Darwin Plus (DPLUS 065) Mapping the Falklands & South Georgia coastal margins for spatial planning (Coastal Mapping)

Long-term coastal habitat mapping & monitoring handbook. Examples based on work undertaken in the Falkland Islands & South Georgia.

Version Control Table

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Cover image top: *View across Yorke Bay minefield, Cape Pembroke, East Falkland.*

Cover image bottom: *Bird Island, South Georgia, as mapped by the DPLUS065 Coastal Habitat Mapping project.*

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1. Introduction

The coastal and inshore marine ecosystems (and their constituent habitats within) and resources of the Falklands and South Georgia are an important ecological, social and economic component of these islands natural capital. The coastal ecosystems around South Georgia for example, provide essential habitat for globally important populations of birds and marine mammals. Knowledge of these coastal environments is essential for their management, yet comprehensive island-wide broad-scale and fine-scale coastal habitat maps are lacking. Comprehensive habitat identification could fill a critical evidence gap and provide an important baseline from which to measure future change, habitat restoration success or human impact.

Habitat models and their visualization as maps are a fundamental element for understanding the distribution and extent of features across the landscape, and can facilitate better management practices, natural capital accounting, ecosystem service mapping, interpreting and targeting biodiversity monitoring and delivering policies. Both the Falkland Island Government (FIG) and the Government of South Georgia & the South Sandwich Islands (GSGSSI) have environmental policies and strategies where a baseline knowledge and understanding of the coastal margin assists related policy decisions.

The Darwin (DPLUS065) Coastal Habitat Mapping project, grant aided by the Darwin Initiative through UK Government funding, created the first broad-scale satellite-derived coastal (and wider terrestrial) habitat maps for both these UK Overseas Territories (UKOTs), using medium resolution satellite imagery alongside other spatial data and local expert knowledge. This three-year project brought together experts from SAERI, Oregon State University, Shallow Marine Surveys Group, the UK Joint Nature Conservation Committee, Falkland Islands Government and the Government of South Georgia & the South Sandwich Islands. Where there was significant uncertainty in these broad-scale maps, or in response to specific priorities from stakeholders, fine-scale habitat maps utilising very high-resolution satellite imagery (via the Digital Globe Foundation grant) or bespoke imagery captured using aerial drones were developed. Together, these broad and fine-scale habitat maps have created a baseline for the Falkland Islands and South Georgia, providing a sound basis for use in future planning, decision-making and monitoring. The project has also shown that this work is possible in even the most remote locations where traditional methods of mapping would normally be used.

An important part of the project has been the post-project legacy, ensuring that the tools and expertise are available in the UKOTs to update the broad-scale habitat maps, refresh aerial imagery datasets (through flying new drone mapping missions), and creating new fine-scale habitat maps. This handbook was created to provide an overview of the Earth Observation (EO) and subtidal mapping technologies used in the Coastal Habitat Mapping project. Earth Observation (EO) has been used extensively to provide a synoptic view of land use, cover and change at a variety of scales. New sensors are being developed and launched at an increasing rate, with some missions making data accessible through open source licensing; such as the Copernicus Programme's Sentinel data[1]. EO is a valuable resource when no other data are available but is most powerful when combined with field data and a

[1] Copernicus is an Earth Observation Programme headed by the European Commission (EC) in partnership with the European Space Agency (ESA). Copernicus provides a unified system through which vast amounts of data are fed into a range of thematic information services designed to benefit the environment, the way we live, humanitarian needs and support effective policy-making for a more sustainable future < https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview3

variety of other data sources to create products that provide critical information, particularly for evidence-based decision-making.

Note: While more traditional habitat survey and mapping methods using transects and quadrats may be more accurate at the fine-scale, this handbook focuses on rapid assessment methods using digital technology and GIS processing tools. However, transect/quadrat methods should still be used in ground-truthing protocols.

1.1. Why is Coastal Habitat Mapping so important; a Falkland Islands Government (FIG) perspective

The Falkland Islands is a UK Overseas Territory with a unique environment. Like many islands, due to its remoteness, the Falklands has knowledge gaps that are important to fill. Remote sensing and modelling offer a time and cost-effective solution to better understand and monitor the Falkland Islands environment. Developing a baseline of the coastal environment is important, and is currently lacking; the DPLUS065 Coastal Habitat Mapping project provides mapping resources that includes an island-wide broad-scale habitat map; this can be used as a baseline from which future habitat changes can be monitored. Broad-scale habitat models can be re-run on the current Sentinel satellite imagery dataset, using the cloud-based toolbox developed by the project. This manual contains examples of what is achievable using remote sensing in the Falkland Islands, which have helped decision-makers improve management practices and protocols, as well as improving our understanding of this unique environment.

1.2. Why is Coastal Habitat Mapping so important; a Government of South Georgia & the South Sandwich Islands (GSGSSI) perspective

South Georgia lies approximately 750 miles south-east of the Falkland Islands in the path of the Antarctic Circumpolar Current and below the Polar Front. Although it has the equivalent latitude as northern England, the South Georgia climate is distinctly Polar. Oceanic currents, nutrient upwellings and depositions from glacial runoffs lead to highly productive waters and this, combined with high concentrations of krill carried north from the Antarctic Peninsula, make the island a wildlife hotspot. Globally important populations of seabirds and marine mammals thrive in this isolated wilderness. It is largely ice covered and mountainous, with the extensive coastline broken by glaciers and fjords supporting a diverse range of habitats. Much of South Georgia is difficult to access and seldom visited, and management of this large, biodiverse, remote island is challenging.

Neither South Georgia's habitats, nor its coastline are static. A number of factors are influencing its changing appearance. Climate change is a serious concern, and glacial retreat is continually changing the shape of the coastline, exposing new geographic features and leaving freshly exposed ground. These areas are extremely sensitive and vulnerable to colonisation by invasive species.

After a long history of exploitation through sealing and whaling, marine mammal populations are recovering. The Antarctic fur seals are believed to have recovered to pre-exploitation levels and now number at least 6 million on South Georgia; which consists of 95% of the world's population. In places the Antarctic fur seals have moved into the tussac fringes, and causing erosion, changing the coastal habitats and redefining the extent of different types of vegetation.

In recent years, major habitat restoration projects have eradicated non-native reindeer and rodents from South Georgia. The grazing pressure, erosion and compaction caused by reindeer has been relieved and the endemic South Georgia Pipit, is now commonly observed throughout the coastal area, where it was once only found in a few rodent-free areas and offshore tussac islands. It seems that, anecdotally at least, there is now a greater diversity and resilience in these habitats.

In short, the ecosystems in South Georgia are in flux and native species have an opportunity to recover. The DPLUS065 Coastal Habitat Mapping project and the possibilities provided by this handbook mean we may establish what that flux looks like.

In addition to environmental changes, human activities have altered considerably in the last 200 years. At first there were few people coming to South Georgia, but they had a significant impact on the environment as they exploited fur seals and whales as a resource. Today there are many more visitors, but they only land at very specific places and their impact is much smaller. They predominantly come to experience the wildlife.

South Georgia is seeing rapid growth in the number of visitors coming each year, the vast majority of whom arrive on expedition cruise ships as tourists. The predictions are that with a number of new expedition cruise ships being built numbers could triple over the next decade. GSGSSI need to carefully manage this, so that tourism doesn't spoil the very thing people come to see. Understanding the coastal environment of South Georgia is important when making appropriate management decisions regarding these visitors.

GSGSSI need to understand how to identify change and how the factors that may threaten the diverse habitats of South Georgia can be managed. There are logistic constraints to monitoring and assessing the actual and potential changes on South Georgia. The rugged landscape, extreme weather and sheer isolation of the island make it one of the most spectacular places on earth, but also one of the most challenging places to work . The weather can change from glorious sunshine to ferocious winds and blizzards in the blink of an eye. Accessing sites can involve negotiating tussac mounds (dense, elevated mounds formed by *Poa flabellatai)*, deep and muddy elephant seal wallows, steep scree slopes and beaches teeming with aggressive fur seals, while being careful not to disturb the high densities of wildlife and native flora.

The DPLUS065 Coastal Habitat Mapping Project has provided a valuable snapshot of South Georgia today and may provide clues to the stresses it is under, but perhaps even more exciting, is the ability to repeat and expand this work over time, so that GSGSSI can begin to understand the temporal changes to inform management decisions to better protect South Georgia.

The injection of expertise and knowledge that research such as the DPLUS065 Coastal Habitat Mapping Project provide are of huge value, but ultimately it falls on the people who use these tools and apply this knowledge, to ensure that this benefit is not just transitory, but provides real and long term gains to the environmental management of the island.

1.3. How to use this handbook

At the start of the handbook there is a decision tree (Fig. 1), which will help you decide which of the EO tools are most appropriate/relevant for the task you are undertaking, and will determine which sections of the handbook you need to focus on in more detail. This handbook provides an overview of options available to you, along with specific points covering some of the challenges of working in remote island territories. It is not intended to be a comprehensive or exhaustive guide, and users will need to look into more detail once their requirements have been finalised.

1.4. Coastal habitat mapping decision tree

Readers should review the coastal habitat mapping decision tree below in Figure 1 when considering which tools may be appropriate for the mapping and monitoring task they wish to undertake.

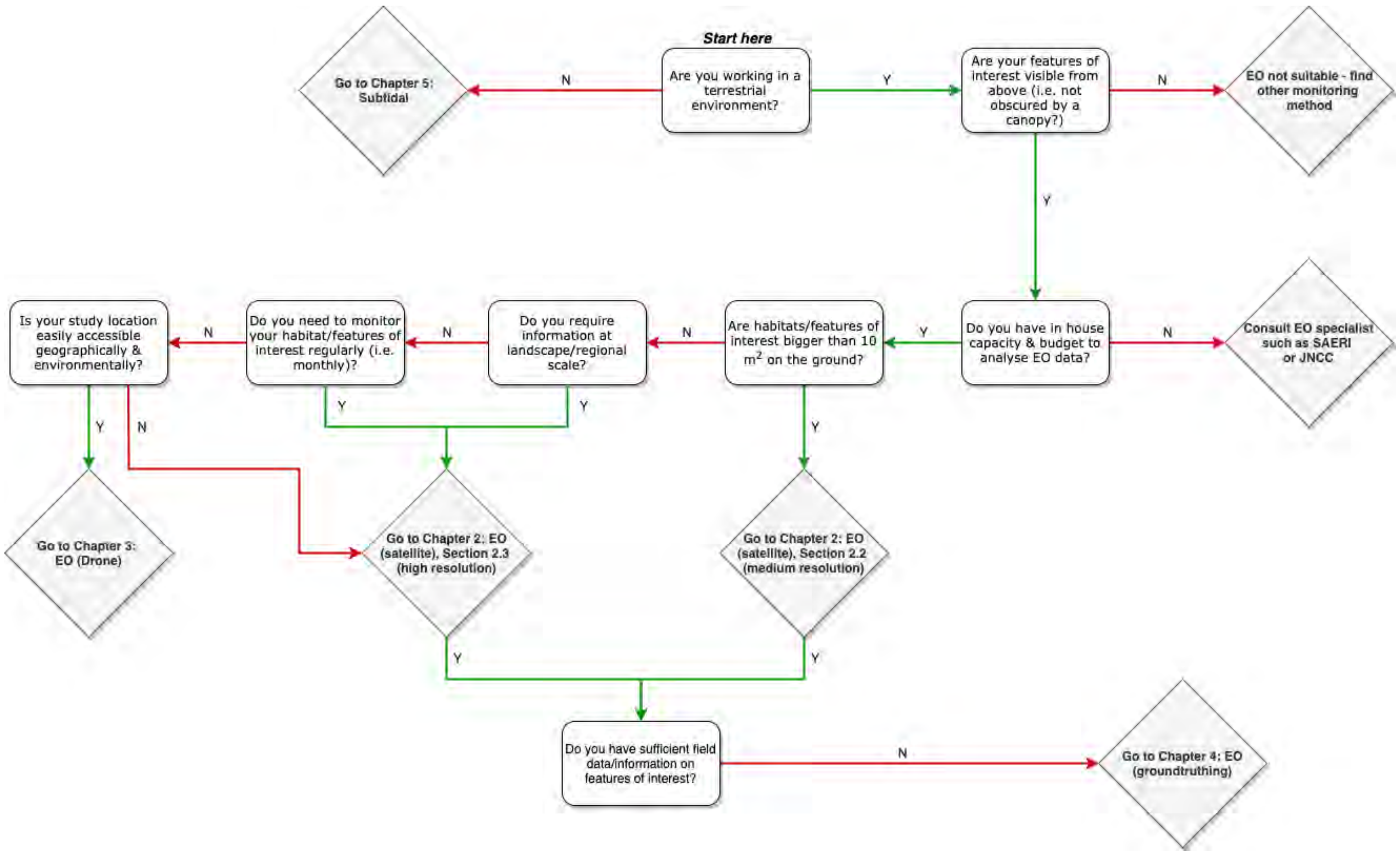


Figure 1: Coastal Habitat Mapping & Monitoring Decision Tree

2. Earth Observation: Satellite

2.1. Introduction

Satellites collect data in a wide variety of formats, with new sensors and missions being launched regularly. There are two main types of sensing from satellites, active and passive. Active sensors have their own source of light or illumination. The most common type of active sensors are on radar satellites that actively send waves and measure the backscatter reflected. Passive sensors measure reflected sunlight from the Earth's surface.

There are some characteristics of earth observation data that will impact what information is possible to extract from the data. These are:

- **Spatial resolution** – the ability of a sensor to identify the smallest size detail of a pattern on an image, usually refers to pixel size.
- **Spectral resolution** – the sensitivity of a sensor to respond to a specific frequency range, often includes visible light and IR.
- **Temporal resolution** – the frequency at which a sensor revisits an area.

For mapping, the spatial resolution of satellite imagery limits what changes can be detected. In this project we used satellite data of two different resolutions, medium and high.

2.2. Medium resolution

In this section we provide more detail on the medium resolution satellite data that was used in this project.

Copernicus datasets were identified as a key data source for this project because of their open access and spatial resolution of 10 metres. In comparison with other open access Earth Observation (EO) datasets, the Sentinel satellites cover the globe more frequently than other EO systems, and are operational as opposed to research-based missions. The Sentinels plan to continue providing open datasets into the future, as they plan to launch more satellites.

2.2.1. Sentinel-2

Sentinel-2 is a polar-orbiting, multispectral high-resolution imaging mission for land monitoring. The mission is also part of the EU's Copernicus Programme and operated by the European Space Agency (ESA).

Temporal resolution: The mission consists of a two-satellite constellation providing orbit revisit times of 5 days at the equator (with both satellites in operation), under cloud free conditions which results in 2-3 days at mid-latitudes.

Spectral resolution: The optical instrument payload samples 13 spectral bands, including red, green, blue, four red edge bands, near infra-red and two short-wave infrared bands. There are also three bands that collect atmospheric information, but are excluded from surface reflectance products.

Spatial resolution: Four bands are 10 metres spatial resolution (red, green, blue and near-infrared), six bands at 20 metres (four red-edge and two short-wave infra-red) and the three atmospheric bands are 60 metre spatial resolution. The orbital swath width is 290 kilometres.

As an optical constellation of satellites, Sentinel-2 imagery is limited by cloud cover. To secure cloud-free data of the area of interest, an investigation was required to identify suitable images. Seasonal changes and differences were considered as these variations can be critical to habitat identification and separation of classes. For example, leaf flushes and snow cover vary between seasons. Sentinel-2 imagery was used to generate the broad-scale habitat maps in this project.

2.2.2. Sentinel-1

Sentinel-1 is a polar-orbiting, all weather, day-and-night radar imaging mission for land and ocean services. The mission is part of the European Union (EU) Copernicus Programme and is operated by the European Space Agency (ESA).

Temporal resolution: The mission consists of a two-satellite constellation providing orbit revisit times of six days.

Spectral resolution: The radar instrument transmits and receives in C-band (5.405 GHz).

Spatial resolution: The resolution of Sentinel-1 is 5 x 20 metres in interferometric wide-swath mode. This is the most common mode that is used over land masses. The data is processed and stored as Level 1 Single Look Complex (SLC) and Level 1 Ground Range Detected (GRD) products by the ground segment of ESA. The SLC product contains the intensity of returns and phase information, whereas the GRD product does not contain the phase information, due to the enhanced processing that it receives. This GRD data is multi-looked and projected to ground range using the earth ellipsoid model.

Sentinel-1 data are transformed into backscatter products from data collected in the Interferometric Wide (IW) swath mode and processed from the Ground Range Detected (GRD) version of the data. These Sentinel-1 data contain data in both VV and VH polarisations. The raw scenes were terrain corrected, radiometrically normalised and processed to Gamma-0 backscatter coefficient in decibels (dB) using the SNAP Toolbox (http://step.esa.int/main/toolboxes/snap/).

As a radar constellation, Sentinel-1 is not constrained to the same limitations as Sentinel-2, because this radar remote sensing tool can image Earth's surface through cloud cover and during periods of darkness. This means that all images are potentially usable. Sentinel-1 data was made available during the broad-scale mapping stage of this project.

2.2.3. Landsat

Landsat missions were established in 1972 and have continually provided a tremendous library of publicly available medium resolution satellite imagery covering much of the globe.

Temporal resolution: Each Landsat satellite has a revisit time of 16 days. There are currently 2 Landsat satellites in operation. Due to issues with Landsat-7 data only Landsat-8 data is used in this project.

Spectral resolution: Landsat-8 has 11 bands: coastal, blue, green, red, near infra-red, two short-wave infra-red bands, two thermal bands, a panchromatic band and an atmospheric band (not used in surface reflectance products).

Spatial resolution: Landsat-8 bands are at 30 metre spatial resolution, except for the thermal bands (90 metres), panchromatic band (15 metres), and the atmospheric band.

In the case of the broad-scale maps produced for this project, Landsat 8 coastal blue band 1 was accessed and utilized rather than the equivalent coastal blue band in Sentinel 2 imagery. This decision was made due to 30 m spatial resolution associated with Landsat's coastal blue band as opposed to the 60 m resolution of the most comparable Sentinel 2 band (*Fig. 2*). Aside from band 1, no other Landsat imagery was utilized in either the fine nor broad-scale maps.

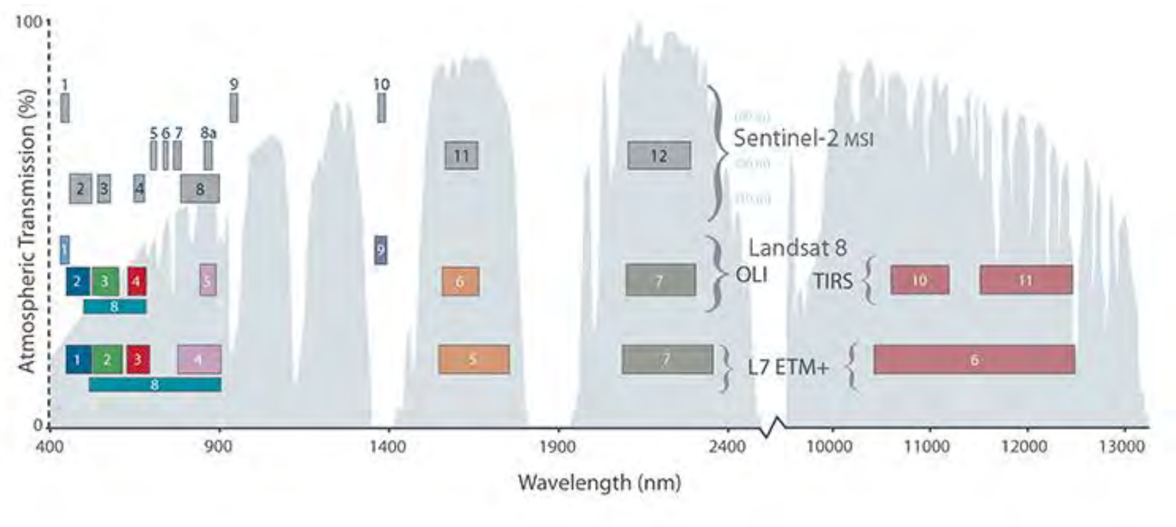


Figure 2: *Comparison of Landsat bands with Sentinel-2 bands (source: https://www.usgs.gov/centers/eros/science/usgs-eros-archive-sentinel-2-comparison-sentinel-2-and-landsat)*

2.3. High resolution

High resolution imagery is only available if purchased.

To make the process of mapping/monitoring as repeatable and sustainable, in terms of financial cost of data, the following factors are recommended for consideration when deciding upon image purchase:

Temporal resolution: Only archive imagery from various providers should be considered, as these are cheaper and allow the user to choose from a variety of available images, which when commissioning a new image the user would not. Tasking is available but at a higher cost. Satellites are controlled by operators which means that not all satellites are collecting data all of the time like the medium resolution satellite constellations. This means that you cannot predict when satellite data will become available if tasked.

Spectral resolution: spectral requirements are a minimum of Red, Green, Blue and Infra-red bands. There are satellites that collect more spectral information such as Worldview-2 that has 8 spectral bands in the visible and near infra-red. No cloud, or as little cloud as possible would be ideal, but cannot always be avoided especially with tasked imagery.

Spatial resolution: The spatial resolution needs to be high enough to separate and classify the features. Many high-resolution satellites collect data at or between 2-5 metres spatial resolution in the multispectral bands (visible to near infra-red) and between 31-50cm in the panchromatic band. Images only need to cover areas where finer features exist.

In this project, Digital Globe's Worldview data was acquired through the DigitalGlobe Foundation and used for fine-scale mapping. Worldview data acquires data with 8 spectral bands (Visible to Near Infra-red) at 2 metre spatial resolution and a panchromatic band at 31-50cm.

2.4. Pre-processing

All satellite data needs to go through a set of processes, which we call pre-processing in the earth observation community, before they can be used for analysis. Although many data are now openly available to download, it is provided in a raw format and requires processing, such as atmospheric correction, cloud correction, geo-referencing etc, to get the data into a useable format before analysis can be carried out to provide robust evidence. Processing of the raw data requires specialist skills and resources that individuals, governments and small businesses are unlikely to have, and this represents a barrier. In this project, all satellite data were processed before analyses by expert users from JNCC (medium resolution) and Oregon State University (high resolution).

2.4.1. Options for accessing pre-processed data

Sentinel-2 data are transformed to produce a topographically corrected surface reflectance product with cloud and topography mask that can be applied to the imagery provided separately. The Atmospheric and Radiometric Correction of Satellite Imagery (ARCSI) software (http://www.rsgislib.org/arcsi) was used to produce this product, as this is the software that has been used during the automation process in the UK (Jones et al., 2017). This process, although developed for UK processing, can be deployed globally, and this saves time in cost and effort while deploying the processing chain to other areas globally. During processing the 20m image bands are sharpened to 10 m through application of linear regression models. The 60m bands are primarily used for atmospheric aerosol correction and processes and are therefore removed from the final surface reflectance product.

Sentinel-1 data are transformed into backscatter products from data collected in the Interferometric Wide (IW) swath mode and processed from the Ground Range Detected (GRD) version of the data made available by the European Space Agency (ESA). These Sentinel-1 data contain data in both VV and VH polarisations. The raw scenes were terrain corrected, radiometrically normalised and processed to Gamma-0 backscatter coefficient in decibels (dB) using the open source image analysis software SNAP Toolbox (ESA SNAP).

Please note that access to a Digital Terrain Model (DTM) is required for all pre-processing.

Landsat data are available as surface reflectance products as they are processed by the US Geological Survey and are Analysis Ready Data. More information on these products is available here: https://www.usgs.gov/land-resources/nli/landsat/landsat-surface-reflectance?qt-science_support_page_related_con=0#qt-science_support_page_related_con. These ARD datasets were used in this project.

JNCC have established processing chains through previous project work (Sentinel-2: Jones *et al.*, 2017[2]; and Sentinel-1: Minchella, 2018[3]). To enable wider use and exploitation of EO data, JNCC are promoting the systematic and regular provision of Analysis Ready Data (ARD). This aligns with the Committee on Earth Observation Satellites (CEOS) work on facilitating access to satellite data through the international CEOS Analysis Ready Data for Land (CARD4L) project. This notion of accepted standards is recognised by JNCC and the wider CEOS community as a vital step for repeatable and comparable analytical work. The use of ARD allows immediate analysis for end-users and removes complex pre-processing. JNCC currently process on a demand basis in our project areas, for more information please go to https://jncc.gov.uk/our-work/analysis-ready-data-ard/.

[2] Jones, T., Wicks, D., Agass, S. & Bunting, P. 2017. Developing standards and automated production for Sentinel-2 Analysis Ready Data. Evidence Project SD1707

[3] Minchella, A. 2018. JNCC Sentinel-1 Backscatter Data Provision Service. SAR processing Methodology

3. Earth Observation: Drone

3.1. Introduction

Recent advances in technology have created an affordable yet powerful and efficient mapping tool. Drones or UAVs (Unmanned Aerial Vehicles) come in a variety of sizes and types, from multirotor to fixed wing. They are ideally suited for collecting aerial imagery and mapping data from areas where physical access or terrain is difficult or dangerous. The recommended extent that can be mapped using drones varies with type; typically fixed-wing drones are better suited to mapping larger areas (up to 400 hectares/4km^2 on a single flight) whereas multi-rotor drones provide more flexibility and are better suited for mapping smaller areas. Within this handbook, we focus on multi-rotor drones; these are easy to fly and are extremely stable.

While small drones provide an opportunity to collect a large volume of information for habitat mapping (in the form of still and video imagery) with relatively little effort, it is important to consider their limitations. Researchers should work through the decision tree in *Section 1.4* and consider their requirements against the different EO technologies available. Suitable applications for small drones include surveys of vegetation types / individual species across moderately large areas (up to 2-3km^2) and surveys of sensitive habitats difficult to access.

There is a large amount of literature available in the public domain on using drones for habitat mapping[4], and this section of the handbook does not seek to replicate this. Instead, the drone mapping protocols developed for the Coastal Habitat Mapping project will be discussed (see Section 11. Appendix C), highlighting the challenges associated with operating drones in remote, windy locations such as the Falkland Islands and South Georgia.

Temporal resolution: Aerial imagery from drone mapping surveys can be undertaken at any time of year, weather dependent of course. Repeat surveys allow a time-series to be established at a temporal frequency determined by the end user.

Spectral resolution: spectral requirements are minimum of Red, Green, Blue. Additional sensors can be fitted to drones to capture additional bands. For example, a RedEdge Micasense camera was used in the project for specific locations, which collected near-infra and red edge, in addition to red, green and blue bands.

Spatial resolution: spatial resolution of the resultant imagery collected by the drone is determined by the altitude the mapping mission is flown. Typical resolutions or Ground Sampling Distance (GSD) for a mission flown at 50m above ground level (AGL) are 1.3cm/pixel. A mission flown at 100m AGL will have a resolution or GSD of 2.7cm/pixel.

[4] http://data.jncc.gov.uk/data/3b1a059f-5c48-493b-8002-ff2f68276b15/JNCC-MMPG-003-FINAL-WEB.pdf

3.2. Case study: A summary of how drones were used by the DPLUS065 Coastal Habitat Mapping project.

The project successfully used the DJI Phantom 4 Pro drone as the primary tool for completing aerial surveys of the coastal margin in specific areas identified through the fine-scale habitat mapping stakeholder prioritisation process.

When considering which model of drone to use, thought should be given to anticipated weather conditions, and in particular wind speed (especially gusts). With this project focussed on the Falkland Islands and South Georgia, both renowned for being windy, it was important to select a drone that had a wide operating envelope with respect to wind speed. The Phantom 4 can operate in wind speeds (and gusts) up to $10ms^{-1}$ (approx. 22mph). Experience with using smaller drones (such as the DJI Mavic Pro) demonstrated that these models can have difficulties in windy conditions, whereas the Phantom 4 provided a more robust and stable platform.

The Phantom 4 Pro has a larger (1") CMOS camera sensor providing higher resolution images and better performance in low light, compared to other models. Note that during the project, a revised (V2) model of the Phantom 4 Pro was released with quieter motors and redesigned propellers to reduce noise; performance and battery-wise, it is the same as the earlier model. This quieter drone has great potential for seabird count surveys, where the reduced noise is advantageous to minimise disturbance.

As well as the standard RGB camera fitted to the Phantom 4 drone, a MicaSense RedEdge-M multispectral camera[5] was also utilised by the project. This camera has the advantage of capturing two additional bands, red edge and near infra-red, allowing vegetation indicies such as the Normalised Difference Vegetation Index (NDVI) to be calculated. These indices are useful datasets to consider from a land/farm management perspective, as well as a useful additional input data layer for any subsequent habitat modelling. Third party integration kits[6] are available which allow the RedEdge camera to be fitted to the Phantom 4 drone. There are a couple of points to note when using the multispectral camera equipped drone:

- To avoid removing and re-attaching the RedEdge camera, and potentially causing damage, we allocated a dedicated drone for multispectral mapping.
- The multispectral camera, with its associated downwelling light sensor (DLS) and GPS unit, significantly added to the weight of the drone, affecting its flight performance and duration; maximum flight times were less than 15 min rather than the standard 25 minutes. This should be factored into any mission planning.
- Best results were obtained by using the RedEdge camera Auto-Capture Mode set to Overlap mode (80%). Note that when setting the target altitude, image capture will cease when the drone descends 50m below the target altitude. Bear this in mind when setting the target altitude over variable terrain, and when taking off from the top of that terrain. It is recommended that where possible, you set your take-off point from the area of lowest terrain, to ensure the camera records continuously.

The project utilised three drones. It is worth considering the colour of the drone; for example, the Phantom 4 Pro was available in black (obsidian) or white. It was found that the black drone was much

[5] https://www.micasense.com/rededge-mx
[6] https://skyflightrobotics.com/phantom/4/pro/micasense/rededge/camera/intergration/kit/

easier to keep track of during the mapping missions, this is especially important when considering that the drone must be kept within visual line of sight (VLOS).

To plan our mapping missions, we paired the Phantom 4 Pro drone with an iPad Mini; we avoided the Phantom 4 Pro + drone with a built-in screen on the controller as at the time, this did not support third party mapping applications. We used MapPilot[7] for iOs as our primary method of planning and flying mapping missions, discussed in a Section 11.2.

[7] https://www.dronesmadeeasy.com/Articles.asp?ID=254

4. Earth Observation: Ground-truthing

Ground-truthing is defined as confirming or validating remotely sensed data by direct observation on the ground, and was an important consideration of the DPLUS065 Coastal Habitat Mapping project. Ground-truthing is important for 'training' habitat models to correctly predict habitats from remote sensing data – part of this ground-truthing dataset (20%) is also held back from the 'training' process in order to validate the models. Specific protocols were developed by the project for collecting ground-truthing data, and are included in *Section 4.1*.

Important aspects to consider when collecting ground-truthing data are:

- **Seasonality:** where seasonality does cause changes in the features being mapped (e.g. vegetation), it is important to collect ground-truthing data in the same season as the remote sensing data.
- **Sensor resolution:** it is important to consider sensor resolution when collecting ground truthing data. For example, if the remote sensing data being ground-truthed has a resolution of 10m, there is no point collecting ground-truthing data for patches of vegetation less than this.
- **GPS errors:** when collecting ground-truthing data, consideration should be given to any spatial positioning errors associated with GPS devices. These need to be considered against the sensor resolution.

Sources of ground-truthing data may include:

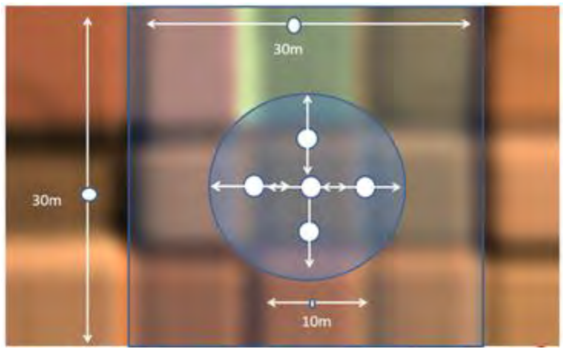
- Field observations
- High resolution aerial imagery
- In-situ spectral measurements
- Maps/charts
- Descriptive reports
- Discussion with experts

4.1. Earth Observation Field Survey Protocol

4.1.1. Considerations

Listed here are questions that need to be considered when undertaking fieldwork specifically for collecting data for training and validating products generated from imagery.

Considerations	***Examples***
What can we see in images?	Resolution is important, i.e. large homogenous patches of habitat/dominant species are likely to have visible boundaries in 'free at point of use' satellite imagery with ground unit (pixel) sizes of 10 x 10 m^2; single plant instances are not visible in the imagery.
If we could isolate/separate a habitat, what state would it be?	Seasonality is key here, i.e. is there a time of year that a habitat is distinctive from its surroundings? Is the habitat covered by snow/ice for part of the year? Is the habitat visible at low tide?
What can we do to give us the best chance of isolating a habitat?	Contextual information may be needed, i.e. does the habitat only occur on steep, south facing slopes? Does the habitat only occur a certain distance to water?
How accurate are our GPS devices?	The accuracy determines where you should consider recording your GPS points, i.e. taking a point on the edge of a habitat type is likely to introduce errors, while standing in the middle of a habitat patch gives the best chance of accuracy (Figure 3). Again, resolution of images is important here:

	 *Figure 3*: Example of how GPS accuracy affects where the user should consider recording a point.
Do we have enough field data to accurately represent the landscape?	Interesting habitats are very important, but other features in the landscape need to be captured too, i.e. bare rock, bare sand

A more detailed explanation of the field protocol developed by the project for ground-truth data collection is shown in Appendix E.

5. Subtidal

5.1. Introduction

The use of satellite and drone imagery for shallow marine benthic habitat mapping is limited to what can be observed through the water column. The majority of the visible light spectrum is absorbed in the top few meters depending on location, leaving little visible information of the seabed to be gathered by remote sensing methods. In addition to light absorption, other factors interfere with satellite/aerial based seabed observations such as water productivity, turbidity, waves, surface light reflection, to name a few. This means that subtidal mapping must be done more or less *in situ*.

These challenges are overcome by way of submerged seabed remote sensing technologies. Although methods such as side-scan sonar, multibeam sonar, and video/still imagery do not have the same large spatial swath as Earth orbiting technologies or even drone imagery, targeted surveys using submerged technology, and/or a series of systematic surveys using a mix of submerged and above-water technologies can be very effective for mapping seabed habitats at a variety of spatial scales.

Subtidal habitat mapping along coastlines has typically been done through direct observation through SCUBA divers and /or video or still imagery, using sampling designs that provide the desired level of statistical inference or interpolation. Although very accurate and detailed data can be collected, drawbacks of diver-based methods include highly-constrained spatial extents that can be surveyed, visibility limits, depth limits, time constraints, and logistical complexity. Diver-based subtidal surveys are outside the scope of this document, but there are some excellent resources to guide subtidal survey design, for example Eleftheriou and McIntyre (2005) *Methods for the Study of Marine Benthos*. 3rd edition. Blackwell Science. 418pp is a good introductory text.

Electronic / remote methods of subtidal habitat surveys are not necessarily limited by the same constraints as divers, however this also depends on what systems you choose to use. Whilst side-scan sonar for example, can give an impression of habitat type at greater depths, across wider areas, and in poor visibility conditions, the results are subject to interpretation and would typically need to be supplemented by an observation of habitat likely by a camera system or diver.

Questions for choosing methods of remotely sensed habitat mapping are similar to any other method insofar as there are trade-offs between spatial resolution vs spatial extent, and constraints on time, funding, personnel, etc need to be considered. Subtidal methods will depend on the answers to such questions as;

- What is being measured - seabed? sea surface (e.g. kelp)?
- What information do you require from the image – species ID? Sediment compositions? Depth? Solid structures (e.g. reefs)?
- For most subtidal work, what platform is available? Is the platform a small or large vessel?
- For acoustic methods, are there people available to trained to set up the instrument, process data and interpret output?

5.2. Optical imaging

5.2.1. Drop-down camera

Drop-down cameras are simple systems where a CCTV type or higher quality video camera is lowered vertically in the water column from a boat to the seabed. Ideally, there is a live video feed up the wire back to the operator in the boat (Figure 4). This is a non-destructive way to collect biodiversity and habitat data (compared to dredges, trawls, or grabs) and can be configured to be towed for collection of quantitative data as well as broader qualitative views of seabed-scapes. Physical collection of samples may be needed for correct species identification.

Figure 4: *Example of simple drop camera (left) and live feed and recording unit (right).*

A light source may be required. Here, choice of video camera is important, where the trade-off is a camera that operates in low light but will give a grainy, low resolution image, where as bright underwater lights may wash-out an image, particularly if on white sandy seabed.

Drop-cameras are easy to deploy from a small vessel as they typically are easy to handle with little extra supporting equipment. If they (ideally) have a live video feed to the surface (Figure 5), then consideration should be given to how the live video will be received, for example on an open deck exposed to the elements? or inside a cabin/wheelhouse? Modern systems are relatively portable and often can be compacted into one or two 'Pelican' type hard waterproof cases.

Two people will likely be needed for deployment; one for lowering/raising the camera and another to monitor the image, record positional data, and feed-back to the other crew what is happening to the camera on the seabed - is it dragging on the seabed, is the image good quality? Sea state (wind, waves) on the surface will have an effect on image quality at the seabed, for example rapid rising and falling of the camera will make it difficult to make any counts of organisms or even identify organisms, but may be fine for ground truthing acoustic data (e.g. side-scan sonar, see Section 5.3).

Figure 5: Live image from a drop camera. note the two laser lights to provide scale. Also note date and time imprinted on the video.

A typical survey strategy might be to deploy the camera and allow the vessel to drift with the current or wind (at the discretion of the Captain) while raising and lowering the camera from the seabed. In this way, a large number of image 'samples' of the seabed can be gathered across a wide spatial extent. This method has the capacity to cover many stations and areas in a day, therefore power should be a consideration when purchasing a camera system. Modern cameras are relatively low power and can be run from a small car battery if on a small boat or off the mains if available on a larger vessel. Lights will draw more power, and may or may not have integrated or separate power supplies. Ideally, if a system can run off the vessel mains, then that would be preferable to having to change batteries while at sea, and limit survey time.

5.2.2. Remote Operated Vehicle (ROV)

Similar to drop-cameras, Remotely Operated Vehicles (ROV's) are also non-destructive and can survey larger areas. ROV's have the advantage of being able to be driven along transects or to investigate areas of particular interest. ROV's can come in many different sizes, and systems are readily available that can be deployed by only two or three personnel from small or medium size vessels. ROV's can have manipulator arms that can be used to sample specific species or pieces of substrate of interest. Today's ROV's can be integrated with GPS units, have built in digital compasses, and excellent quality imaging systems. They can be driven with good manoeuvrability such that they are able to explore highly 3-dimensional seabed of biogenic structures better than drop cameras.

Limitations to ROV's are primarily that they are more expensive when compared to drop cameras for reasonable quality video imaging and good manoeuvrability required for water surge or currents. Cable management is more complicated as the ROV is driven away from the vessel, with the cable causing drag in current and creating risk of entanglement in kelp, around rocks and boulders, or the vessel. Power is more of an issue for ROV's as they require thrusters and have integrated light systems. Good quality ROV's are technically more complicated to maintain and service so may be less desirable in remote locations with limited facilities.

Modern, portable systems can be run from a laptop and video is streamed back live, therefore operators should consider cover from weather when operating on small boats. Figure 6 shows a variety of small ROV's ranging in cost and capability.

***Figure 6**: A range of small portable ROVs on the market; Top left – relatively expensive, off the shelf, highly capable, adaptable, low level of technical expertise. Top right – mid price, open source, highly adaptable, requires higher level technical expertise to operate. Bottom - least expensive, basic capabilities, easy to operate, low level of technical expertise, highly portable but limited by battery power.*

5.3. Side-scan sonar

Side-scan sonar is an active sonar system which implements two sideways looking, narrow beam channels from a towed body. Unlike a depth sounder or fish finder, the side-scan sonar system has been defined as an acoustic imaging device and they are used extensively to locate objects on the seafloor, such as wrecks or pipelines. Because the imaging process utilises backscatter of sound, known as side-scan, the image received is an impression of the difference in absorptive properties of the scanned surface a well as acoustic "shadows". This means that in the context of habitat mapping, it can provide a wide-area and large-scale impression of seafloor physical features of different densities and shapes (rock, gravel, mud, dunes) or biological features (biogenic reefs, kelps).

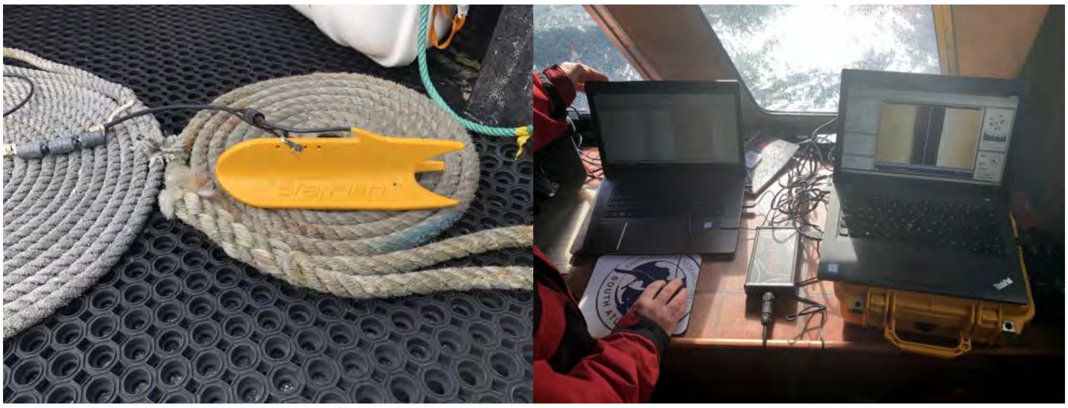


Figure 7: side-scan sonar equipment. Left - towed "fish". Right - live image of signal from towed fish and operator recording site, station, and tow event details.

Side-scan sonar such as shown in Fig 7 is ideal for shallow water habitats, down to approximately 50m. In the context of habitat mapping, it provides fine resolution of seabed type compared to multibeam echo sounders, which although are more accurate for mapping depth, are less suited for measuring fine features such as sand ripples, differentiating between seabed grain size along fine gradients, or detecting biogenic structures such as reefs or sub-surface kelp beds.

The towed 'fish' is easily deployed and towed behind small RIBs or other vessels, but does required multiple personnel to monitor readings and adjust the towed fish height off the seabed, and constant communication between operators and vessel skipper/crew is necessary. Additionally, there is a great deal of trial and error and fine-tuning of the system and operation for best results when mapping different habitat types at different depths, including making adjustments for weather conditions (for example surface waves can cause the vessel to pitch over waves, which in turn cause the towed fish to rise and fall in the water column). However, the process is relatively straightforward once the operator and vessel crew are familiar with operations and procedures.

Data collection is also critical for side-scan work, with many factors which need to be recorded to best inform post-processing (e.g. Figure 8). Processing of data requires relatively high level of specialist analysis, an example of side-scan visual output is shown in Figure 9. Data require a considerable amount of post-processing "cleaning" that cannot necessarily be automated - e.g. addressing particles in the water column, vessel pitch and roll, image contrast/gain, etc. In addition, ground truthing will be required to validate seabed characteristics, which can be done using a simple drop-camera system.

Despite technical and operational challenges, side-scan sonar is a relatively inexpensive and easily deployed method for conducting seabed habitat mapping across wide areas.

Date:

Boat:

Area name:

Surveyor names:

Sea State:

Station No.	Set No.	Approx Bearing (deg)	Approx Start Depth (m)	Start Location (Latitute)	Start Location (Longitude)	Start Time (24 hr)	End Depth (m)	End Location (Latitute)	End Location (Longitude)	End Time (24 hr)	Habitat verification required? Y/N and location if possible	Habitat verification completed? Y/N	Layback (m)	Sea State	Notes and observations
eg S140601	eg 1-5	eg 85	eg 20	eg 15.93628 S	eg 5.74185 W	eg 10.00	eg 20	eg 15.93850 S	eg 5.74825 W	eg 10.10	eg Y - 15.93726 S, 5	eg Y - photo taken			eg dolphins, other boats, noise etc

Figure 8: Example data basic data recording sheet for side-scan sonar.

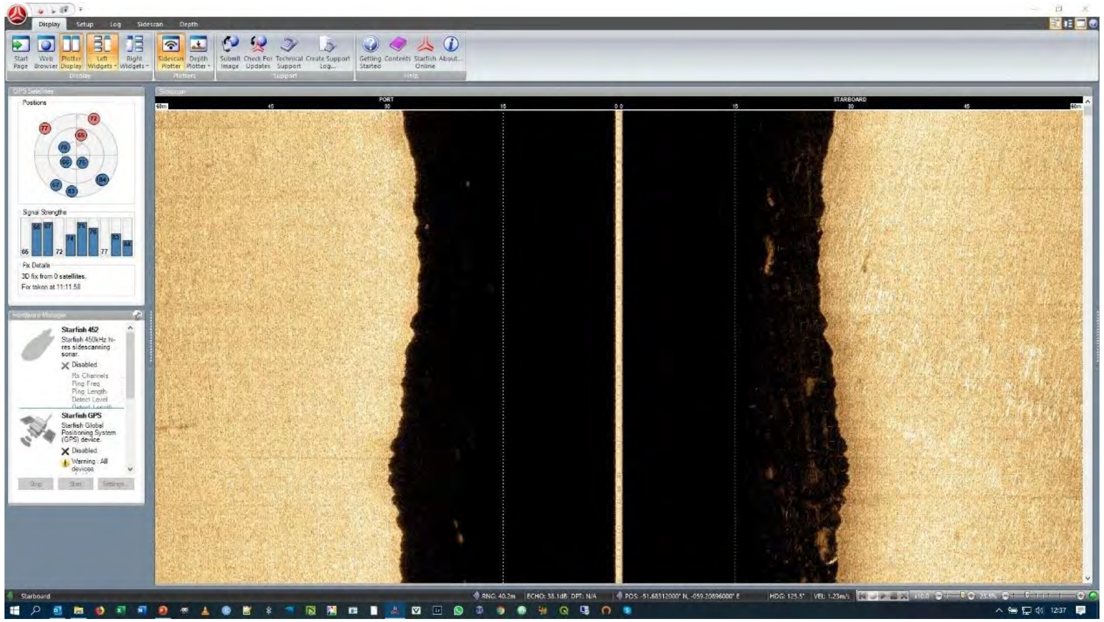


Figure 9: - Screenshot of side-scan sonar image as retrieved in real time.

5.4. Aerial drone surveys at sea

Drones can be operated relatively easily from small boats (e.g. RIB or launch up to 10m with one or two crew) for coastal work. Details of surveys using drones is captured in Section 3. At sea, drone surveys from small vessels have the advantage of being able to access areas of coastline that would be difficult or impossible to access by land. Considerations for using drones from sea are similar to any other operations where weather, proximity to wildlife etc should be considered. The main difference is that the boat will typically move from where the drone was launched. This means that good drone manual flying skills are required to retrieve the drone rather than relying on automated systems. Anchored vessels can swing 10's of metres back and forth depending on conditions. Anchoring the vessel however is not always necessary as it may be that the vessel is needed to follow the drone as directed by the drone pilot, but this requires good communication between drone pilot and vessel skipper, and a dedicated visual observer would be critical for keeping watch e.g. for any approaching hazards or in case the vessel moves into a more operationally active (from an aircraft perspective) area. Weather conditions at sea, even if only a short distance from land, can vary in different ways than on land and caution should be taken when operating at sea. Operators of drones working from a vessel will need to consider physical hazards on the vessel, such as antenna arrays, A-frames, wires/ropes, etc (Fig 10). Operators should also consider the impact of radio, radar, or other electronic equipment on board, including proximity to metal (i.e. the engine) during pre-flight calibration of the drone sensors. In addition, it is recommended that at least one crew is observing the drone operator for positioning on the boat deck to avoid under-foot tripping hazards especially if the boat is rolling even slightly. The dedicated drone visual observer can assist with drone retrieval by hand, rather than landing the drone on the boat deck. Suitable protective clothing (face shield, gloves) should be worn when retrieving drones by hand.

Figure 10: *Typical hazards surrounding the drone pilot and observer on a small vessel.*

5.5. Case Study – Cochon Island, Falkland Islands

Cochon Island (Fig. 11) is located at the entrance of Berkeley Sound, Falkland Islands. It is designated a National Nature Reserve (NNR), and as such the terrestrial areas of the island is afforded protection status. The subtidal habitats currently have no protection. It was of interest to use remote sensing to map both terrestrial and subtidal habitats of Cochon Island to contribute to management of the NNR.

Drone imagery of the terrestrial and coastal habitats of the island were collected from a vessel. A drone was utilised because Cochon Island is notoriously difficult to land on, being largely surrounded by kelp and steep, rocky cliff faces. This is very clearly evident from imagery in Figure 11, where *Macrocystis pyrifera* (bladder kelp) is found in the southern shore, whilst the northern shore is a steep, exposed cliff.

The subtidal areas of Cochon Island have been studied by way of divers classifying habitats through transect surveys (Shallow Marine Surveys Group, unpublished data), however the deeper subtidal areas beyond 20m depth have not previously been surveyed. Side-scan sonar was used to map deep subtidal areas surrounding the islands. A number of unknown habitat features of the surround seabed habitat were elucidated for the first time (Fig. 11). For example, the sonogram shows a subtidal extension to the east of the rocky reef system, highlighted by complex shadow regions in the sonogram; coarse cobble and sand substrate to the north of the island depicted by bright, highly reflective areas; and darker (high sound absorbance) areas in the sonogram depicting softer sediments.

Validation of habitat types was done through ground truthing these features using a drop camera. The reef extension to the east is characterised by rocky, encrusted ridges with abundant tree kelp (*Lessonia sp*) and other invertebrates. The coarse sand/cobble areas were confirmed, and using twin lasers mounted to the camera, the size of the cobbles could potentially be quantified. Soft sandy areas to the north were confirmed, with numerous squat lobsters (*Munida gregaria*) and the large sun star, *Labidiaster radiosus*.

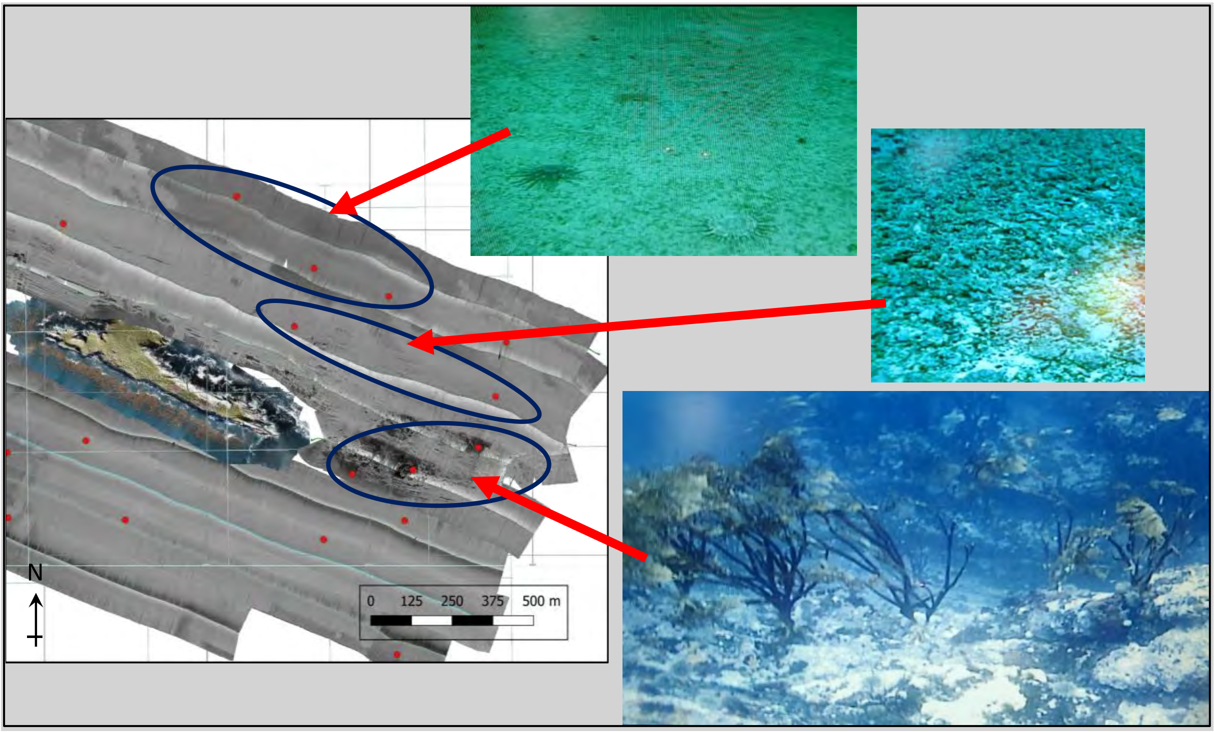


__Figure 11__. Terrestrial, coastal-marine and subtidal habitat mapping of Cochon Island, Falkland Islands. Shown is the drone-based image of Cochon Island including coastline and kelp forest, Side-scan sonargram of areas deeper that 20m depth, subtidal drop-cam stations used to validate sonargram, and images from the drop-cam showing different habitat types.

6. Habitat modelling & mapping

6.1. Broad-scale Mapping Methods: Google Earth Engine Pixel-Based Map Creation for the Falkland Islands and South Georgia

The broad-scale land cover classification maps completed in the first year of the Coastal Habitat Mapping project were created through the use of Google Earth Engine's cloud based platform. Prior to the execution of these maps, input imagery was first prepared and uploaded to Earth Engine, as were ground-truth datasets collected representing the habitat classes to be mapped throughout the Falklands and South Georgia islands. Various additional metrics (such as EVI, NDVI, Geary's C, and so on) were calculated and incorporated into the broad-scale project workflow, while final inputs and configurations for the Random Forest classifier were managed through the project scripts. The following sections briefly outline the principal steps associated with the broad-scale mapping workflow. For further technical detail and full project pseudocode (as well as a link to example code and input data), please reference Appendix A.

Input imagery from a wide variety of sources were compiled via the broad-scale map's JavaScript-based project code. These imagery sources are outlined as follows:

6.1.1. Imagery Inputs: South Georgia

- JNCC Processed Imagery (single "clear sky" day on February 22nd, 2018):
  - Sentinel 1, band 1
  - Sentinel 2, all 10m bands (visible, various NIR, SWIR)
- SRTM (Shuttle Radar Topography Mission) data products:
  - Slope, aspect, and elevation data
- Landsat 8, band 1, 30m coastal aerosol band

6.1.2. Imagery Inputs: Falklands

- JNCC Processed Imagery (2nd February 2018):
  - Sentinel 1, band 1
  - Sentinel 2, all 10m bands (visible, various NIR, SWIR)
- SRTM (Shuttle Radar Topography Mission) data products:
  - Slope, aspect, and elevation data
- Landsat 8, band 1, 30m coastal aerosol band

6.1.3. Ground-truthing Inputs: South Georgia

- 2017 DPLUS065 Coastal Habitat Mapping South Georgia Expedition non-grass points
- 2005 - 2007 Giant Petrel survey (habitat information data) (courtesy of Sally Poncet)
- Shallow Marine Survey Group's South Georgia dive data
- Points digitized from February 22nd, 2018 Sentinel 2 "clear sky" imagery for kelp, barren ground, ice, and cloud

6.1.4. Ground-truth Inputs: Falkland

Ground-truthing for the broad-scale mapping was collected for the R-based random forest Natural Capital habitat map project (Marengo, 2018[8]), as well as later points collected in 2018 and 2019 by the DPLUS065 Coastal Habitat Mapping project[9] to fill gaps in coverage or habitat class type. Further detail on the role of ground-truthing within the model workflow is to be found in the following section.

6.1.5. Broad-scale Model Basic Workflow

Note: What follows is an outline of the essential steps taken to create the island wide broad-scale habitat maps for the Falkland Islands and South Georgia. For a more detailed workflow discussion, please see Appendix A: Broad-scale Modelling Procedures.

The Sentinel 2 imagery, previously processed by the JNCC, was first imported into Google Earth Engine as an asset. Landsat 8 imagery band 1 (coastal blue, 30m resolution) was also imported. All imagery was then clipped to the mapping area of interest and a cosine terrain correction was applied to the Sentinel 2 imagery for use in addressing the conflicting effects of shadowing and very bright surfaces on classifier.

Cloud masking was applied for the Falkland Islands, although in the case of the original South Georgia broad-scale map cloud masking was not utilized due to low cloud coverage in the processed imagery (acquired on 22nd February 2018). NDVI (**N**ormalised **D**ifference **V**egetation Index - measure of vegetation), EVI (**E**nhanced **V**egetation **I**ndex - similar metric to NDVI, but less sensitive to error pertaining to dry vs. bare ground), NDWI (**N**ormalised **D**ifference **W**ater **I**ndex - measure of “wetness”), Geary’s C (texture analysis, which helps with subtidal rock classification) on Landsat 8’s band 1 (coastal aerosol) were calculated as further metrics of use for input into the model classifier.

The characteristics of selected bands at each ground-truthing point (location where “real-world” classification is recorded in ground-truthing dataset) were extracted and saved to a new ground-truth training library. The classifier operated by examining the map area on a pixel-by-pixel basis and identifying the best “match” for the pixel in question compared to the various land cover types listed in the ground-truth training library. A Random Forest classifier utilizing the recently created ground-truthing table (80%/20% split in training and validation) and 1000 trees was run, creating the output pixel-based land cover classification map. A confusion matrix (a report that compares the output map’s classification type to the classification noted at each validation point and lists the distribution of the points that were correctly and incorrectly classified) was then exported as a text file alongside a geotiff of the classified map area.

6.1.6. Broad-scale map improvements:

The following is a short description of specific proposed approaches that provide future avenues of potential research for the broad-scale maps:

- Clouds/bare grounds: some artefacts remain around areas of high cirrus clouds or at the edge of cumulus clouds where the classifier assigns a value of “bare” rather than “cloud”

[8] Marengo, I., 2018. Falkland Islands broad scale habitat map from Earth Observation techniques. 27th March 2018. https://www.south-atlantic-research.org/wp-content/uploads/2018/06/FINCA_habitat_mapping_report_May_29.pdf

[9] https://www.south-atlantic-research.org/research/terrestrial-science/coastal-mapping-project/

- Seasonal opacity of water: determine subtidal areas more likely impacted by glacial output
- Non-grass vegetation classes: additional ground-truthing may greatly improve class accuracy
- Further integrate Worldview 2 and 3 imagery: supplement existing ground-truthing with additional points derived from drone and Worldview imagery?

6.2. Object Based Fine-scale Maps in Falkland Islands and South Georgia

6.2.1. Imagery Sources:

Worldview 2 and 3 imagery were used more extensively in the fine-scale mapping areas of the Falklands compared to South Georgia in large part due to the greater number of South Georgia drone surveys flown with the express purpose providing imagery input for fine-scale maps, as well as the greater prevalence of ice and snow often limiting the ground visibility of Worldview 2 and 3 imagery at South Georgia sites. The fine-scale modelling approach utilized in this project was found to be capable of accommodating both imagery types; however, it should be noted that drone imagery based maps require significantly longer processing times than their Worldview 2 and 3 mapping counterparts.

6.2.2. Example Fine-scale Mapping Sites: Minefield 7 (Falklands) and Gold Head (South Georgia)

Nine fine-scale maps were completed at varying sites at both the Falklands and South Georgia. For the sake of brevity, most project site descriptions have been listed in Appendix B. For demonstration purposes, however, the Falkland Island's Minefield 7 and South Georgia's Gold Head study areas are both mapped and described below. The example fine-scale mapping sites were selected not only to demonstrate the wide array of land cover classes captured at both map sites, but also to illustrate the highly differing patterns of mappable land cover distributions observed at Falklands vs. South Georgia mapping sites.

The Minefield 7 site on the northern shore of Cape Pembroke is located only a few miles from the town of Stanley. This site consists predominantly of sand dunes and a scattering of dune grasses, and was originally surveyed via drone in a joint project between the Falkland Islands Government and SafeLane Global. Gold Head is situated along the southwest coast of South Georgia at Gold Harbour. The site was mapped by drone during the 2019 Coastal Habitat Mapping South Georgia expedition, which served as the main source of its imagery, and displays many of the habitat classes typical of the other coastal South Georgia fine-scale mapping sites.

6.2.3. Basic Workflow:

Note: The following section provides a basic outline of the workflow involved in creating this project's fine-scale maps. For a more detailed workflow discussion, please see Appendix B: Fine-scale Modelling Procedures.

The fine-scale modelling process employed in this project was designed to the greatest extent possible for use by non-geospatial experts. A related mapping procedure is currently under development by project partner Oregon State University, that will streamline the fine-scale modelling workflow and reduce the number and complexity of steps currently required of the map creator. Currently, the fine-scale modelling workflow is executed using QGIS (at the time of these maps' creation in 2019) stable version 3.4 (Madeira), dzetsaca plugin (run in QGIS, requires Python 3 installation and importation of scikit-learn and related libraries), and SAGA 7.2.0, all of which program options are free and publicly accessible. Please note that previous or concurrent installations of Python 2.x and, occasionally, QGIS 2.x may lead to technical difficulties relating to conflicting file paths settings typical of Python 2 and Python 3 installations.

Prior to running the model, various input datasets must be created. All data that will later be extracted from imagery or similar sources must be extracted and merged as individual bands into a single output raster file. Datasets included in the original fine-scale model process include: either Worldview 2 or 3 (8 bands) imagery or visible (3 band RGB) drone imagery, calculated NDVI (in the case of Port Sussex), DEM (derived from GMRT project (online map/download tool link: https://www.gmrt.org/GMRTMapTool/) for maps primarily utilizing Worldview 2 or 3 imagery or those produced from drone imagery elevation products processed by the South Atlantic Environmental Research Institute (SAERI)), a buffered shapefile of onshore regions, terrain rugosity index calculations for both the DEM and visible bands of the principle imagery sources, flow accumulation (created by identifying the highest points in an input DEM and calculating the number of cells that "flow" into each remaining cell within the DEM), slope, and aspect. Once all input rasters were created they were merged as individual bands within a master output raster dataset (saved in a .tiff file format) and then clipped to the areas of interest surrounding the study sites to reduce both file size and processing times in model runs. The clipped .tiff was employed as one of the principle inputs in the application of the random forest classifier.

Rather than taking the pixel-based approach, which classifies each input cell within the raster dataset on a case-by-case basis, we employed an object based image analysis (OBIA) classification system for the fine-scale maps that involved the classification of the map area as defined by objects, or shapes, visible in the landscape. The creation of these shapes, or objects, involved the process of segmentation, where input imagery was delineated in such a way to represent recognizable features on the ground through an automated process completed through SAGA 7.2.0. In the case of most study sites it was found that the segmentation approach yielded polygon shapefiles that fairly accurately described features visible to the human eye, although it should be noticed that on occasion, particularly in larger study areas, the creation of slightly coarser polygons was necessitated due to processing limitations relating to file size, which resulted in some challenges when classifying these objects.

Ground-truthing was collected through a variety of means, both in multiple field excursions for on-site data collection employing an ODK field data input app form tailored specifically for Falklands and South Georgia field sites, respectively, and also later ground-truthing collected through investigation of drone and Worldview 2 or 3 imagery as needed to bolster field collected data. Ground-truthing points were then associated with relevant segmented polygons that were later split into two randomly selected groups - training (80% of input points) and validation (20% of input points) datasets.

Once the merged input raster datasets and ground-truth -derived training and validation datasets were completed, they were used as the primary inputs within the dzetsaka plugin in QGIS 3.4 (Madeira). Default settings (1000 trees) were applied, while the validation dataset was kept separate from the classification process. Once the output map created using the dzetsaca plugin was created, it was employed in conjunction with the original segmentation shapefile within the QGIS zonal statistics tool using the majority (mode) statistic to identify the most commonly occurring land cover classification within the classified pixels falling within the segmented polygons and assigning that most "common" value to a new field within the polygon dataset. This approach was taken principally in order to allow the derivation of both a pixel and object based map from the modelling process. Upon the completion of the dzetsaca plugin the map output was applied jointly with the reserved ground-truthing -derived validation polygons in the SAGA 7.2.0 Confusion Matrix tool, the outputs of which were exported for the final model run of each map area.

Typically, the first two or three model runs for each map site identified areas that required further attention in the ground-truthing selection process, leading to misclassifications commonly due to such factors as shadowing, variation in the appearance of a single class depending on site (for example maturity or senescence of grasses), opacity or reflectance of water bodies, presence of clouds, the necessity for additional examples of certain originally under-represented classes, and so on. Apparent map errors were addressed through a short series of trial-and-error model runs designed to address such issues without biasing map outcomes.

Upon the completion of a final product of good quality, the segmented polygons now carrying the land cover class ascribed by the zonal statistics based on the random forest classifier were "dissolved" in QGIS and later cleaned using the "v.clean" tool. The dissolving process involved the removal of boundaries between polygons assigned the same land cover classification, allowing a significant simplification of the final object-based map output.

7. Overarching Issues and Challenges

7.1. Scale

In both the fine and broad-scale models, scale was a considerable limitation which impacted the practicality of undertaking both mapping and modelling activities. For broad-scale models, running the models at their highest practical resolution (10m, to match the 10m spatial resolution of the input Sentinel 2 imagery) took significantly longer at island-wide scale than for specific mapping sub-regions. For the fine-scale models, those models based on the 2m Worldview imagery ran significantly faster (five to ten times faster) than drone imagery models of comparable size footprints, and also required substantially shorter processing times in the data preparation process leading up to running the model. File sizes associated with WorldView-based data products also had significantly smaller file sizes in comparison to drone-based data products.

While drone products do provide the opportunity to capture smaller "features" – for example, invasive plants such as calafate or young patches of sheep sorrel – using higher resolution drone imagery over larger spatial extents (scales) will lead to longer processing times, as will large study areas for Worldview-based sites (such as the larger Stanley Common/Cape Pembroke or Steeple Jason map areas). The choice to map over larger extents or at higher resolutions is best made when there is a clear and motivating reason to map over such areas or with higher resolution imagery.

7.2. Repeatability

We have worked to create methods for both the fine and broad-scale models that will translate well into the creation of future map series that span a given period of time. It will be necessary, though, to update input imagery and associated ground-truth datasets as time passes before these map series may be re-created. This new satellite imagery can either be extracted from Google Earth Engine's extensive satellite image library, or bespoke analysis can be undertaken on Sentinel 1 & 2 imagery. For the fine-scale model series, the purchase of additional WorldView imagery of the same image tiles used in the existing maps would be necessary for the construction of a WorldView-based imagery time series, while for drone-imagery based sites repeat surveys over the original survey footprints (preferable at comparable elevations and at a similar image overlap) would be required. For both the drone and Worldview based maps seasonality is another factor to consider; the choice of whether or not it is best to acquire new imagery at the same or opposing seasons as the existing maps needs to be determined. As with the broad-scale models, an update of the ground-truthing for each new fine-scale model series would be necessary to coincide with the timing of the newly acquired imagery.

7.3. Connectivity (bandwidth)

Monitoring and research using earth observation data is bandwidth intensive involving the download and upload of terabytes of data. Field workers do not have this bandwidth available in remote locations. Also, many remote small countries and territories do not have the bandwidth and upload and download speeds necessary to fully utilize the functionality of software for geospatial analysis at a national level. This limits the scope and sophistication of research and monitoring using Earth Observation (EO) data in these locations. Cloud computing services such as ESRI's Arc Pro and Google's Earth Engine are helping to alleviate some of these challenges; the latter was used successfully by this project. EO data can be downloaded to a cloud system and be managed there, rather than requiring large amounts of data to be downloaded or uploaded to a remote location with limited bandwidth. The uploading of data collected in remote locations is more problematic. Rather than upload raw imagery, the upload of data with the greatest value to the question/problem being tackled, should be prioritized.

7.4. Sources of error and error estimation

A map created from EO data in combination with field data is only a representation of the landscape, and can be subject to a variety of interpretations. During the creation of ground-truthing datasets, the determination of which class any given location is best described by, even with carefully defined classification systems, requires at least a certain degree of interpretation and application of "common sense". Other decisions made throughout the modelling process, such as the choice of imagery source, the amount of resources applied to data collection, ground-truthing, or processing procedures will all affect the quality of the final model results and thus have the potential for significant impact on the final error.

To date, classification accuracy has been assessed on a class by class basis through the application of confusion matrices, which is a standard method of class accuracy for land cover classification maps. Improvements to map accuracy may be achieved through the inclusion of further ground-truthing or the addition of new descriptive data sources to the model (for example, multispectral drone imagery for other drone mapping sites in addition to the Port Sussex location). Adding alternative classifiers to the Random Forest approach utilized in both the fine and broad-scale maps may also increase map accuracy at some sites, although testing would be required to best determine classifier-related map error.

8. Outlook and Future Opportunities

There are two broad categories of future opportunities:

- Technological advances where developments in platforms and sensors, cloud computing, machine learning and artificial intelligence allow Earth Observation data to be collected, processed and applied to scientific research and environmental management at finer scales over shorter time periods at lower cost.
- Applications that both evolve from and drive technological advance. These include feature identification, change detection and environmental prediction.

8.1. Technological advances

Earth Observation sensors using passive imaging are becoming increasingly sophisticated, collecting data at many bandwidths and at higher resolutions. These sensors are deployed on space-borne and aerial platforms that allow for shorter return periods. Unmanned Aerial Vehicles (UAV's) are cheaper and more capable than ever of carrying affordable multi-spectral and active sensors. Providers of UAV sensor systems provide complete cloud-based workflow solutions from flight planning to image processing and classification.

Multi-spectral medium and high-resolution satellite imagery is available in pre-processed and processed form and is increasing integrated into accessible cloud-based geospatial data platforms such as Google Earth Engine and ESRI's Arc Pro. A wider range of private satellite operators provide "bespoke" high-resolution (sub-metrer) imagery at relatively low cost. This imagery requires less ground-truthing than in the past, dramatically reducing field and logistic costs.

Active imaging satellite systems using high resolution LIght Detection and Ranging (LIDAR) or RAdio Detection And Ranging (RADAR) remain less accessible than multi-spectral systems due to higher costs though it's reasonable to expect this type of imagery to become more widely available in the medium term. UAV's and aircraft are increasingly using LIDAR for Earth Observation applications and although still somewhat bespoke and expensive, LIDAR imagery is becoming more competitive cost wise and applied to a wider range of research and environmental management problems.

Similar trends are apparent in remote sensing of marine and coastal environments. Autonomous Underwater Vehicles (AUV's), Remotely Operated Vehicles (ROV's) and multi-beam sonar systems are increasingly affordable, deployable and capable. They do however require supporting surface vessels and have high operational costs due to the expense of operating and crewing support vessels – even small inshore ones.

Cloud-based computing systems create global communities of practice that allow researchers and institutions working in remote locations to access immense computing power utilizing limited bandwidth. These same organizations can access on-line support from cloud-based providers to analyse the data collected, often using cutting edge machine learning and emerging artificial intelligence technologies.

These trends have three major implications for organisations operating from, or carrying out research activities in remote locations:

- Earth Observation (EO) data will become even more ubiquitous as a regular component of work programs, either as a source of primary data or as support to primary data collection. In some instances, high resolution and frequent return coverage may mean that a physical presence in a remote location is no longer required to collect data and/or that remote locations can be monitored with EO systems much more frequently than was possible previously.
- The expertise and experience necessary to utilize sensors and cloud-based geospatial computing systems is decreasing. This means small organisations with limited budgets can train existing personnel to become competent in the acquisition and analysis of geospatial data rather than needing to recruit staff with highly specialized programming and image processing knowledge.
- Organisations no longer have to invest in expensive computer processing power and storage capacity to utilise an increasing array of EO data. Increasingly affordable hardware and data storage further shift in-house EO data analysis capabilities from the "desirable but non-essential" category to an operational necessity for many small and medium size organisations.

8.2. Applications

Our research program and its future iterations build on the technological and related developments outlined above. A wide range of applications exist and here we highlight several key ones:

Firstly, high-resolution drone and satellite imagery can be used to improve the accuracy of broad scale feature habitat classification in remote environments. Freely available medium resolution satellite imagery (e.g. Sentinel and Landsat imagery) is available for nearly every region of the world. However, its resolution is limited to 10 metres. This means the classification of features and habitat can be challenging, especially when individual attributes are small and/or highly variable. High-resolution imagery can be used to reduce uncertainty in classifications and can reduce the need for time-consuming fieldwork. Satellite data can be acquired for, or UAV's flown over, sample areas of habitat or features whose classification have a high uncertainty associated with them. This fine-scale information can then be used to reclassify these features or habitats of interest in the broad-scale maps. This negates the need to classify an entire area of interest using high-resolution imagery from satellites or UAV's that can be costly and time consuming to acquire and analyse.

Secondly, a combination of medium and high-resolution imagery can be used to monitor environmental change of high-quality and/or sensitive habitats and productive lands. Once the habitat or features of interest have been classified, repeat imaging can detect change or guide management or restoration activities. Examples identified from our current project include:

- Soil and coastal erosion in remote locations;
- Coastal inundation from sea-level rise;
- Invasive species presence or absence detection including developing habitat suitability maps for key invasive species;
- Habitat recovery from restoration efforts including invasive species removal and/or vegetation planting;
- Habitat change from climatic change and/or glacial retreat;
- Near shore and intertidal habitat mapping;
- Identification and monitoring the condition of archaeological and heritage sites;
- Visitor impacts and movements on sensitive and/or high use areas and habitats;
- Pasture and productive land improvement;
- Soil moisture and soil fertility monitoring;
- Vegetation and habitat mapping for restoration following large scale disturbances such as infrastructure construction or minefield clearance;
- Monitor wildlife breeding sites to detect population changes (abundance and location) and possible range shifts; and
- Identify non-permitted structures and illegal and illicit activities.

8.3. Improving the Value of Information

Another area of further work is to develop usable Value of Information (VOI) functions within geospatial analysis and associated workflows. Earth Observations systems generate immense amounts of data. A key question that needs to be addressed is how much data is needed, when it is needed and where it is needed. As researchers we would all like to have the highest resolution images possible of all our potential research areas collected frequently. Those passionate about fieldwork would spend as much time as possible flying UAV's in remote and exotic locations. As managers, however, we know that data comes at a cost. It requires computing capacity, skilled people, risk management for field research and time away from other projects and research opportunities. Managers need to ask what is the Value of Information generated by additional data acquisition.

Value of information is an important strategic and operational concept. It has technical and management components. Both ask how does additional data add value to the information needed to complete a monitoring task or answer a research question? For example, an initial habitat classification may have acceptable 'technical" levels of uncertainty associated with land level classes, but is this uncertainty raising doubts among users of the data products? High-resolution satellite data or UAV-based imagery is likely to reduce this uncertainty and appeal to data product users.

The technical component of an operational VOI function would guide the project managers in determining what resolutions, bandwidths and area are needed to reduce uncertainty to an agreed level. The potential costs and resources needed to achieve this level of accuracy can then be compared to available funds and resources. The management component asks which information is most important to the research problem, monitoring task or programme stakeholders? When combined, these two components give managers a way of systematically prioritising the collection of additional observation data.

Though attention has been paid to demonstrating the benefits of Earth Observations to the economy and society[10], less effort has been devoted to integrating explicit VOI functions into Earth Observation workflows.

[10] Pearlman, F., Lawrence, C.B., Pindilli, E.J., Geppi, D., Shapiro, C.D., Grasso, M., Pearlman, J., Adkins, J., Sawyer, G., and Tassa, A., 2019, Demonstrating the value of Earth observations—Methods, practical applications, and solutions—Group on Earth Observations side event proceedings: U.S. Geological Survey Open-File Report 2019–1033, 33 p., https://doi.org/10.3133/ofr20191033.

9. Appendix A: Broad-scale Modelling Procedures

The broad-scale model was run through Google Earth Engine's cloud platform. The code used to run the Falklands model may be found at:

https://code.earthengine.google.com/bc0c15472711b3de3fec264bbc55998e

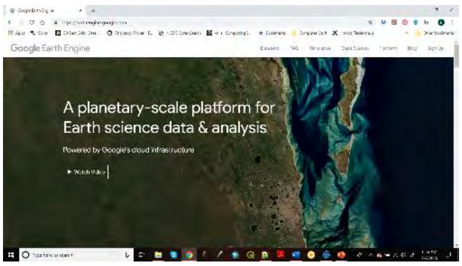
The code for the South Georgia model may be found here:

https://code.earthengine.google.com/5483be9498f1f02dcc2a200b08828c72

9.1. Broad-scale Maps Tutorial

This document outlines the basic process of creating pixel-based land cover classification maps created through a random forest classifier for the Falkland Islands. Please note that the mapping process and scripts for the South Georgia project map follow the same workflow as the process outlined below.

9.1.1. Google Earth Engine Background and Login Information

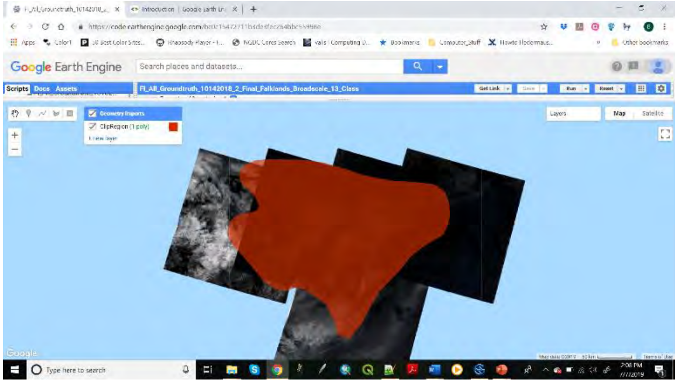


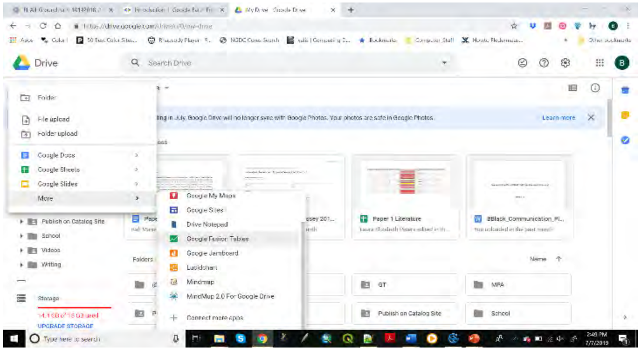
Google Earth Engine is a cloud-based platform with a user-friendly API (user interface) designed to permit users scripting capabilities (JavaScript, Python) and access to Google's library of open access satellite imagery (and related data products). To log into Google Earth Engine, go to the page displayed below (link: https://earthengine.google.com/) and click on the "Sign Up" link to start an account.

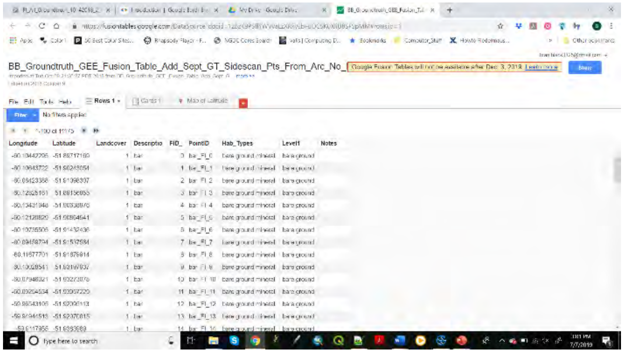
9.1.2. User Inputs and Pseudocode

This broad-scale modelling script has been set to map only the area specified by the ClipRegion polygon drawn by the user (red polygon in image below and to the right). Selecting the "Geometry Imports" dropdown menu permits users to modify the area over which the ClipRegion polygon is drawn, therefore adjusting the area mapped by the script. In the example provided, the entirety of the Falklands will be mapped.

As outlined previously in this workshop's map theory component, ground-truthing is a key component of the mapping process that impacts the ultimate quality and outcome of the mapping product. In this script, ground-truth points are collected in the field, formatted consistently (both Excel and QGIS work equally well for this step), and then imported into Google Drive (personal or business) as a fusion table (image below) with the format displayed in the image below. Please note that the landcover type recorded in the fusion sheet must be recorded in numerical format.







What follows is a summarization of the broad-scale script's important components in the form of pseudocode, a more readable format to interpret than the project's JavaScript code.

Steps described in the pseudocode requiring user input are denoted with three asterisks (***), while steps where user inputs are optional but unrequired are marked with three percent signs (%%%).

1) ***Import specified imageCollection (set of images) time/date, location and sort lowest to highest cloud cover for Sentinel 1, 2, and Landsat 8 images
    a. Note: broad-scale maps used Sentinel 1 and 2 imagery processed by Gwawr Jones at the JNCC
    b. At this point – if accessing imagery from Google Earth Engine would apply a cloud mask to extract cloudy area from series of images
2) ***Set centre of map and scale
3) Add layers to the map view if wanted
    a. Provide settings for map view
4) Import SRTM data (worldwide DEM dataset)
5) Apply a topographic correction (in this case, a cosine) to the input imagery to reduce the impact of shadows and light produced by local terrain
6) ***Import ground-truth from fusion table
7) Merge land cover types found within ground-truthing into single new point dataset "training_pts"
8) Extract values of Sentinel 1, 2, and Landsat 8 (band 1 only) to training_pts dataset

9) Extract slope, aspect, elevation, and hillshade bands from SRTM data and extract to training_pts
10) Calculate NDVI (traditional vegetative index) and extract to training_pts
11) Calculate Geary's C (association of spatial characteristics) and extract to training_pts
12) Calculate EVI (vegetative index better suited to deal with water) and extract to training_pts
13) Calculate NDWI (index to assess plant water content)
14) %%%Assign a random seed to help generate truly random number assigned to each record in the training point dataset
15) %%%Split validation data from training dataset using assigned random numbers along the input at user defined break-point (entries with random numbers above break point assigned to validation dataset, entries with random numbers below break point remain in training dataset)
16) ***Set parameters for classifier
17) Apply classifier to training dataset
18) %%%Configure confusion matrices for training and validation data
19) Display land cover classification in Google Earth Engine API using provided palette (color) options for display of each land cover type
20) %%%Export classified land cover geotiffs and confusion matrices to personal Google Drive

9.2. Useful Links

Free online course to learn basic-intermediate JavaScript (language used in project code): https://www.w3schools.com/js/

A useful website to get started on understanding Google Earth Engine's capabilities and options: https://developers.google.com/earth-engine/

10. Appendix B: Fine-scale Modelling Procedures

10.1. Fine-scale Modelling Sites

The Falkland Islands Minefield 7 and the South Georgia Gold Head study sites were introduced in Section 6.2.1.1. Several other maps at both islands were also completed in the fine-scale mapping component of this project. The sites associated with these additional maps are described below.

Falklands Sites:

10.1.1. Port Sussex

Port Sussex is located on East Falkland, on the west side of the island near Falkland Sound. It is a site with a history of the spread and subsequent treatment of the invasive weed calafate. Drone based imagery (RGB and multispectral) NDVI data was collected at this site, which was not available at other project drone-based map areas. The intent of this map was in primarily to determine how effectively the fine-scale mapping method detects smaller groupings of calafate associated with younger, newly established plants.

10.1.2. Stanley Commons and Cape Pembroke

Stanley Commons and Cape Pembroke near Stanley were mapped relying primarily upon Worldview input imagery and this combined map is the largest fine-scale map created within the project. More developed areas in and around Stanley were mapped, as well as the Cape Pembroke area that is less directly impacted by local development.

10.1.3. Steeple Jason

Steeple Jason island, to the northwest of West Falkland, was mapped in its entirety with special attention paid to the invasive sheep sorrel plant. As with the Stanley Commons and Cape Pembroke map, the primary imagery input for this map was Worldview imagery.

10.1.4. Cochon Island subtidal and terrestrial map

Cochon Island is located on East Falkland north of Stanley.This map is under development and differs from other fine-scale maps in its incorporation of additional offshore data, primarily through the addition of sidescan sonar surveys, Shallow Marine Survey Group survey data, drop camera sources, and more in-depth interpretation of kelp beds. Worldview was the primary onshore imagery source for this site.

South Georgia Sites:

10.1.5. Fortuna Bay

The Fortuna Bay site is located along the north-central shore of South Georgia near Stromness, covering the western third or so of the bay and extending about 1.5km inland. Drone surveys were the primary source of visible imagery for this site.

10.1.6. Grytviken

The Grytviken site is set in King Edward Cove, and covers the historic Grytviken whaling station. The drone survey used largely to construct this fine-scale habitat model was conducted by Geometria. Structures associated with the whaling station were mapped in the coastal north-central region of the output map.

10.1.7. Jason Harbour

Jason Harbour is situated on the western shores of Cumberland West Bay. The oceanic waters on the western side of this site had significantly higher opacity (apparently due to nearby glacial sedimentary output) than the relatively clearer waters found along the eastern coastline of the site. Drone surveys were the primary source of visible imagery utilized for this location.

10.2. Fine-scale Modelling procedures

The fine-scale modelling process was conducted using the software packages of SAGA 7.2.0 and QGIS 3.4 (Madiera, the current stable QGIS release as of Fall, 2019). Both programs are open source, and available for free download. The Random Forest classification was accomplished through the dzetsaka plugin in QGIS. Please note that to run the dzetsaca plugin, Python's Sci-Kit learn library (also open source and free to download) must be installed on the computer used to run the plugin. Both pixel- and object-based maps were produced through this process.

The first step within the modelling process entails imagery preparation. Sites with drone surveys available used those imagery as the primary source of input into the model, while other fine-scale modelling sites without drone imagery relied more heavily on Worldview 2 and 3 imagery. Drone imagery based projects had significantly longer processing times and associated project file sizes, but also arguably resulted in maps portraying finer scaled features not always captured in the Worldview based maps.

Please note that unless specified otherwise, the steps described below were run in QGIS 3.4

1) Clip area of interest in drone or Worldview imagery
    a. Note: if open water areas are not of interest, clipping water areas may reduce file size
2) Clip DEM data to footprint of land only
    a. DEMs should not extend over water
    b. DEMs used in this project were sourced from drone imagery in the case of drone surveys and SRTM DEMs for Worldview based sites
3) Run Slope tool on clipped DEM data
4) Run the Aspect tool on the clipped DEM data
5) Run an inward buffered contour from clipped DEM data
    a. This dataset helps differentiate coastal areas from more inland zones
    b. In this project, the first 200 m inland had 10 m intervals, then 50 m intervals for 300 m further inland, then 100 m intervals for another 500 m inland
6) In SAGA 7.2.0, load the imagery (drone or Worldview) of the site and run the Terrain Ruggedness Index (TRI) tool
    a. Troubleshooting step: if the tool crashes or you are unable to load the full dataset, try loading the blue band of the imagery (typically this is band 1 or 2, depending on your dataset) and running the tool on just one band
7) In SAGA, Load the clipped DEM data and run the TRI tool a second time
8) While still in SAGA, run the "Flow Accumulation (Flow Tracing)" tool on the clipped DEM
    a. Leave all values default
    b. This tool calculates the hypothetical cumulative flow from the highest points in a DEM downslope throughout the entire input file. In this model, it serves the purpose of highlighting well drained vs. "boggy" areas, even in areas outside mappable water bodies

9) Back in QGIS, use the Merge tool to collect the layers resulting from steps 1 through 8 into a single raster file (each layer will appear as its own band in the raster output from the Merge tool)

After the imagery has been prepared for use within the model workflow, it is now possible to create the segmented polygons that will be used to map identifiable features within the mapping areas. Essentially, the segmentation process vectorizes (makes a "line drawing") of features detectable within the input imagery. For example, segmenting imagery of a thicket of trees that opens into an open grassy area will produce polygons surrounding the trees and the grassy areas and allow for the automated distinction of the grassy vs. wooded areas. These segmented polygons will become the "shapes" that are classified by the random forest classifier later in the workflow.

10) Import the results of the Merge tool created in QGIS into SAGA and run the "Object Based Segmentation" tool.
    a. You can leave most settings in the Object Based Segmentation tool default, but will need to determine what bandwidth and neighbourhood method to use
        i. The ideal bandwidth varies depending on the spatial scale (size) of the features being mapped and the input imagery type. In this project, for the drone imagery, the typical bandwidth value applied was 10. Worldview imagery segmentation bandwidths were typically between 5 to 15.
        ii. Large map areas may require larger bandwidth values to run (tool may "time out" otherwise). Drone imagery likewise may time out with low bandwidth values due to its high spatial resolution.
        iii. Neighborhood was set to "Moore", rather than the default of Neumann, due to better apparent coherence between resultant polygons and features on the ground
        iv. All other values were left as default when segmenting polygons for this project
        v. If time out errors occur in SAGA while segmenting, try loading the blue band only (not all the bands in the tiff) and segmenting values based on that band alone, which will significantly reduce the processing load of the tool

Once the segmented polygons have been created, it is then possible to add the ground-truthing values to those polygons that will later be used as one of the primary inputs within the random forest classifier.

11) Load existing ground-truthing data to the QGIS project you have your compiled imagery created in step 9.
12) Finalize the classes you intend to attempt to map
    a. List the classes you determine necessary to describe all areas on your map.
        i. All land cover types within your map area must be accounted for. For example, even though you may not be interested in mapping clouds, if there are clouds present in your imagery you will need to account for them with their own class number
        ii. Chose a unique class identification number and use for entire ground-truthing dataset – the value "1" should always be associated with the same class, as should "5", "27", etc.
13) If you have a point shapefile of ground-truth points, you may want to run the Add Point Attribute to Polygon tool to update attributes of polygons with ground-truth that falls within their border

    a. Please note that the classifier will require that the ground-truth classes each have their own unique numerical value for each class – example, tussac = 1, kelp = 9, etc. No text or other special characters will work in classifier, and the field should be an integer data type.

14) Add ground-truthing to other polygons as needed
    a. Add a new integer field to the segmented polygon shapefile
    b. Add ground-truthing to a subset of the segmented polygon shapefile by updating the new integer field with the appropriate classification number within the polygons you have chosen to represent your ground-truthing areas. Please be sure to save your edits before closing the table.
        i. A minimum of approximately 100 ground-truthed polygons for each mapped class are required for reliably accurate classifications
        ii. Utilize the classification system decided upon in step 12

15) After you have completed the addition of your ground-truthing to your segmented polygon shapefile, you will need to separate your ground-truthed polygons into validation and training datasets.
    a. First, select all polygons in your segmented shapefile that have ground-truthing values assigned to them (for example, all polygons with values in the ground-truthing field you added in step 14a greater than one)
    b. Export these selected polygons to a new shapefile containing only ground-truthed polygons
    c. In the selected polygons shapefile, create a new integer field. Run the "Random Selection" tool in QGIS to randomly select 20% of the polygons within the shapefile.
    d. Go to the selected polygons shapefiles's attribute table, make sure you are in "Editing" mode (the pencil icon on top-left of screen), display only the selected polygons (dropdown menu in bottom-left of screen will allow you to do so), and then select the field you wish to edit in the dropdown box (just below the pencil editing tool icon in top-left part of screen), then enter a value of "1" (no quote marks) into the box just to the left of the dropdown box you just selected the new field with.
        i. By creating a new integer field in the ground-truth only polygons shapefile, randomly selecting 20% of those ground-truthed polygons, and then recording a value of "1" in those randomly selected polygons (while leaving the remainder of the polygons with either a "0" value or "null", depending on how the field was created), it becomes possible to split your ground-truthed polygons into randomly categorized groups comprising 20% and 80% of the entire ground-truthing dataset.
        ii. In the QGIS Content window (far left side of the main QGIS map viewing screen where layers are displayed), right click on the selected polygon shapefile you have been working in and go to "Export" and the choose the "Save Selected Polygons As" option to save the new **validation** shapefile
        iii.
            1. The 20% of randomly selected polygons will become the **validation dataset** for the classifier
            2. The 80% of the randomly selected polygons will become the **training dataset** for the classifier (more on creating the training dataset in steps 15i-j)
    e. The randomly assigned 20% of total points denoted with a value of "1" in the new integer field can then be exported as the training dataset

f. While the 20% of the total polygons are still selected, leave the attribute table of the polygon shapefile you have been working in and go instead to the same shapefile in QGIS's table of content and right click on the selected polygon shapefile you have been working on
g. Go to "Export" and choose the "Save Selected Polygons As" option to save the new **validation** shapefile
h. Go back to the attribute table o the selected polygons shapefile
i. Click on the "Invert Selection" icon (a white and yellow triangle in the shape of a square located in the top-middle portion of the attribute window)
    i. The remaining 80% of points are now selected
j. Repeat step 15g to export the new **training** shapefile
k. You now have two new ground-truthing datasets for use in first running the Random Forest classifier (the **training** shapefile) and then verifying output map land cover class accuracies (the **validation** shapefile)

Now that your imagery has been processed and your ground-truthing training and validation shapefiles are completed, you can now move on to running the Random Forest classifier in the dzetsaka plugin in QGIS.

16) In QGIS, after having installed the dzetsaka plugin (which requires that scikit-learn Python library has been installed on the computer you are running the dzetsaka plugin in from), launch dzetsaka from the "Plugin" menu (chose the "Classification Dock" for easy access to important plugin features in one interface)
17) In the first dropdown box (to the right of the blue checkerboard raster icon), select the final raster you created in step 9 (you may need to ensure that raster has been loaded to your QGIS project before you can select that layer from the dropdown menu)
18) In the next dropbox below, select the **training** shapefile you created in step 15j
19) In the third dropdown box (to the right of the small "table" icon) select the name of the integer field in the **training** shapefile that has each polygon's ground-truth type recorded to it
20) Select the "Settings" icon (icon of a gear) to adjust plugin settings. The plugin will default to "Random Forest" as the classifier type.
    a. Note: it is possible to control more settings on how the model is run by selecting the "Load Model" option
21) Click the "Perform the Classification" button once all settings are loaded
22) Let the plugin run at this point.
    a. Smaller map areas or lower resolution imagery will run faster in the plugin than higher resolution imagery or larger map areas
    b. The model could run as quickly as in a few minutes for a small map (such as of a single small beach) or two hours (across several kilometres of Worldview imagery)
    c. Important note: it is very likely that after the first time you run the dzetsaka plugin and visually inspect the resultant raster, you find cases where the classification did not function completely properly – such as misclassification of the edge of clouds as "bare earth" or the indication of the incorrect vegetation type in shadowed areas. In order to address such errors, familiarize yourself with the map results from the plugin, then add further ground-truthing in the same site settings that were found to often be misclassified (example: specify further "wispy" cloud polygons as being "cloud" to better later familiarize the classifier with the full range of how cloudy pixels are represented within the imagery, reducing the likelihood that pixels that are actually cloud will be misclassified as bare earth)

23) In QGIS, go to the "Zonal Statistics" tool.
    a. For Raster Layer, select the raster you just created with the dzetsaka plugin
    b. For Vector Layer Containing Zones, select the original full segmented polygon you created in step 10 (not the ground-truth -only segmented polygons)
    c. In the Statistics to Calculate, make sure at least one of the statistical options checked off is "Majority" (same thing as a statistical mode – which will report the most commonly occurring pixel type (land cover classification) that falls within each segmented polygon
24) Run the "Dissolve" tool on the output of the "Zonal Statistics" tool from step 23
    a. There are multiple "Dissolve" tools available in QGIS. Whichever version is chosen, import the zonal statistics polygon as the input layer, and select the field you recorded "Majority" to from the Zonal Statistics" tool
        i. Aggregating polygons with the same recorded land cover classification makes the visual interpretation of the map results much simpler
    b. The "Dissolve" tool will combine adjacent polygons with the same recorded classification type
    c. If after running the "Dissolve" tool small detached lines remain inside the dissolved polygons, try running the "v.clean" tool on the dissolved polygons

In order to create an accuracy assessment of "how well" the classifier performed on a class-by-class basis, a confusion matrix can then be prepared. In the confusion matrix, the land cover classes within a classification map are compared to a **validation** dataset separated from the training dataset used to create a classification map. The number of times the mapped classification matches the **validation** dataset is recorded, as well as the number of times each other type of land cover class is misclassified (and what class that misclassification fell into) for each other validation point. The results of this analysis are reported to a table – the confusion matrix

25) In order to run the confusion matrix on the classified map and **validation** dataset, load the classification map to be assessed and the **validation** dataset shapefile, and then open SAGA and search for the "Confusion Matrix ("polygon/grid" for assessing object-based classifications, two grids for "pixel-based classifications") tool.
26) Select the classified map to be assessed
27) Under value interpretation, go to "Values are Class Identifiers"
28) In the "Shapes" section, select the **validation** dataset shapefile, and set the integer field used to record the ground-truth in the "Classes" dropdown
29) After the "Confusion Matrix" tool has run, you can right click on the resultant file and export the tool's findings as .csv files.

11. Appendix C: Drone mapping protocols developed by the DPLUS065 Coastal Habitat Mapping project, highlighting the challenges associated with operating drones in remote, windy locations.

11.1. Legal & permitting requirements

Any drone flights within UK Overseas Territories must comply with the Air Navigation (Overseas Territories) Order 2013[11]. As a rule of thumb, flights should typically take place no higher than 400ft (~121m) and drones should be operated within Visual Line of Sight (VLOS). However, it is the drone pilots' responsibility to ensure they are operating within the law prior to any drone flight.

Within the Falkland Islands, specific terms and conditions will be specified in any permissions or exemptions for Aerial Work granted by the Falkland Islands Civil Aviation Department (FICAD). In the vicinity of Stanley and RAF Mount Pleasant Airport, permission should be sought from air traffic control due to Falkland Islands Government Air Service (FIGAS) and military flights. Note that DJI have recently (May 2019) implemented geo-fenced no-fly and flight restriction zones around these locations, through their Fly Safe Database updates. A Research Licence from Falkland Islands Government is also required for any environmental and scientific research undertaken in the Falklands, regardless of whether a drone is used[12].

Within South Georgia, an application for operation of a Small Unmanned Aircraft (SUA) must be made to Air Safety Support International (ASSI)[13], on behalf of the Government of South Georgia & the South Sandwich Islands. A Regulated Activity Permit[14] is also required prior to any research/work commencing on South Georgia. Permitting is subject to various conditions, so please check each Government website (www.gov.gs) for the latest rules and regulations.

Legal and permitting requirements vary between Territories, and it is ultimately the drone pilot's responsibility to ensure they are operating within the law.

As part of the Coastal Habitat Mapping project drone operations, SAERI developed an Operations Manual which provides details of how drone flights will be conducted, as well as standard operating protocols and risk assessment procedures. A copy can be found in *12. Appendix D*. SAERI also holds a Standard Permission for Commercial Operation (PfCO), issued by the UK Civil Aviation Authority. While this permission is not currently required by law in the Falklands or South Georgia for scientific research (this or equivalent is required for commercial work), future legislative changes may make this a requirement in the future, and we would recommend that some form of formal pilot training is factored into scientific research projects where drone use is planned.

[11] http://www.legislation.gov.uk/uksi/2013/2870/contents/made
[12] http://www.fig.gov.fk/epd/environment/19-environment/63-research-licence-application
[13] https://www.airsafety.aero/Aircraft/Small-Unmanned-Aircraft-(SUA).aspx
[14] http://www.gov.gs/visitors/regulated-activity-permit/

11.2. Effective mission planning

The MapPilot iOs app was used for mission planning. The MapPilot app has the ability to plan multi-battery missions, as well as having a terrain awareness function, which utilises the Shuttle Radar Topography Mission[15] global digital elevation model to vary the altitude of the drone during the mission to maintain a near-constant field of view. The app performed well, allowing the saving of mission planning data (such as base maps and terrain data) whilst connected to the internet, to ensure that this information was available when in the field where no internet was available.

At least 24hrs before the mission, a pre-flight assessment should be completed. This is effectively a risk assessment which details information such as expected terrain, weather, permissions for land access and airspace access, and other aspects to consider. This includes contacting landowners, air traffic control etc. A written record should be made of who was contacted, and when.

A variety of mapping missions can be planned, with the one of the primary considerations being the density and elevation of images over the region of interest. Reconstruction of orthomosaics and Digital Terrain Models requires a high density of images that provide overlapping views of the landscape. A typical sampling strategy will establish a grid of aerial transects. This method was employed by the Coastal Habitat Mapping project.

Minimal imaging densities will depend on the flight elevation along with the topographic relief and complexity of vegetation elevation. Higher densities of images may be needed to ensure that there is adequate image overlap in portions of the landscape that are between large bushes or other vegetation such as tussac. The Coastal Habitat Mapping project typically used an along track and across track overlap of 80%, which yielded good results. The camera angle was pointing vertically downwards along the nadir.

11.3. Geographic location & scale

Consideration should be given to both geographic scale and location when considering if drone mapping surveys are appropriate.

Geographic scale relates to the size/extent of your study area. It is important to bear in mind that small drones such as the Phantom 4 Pro have a maximum flight time of around 25 minutes (assuming you return to home with 20% battery life, which is best practice). Flight time can be reduced to 15 minutes with additional payloads (such as a multispectral camera). When planning your mapping survey, consideration should also be given to the size of the area, in relation to line of sight distances. The law requires that visual line of sight (VLOS) must be maintained at all times, so it will be necessary to split your survey area into smaller sections of approximately 1km in width when mapping larger areas. This distance could be extended if the pilot could move in the direction of the flight path, but this is generally not advisable on foot, as walking in rough terrain while trying to track the drone is challenging and potentially dangerous. An example of how this may be done is shown below in Fig.C1, with a large (270 hectare) survey area at Fortuna Bay, South Georgia, split into three sections.

[15] https://www2.jpl.nasa.gov/srtm/

Apart from weather conditions, the main limiting factor for coverage during a drone mapping mission is battery life. Having multiple batteries available is advisable; the mission shown in Fig C1 required 11 batteries.

It is important to consider anticipated environmental conditions where you will be undertaking drone-mapping missions during the planning process. The Coastal Habitat Mapping project flew mapping missions in both the Falklands and South Georgia; each had their own challenges, both from a weather and logistics perspective.

The Falkland Islands are typically characterised by predominantly windy, rapidly changing weather and light conditions. Ideal conditions and timings for drone mapping surveys are light/no winds and overcast conditions around midday. However, in reality, aerial mapping surveys were completed when wind conditions permitted, regardless of time of day and whether in sunny or cloudy conditions. Realistically, there will likely be one or two days per week when drone flying may be possible. Weather forecasting apps such as UAVForecast provide useful information on wind speed (including gusts) at different altitudes. Internet connectivity, while available in Stanley (note that bandwidth is very low), is more limited out in Camp. Mission planning apps such as MapPilot require internet connection to download basemaps and terrain data, but they allow you to save missions for offline use away from an internet connection.

South Georgia is also characterised by windy, rapidly changing weather, although depending on location, there are typically longer periods of favourable weather, which may provide a wider weather window for drone mapping operations. Lack of internet connectivity can provide a challenge for planning drone missions, requiring that missions are planned/saved offsite for use offline. If operating from a vessel, which would be the norm around South Georgia unless operating from around the King Edward Point Research Station, having access to satellite data & internet connectivity from providers such as Iridium/MailASail is advantageous. Terrain on South Georgia presents its own challenges and use of the terrain-awareness functionality within MapPilot (which alters the flying height of the drone in line with SRTM DEM data) proved to be very useful in ensuring that the field of view remained relatively constant.

11.4. Data management

Aerial imagery, whether from satellites or UAVs, takes up significant amounts of storage capacity. The imagery alone from the Fortuna Bay mission on South Georgia (Fig. C1) required 33GB of storage space. Note that this data was recorded as JPEG images; depending on the features being mapped, it may be necessary to record images in a proprietary RAW format, which will require even further storage space.

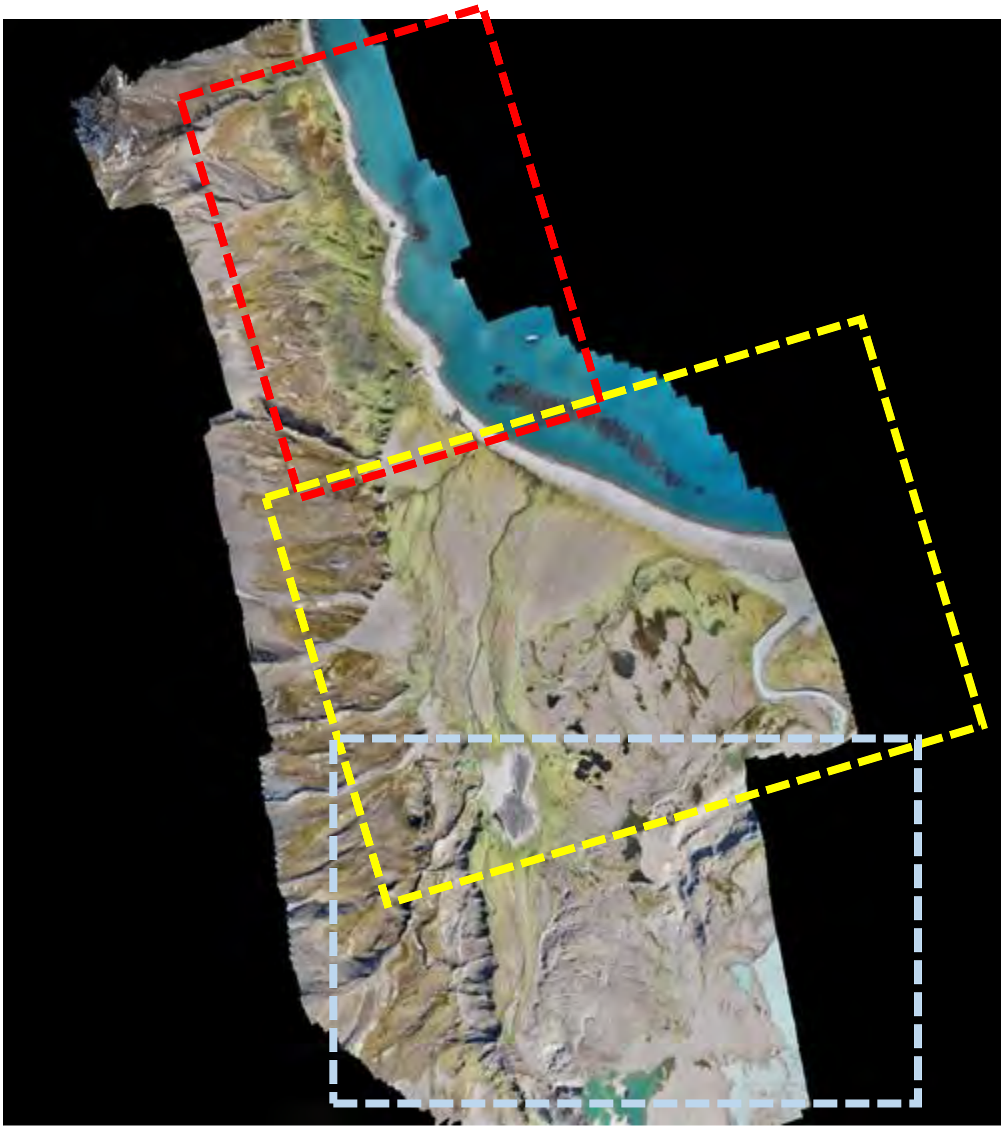


Figure C1: Fortuna Bay, South Georgia. This drone mapping mission was split and flown in three sections, ensuring the VLOS between the pilot and the drone was maintained at all times.

11.5. Processing imagery

There are a variety of software solutions available, both open source and commercial, for the photogrammetric processing of UAV imagery. The Coastal Habitat Mapping project used AgiSoft Metashape[16]. Agisoft requires a very fast workstation, ideally with significant amounts of memory (recommend at least 64GB) and at least one (ideally two) very powerful graphics cards (such as one designed for CAD/PC gaming). Processing the data in low quality is extremely useful for undertaking validation checks of the data following data collection; processing at higher quality takes longer. A variety of products can be made from the UAV imagery – the output primarily used was the orthomosaic (as seen in Fig. C1), and this was taken forward for creation of the fine-scale habitat models as outlined in Section 6.2.

[16] https://www.agisoft.com/

12. Appendix D: SAERI Commercial & Research Flight Operations Manual

https://www.south-atlantic-research.org/wp-content/uploads/2019/12/026a-SAERI-Commercial-Research-Flight-Operations-Policy_v1_5.pdf

13. Appendix E: Field protocols for ground-truthing

A short field protocol was established for collecting ground-truthing data during the DPLUS065 Coastal Habitat Mapping project:

13.1. Instructions in the field

1. Locate a habitat/feature and navigate to the most central point of the habitat. ***See Suggested way of taking the points (Section 13.1.2).***

2. Record a GPS point on your device, you may want to wait a few seconds/minutes for the device to calibrate.

3. While the GPS point is being recorded, fill in the recording form.

4. Take a picture of the habitat from above, to mirror what satellite images would see, and of the surrounding landscape to provide context for the habitat/feature. ***See Suggested order of the pictures (Section 13.1.3)***.

5. Take a photo of your recording form.

13.2. Suggested way of taking the points

For each habitat: if the environment comprises of various habitat try to provide the same amount of point per habitat type and try to scatter the points as much as you can. DO NOT FORM CLUSTERS (see Fig. E1).

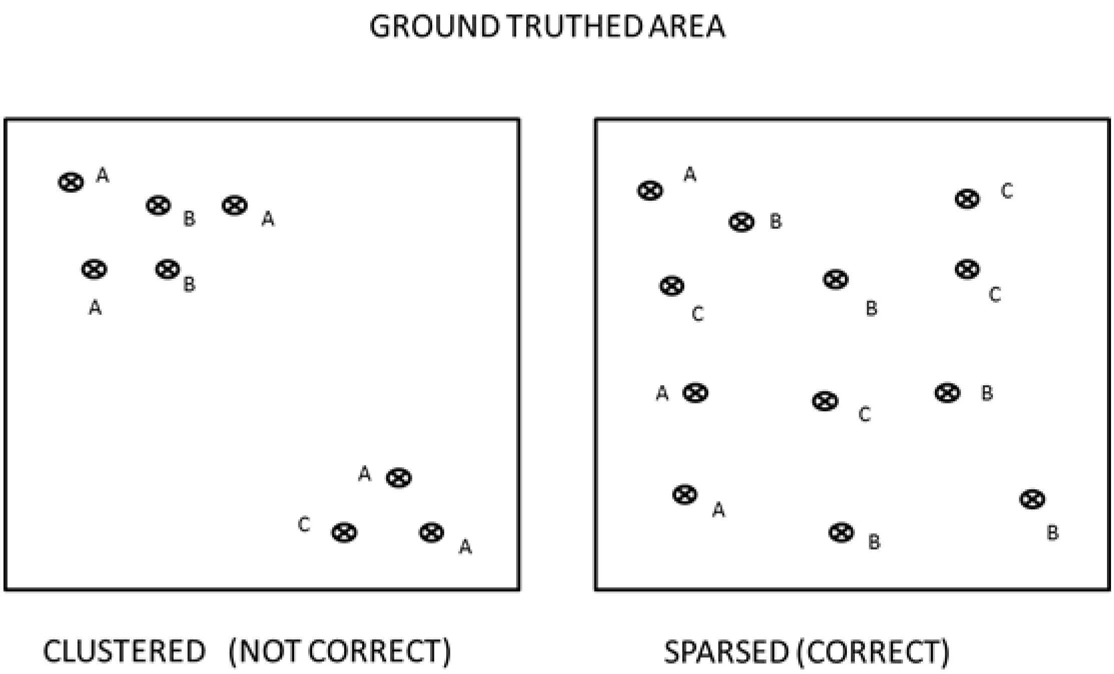


***Figure E1**: Clustered points versus sparse points. The rectangle is a simplification of one of the areas of study and the points are the locations at which sampling occurs.*

Below is an example of a suggested way of sampling point and matching imagery habitat based on resolution of imagery available. The various shapes represent different habitat types called A, B, C and D. It is suggested that surveyors should:

- assume that the highest resolution of imagery is available and work at the finest scale
- consider the dominant habitat in each finest patch and classify the location point according to the dominant habitat
- locate themselves in the middle of the habitat that they are going to sample

Although in the example below (Fig. E2) there are sampling points every 10 metres, surveyors are not requested to sample at this distance everywhere. For instance, if the surveyors are in an area where one habitat dominates extensively (more than 2,500 square metres) they can gather a point in the middle of the habitat. If the surveyors are in an area which has a more fragmented habitat, then sampling the transitions (the point at which the habitat changes) is important and more points are needed. In a location with fragmented habitat surveyors must be aware of the coverage of the transitions. If a transition is less than 100 square metres it will not be visible from the satellite, and therefore it is not necessary to record any points, but surveyors should make a note in the recording sheet and classify the habitat according to the most dominant features.

In the image below (Fig. E2) in the first three cells, habitat B (triangles) breaks the continuity of habitat A (circles), however, not in way that is visible to the satellite. Hence the surveyors should consider that entire area as habitat A.

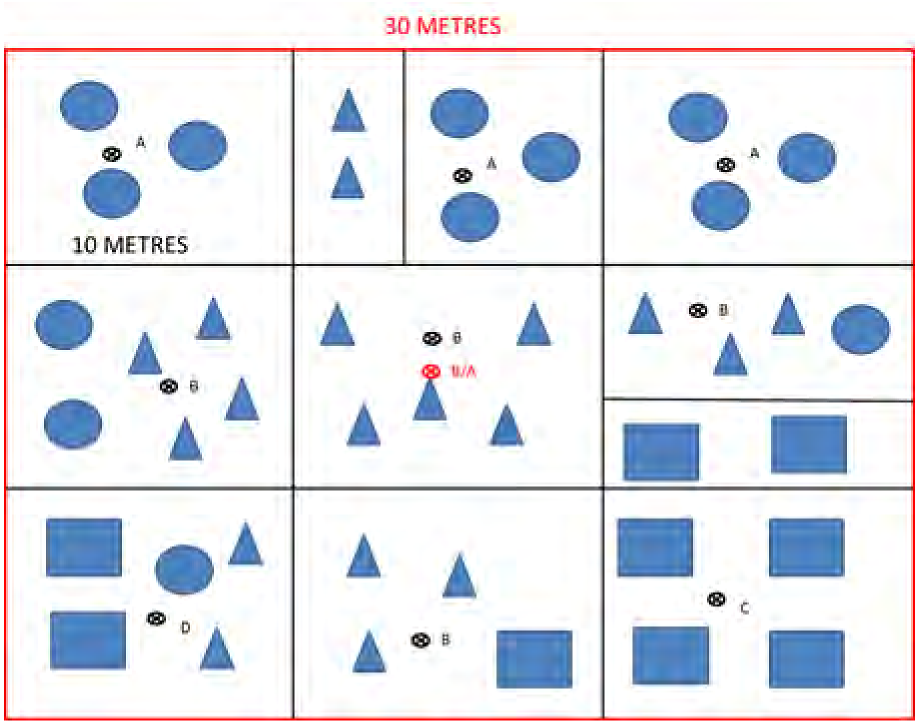


Figure E2: *Example of a suggested way of sampling with consideration to image resolution. This example is related to Sentinel-2 imagery (10m spatial resolution), and Landsat imagery (30m spatial resolution).*

13.3. Suggested order of the pictures

First photo ground, second photo looking north, third east, fourth south, fifth west. Sixth photo (always the last one) your recording sheet. Please follow the order as much as you can and try to get a single picture for each shot. As soon as possible after your recording session has ended, save your images to a designated folder, ensuring that files are appropriately labelled in a manner that will allow anyone using the images to easily cross reference them to corresponding metadata including site and GPS point.

13.4. Data backup

Data from the GPS and camera devices should be backed up daily on the provided external memory drive.