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Summary:	This document indicates the procedure to survey the coastal zone using high-resolution multispectral or hyperspectral sensors on board aircraft. It gives hints on the variety of systems available and the feasibility of getting low-tide imagery. It also looks at post-processing the imagery to produce documents ready for use by habitat interpreters.
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Recommended operating guidelines for airborne digital imagery

1. General principles of operation

This section deals with the main aircraft-deployed (planes, helicopters) electro-optical data acquisition techniques used to help in the fine-scale physical characterisation of the seafloor. When applicable, these techniques can generally provide large coverage data on seafloor topography and/or benthic habitat conditions. They are widely used for mapping both the tidal zone and also clear and shallow waters.

Although of very high spatial resolution in which satellite data are now becoming available, the lack of flexibility in the timing of data acquisition is still a limitation. The main advantages of airborne remote sensing for the coastal environment are its greater spatial resolution and the ability to obtain data at optimal times (e.g. with respect to weather conditions and the tidal cycle). Also, many airborne instruments have greater spectral resolution and programmable wavebands. The greater spatial resolution of airborne optical remote sensing has been useful for relatively limited site-specific areas. However, there are major problems with the georegistration of airborne images because aircraft movements generate distortions that are difficult to correct. Nevertheless, successful examples have been provided by Bajjouk (1996) in France and Yates *et al.* (1996) in the UK.

Most of the airborne electro-optical techniques operate within the visible and near infrared portions of the spectrum (400-900 nm), which can penetrate water to certain depths (Table 1). Ten metres of clear ocean water can transmit almost 50% of the incident blue and green wavelengths (400-600 nm) and less than 10% of the red light (600-700 nm) (Sabins 1997). They may also support spectral bands in the mid-infrared that allow further distinction between vegetation types and other features.

Many private sector vendors are currently deploying airborne multispectral (MS) camera systems (Table 1). These sensors are complex systems, incorporating multiple cameras, different storage solutions, airborne inertial measurement units (IMU), Differential Global Positioning Systems (DGPS), and specialised software for georeferencing, mosaicking and colour balancing. These multispectral systems can collect stereo black and white, colour infrared, and true-colour imagery using a single pass at the customer-required ground resolution.

Sensors are said to be ‘multispectral’ when they feature a combination of a limited number of spectral bands (e.g. the Daedalus multispectral imager) and

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‘hyperspectral’ when they have a higher number of spectral bands (e.g. the CASI – Compact Airborne Spectrographic Imager).

Table 1. Specifications for a few of the existing airborne multispectral systems (from CSC NOAA website: *http://www.csc.noaa.gov*).

Sensor	Sensor configuration	Spectral Resolution	CCD Array	Radiometric resolution
Z/I Imaging DMC	4 lenses (pan), 4 lenses (Multispectral)	4 MS bands (B,G,R, NIR)	MS 3 K X 2 K	12 bit
		1 band panchromatic	PAN 7 K X 4 K	
LEICA ADS 40	Single lens with beam splitter	4 MS bands (B,G,R, NIR 1, optional NIR 2)	12 K X 2– pushbroom sensor	8 bit
		1 band panchromatic (visible range)		
Geovantage GeoScanner	4-lens system	4 MS bands (B,G,R, NIR)	1.4 K X 1 K	8 bit
Applanix Emerge DSS	Single lens with beam splitter	3 MS bands (B,G,R) or (G,R,NIR)	4 K X 4 K	12 bit

Today, airborne multispectral camera systems are usually based on Charge Coupled Device (CCD) arrays and fall into two categories: frame sensors, which use square or rectangular CCD arrays (and have geometric characteristics similar to those of a film camera), and line sensors (‘pushbrooms’) or scanners, which use linear CCD arrays and therefore have geometrics similar to satellite sensors.

The main factors complicating multispectral mapping of coastal areas are similar to those limited satellite imagery; namely clouds, narrow tidal windows, atmospheric effects and, in shallow water, the attenuation affect of the water column overlying submerged vegetation. Clouds can be avoided and imagery obtained during low-tide windows by careful planning of aerial data acquisition. Cloud-free mosaics can usually be generated, even with 40% cloud cover. The other effects can generally be minimised or eliminated during image processing. In the case of CASI or other such instruments, multiple narrow bands and small pixel size are critical when the objective is to distinguish vegetation types in a heterogeneous environment (such as a marsh) and when mapping linear vegetation features (such as algae along a shoreline).

Hyperspectral sensors are generally mounted on light aircraft, but can also be placed on satellite platforms. Data are collected at contiguous, narrow-band wavelengths for a specifically defined portion of the electromagnetic spectrum (usually between 400 and 900 nm). In order to determine what the reflectance represents, the reflected spectral data obtained by the hyperspectral sensor are compared and matched to spectral data of known absorption features. While spatial resolution depends on the altitude of the aircraft and usually ranges between 1 and 20 m, the spectral bands measured and the

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bandwidths used can be programmed to meet user specifications and requirements. Using a high number of bands results in a compromise within resolution as both vary conversely. Hyperspectral imaging also has its limitations in that it has limited availability and may not be cost-effective. Also, because of its capacity to collect several hundred bands of data at high resolution, somewhat advanced software is needed to process and analyse these data.

2. Variety of systems available

2.1 Compact Airborne Spectrographic Imager (CASI)

The Compact Airborne Spectrographic Imager (CASI, manufactured by Itres Instruments Ltd of Calgary, Canada) is a pushbroom sensor that simultaneously acquires data in up to 288 visible and near IR channels between 0.4 and 1.05 µm for the latest CASI-3 sensor. CASI has become a very widely used system over the last ten years and many references are available. Several studies have shown that among the 288 spectral ranges, 11 non-continuous ones (Table 2) can discriminate intertidal vegetation (Berry *et al.* 1997). Studies showed that some bandsets could be used especially for intertidal habitat mapping (Thomson *et al*. 2003). In order to obtain ground-truth data on which to base the habitat analysis of the imagery, a ground-level survey must be made of the areas surveyed. Pure beds of the target habitat classes can be identified in the imagery from GPS coordinates, and from them spectral signatures are generated for each of the classes (Figure 1).

Table 2. CASI bands used for intertidal discrimination purposes (from Berry *et al.* 1997).

Band	Wavelengths	Purpose
1	470-515 nm	Chlorophyll *b* absorption at 480 nm; Carotenoid reflectance peak at 500 nm; Penetration of clear water
2	540-560 nm	Green vegetation reflectance peak (eelgrass and green algae); Penetration of turbid water
3	575-590 nm	Brown algae absorption well
4	600-615 nm	First reflectance peak for brown algae
5	625-635 nm	Well between reflectance peaks for brown algae
6	640-655 nm	Second reflectance peak for brown algae, chlorophyll *b*; Absorption at 650 nm (eelgrass)
7	670-690 nm	Absorption well for chlorophyll *a* (all vegetation)
8	704-714 nm	Red rise, near infrared reflectance for shallow submerged and floating vegetation, but avoiding 720 nm water vapour feature
9	743-755 nm	Near infrared reflectance for submerged and floating vegetation, but avoiding 762 nm water vapour feature
10	775-786 nm	Near infrared reflectance for emerged and marsh vegetation,

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11	854-876 nm	substrate delineation

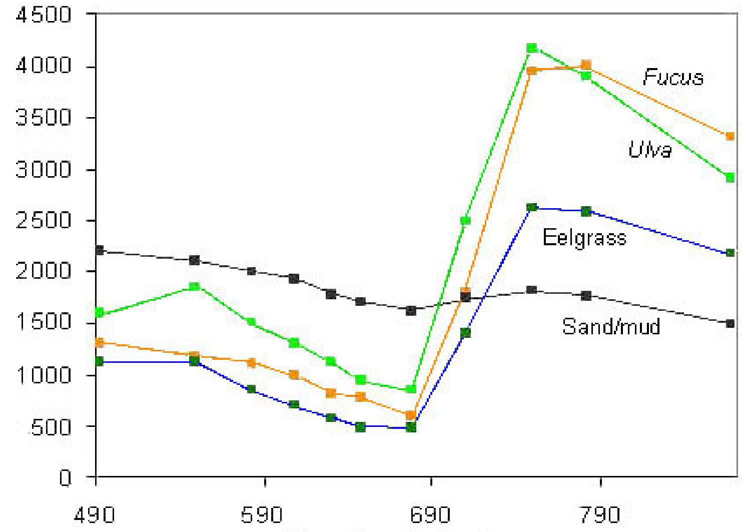

Figure 1. Spectral signatures for representative Prince Rupert Harbour habitat classes (Canada) (from *http://web1.borstad.com/papers/rupertpaper.html* : Mapping Intertidal Habitat in Prince Rupert Harbour, 1996).

While spatial resolution depends on the altitude of the aircraft, the spectral bands measured and the bandwidths used can all be programmed to meet the user's specifications and requirements. Such hyperspectral sensors can be important sources of diagnostic information about a specific target's absorption and reflection characteristics, effectively providing a spectral 'fingerprint'.

2.2 Daedalus Airborne Thematic Mapper (ATM)

The Daedalus AADS1286 Multi-Spectral Scanner (ATM) records across a swath of 716 pixels (covering a wider angle than CASI) in 11 fixed wavebands (Table 3) covering visible, near, middle and thermal infrared. The scan mirror has three synchronised speeds (12.5, 25 and 50 Hz) to optimise the scan-rate to more closely match data acquisition and coverage over the ground at various altitudes, thus avoiding any under-sampling or too much over-sampling of the data in the along-track (flight-line) direction. Approximately 10% overlap of successive scans is normally used to avoid missing areas on the ground caused by changes in aircraft velocity or attitude. Actual pixel size (ground spatial resolution) will be dependent on the aircraft's altitude, since

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the ATM sensor has a fixed Instantaneous Field of View (IFOV) of 2.5 mrad (~0.14°).

Table 3. Spectral bands available from the Daedalus ATM and current satellite systems (from Thomson *et al*. 2003 and http://www.airtargets.com.au webpage).

Wavelengths (µm)	**visible**						**near infrared**		**middle infrared**		**thermal infrared**
	420-450	450-520	520-600	605-625	630-690	695-750	760-900	910-1050	1550-1750	2080-2350	8500-13000
Daedalus 1286 ATM	1	2	3	4	5	6	7	8	9	10	11
SPOT satellite	-	-	PA (Panchromatic mode)				-	-	-	-	-
	-	-	XS1	XS2			XS3	-	XS4	-	-
Landsat TM satellite	-	1	2	-	3	-	4	-	5	7	6

3. Planning considerations

Airborne operations must be carefully planned to cover all eventualities. Weather conditions obviously have to be suitable for passive imagery; preferably blue sky conditions or alternatively homogeneous high cloud cover that provides uniform downwelling sunlight.

Besides seeking low-tide situations, the season should be chosen with respect to plant phenology and light conditions as well as the period of the day. Generally, sun elevation that could generate glint in the imagery should be carefully avoided. This happens when sun incidence is close to sensor maximum incidence angle.

If underwater mapping in the shallow zone is contemplated, low turbidity conditions will be required. This may mean surveying in neap-tide conditions, depending on the oceanographic conditions of the area.

A comprehensive review of surveying the coastal zone with CASI and interpreting its data are given by Brown *et al*. (2003) with a focus on Special Areas of Conservation (SACs).

4. Post-processing the imagery

Remote sensing data processing means the operations necessary to bring the imagery into a state where it can be delivered to interpreters. These operations are covered in *Progress in Phycological Research*, Volume 12,

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Chapter 4 (Round & Chapman 1997), as well in the *Remote Sensing Handbook for Tropical Coastal Management* (Green *et al.* 2000). Basically two types of processing are concerned:

- Geometric corrections are required to georeference the imagery, i.e. to plot the data into a mapping system, ensuring registration with other data. These corrections are made necessary because both satellite and airborne platforms only deliver raw imagery. The viewing geometry and the platform attitude are, however, both precisely known, making it possible to resample the imagery at a given mapping reference. Depending on the way these corrections are performed, any section of satellite data can be assigned a position with accuracy to within a decametre (while airborne data are currently accurate to a metre, see below). It is noteworthy, however, that despite an absolute position (still closely dependent on pixel resolution), relative accuracy (i.e. the internal coherence of the imagery) is excellent in satellite imagery thanks to the stability of the space platform.

- Radiometric corrections are required for any remotely sensed data, whether satellite or airborne, in order to retrieve highly defined quantity; the normalised measurement of backscatter called reflectance. The intrinsic feature of a ground target when imaged by an electromagnetic system is its ground reflectance. This quantity, being unique to a given target, can be compared and monitored over time. Most systems, however, fall short in measuring reflectance in two aspects: a) they are too far from the target and only record 'at-sensor radiance', so reaching ground reflectance will then require some additional effort; and b) the radiance itself is affected by atmospheric noise, i.e. the influence of the air column between the ground and the sensor. While some users are satisfied with the relative value (the radiance) allowing one-time classifications, others need to retrieve reflectance, as the only way to deal with multi-date studies. These corrections have been fully described by Green *et al.* (2000). They are performed either by using invariants (stable targets whose reflectance is known once and for all) and regression or by using special software which takes the atmospheric content into account.

5. Current usage

Airborne digital imagery is at a crossroads, as the various techniques are tending to converge in terms of current capabilities. On one hand, satellite imagery is currently reaching metric resolutions in colour mode, and improved platforms and ground segments are capable of delivering high-quality homogeneous imagery in requested time windows, which makes it a strong competitor for airborne techniques. On the other hand, airborne cameras

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show very promising swath, resolution and sensitivity with the latest CDD arrays (12,000 pixels), although they operate only in a few classical spectral bands (typically B,R,V and IR) and are still prone to technical flaws.

Formerly, elevation and planimetric data had to be acquired in two separate surveys: a) a colour photography survey (with a choice between true colour and infrared colour); and b) a black and white photography survey for relief extraction by stereoscopy. Note that IRC (infrared colour) surveys were very rare, as they only satisfied a small community dealing with vegetation. In terms of heights, obtaining vertical accuracy of 25 cm required photographs on a scale of 1:12,000.

By flying today's cameras at proper altitude (similar to conventional aerial photography, i.e. in a range of 2000-4000 m), it is possible to achieve in a single flight: a) pixel size of 25-50 cm; b) vertical accuracy of 25 cm obtained by stereoscopy either sideways with sufficient overlap between flightlines or in backward/forward mode; and c) high rate of coverage.

Processing atmospheric effects, which is compulsory for data acquired at such altitudes, has become commonplace. Besides, the 12-bit sensitivity of recent CCD arrays allows easier band matching for seamless mosaicking (edge effects being a well-known complication of classic aerial photos). This improved sensitivity also allows more efficient automatic correlation in less textured areas, a key condition in order to keep vertical accuracy nominal overall. The associated DTM is then used to produce digital ortho-images.

As a result of these advances, multipurpose ortho-image mosaics with full four-band capability are now readily available for use by various practitioners, as well as by the wider public. Costs are expected to be around €100 per km², which is a cheap alternative to other combinations of sensors (see CASI and LIDAR). The benthic mapping community will, however, have to accept vertical accuracy of only about 25 cm at best, which may be of limited value for some habitats, such as macrophyte belts.

CASI-type hyperspectral instruments remain rare and highly specialised. Although apparently quite versatile, airborne systems will always suffer from a few inherent limitations, namely the need for very clear days (especially when a higher flight altitude is required) and the low geometric quality of the data, which require considerable work to be produced in geo-registered mosaics.

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