfM) from UAV derived imagery and Terrestrial Laser Scanning (TLS). Data acquired were compared to baseline differential GPS (dGPS) data to assess the value, effectiveness, and limitations of each technique. Issues such as accuracy, resolution and differences of DEMs and relative performance over variations in terrain types were examined.

The study was conducted on the northwest coast of Northern Ireland. A total of 27 TLS scan locations were established over the ~8000m^2 area and scanned using a Faro Focus 3D X330 single return laser scanner with overlap, resulting in coverage of 11,520m^2. Six reference spheres were surveyed-in using RTK dGPS for later georeferencing. Post-processing comprised scan registration, model georeferencing, data filtering, vegetation correction and the generation of a DEM. Faro Scene software was used.

Surveys were conducted using an eBee fixed-wing UAV with an automatic gridded flight plan generated using eMotion software. An onboard 18.2MP RGB camera was used to acquire overlapping images with a GSD of 2.75cm. Data was acquired from a fixed altitude of 115m with a 70% forward and 80% lateral overlap of images, with all images collected off-nadir. A total of ten GCPs were placed throughout the survey area and were RTK dGPS fixed. Post-processing was undertaken using Pix4D software to perform georeferencing and vegetation correction and to generate a DSM and DEM. Differences in the DEMs generated from each technique were compared.

To facilitate the separation of bare earth and vegetation canopy, a series of representative 2m x 2m quadrats were evaluated by taking GPS field-measurements at ground level. The study identified that sensor performance is highly dependent on terrain, with factors including undulation, slope and degree of vegetation cover influencing data quality. The use of TLS produced better results over flatter topography with limited vegetated areas than for areas of more complex landforms. The SfM from UAV-derived imagery performed well over differing terrains, however relatively flat, featureless areas resulted in poor quality data - such areas included sandy beaches and dense vegetation. The speed of data acquisition was significantly faster when using UAV-derived imagery, with acquisition 30x faster than a TLS.

[5] Marine Monitoring Method Finder: http://jncc.defra.gov.uk/page-7171

Most habitat monitoring surveys aim to identify substrate, taxonomic, and / or condition information from the imagery and to enumerate taxa in some way. Data obtained by UAV surveys will vary considerably depending on the aims and objectives of the monitoring survey and the payload(s) that have been chosen to meet these needs. It is beyond the scope of these guidelines to address specific interpretation guidelines for all the data types collected by such a range of sensors.

However, a non-exhaustive list of potential applications of UAV-derived products is given in Table 5. For more detailed taxonomic analysis and condition assessment, the UAV survey may need to be supplemented with a walkover of the site.

Table 5. List (non-exhaustive) of potential marine monitoring applications for UAV-derived products.

Data Product	Potential marine monitoring applications
Video	• Enumeration of taxa, e.g. density, percentage coverage and frequency, utilising abundance scales from the Joint Nature Conservation Committee[6] or Marine Science Scotland[7]
Individual images	• Enumeration of taxa
Orthomosaic or Reflectance map	• Production of broadscale habitat or biotope maps through automated image analysis (object-based or pixel based). These may use standard classification systems, e.g. Marine Habitat Classification for Britain and Ireland v15.03[8] or the European Nature Information System (EUNIS)[9] • Habitat condition monitoring, e.g. measuring density of seagrass bed. • Site condition monitoring by generating metrics for habitat patch size, connectivity, *etc*. • Production of vegetation indices from reflectance map e.g. Normalised Difference Vegetation Index (NDVI) to aid predictive mapping or monitor condition of macroalgal communities. • Monitor anthropogenic impact and/or recovery, e.g. pollution incident, scars from bait digging or anchoring, litter. • Detect and monitor spread of non-native macroalgae. • Spatial measurements, e.g. habitat area, footprint of aquaculture structures.
3D topographic models (point clouds, Triangulated Irregular Network (TINs), Digital Surface Models (DSMs))	• Topographic complexity measurements, because topographic complexity is correlated with species richness and abundance in many marine and coastal environments. • Volume measurements, e.g. to monitor erosion and accretion. • Combination with orthomosaic or reflectance map to aid predictive habitat mapping. • Derivation of ancillary data such as slope, aspect, topographic position index to aid predictive habitat mapping.
Thermal imagery	• Enumeration of taxa, e.g. seals or ground-nesting birds. • Monitoring of anthropogenic impacts, e.g. warm water outflow.

[6] Connor and Hiscock, 1996
[7] Allan *et al*. 2012
[8] Connor *et al*. 2004
[9] http://eunis.eea.europa.eu/habitats-code-browser.jsp?expand=A#level_A

Parsons, M., Bratanov, D., Gaston, K. & Gonzalez, F. (2018). UAVs, Hyperspectral remote sensing, and machine learning revolutionizing reef monitoring. Sensors 2018, 18.

Parsons *et al*. (2018) used UAV imagery to monitor coral reefs and determine type and signs of bleaching. A methodology utilising a range of sensor technologies is described along with details of the UAV, flight operations, and data processing workflows.

Field surveys comprised both UAV-based and diver surveys. UAV surveys utilised a 6kg hexacopter UAV capable of carrying a maximum payload of 2kg. High resolution RGB and hyperspectral imagery were acquired using a 50.6 mega-pixel DSLR and Headwall Nano-Hyperspec sensor respectively over an area of 8 hectares. Sensor stabilisation was identified as important for performance during windy conditions and for obtaining consistent image overlap; this was achieved through the use of a 2-axis gimbal. A smaller quadcopter UAV was utilised for surveying a wider area (62.3Ha) of reef using a lower resolution RGB camera.

Aerial imagery was orthorectified and verified by comparison with underwater contours of reef. Hyperspectral data were processed for radiance using open source and proprietary software and a water correct reflectance dataset was derived. Depth correction by both ENVI and Agisoft Photoscan was undertaken for comparison. In-water survey data were matched to aerial imagery and the spectral signature for different corals with different levels of bleaching extracted. Coral bleaching indices were calculated for different species and degree of bleaching. Classification of aerial acquired data was then undertaken using ENVI and Scyven image analysis and support-vector machine learning software.

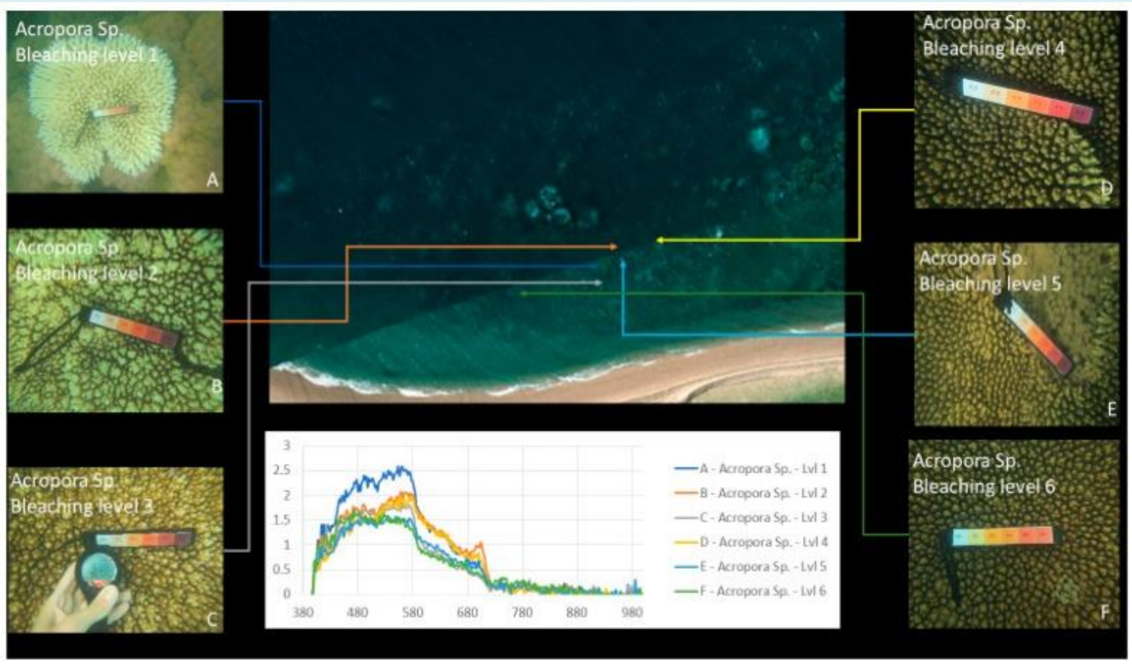

Figure 4. Image: Copyright © 2018 Parson, M., Bratanov, D., Gaston, K.J. & Gonzalez, F., published in Sensors, under CC BY 4.0 licence. Available from: https://doi.org/10.3390/s18072026

Limitations within the methodology are highlighted and detailed planning is recommended to ensure the overall feasibility and accuracy of final classification. Environmental conditions, such as turbidity, tidal conditions and weather are identified as having an effect on the overall quality of data outputs. The study demonstrates the potential for using UAV-derived hyperspectral imagery for the detection, grading / quantification and monitoring of coral bleaching over large areas and a range of coral species.

Quality assurance measures

At the time of writing, no quality assurance measures apply specifically to UAV operations. However, several factors influence the quality of raw and processed data and should therefore be communicated clearly to clients and end-users in the survey metadata and survey report. For collection and processing of optical imagery, these include:

Data collection

- Platform and sensor make and model, including accuracy of onboard GNSS
- Time of flight and weather conditions during flight
- Use of Ground Control Points (GCP) and/or check points (number used; distribution pattern; make, model and accuracy of GNSS equipment used to geolocate them)
- Use of downwelling light sensor and/or calibrated reflectance panel
- Flight plan:
    - ‘Lawnmower’ pattern or perpendicular intersecting flight lines
    - Altitude
    - Degree of forward and lateral image overlap
    - Image capture angle (nadir or oblique)

Data processing

- Radiometric correction method (if applicable)
- Software used for data processing.
- Data processing parameters, e.g. image compression and depth filtering.

There is no ‘best’ configuration of the above factors, this depends on the survey aim and desired outputs. For example, if the aim is to create an accurate 3D model of complex terrain, GCPs should be deployed and oblique as well as nadir imagery should be collected; if the aim is to monitor vegetation change through repeat surveys, radiometric calibration should be applied. If users are provided with information on these factors, they will be more able to evaluate whether the data are fit for purpose and to replicate the survey if required. To further help end-users evaluate the quality of processed data (orthomosaics and surface models), the following metrics should be provided:

- Mean Ground Sampling Distance (GSD)
- Number of calibrated and geolocated images
- Mean reprojection error
- Root mean square error (RMSE) of GCPs (if used)

There are established methods for evaluating the quality of interpreted outputs, usually through comparison with ‘ground truth’ data collected by direct observation or measurement. The most common way of evaluating habitat maps is to provide a confusion matrix with statistics for overall accuracy, user’s accuracy and producer’s accuracy (Medcalf *et al*. 2014), while the most common way of evaluating topographic models is to cite the horizontal and vertical RMSE. In both cases, the survey report must state when and how the ground truth data were collected, including the sampling protocol used (e.g. random, stratified random, systematic). Species counts derived from UAV imagery are often evaluated through comparison with manual counts made in the field and/or by comparing counts obtained from automated image analysis with those obtained from human interpretation of the same imagery. A recent study showed both manual and semi-automated bird counts derived from UAV imagery were more accurate and less variable than counts made by observers on the ground (Hodgson *et al*. 2018).

There is potential to use standard guidelines on quality assurance in marine biological monitoring where applicable (e.g. North East Atlantic Marine Biological Analytical Quality Control (NMBAQC) scheme; Turner *et al.* 2016). Furthermore, quality control systems for data products such as photogrammetry could be applied, though not specifically designed for biological data, e.g. the specific Accuracy Standards for Digital Orthophotos Class used in the US.

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Annex 1. Additional survey considerations

Legal Requirements
These guidelines aim to promote best professional practice and legislative requirements. As such, it is imperative that the potential UAV user conforms to a number of essential points:

1. The Air Navigation Order (2016), and most recent amendments to the CAP 722 (detailed in CAP 1763), state that any flight that is undertaken *"in return for remuneration or other valuable consideration*" should be performed under a PfCO. The PfCO is the legal authorisation to undertake UAV flights in UK airspace. Any organisation undertaking UAV work should hold a PfCO. Any organisation subcontracting UAV flights should ensure that subcontractors are PfCO holders[10]. Please note that the obligation of obtaining and maintaining a PfCO includes a range of organisations, outside of the more obvious commercial user e.g. governmental bodies, charities, educational establishments, and clubs.

2. The PfCO defines the limit of legal use of the UAV under flight. Ordinarily, it will dictate size and class of UAV, along with distance of flight away from the UAV Operator, and the maximum altitude of the aircraft above ground level. It will also outline minimum distances from people, structures and vessels, along with any permissions for flying over congested areas. Operators must not operate outside of the conditions set down in their PfCO.

3. At the same time, each PfCO is partially dependent upon the Operator's Operations Manual. In addition to the limitations of operation outlined in the PfCO, the Operator's Operations Manual outlines aircraft and ancillary maintenance requirements and measures needed to maintain pilot competency. The PfCO, and insurance, will only apply when flying is within the terms set down in the Operator's Operations Manual. Thus, the methodologies described within these Guidelines should be seen as generic and precedence is always given to the terms of the Operator's Operations Manual and PfCO and changes in legislation.

Preparation
The specifics of pre-flight preparation should be detailed within the Operator's Operations Manual. Generally speaking, before any flight is undertaken, the Operator is obliged to perform a pre-flight desk study. The study may involve considering aeronautical charts to access airspace designations, restrictions and hazards; Ordnance Survey maps for aerial obstructions such as power lines or areas where the public may be congregated, and access issues; Notice to Airmen (NOTAM) and weather forecasts. A separate Operating Safety Case, approved by the CAA may be required where flying at a distance from the Operator or other issues may result in a loss of visual contact with the UAV, flying closer to persons, vehicles and infrastructure not directly under the pilot's control or in certain other situations as outlined within legislation. Flights within certain airspace designations may also require permissions from the relevant ATC. Failure to consider relevant legal and operational safety considerations will render any flight plan illegal, and the survey may not be undertaken unless is approved.

Access and Privacy
Each flight plan must also consider approaches to accessing land for safe take-off and landing. Even if flown legally in accordance with the ANO, their Operations Manual, and with due consideration of airspace designations, flying over someone else's property may be considered trespassing if it reasonably 'interferes with another person's ordinary use and enjoyment of land and the structures upon it'. When using any surveillance aircraft, issues of identification of individuals and subsequent storage of personal data should be taken into consideration (although the 50m minimum separation distance outlined within CAP 722 is designed to stop this at present). It is generally seen as courteous, and good practice, if Operators inform the general public of aerial work within an area. Please note that permission to fly over somewhere is not the same as a permission to access other land for take-off, landing, or the retrieval of a crashed UAV. The law of

[10] The official CAA list can be accessed at https://bit.ly/1oFjQk7.

trespass prohibits such action without agreement of the landowner. Please note that some land-owning organisations, such as the National Trust, have a no-fly policy above their property, in accordance with an existing bylaw. It is the responsibility of the UAV Operator / pilot to ensure they are fully compliant with the relevant legal requirements at the time of flight.

Survey flight design
The mission plan decided upon by the Operator will depend upon the subject of the survey and the type of platform that is being used. Clearly the different types of platform perform in markedly different ways, such that they can only be used under certain circumstances.

For habitat assessment studies that require the creation of aerial imagery, it is important to fly the UAV in a way that optimises the performance of the aircraft yet delivers in terms of capturing images that perform well in photogrammetry algorithms.

For photogrammetry, it is important that overlap between images is sufficiently high and consistent. Too much overlap results in redundant data and increases processing time. Under certain circumstances (such as surfaces with low textural variety) it may also create difficulties within the photogrammetric process. Too little overlap has been shown to significantly reduce the relative and absolute accuracy of the final mosaic[11]; an important consideration if assessing spatial change. In order to ensure that overlap is consistent between images these parameters are often fixed within flight control software. It is recommended that such software is used when designing surveys where photogrammetric and surface elevation outputs are required, as well as where surveys may be compared with others to establish environmental change over time. As such, survey plans often follow the lawn mower pattern of forward and backward parallel flight lines.

Surveys that require the capturing of more oblique surfaces, such as cliff faces, will require a modification of both these survey designs. If using a fixed-wing system then there is some argument for flying two sets of lines, one that runs along the flight lines designed by the control software, followed by another set of lines at 90° to the original flight plan, thus giving a grid pattern. In multi-rotor systems[11], the camera on the UAV may be manipulated whilst in flight, so that the camera takes images off-nadir.

Constraints to consider
Specific consideration should be given to the constraints of the chosen payload. Things to consider include sensor resolution, shutter speed and interval (rolling shutters are common in Complementary Metal-Oxide Semiconductor (CMOS) sensors), stability and control of sensor payload. In particular, the resolution and focal length of imaging sensors combined with the flight height of the platform will dictate the GSD, a measure of the distance between pixel centres measured on the ground.

The constraints of any given platform need to be considered when planning the survey. Factors such as battery life and replaceability, flight speed, flight height, aircraft manoeuvrability, inbuilt GNSS (or lack thereof), failsafe mechanisms and potential indirect factors such as disturbance to the target species or other species all need to be considered.

Environmental conditions also need to be considered when planning the logistics of the survey. Weather conditions such as wind, visibility, cloud base, rapidly changing air pressure and precipitation can affect the safety and repeatability of operations. Most UAVs are not waterproof and cannot be safely operated during periods of precipitation. The likelihood of encountering adverse weather conditions will increase with distance from the coast and relative exposure of the survey site. Terrain needs to be more carefully considered in regard to take-off and landing sites for fixed-wing UAVs. In addition, many environmental factors affect data quality. Wind, precipitation, angle of the sun, cloud cover, water clarity, sea state/waves, can all affect the quality

[11] See https://support.pix4d.com/hc/en-us/articles/115002471546-Image-acquisition

of data acquired. Consideration should be given to the tidal state when surveying in intertidal areas, with surveys targeted over the low water period to maximise the extent of surveyed area.

Navigation and positioning
Most UAVs have on-board GNSS capability, with the ability to receive signals from at least one if not a combination of the United States GPS, Russian Glonass, European Galileo (when fully functional) and the Chinese BeiDou Navigation Satellite System constellations. In addition, some on-board GNSS can acquire data from regional Satellite-based Augmentation Systems (SBASs) such as the European Geostationary Navigation Overlay Service (EGNOS). The on-board GNSS system is used for both navigation of the aircraft and in most cases geotagging of images acquired during the survey (although some systems have separate GNSS for each function). On more advanced UAVs, multiple redundant GNSS systems are present, to mitigate failure and errors. In addition to the on-board GNSS, on-board inertial measurement units (IMUs) measure specific forces, angular rate, and sometimes the magnetic field associated with the aircraft, using a combination of accelerometers and gyroscopes, sometimes magnetometers. Some aircraft also utilise on-board barometer(s) to measure altitude changes. The flight controller combines information from these sources to maintain aircraft attitude (orientation in space), position, heading, speed, altitude and pitch/roll/yaw as per pilot input or in accordance with the pre-programmed flight plan.

A note on UAV failsafes
During flight planning, consideration must be given to UAV failsafes. Failsafe mechanisms and protocols fall into two categories, those that prevent the starting of a flight mission and those that are triggered during flights due to unsafe/abnormal conditions. The aim of both being to mitigate risk to aircraft, persons and property. Failsafe triggers differ by UAV platforms and manufacturer and can include but are not limited to the following:

- Loss of GNSS positioning;
- Loss of radio / telemetry communications links;
- Low or abnormal battery conditions;
- Motor failure;
- Geofencing:
    - UAV positioned within restricted airspace;
    - UAV outside of acceptable flight envelope in terms of position and altitude;
- Crash detection;
- Proximity sensor detections; and
- Kalman filter or other software errors.

The UAVs response to each failsafe trigger is dependent upon the aircraft, setup/configuration and manufacturer. Typical responses include:
- Prevention of arming of UAV or take-off;
- Return to Home - whereby the UAV returns to the launch site or other preconfigured location; and
- Landing - the UAV instigates a controlled automatic landing at or near its current location.

The Operator/pilot must be fully aware of the modes of failsafe for the UAV in question and consider how they will affect safety during the planned mission. Examples to consider include:

- Should the aircraft Return to Home - is the flight path between any failsafe trigger location and the home location clear, safe and legal?
- Landing - if flying over water, a landing in the water will result in significant damage or loss of aircraft;
- Motor failure - some aircraft can maintain attitude in the event of a single or multiple motor failures, others have no such redundancy; and
- Ability of the flight crew to ensure people are away from the emergency landing site.

Personnel requirements

UAV Operators may not have a background in environmental science and it is important that survey design is done in tandem with an 'informed client'. Similarly, unless they have knowledge of land survey protocols, it is suggested that a surveyor is consulted about the laying out and recording of GCPs and CPs.

Annex 2. Survey costs and time

The overview table for this procedural guideline (Table 6) provides estimated survey day rates. It is intended that these costs serve as an indicative guide only. For actual costs, a survey manager must always consult with organisations that hire UAVs and if required, pilot or plan monitoring surveys based on the most up to date information. This annex expands on the costs estimated in Table 1 to provide additional budgeting support to survey managers.

Survey costs are dependent upon the area covered, complexity of environment, need to use GCPs, variable aviation and conservation constraints, but assumes standard PfCO conditions.

When considering whether to purchase a UAV or hire a contractor to undertake the work, the frequency and longevity of use must be taken into consideration. UAV technology and legislation are changing rapidly, and the overheads associated with training, legal compliance, upgrades etc. could be significant. Investment in the purchase of a UAV and associated staff training is more likely to be cost-effective when the platform can be used regularly over multiple years.

Cost of survey (if hiring)

Equipment costs
Detailed below in Table 6 are the estimated equipment costs (at the time of writing) for hire of different UAV systems on a per day basis–. Whilst there is some variation in UAV price, this is lower for fixed-wing than multi-rotor UAV. The prices quoted for each UAV type are an average of the prices for common commercial systems. The cost range provided includes any UAV accessories that may be specific to the system and/or optional, but exclude costs associated with highly specialised/unique and custom-built payloads. Dependent on survey requirements, additional costs may be required relating to UAV batteries, ancillary equipment, the cost of PC with sufficient processing and graphics capacity and specific software/hardware options such as Trimble Catalyst, Agisoft Photoscan and DJI Terra.

Different methods of UAV positioning will incur different costs. GCPs can be placed over the survey area at known locations for georeferencing during post-processing. GPS correction technology such as Real Time Kinematic (RTK) may be a required to provide real-time corrected GPS data during the flight. RTK services require an extra equipment cost (Table 6) and may also require a Virtual Reference Station (VRS) licence at an additional *circa* £2,000 per year.

Personnel costs
Included in the personnel cost is pre-, during and post-survey costs for personnel time. As a minimum, one person must be present during the survey, the cost of which is reflected in the total cost of the survey. However, additional personnel may also be required, be it for adding in the GCPs, or as observers for keeping lookout, which would naturally increase the cost of the survey. Training and certification costs are not included to qualify people in UAV survey specialist roles (e.g. flight planning, safety audit, pilot, GCP management and sample processing). It is assumed that services that are contracted out will include trained and certified staff to carry out the service. Note that the table does not include the cost for personnel time from the organisation hiring the contractor.

Day rates for UAV survey specialist roles vary between £350-750 per person, depending on level of experience. Personnel experienced in UAV ecological survey techniques would likely be required for the specialised survey techniques described. These UAV techniques differ significantly from those provided for more simple UAV services such as real-estate or wedding image acquisition; therefore, day rates will likely be at the higher end of the range.

Table 6. Per day cost of equipment hire and personnel for UAV surveys (equipment includes basic RGB camera). Please note this is costing for basic equipment needs and additional costs may be incurred dependent on survey needs.

UAV type	**Multi-rotor**	**Fixed-wing**
Equipment hire (per day)	£100-200	£250-500
RTK rover (per day) (*optional*)	£250	
Pre-survey planning – flight plan, safety audit per survey (estimated one day)	£350-750	
During survey staff time (per day per person)	£350-750	
Post-survey sample processing (per day)	£250-500	
Total (per day)	£1,300-2,450	£1,800-3,500

Cost of survey (if purchasing)

Equipment costs

Outline cost estimates for platform purchase (in 2019) are shown below in Table 7. Not included are the range of optional payloads available, as these will be required on a survey-specific basis. Dependent on survey requirements, additional costs may be required relating to additional payloads (multispectral, hyperspectral and thermal cameras, LiDAR, 4K HD video and high specification DSLRs), UAV batteries, ancillary equipment, the cost of PC with sufficient processing and graphics capacity and specific software/hardware options such as Trimble Catalyst, Agisoft Photoscan and DJI Terra.

Personnel costs

Outline cost and time estimates for personnel costs and training (in 2019) are shown below in Table 7. For some aspects of the survey requirements, it is not possible to estimate a cost as it will depend on the day rate of the personnel; therefore, a proxy of estimated days has been included. The costs are broadly the same irrespective of the type of UAV to be used.

Staff time is not included in the cost per annum. The one-off cost is based on a single pilot.

Table 7. Estimated costs, and/or estimated days for successful completion (number of days shown in brackets), associated with conducting a UAV survey without using sub-contractors. A hyphen in place of an estimated cost signifies that there is not set cost associated with this item, as it would be broadly dependent on the rate of the individual(s) required. *Average cost of a two-day Ground Course and Exam.

Stage	**Item**	**Multi-rotor**	**Fixed-wing**
One-off upfront cost	**Equipment cost (including basic RGB camera (and video for the Multi-rotor))**	£1,500-10,000	£6,000->20,000
	Ground course per pilot*	£1200* (*2*)	
	Flight test per pilot	£500 (*1*)	
	Flight practice (Multi-rotor)	- (*5*)	

	Operations Manual preparation per organisation	- (*5*)	
	Operations Manual processing by CAA	£250 (*14*)	
	Photogrammetry software	£4000	
	Data processing training to minimum competency	- (*5*)	
Year on Year (recurring)	**Insurance**	£500-2,000	£1,300-1,500
	Flight practice as per Operations Manual per pilot per annum	- (*4*)	
	Revisit of Operations Manual	- (*1*)	
	Re-application for PfCO from CAA	£180	
	Small Unmanned Aircraft Operator	Not possible to quantify as depends on efficiency savings across the UAV programme. However, the operator will need to ensure drones are insured, pilots competent and flying in accordance to Ops Manual. They will also to be involved in investigating and potentially reporting on any near hits or incidents and equipment failures.	

Totals	£7,450-15,950 (one off) + *37 days* + £680-2,180 pa	£20,950-25,590 (one-off) + *37 days* + £1,480-1,680 pa

Data archiving

The costs of archiving data from UAV surveys is likely to be similar to archiving data from ROV and AUV surveys. Please see the Procedural Guidelines for these survey types for representative costs for data archiving.

Cost variability

Key factors that lead to cost variation between surveys include:

- Purchasing vs hiring equipment, personnel etc. for the survey.
- Complexity of operations, environment, and aerial coverage:
    - Planning requirements will be greater;
    - Increasing number of fly overs for greater temporal coverage;
    - Larger aerial coverage will need UAV with greater flight duration or multiple flights;
    - Complex environment will require more planning for take-off and landing; and
    - Complex data acquisition will require more advanced payloads and suitable support systems.
- Intended system for positional information system/drone mapping
    - Using GCPs will increase survey planning and personnel; and
    - RTK capability would require an additional rover and possibly a VRS licence.
- Sample processing post-survey will vary considerably depending on the type and amount of data collected.

Annex 3. Alternative options for surveying / sampling

As previously mentioned, new survey methods can produce spurious changes in the measured variable e.g. habitat extent or population size etc. This issue is not just specific to UAVs but needs to be taken into consideration and weighed against any advantages or limitations to the accuracy and precision of the survey requirements and subsequent outputs. A decision must be made as to whether UAVs are the correct platform and/or need to be used in conjunction with another method bearing in mind survey aims, costs and other factors. For example, a UAV may be used to conduct a broadscale survey of an intertidal habitat with a walkover survey used to provide species information and detail on habitat transitions. This Annex briefly outlines key advantages and limitations of other sampling platforms which may be used instead of, or in conjunction with, UAVs.

Walkover surveys
For intertidal and coastal habitats, a walkover survey can provide additional detail on species identity and substrate, either through direct observation or field sampling. This information can be analysed together with mosaics of aerial imagery to produce detailed biotope maps and carry out feature condition assessments.

Walkover surveys sample different attributes of benthic habitats to UAV surveys. UAV surveys are more suited to monitor broad physical structure, habitat extent and distribution, and some supporting processes. Walkover surveys provide detailed information on community composition, fine-scale structure (<10m^2), and characteristic benthic species.

UAV surveys can be employed in some areas where habitats are sensitive to trampling from walkover surveys. Alternatively, it might be possible to carry out walkover surveys in some areas where there are restrictions on UAV usage due to vulnerable bird species or flight restrictions.

Earth Observation/Remote Sensing Surveys
Remote sensing or Earth observation is the acquisition of information about features without coming into physical contact with those features. Active sensors such as LiDAR, radar or sonar emit a signal and capture the reflected response, while passive sensors such as cameras and thermal imagers capture energy reflected or radiated from the Earth's surface. UAVs, manned aerial vehicles and satellites are all types of remote sensing platform able to carry different sensors. Broadly speaking, there is a trade-off between spatial resolution and extent of coverage of these platforms, with satellites providing the greatest coverage at lowest spatial resolution, followed by manned aerial vehicles and finally UAVs providing the smallest coverage at the highest spatial resolution. The size and spatial complexity of the survey site will therefore be an important influencing factor, but other considerations which may influence choice of manned aircraft or satellites as alternative or complementary platforms to UAVs are discussed below.

Manned aerial vehicles
Manned aerial vehicles, such as small piloted aircraft and helicopters, are larger than UAVs and therefore able to carry heavier payloads, cover larger areas and are less restricted by adverse weather conditions such as wind and rain. Flights can be planned to coincide with low spring tides, but the greater costs involved make manned aircraft a less flexible option than UAVs for rapid deployment. Typically, payloads on UAVs are more limited than on manned aircraft, although the larger and more expensive UAVs may carry LiDAR or hyperspectral sensors.

Unlike satellite imagery, imagery collected by manned aircraft is not impacted by cloud cover and atmospheric distortion, although like UAV imagery it can be impacted by cloud shadows. Manned aircraft are subject to similar legislation to UAVs in the UK, but due to their greater altitude and lower resolution imagery they are not restricted from flying over congested areas or private property. Processed aerial imagery and LiDAR data collected by public sector bodies in the UK are often made freely available for re-use under the Open Government Licence. For example, aerial and LiDAR surveys of the English coast are undertaken at periods ranging from 6 months to 3 years to inform shoreline management plans and the data are made publicly available via the Channel Coast Observatory (https://www.channelcoast.org/).

Satellites

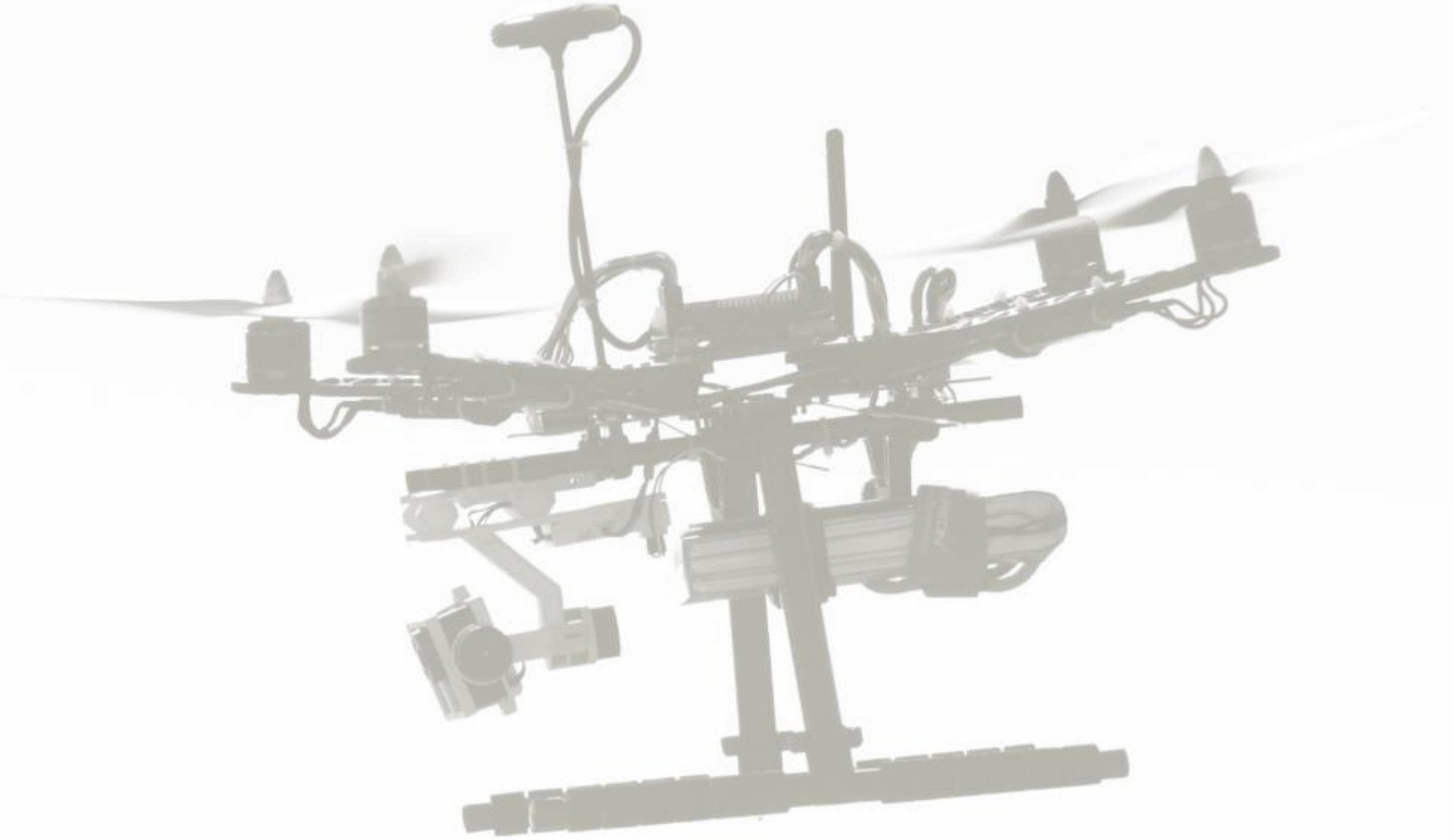
Satellite imagery is of lower spatial resolution than data collected by UAV or manned aircraft, but a single image can cover hundreds of square kilometres. Multispectral imagery is available free of charge at 10m resolution from the European Space Agency's Copernicus programme and at 30m resolution from NASA's LandSat missions, while commercial satellites such as WorldView-3 deliver multispectral imagery at up to 1.3m resolution. The longevity and high temporal resolution of satellite missions, with revisit times in the order of 1-16 days, make satellite imagery especially suitable for long-term monitoring and change detection. Optical imagery can be obscured by cloud, but the frequent revisit times increase chances of obtaining cloud-free imagery. Synthetic aperture radar (SAR) imagery is not affected by cloud cover. Processing satellite imagery to apply geometric, atmospheric and radiometric corrections requires expertise and specialist software, although the emerging provision of analysis-ready data should increase accessibility and uptake. The ability to produce standard processed outputs, such as reflectance maps, is a key benefit of satellite imagery, enabling like-for-like comparison of images from different dates.

Integration of survey methods

Each of the above platforms has advantages and limitations for marine and coastal monitoring. It is therefore beneficial to integrate ground survey methods and remote sensing data from multiple platforms into a combined, nested approach to deliver survey aims. Automated or semi-automated analysis of lower resolution imagery can highlight areas of interest for more detailed investigation using a UAV and help to target ground survey effort more effectively.

The broad coverage, rapid revisit time and standard processing methods of satellite imagery make it ideal for mapping and detecting change in the extent and distribution of habitats or features at coarse thematic and spatial scales over a wide area. Aerial imagery and LiDAR data collected on low spring tides can provide more detailed information on spatially complex areas such as rocky shores, in which features of interest may be smaller than single pixels in satellite imagery. UAVs provide the highest resolution remote sensing data, have the flexibility to be deployed rapidly in response to events such as storm surges and can cover areas which are difficult to access on foot.

Some UAV sensors have been designed to facilitate integration with satellite imagery, for example the Buzzard cameras which are compatible with the European Space Agency's Sentinel-2 satellites (https://buzzard.camera/). Ground survey will always be necessary to provide levels of taxonomic detail which cannot be obtained using even the highest resolution remote sensing imagery (Konar & Iken 2017; Murfitt *et al*. 2017) but can be targeted to priority areas identified through interpretation of remote sensing data. Field survey may also be used to generate ground truth data to train predictive models and validate outputs derived from remote sensing imagery.



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