SMALL FORMAT DIGITAL AERIAL PHOTOGRAPHY FOR MAPPING AND MONITORING SEAGRASS HABITATS IN SHALLOW TEMPERATE MARINE WATERS

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Dedication

To my beloved Marylyn, who glows brighter than any sun glitter could ever do…
Declaration

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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The majority of Chapters 1 and 2 is in press as:


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Abstract

Seagrasses are core components of the nearshore environment and there is sustained interest in developing mapping and monitoring techniques of their extent and condition for management purposes. An identified gap in mapping methods is the capacity to monitor at landscape scales, that is, areas that are larger than the 1 m² quadrat and smaller than those covered by broad area mapping (approximately 5km² or greater). Monitoring at the landscape scale is required to investigate the dynamic patterning and patchiness present in seagrass beds, as well as providing inputs and validation for predictive modelling. However, the acquisition and use of remote sensing images for these purposes provides many challenges to the practitioner. The primary aim of this thesis is to develop effective optical remote sensing techniques for mapping and monitoring seagrass habitats in shallow temperate marine waters, over depth ranges of approximately 0-10 m and spatial scales of hundreds of square metres.

Image capture is often compromised because of environmental conditions, such as sun glitter, water clarity, cloudiness and wind. Small format digital aerial photography was selected as the remote sensing platform for its flexibility and responsiveness regarding deployment when environmental conditions are favourable and its low cost, rapid access to imagery. To address the problem of sun glitter, a simplified algorithm was developed that allows the precise prediction of the extent of sun glitter on vertical, downward-looking imagery with the readily available inputs of sun elevation angle, wind speed and sensor field of view (FOV). Subsurface illumination was also investigated via the modelling of reflection and refraction at the water surface. These improvements and investigations enable more efficient and accurate image capture. Problems are also typically encountered during image interpretation, in part due to the characteristics of the seagrass habitats, including the common occurrence of uncertain boundaries and the high variability of vegetation density. Limitations on the detectability of the maximum depth limit (MDL) of seagrass were examined, with the discovery that if imagery is captured when water clarity is higher than the annual average, the limiting factor is the contrast between the seagrass and the surrounding substrate or submerged aquatic vegetation (SAV). A simple and inexpensive measurement of water clarity, Secchi depth (Zsd), was found to be suitable when applying this monitoring method. These findings have substantially increased the feasibility of monitoring seagrass condition and extent via the MDL, as well as the water quality parameter of average annual water clarity (Kz).

A major challenge for image interpretation is presented by the high attenuation of light in water, which often means that spectral methods of image analysis, such as image classification, produce poor results. In response, an improved depth correction approach
was developed that uses digital bathymetry (DEM) to assist in removing the spectral attenuation of light by the water column. The method lifted the accuracy of mapping seagrass epiphyte abundance (i.e. the amount of associated algae including epiphytic and drift algae present, related to biomass) by an average 25% to an overall average accuracy of 75%, though it made no difference to the accuracy of SAV density mapping (Note: SAV density relates to the proximity and length of the SAV blades such that high density SAV obscures the substrate and creates high levels of shadowing while lower densities have less shadowing and allow the substrate to be observed.). The improved depth correction method also enabled, for the first time from aerial photography, the production of a spatially explicit map of epiphytic biomass in the form of a continuous prediction surface with values ranging from 4 to 58 g dried weight m$^{-2}$. In response to the shortcomings of the existing field observation measurements of seagrass density and cover for image interpretation purposes, a new measurement was created, called $SAV$ structural density or SSD, which is designed to improve thematic coherence between aerial photography and field observations, such as downward-looking benthic videography or dive quadrats. This new measurement enabled the consistent discrimination of high and low density SAV with average overall accuracies of 77%, which supports the assessment of seagrass condition, particularly when complemented by the new maps of epiphyte abundance. This thesis presents methods that improve the quality of remote sensing of shallow marine habitats and provides a more reliable basis for further investigation of habitat change detection via spatial metrics and predictive modelling at landscape scales.
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There are a very large number of people who have assisted bringing this thesis to fruition. I would especially like to appreciate my team of supervisors, who never once managed to contradict each other and remained exceptionally generous with their financial and intellectual support. I would particularly like to deeply appreciate my supervisor, Alan Jordan, who guided me gently but firmly through every stage of the project, yet allowed me full carriage of the intellectual content. His ability to produce resources and his willingness to support the more innovative aspects of my work are greatly appreciated.

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Chapter 1

Background

There are a large number of problems in monitoring marine ecological systems or their constituent parts such as habitats. Understanding the ecology of the coastal, estuarine and marine environments is made challenging because of the complexity of the relationships between species and the physical environment. This is partly because of the dynamic nature of the environment, where species move between habitats during their life cycles (Edgar, 2001). In addition, seasonal, interannual and decadal variations result in constant change. Often scientific study can only measure a small subset of the relationships, in a few locations and over small periods of time whereas the interactions are often extremely complex and take place over large areas and evolve over long time scales. The difficulties generated by this complexity often means that a simplified type of environmental grouping is studied. For example, the concept of “habitat” is used to represent, or act as a surrogate for, ecological diversity, as it can be argued that different habitat types reflect different ecological and environmental conditions and, therefore, different components of biological diversity (Saunders et al., 1998), though there are conflicting opinions about the assumptions underpinning this approach (Ward, 2000; O’Hara, 2001).

Spatial science offers the ecologist resources to support new types of scientific investigation, through increased access to information on the spatial distribution, extent and condition of seabed habitats, particularly at the landscape scale (i.e. hundreds of square metres). It also offers improved analytical tools, such as a spatial metrics and enhanced interpolation and modelling methods (Foody, 2004a; Longley et al., 2005; Jensen, 2005). The application of these methods to coastal and marine spatial data requires an understanding of how it differs from terrestrial data, particularly in the degree of temporal and spatial variability produced in an energetic aqueous environment (Goodchild, 2000). For example, while the coastline is often used to establish a datum for depth and area

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measurements, its actual location is disconcertingly unclear. Other characteristics include the three-dimensional structure of the subtidal environment, large across and along shore variations and vertical (depth) gradients, as well as the frequent lack of data relative to its variability. All these factors provide an incentive to the spatial scientist to develop techniques that can quantify and reduce the uncertainty and errors in the data and analyses.

The primary method of presenting spatial data is in the form of maps, which are often created through the application of remote sensing techniques. The collection and interpretation of remotely sensed imagery to produce subtidal benthic (seafloor) vegetation maps is subject to the difficulties just outlined and complicated by a large number of variables including the characteristics of the target habitats and environmental conditions such as the water column state and sun glitter (Phinn et al., 2000). Further, only the visible, or “optical”, wavelengths are available because water effectively absorbs all the other wavelengths of the electromagnetic spectrum. As such, current benthic mapping techniques are prone to significant errors (Meehan et al., 2005) and are largely limited to coarse assessments of gains or losses of benthic habitats.

One of the uses of subtidal benthic vegetation maps is to monitor the location, extent and condition of seagrass beds. Seagrasses are important as they are an essential component of the marine ecosystem and act as nursery grounds for fish and crustaceans, provide protection to juveniles against predatory species, act as a filter and trap suspended sediment in the water and a stabiliser to the underlying sediment. Seagrasses are often associated with algae and epiphytes, the detritus of which is an important component of the nutrient cycling in coastal ecosystems (Kirkman, 1996; Short et al., 2001). A critical aspect of improving the application of remote sensing techniques to seagrass monitoring is to understand the target species under investigation and current monitoring methods.

1.1 Study site

The main study area is in North West Bay, a sheltered small estuary in southeastern Tasmania, Australia (43°S, 147.25°E) (Figure 1-1) that is approximately 7 km². It was selected to cover seagrass beds growing under a range of typical estuarine conditions. The beds are mainly fringing along-shore beds as well as some areas of mixed density and patchiness on wider banks and delta formations. Secchi depth values grade from 2-4 m in the north of the bay near the main river delta to 4-9 m in the south where there are occasional very clear values of 12-14 m (Jordan et al., 2002). Average water temperatures vary between 9° C in winter and 19° C in summer, though more extreme temperatures are found in the shallow waters. The salinities recorded in the estuary, show low levels of
stratification with most values at the marine norm, though occasional minor stratification occurs in the surface layers after heavier rainfalls, particularly in the northern end of the bay (Jordan et al., 2002). The tides are semi-diurnal with an average tidal range of about 0.5 m and a maximum of 1 m. The tidal prism is 9.52 million m$^3$, which is only about 3.4% of the total low water volume of the bay (277 million m$^3$) (Matthews and Volframs, 1978).

The average residence time of nutrients is around 7 days (Matthew and Volframs, 1978), which provides little opportunity for nutrients to remain in the system and drive biological processes. It has been estimated that estuaries with a residence time of around 7 days export ~90% of nitrogen from the system (Nixon et al., 1996). It is often difficult to definitively assess the impacts of increased nutrients on seagrass habitats due to the relatively frequent natural variations of these habitats, the lack of historical monitoring data, the lack of suitable controls for comparison; and a poor understanding of the fate and fluxes of nutrients in the system. In addition, as North West Bay is subject to seasonal inputs of nitrate rich oceanic water (CSIRO Huon Estuary Study Team, 2000), the natural responses to this high nutrient level may be different to that defined for coastal areas that are dominated by nutrient poor water.

Figure 1-1. Location map and Landsat image of North West Bay, Tasmania.
1.2 Seagrass characteristics and monitoring methods

1.2.1 Seagrass ecology in Tasmania

Seagrasses are flowering macrophytes that grow and reproduce in the subtidal and intertidal zones of shallow marine waters, particularly sheltered estuaries and bays. Typically, they form variable sized patches, or beds, via the extension of subsurface rhizomes through unconsolidated sediments and develop leaves above the substrate. Seagrass species generally separate into either temperate or tropical species, though there is overlap in the ranges of some species. Similarly, there are differences in the distributions of species between the northern and southern hemispheres (Short et al., 2001). In southern Australian temperate waters, the dominant species is usually a member of the Posidonia genera (Short et al., 2001; Kendrick et al., 2002); however, in the region containing the study area for this thesis, the dominant species is Heterozostera tasmanica (Rees, 1993; Barrett et al., 2001). In general, seagrass maximum depth limit (MDL) is most often limited by light availability and, at the shallower edge, by desiccation, sunburn, freezing, UV-B damage and photo-inhibition (Short et al., 2001).

Six species of seagrass are commonly found within Tasmania: the eelgrasses Heterozostera tasmanica (Martens ex. Asch.) den Hartog and Zostera capricorni Ascherson, the strapweeds Posidonia australis Hooker and Posidonia angustifolia Cambridge & Kuo, the paddleweed Halophila australis Doty & Stone, and Amphibolis antarctica (Labillardière) Sonder & Ascherson ex Ascherson (Rees, 1993; Edgar, 1997; Jordan et al., 1998). Some also consider a seventh species of widely distributed aquatic macrophyte, Ruppia megacarpa Mason, a seagrass, though opinions differ (Edgar, 1997). It is often found in upper estuarine areas as it tolerates freshwater well, though it is also found in seawater and occasionally in hypersaline water (Short et al., 2001). There is also debate about the naming of both H. tasmanica and Z. capricorni. Les et al. (2002) consider that, while H. tasmanica should remain a separate species, it needs to be renamed Zostera tasmanica on morphological and DNA evidence, and, on similar grounds, that Z. capricorni Ascherson is synonymous with Z. muelleri Irmisch ex. Ascherson. On the other hand, Kuo (2005) argues for splitting Heterozostera tasmanica into four new species, H. tasmanica, H. nigricaulis, H. polchlamys and H. chilensis, of which the former two occur around Tasmania. The names adopted here are: Heterozostera tasmanica (Martens ex. Asch.) den Hartog and Zostera capricorni Ascherson.


1.2.1.1 **Target species characteristics**

The target habitats for this thesis are dominated by the two temperate subtidal seagrass species found around southeastern Tasmania – *H. tasmanica* and *H. australis* (Rees, 1993; Barrett *et al*., 2001). Each species has a distinct growth habit (formation) described in Table 1-1 and illustrated in Figure 1-2.

Table 1-1. Typical growth habits of temperate subtidal seagrass species found at the study site in southeastern Tasmania

<table>
<thead>
<tr>
<th>Species</th>
<th>Density</th>
<th>Spatial Arrangement</th>
<th>Bed Boundary</th>
<th>Height (mm)</th>
<th>Depth range (m)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Heterozostera</em></td>
<td>Very dense to sparse</td>
<td>Continuous beds to highly fragmented</td>
<td>Abrupt to very gradual</td>
<td>100 to 2000</td>
<td>1 – 15</td>
<td>Highly variable morphology</td>
</tr>
<tr>
<td><em>tasmanica</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Halophila</em></td>
<td>Low density to sparse;</td>
<td>Often occurring around the fringes of</td>
<td>Gradual</td>
<td>~70</td>
<td>1 - 40</td>
<td>Fringes beds of <em>H. tasmanica</em> on deep and shallow sides</td>
</tr>
<tr>
<td><em>australis</em></td>
<td>substrate clearly visible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1-2. Target seagrass species – *H. tasmanica* and *H. australis*

The growth habit of *H. tasmanica* is highly variable (Kuo, 2001; Les *et al*., 2002) producing uncertain bed boundaries and high within-bed density variations, while *H. australis* is very sparse and uniformly short with a lot of substrate visible between the leaf blades. The bed structure of *H. tasmanica* in southeastern Tasmania ranges from well-defined bands fringing a bay in consistent depth ranges (typically 0.5 to 12 m), to patchily distributed beds covering areas of flat or slightly undulating unconsolidated substrate (Rees, 1995; Barrett *et al*., 2001).

There are seasonal variations in the growth of *H. tasmanica* with the maximum biomass present in late summer (Bulthuis and Woelkerling, 1983). The combination of high
variability in density, patchiness and boundary definition make *H. tasmanica* a difficult species in which to determine clear bed boundaries, particularly the deeper edges (Rees, 1993), which is also the case with other seagrasses (Norris *et al.*, 1997; Pasqualini *et al.*, 1998, 2001). When coupled with the presence of algal epiphytes within the beds and across bed boundaries (see next section), bed extent and levels of vegetation density are often difficult to distinguish in aerial photography (Rees, 1993). Similarly, *H. australis* creates problems for detection in aerial photography because of its sparse growth habit and low aboveground biomass. A number of authors report that separating seagrass species in aerial photography is problematic (Robbins, 1997; Kendrick *et al.*, 2000; Lathrop *et al.*, 2004).

**1.2.1.2 Epiphytic and associated filamentous algae**

Filamentous algae, either loosely associated or growing epiphytically, are a natural and commonly occurring component of most seagrass beds (Kendrick and Lavery, 2001). The algae contribute substantially to ecosystem functioning via primary and secondary production, biogeochemical processes and nutrient cycling including nitrogen fixing (Vanderklift and Lavery, 2000; Irlandi *et al.*, 2004). They can also have adverse effects on seagrass where nutrient levels are elevated, as increased epiphyte growth can lead to increased seagrass shading (Silberstein *et al.*, 1986; Fitzpatrick and Kirkman, 1995; Hauxwell *et al.*, 2003). Excessive nutrient inputs into estuaries have led to widespread loss of seagrasses via this mechanism at many locations in Australia and overseas (Shepherd *et al.*, 1989), though it should be noted that increased associated algae does not necessarily reduce seagrass biomass or productivity (Irlandi *et al.*, 2004). For example, Ruiz *et al.* (2001) found the reverse situation when assessing the effects of scalefish farming on *Posidonia oceanica* meadows in the Mediterranean Sea. Similarly, Irlandi *et al.* (2004) also identify some potential benefits of drift algae to seagrass in the form of reduced epiphyte growth. While there are clearly complex interactions between epiphytes and seagrass, advancing the understanding of those interactions will assist in seagrass management. For example, Vanderklift and Lavery (2000) and Lavery and Vanderklift (2002) suggest that the scale of the epiphyte patchiness is related to the ecological processes at work in the seagrass beds and, therefore, should be taken into account when creating sampling designs. In particular, they found that, while there was little variation in epiphyte loads within 50 cm, there was substantial variation at the scale of metres.

A listing of associated and epiphytic filamentous algae found in the main study sites is presented in Table 1-2. The most abundant species are red-brown algae from the *Polysiphonia* genera (Sanderson, pers. comm.)
Table 1-2. Algae associated with seagrass beds in North West Bay (Sanderson, unpub.)

<table>
<thead>
<tr>
<th>Algae Name</th>
<th>Algae Name</th>
<th>Algae Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asperroecoccus</td>
<td>Colpomenia peregrina</td>
<td>Lomentaria australis</td>
</tr>
<tr>
<td>Berkeleya sp.(diatom)</td>
<td>Colpomenia sinuosa</td>
<td>Lyngbya sp.</td>
</tr>
<tr>
<td>Callithamnion sp.</td>
<td>Cutleria multifida</td>
<td>Notheia anomola</td>
</tr>
<tr>
<td>Anotrichium subtile</td>
<td>Dicyota dichotoma</td>
<td>Notheia anomola</td>
</tr>
<tr>
<td>Anotrichium tenera</td>
<td>Ectocarpus siliculosus</td>
<td>Polysiphonia decipiens</td>
</tr>
<tr>
<td>Antithamnion delicatulum</td>
<td>Encrusting Corallines</td>
<td>Polysiphonia pungens</td>
</tr>
<tr>
<td>Bronniaratella australis</td>
<td>Enteromorpha compressa</td>
<td>Polysiphonia sertularioides</td>
</tr>
<tr>
<td>Centroceros clavulatum</td>
<td>Enteromorpha flexuosa</td>
<td>Polysiphonia scopulorum</td>
</tr>
<tr>
<td>Ceramium tasmanicum</td>
<td>Gracilaria cliftonii</td>
<td>Sarchotrichia tenera</td>
</tr>
<tr>
<td>Ceramium cliftonianum</td>
<td>Griffithia crassicaulis</td>
<td>Sporochnus comosus</td>
</tr>
<tr>
<td>Champia zostericola</td>
<td>Herposiphonia versicolor</td>
<td>Sypirdia filamentosa</td>
</tr>
<tr>
<td>Chondria succulenta</td>
<td>Hypnea charoides</td>
<td>Trithamnionb cf. gracillissimum</td>
</tr>
<tr>
<td>Cladophora sericea</td>
<td>Jania verrucosa</td>
<td></td>
</tr>
<tr>
<td>Cladophora laevivirens</td>
<td>Laurencia tumida</td>
<td></td>
</tr>
</tbody>
</table>

1.2.2 Seagrass monitoring

As there is clear evidence for increased sediments and nutrients from catchment sources in coastal waters over the last 200 years (e.g., Krause et al., 2003; Loughran et al., 2004; Edgar and Samson, 2004), there is little doubt that some changes in seagrass extent and health have occurred due to recent anthropogenic influences (e.g., Edgar and Barrett, 2000). Maximum seagrass loss occurs in areas closest to population centres where the water clarity and nutrient levels are impacting the most (Rees 1993, Dennison and Abal, 1999). However, there is considerable uncertainty about how much of the changes are due to natural variability compared to human induced impacts (Edgar and Barrett, 2000).

Other anthropogenic impacts include boating activities, which can directly affect the seagrass through propellers and hulls impacting the bottom, as well as indirectly via mooring scouring, channel dredging and shading by boats and jetties (see Figure 1-3). Further impacts can arise from some fishing and aquaculture practices, either through direct physical destruction or shading and nutrient overloading (Short et al., 2001).

1.2.2.1 Status of seagrass monitoring techniques

The science of seagrass monitoring is not well enough developed to give management what is needed as the research effort is largely focused on descriptive studies and limited to a small range of seagrass species and locations (Duarte, 1999). Duarte (ibid) points out that what management requires is, “the power to predict the time course of seagrass decline and recovery following perturbation”. While any such prediction must be based on robust
understandings of the ecology of seagrass, management also needs accurate methods for measuring change – whether of decline or recovery. The degree of accuracy required needs to reflect the consequences of change from a management perspective as well as the uncertainties entailed in measuring change.

Figure 1-3. Effects of mooring chain scour on seagrass beds in North West Bay, Tasmania.

Clearly, the method of monitoring needs to match the information requirements of the stakeholder, which vary according to the purpose of the study. The commonly used techniques for monitoring seagrass usually examine extent and biomass (Wood and Lavery, 2000; Duarte and Kirkman, 2001; Short and Duarte, 2001). Extents of seagrass beds are typically determined from optical remote sensing, with the mapping refined via ground surveys to confirm parameters such as species composition, deep edge boundaries and biomass (Kirkman, 1996). However, Hauxwell et al. (2003), Hillman et al. (1994), McKenzie et al. (1996) and Jernakoff and Nielsen (1997) argue that monitoring for extent and biomass may not be adequate for informing conservation management as the high variability of seagrass habitats means that most monitoring designs have low explanatory power. Thomas et al. (1999) also suggest caution in the use of traditional quadrat-based methods for similar reasons. There are a large number of other possible monitoring variables including: patchiness, epiphyte abundance, seagrass depth range, light penetration,
sediment analysis, local hydrography (exposure and tidal currents) and clonal growth (e.g., rhizome extension) (Kirkman, 1996; Duarte, 1999; Short et al., 2001; Ruiz et al., 2001). The majority of seagrass monitoring work is conducted either at the local scale – typically focusing on the 1 m² quadrat – or the broad area mapping and resource inventory style studies covering 10’s to 1,000’s of km² (Duarte, 1999), and, currently, there is a lack of landscape scale studies, such as those conducted by Fonseca and Bell (1998) and Kendrick et al. (1999).

Duarte (1999) highlights the need for studying seagrass at the landscape or meadow scale of 10’s to 1000’s m². In addition, Vanderklift and Lavery (2000) suggest that the patchiness of epiphytes need to be more closely studied at a variety of spatial scales to increase understanding of their role in seagrass ecology. Further, when reviewing the impact of monitoring programs on management decisions, Thomas et al. (1999) found that map-based programs had high levels of uncertainty and that few programs were based on substantial conceptual models of seagrass growth and reproduction. An assessment of the reliability of old habitat maps by Leriche et al. (2004) found that, for their study area, the majority of the older maps were totally unreliable and even the best quality maps had to be treated with caution. These findings provide a challenge to improve methodologies and techniques.

1.3 Habitat mapping with optical remote sensing in shallow marine waters

Mapping of seabed habitats in shallow coastal waters using airborne optical remote sensing has been conducted in many locations around the world for several decades, traditionally through the use of aerial photography, with the purpose of identifying benthic habitat extent and distribution at a range of spatial scales, from tens to hundreds of square kilometres (e.g., Slama et al., 1980; Pasqualini et al., 1998, 2001; Kendrick et al., 2000, 2002; McKenzie et al., 2001; Finkbeiner et al., 2001; Ekebom and Erkkila, 2003; Orth et al., 2004). Optical remote sensing is most commonly used because water only transmits the visible wavelengths readily. Imagery types include digital and film aerial photography, multispectral and hyperspectral airborne scanners and the visible bands of satellites such as Landsat, SPOT and IKONOS (Lillesand and Kiefer, 2000). Any of these satellite sensors provide an effective approach for mapping seabed habitats over large areas (>20 km²) and in remote locations (Ferguson and Korfimacher, 1997; Mumby et al., 1999), particularly where the habitats are large and continuous. Recent developments in digital multispectral and hyperspectral remote sensing have resulted in an increase in the use of these methods to map and monitor seabed habitats in shallow waters due to improved performance (e.g.,
Phinn et al., 2001; Andréfouët, Hochberg et al., 2003; Andréfouët, Kramer et al., 2003; Andréfouët, Payri et al., 2003; Malthus and Karpouzli, 2003; Joyce et al., 2004; Dekker, Anstee et al., 2005).

The following sections introduce the stages of map production from a remote sensing perspective: firstly, image capture methods – including a conceptual model of light pathways within and over shallow water – and then image processing and, finally, image interpretation. This brief introduction will also identify the key issues and challenges requiring further methodological development; that is, it constitutes a statement of the problems in the field.

1.3.1 Image capture and the optical conceptual model

For image acquisition, a key concept for benthic (seafloor or seabed) habitat mapping is that of optical depth. Optically deep water is defined as water where no part of the signal measurable at the sensor originated from the bottom (Apel, 1987), whereas optically shallow water is where there is a measurable reflectance from the seabed. There are many factors that influence optimal image capture and, therefore, the depths at which habitat type can be detected and the accuracy with which habitat boundaries and spatial structuring can be delineated. Airborne and satellite remote sensing of the seabed is based on the principle that a remote sensing instrument can ‘see’, either directly or indirectly, the substratum and/or the vegetation growing on that substratum, although the reflectance recorded by a remote sensing instrument consists of a considerable number of components (Figure 1-4).

Firstly, light from the sun is scattered in the atmosphere (path radiance), with some absorbed by the atmosphere and some backscattered into the field of view of the sensor. This backscattered light may make up a large portion of the signal recorded, especially in the blue and green regions (400-500 nm) of the spectrum. The remaining portion of the light from the sun, and that from the sky, is reflected or refracted at the water surface. The portion of light that enters the water column is either backscattered by the suspended particles including algae (that is, total suspended solids, or TSS), or absorbed by the coloured dissolved organic matter (CDOM), the TSS or the water itself. Some light reaches the seabed where it is either absorbed or reflected back as upwelling radiation. This bottom reflected signal again goes through the various processes of attenuation in the water column, reflection and refraction at the water-to-air interface and atmosphere before it reaches the sensor. The proportion of light reaching the sensor is in the order of about 5-6% of the light that originally entered the water (Apel, 1987), indicating the very large amount of attenuation taking place in the water column.
While many of the components of the signal arriving at the sensor can be described conceptually, questions arise concerning the relative importance of the components, such as, “What does a mission planner measure to ensure the critical barriers to optimal image capture are removed or moderated?” For example, is the tidal state (affecting turbidity depth) a stronger limiting factor than sun elevation angle (influencing sun glitter and subsurface illumination levels) or, alternatively, is recent heavy rainfall (affecting CDOM and turbidity levels) more important than anticipated algal bloom conditions? Do turbidity, plankton levels and CDOM need to be measured individually or would Secchi disk depths ($Z_{sd}$) suffice as an integrated measurement of water clarity? While there are some useful guidelines published regarding these factors (Finkbeiner et al., 2001), some are poorly defined, such as those relating to sun glitter (e.g., Strandberg, 1967), which are no more than rules of thumb, yet sun glitter reflecting from the water surface and obscuring the subsurface features is identified as significant image quality issue (e.g., Meehan et al., 2005; Calvo et al., 2003; Gilvear et al., 2004).
In reality, these environmental conditions are limiting in an additive manner, meaning that while any one of them can significantly reduce image quality, all the factors combine to produce the total attenuation loading. Ideally, the influence of all these factors is minimised at the time of capture in order to optimise the quality of the imagery (Mumby et al., 1998). It should be noted that many of these environmental factors are also shaped by regional differences in lithography, oceanography, rainfall, water temperature, biota and coastal geomorphology. For instance, there are considerable differences in sun angle (i.e. sun elevation angle above the horizon or 90° minus the solar zenith angle), tidal range, nutrients and general turbidity levels between tropical and temperate environments (Thomas et al., 1999; Short et al., 2001).

Habitat characteristics also affect image quality, including the architecture and growth habits of the target habitat species (as described in section 1.2), as does the acquisition methodology, including the choice of sensor and sensor platform. Overall image quality is controlled by interactions between habitat characteristics, acquisition methodology and environmental conditions. In the shallow marine environment, the available opportunities for image acquisition are strongly limited by these complex interactions, so significant attention must be applied to each stage of the mission planning process.

1.3.1 Platforms and sensors – aerial photography

The choice of platform, including sensor characteristics and logistical considerations, is a critical component of mission specification (The relative qualities of optical remote sensing platforms operating in the coastal environment are presented in detail in Table 2-1). Small format digital aerial photography was selected as the preferred platform for the bulk of the optical remote sensing work conducted for this thesis. In general terms, the reasons for this choice include lower overall costs, the widespread use and understanding of the technology, greater logistical flexibility, imagery at a scale suitable for seagrass monitoring (10s to 100s m²), and the ready transferability of the information obtained to other platforms.

Aerial photography is defined here to include film and digital imagery captured from an airborne platform with a rectangular instantaneous field of view, not acquired via line scanning or “pushbroom” sensors. Though water effectively absorbs almost all electromagnetic radiation apart from the visible, near infrared photography is included, as it has proven useful for a number of shallow marine applications, including the removal of sun glitter (Hochberg, 2003) and mapping surface vegetation canopies of, for example, *Macroscystis pyrifera* (North et al., 1993; Deysher et al., 1995) and emergent vegetation or
vegetation in the intertidal zone (Rutchey and Vilchek, 1999; Valta-Hulkkonen et al., 2003; Murphy et al., 2004;).

In spite of its continuing use in operational habitat surveys, the use and methods of large format aerial photography today often go unreported in the scientific literature (Malthus and Mumby, 2003). The result is a large number of grey literature reports that document the regular use of aerial photography for habitat mapping (e.g., Ferguson et al., 1989; Kendrick et al., 2002; Lathrop et al., 2004). Aerial photography provides the basis to established and commonly used methods for mapping shallow seabed habitats and features, including seagrass, geomorphic facies, coastlines, and bathymetry. As such, many of the methods and products of aerial photography are well known and accepted (see Chapter 2 for more details). However, there are also criticisms made of large format aerial photography including, for example, that it is a limited platform for remote sensing due to a lack of spectral resolution and cost, especially for stereo-photogrammetry (Mumby et al., 1997).

However, the high rate of technological development and improved accessibility to sensors, combined with the complexity of remote sensing over optically shallow waters and advances in remote sensing techniques, means that there are an increasing number of remote sensing opportunities – and challenges – tractable to aerial photography. The recent peer-reviewed literature continues to show evidence of its ongoing use as a research platform. For example, Pasqualini et al. (1998) reviewed a number of studies to ascertain seagrass detection depths and they found that half of the studies used aerial photography. Studies using aerial photography documented in the literature include: Chauvard et al., 1998; Mumby et al., 1999; Kendrick et al., 1999, 2000, 2002; Pasqualini et al., 1999, 2001; Beanish et al., 2002; Cuevas-Jimenez et al., 2002; Agostini et al., 2003; Ekebom and Erkkila, 2003; and Calvo et al., 2003. There is also some evidence of a revisiting of aerial photography with sophisticated new remote sensing techniques (e.g., King, 1999; King, 2002; Tuominen and Pekkarinen, 2004, 2005), largely due to the advantages conveyed by its very high spatial resolution and ready availability.

High temporal resolution monitoring using small format aerial photography is being more regularly conducted, where film and digital cameras with image sizes smaller than the standard 230 x 230 mm aerial film negatives are used to capture smaller, specific targets at scales of hundreds of metres to one to two kilometres (Goba and Senese, 1992; Warner, 1994; Warner 1996; Warner et al., 1996; Abd-Elrahman et al., 2001; Mills et al., 2002; Sandmann and Lertzman, 2003). Through the use of low cost local aircraft charter and camera equipment, missions can be carefully targeted to respond to local environmental conditions and logistical constraints enabling greater control of image quality. The
experience gained through planning and completing multiple missions will considerably benefit later missions. Further, many of the issues of mission planning are very similar whether aerial photography or airborne multispectral or hyperspectral sensors are utilised, including identifying spatial and temporal resolutions and suitable environmental conditions such as sun angles, wave state and cloudiness. This means that methods developed for small format aerial photography are often transferable to other sensors and platforms. It also means that the limitations of data collected with other platforms and sensors are readily recognised.

There are some disadvantages that curb the value of small format aerial photography, including the relatively small field of view and ground footprint compared to satellite imagery, which can exacerbate difficulties with establishing adequate ground control (Warner and Blankenberg, 1995), and attaining good colour balancing in mosaics, particularly in dynamic and submerged coastal environments (DAL, 2000). The fixed rectangular instantaneous field of view of vertical aerial photography creates larger sun glitter problems compared to “pointing”, line scanning or “pushbroom” sensors (e.g., Quickbird imagery (Mobley, 1999)) and thus reduces the available time for image acquisition. High costs are associated with stereo-photogrammetric interpretation and orthophoto production (Mumby et al., 1999), with added difficulties over water due to poor automatic digital elevation model (DEM) generation because of water surface reflections and errors in depth estimation due to refraction. There is a relatively long time required from image acquisition on film to digital image interpretation or classification compared to direct digital image capture (Mumby et al., 1999), including complicating issues such as scanning artefacts (Coburn, 2001). For archived (historical) aerial photography, quality is regularly poor over the water, particularly if originally captured for terrestrial purposes (personal observation).

Small format digital aerial photography is identified as a useful research platform that is capable of the flexibility necessary for obtaining good quality imagery under difficult environmental and logistic conditions for costs that fall within a modest research budget. The sensor enables research into key image acquisition problems such as sun glitter and suitable water clarity measurements as well as providing images of areas large enough to support the study of seagrass monitoring.

1.3.2 Image preparation and processing

After image capture, a series of steps are required to transform the raw image into a state that supports the image interpretation and analysis stage of map preparation (Schowengerdt,
For multispectral and hyperspectral digital imagery, these steps usually include geometric, radiometric and spectral transformations, though changes to spatial resolution and the creation of band ratios are also common, while data reduction transforms such as principal component analysis (PCA) and canonical analysis (CA) are also used, though less often (Jensen, 2005). Normalisations of image pixel values are utilised in an attempt to obtain values closer to the actual reflectance of the target habitats. For example, atmospheric corrections can be applied to remove the path radiance (Richards, 2005; Jensen, 2005) and depth corrections can be applied to remove the systematic water column effects (Malthus and Mumby, 2003; Jupp et al., 1985). However, care must be exercised, as pertinent information can be lost in the process – for example, a contrast stretch alters the relative brightness of image pixels, which may enhance viewing of an image, but conversely may seriously compromise any band ratios or other transformations (Harrison and Jupp, 1990; Lillesand and Keifer, 2000).

Transformations are rarely applied to aerial photography, apart from geometric ones, though with the rapidly increasing use of digital photography and image processing software some of the techniques are being reassessed (e.g., Tuominen and Pekkarinen, 2005). For example, while depth corrections that account for the attenuation (absorption and scattering) of light in the water column is an active area of research with multispectral and hyperspectral imagery (Ackleson, 2003; Anstee et al., 2004), they also have the potential to improve the quality of aerial photographs (Malthus and Mumby, 2003). The application of new remote sensing techniques to digital small format aerial photography provides a pathway to low cost, utilitarian image analysis that is broadly accessible.

### 1.3.3 Image interpretation and analysis

Traditionally, interpretation of aerial photography depends on the perception of contrast thresholds by a human interpreter to outline areas of homogeneous habitat type and, thus, produce maps of benthic habitats. The process typically involves digitising features from the geo-referenced and rectified image (Lillesand and Kiefer, 2000). Interpretation and analysis of multispectral and hyperspectral images can vary in complexity, ranging from sophisticated inverse modelling of hyperspectral remote sensing signals using analytical or radiative transfer approaches and spectral libraries to simpler image classifications (Dekker, Brando et al., 2005). There are a very large number of such remote sensing techniques available, generally focussed on discriminating and labelling discrete habitat classes, including image segmentation (e.g., Lathrop et al., 2004) and fuzzy classification (e.g., Urbanski and Szymelfenig, 2003). Another approach is to produce continuous field surfaces of target variables (such as biomass, euphotic depth or phytoplankton) derived through...
regression, or modelling, of image pixel values with field samples (e.g., Armstrong, 1993; Mumby et al., 1997; Malthus and Karpouzli, 2003).

Similarly, there is a very large suite of spatial metrics (e.g., McGarigal and Marks, 1995; Gustafson, 1998; O’Neill et al., 1999) and spatially explicit modelling and interpolation techniques (e.g., Kelly et al., 2001) that make use of classification outputs and other suitably prepared and processed imagery. Texture and semivariances (variograms) commonly form a part of the analysis (e.g., LeDrew et al., 2004). Spatial metrics are developing as a tool for characterising habitat dynamics at intermediate, landscape scales in near-shore marine environments and other fields (e.g., Fonseca and Bell, 1998; Bell et al., 1997; Manson et al., 2003).

In the light of such a plethora of techniques available for image interpretation and analysis, there are clearly a very large number of alternative approaches possible. Ideally, the first approach is to attempt to obtain a simple direct relationship between variables of interest and the prepared imagery via regression techniques (Jensen, 2005). This approach seeks to explicitly utilise the spectral and radiometric information available in the image rather than rely largely on contrast. In accord with this idea and consistent with the intention of improving the spectral quality of the imagery with depth corrections, other techniques that could be applied are a standard image clustering technique (maximum likelihood classifier) and a newly proposed fuzzy logic method (visual supervised fuzzy c-means classifier (Lucieer and Kraak, 2004).

1.3.4 Accuracy assessment

The purpose of the map should inform every stage of map production (Agumya and Hunter, 1997) including the level of uncertainty or error that is acceptable to the end user (Agumya and Hunter, 2002, Atkinson and Foody, 2002). In general terms, map accuracy and precision is dependent on: selecting the spatial and spectral resolution of the imagery to best match the habitat characteristics, cartographic decision rules, geometric corrections, mapping output requirements and the ancillary data such as benthic video, acoustics and sediment sampling (Phinn et al., 2000). As such, there are constant challenges to the mapmaker to realistically assess the thematic and positional uncertainty of the data they are using at every stage of map production (Agumya and Hunter, 2002; Foody, 2002). These challenges are particularly confronting in the marine environment, as the collection of independent reference data for habitat mapping such as diver observations of the benthic environment is expensive and complicated by a lack of strong positional control beneath the surface (Wright and Bartlett, 2000).
Yet, there are increasing expectations on practitioners for such assessments to become routine (Malthus and Mumby, 2003). The dynamic nature of the environment often necessitates logistically challenging simultaneous fieldwork, such as deployment of temporary ground control and \textit{in situ} measurements of water quality, vegetation and conditions. The compounded positional error of aerial photography and field collected reference data can create problems (Stehman and Czaplewski, 1998). This is particularly the case in heterogenous environments (King \textit{et al.}, 1999; Smith \textit{et al.}, 2002; Foody, 2004a), where a great many environmental boundaries are vague or ambiguous, such as that between silt and sand or optically deep and shallow water (Urbanski and Szymelfenig, 2003). Many practitioners in the marine and coastal fields currently use their field data to assist with both the classification process and the accuracy assessment rather than collect two independent data sets, one for each function (e.g., Thomson \textit{et al.}, 2003; Lathrop \textit{et al.}, 2004).

Pasqualini \textit{et al.} (1997) and Agostini \textit{et al.} (2003) present an alternative approach to accuracy assessment based on cartographic reliability, with a series of weighted factor scores. The challenge is to improve methodologies and techniques to ensure that mapping error is reduced sufficiently to enable change to be detected.

### 1.4 Thesis aim, research questions and structure

The overarching objective of this thesis is to develop optical remote sensing techniques for mapping and monitoring seagrass habitats in shallow temperate marine waters. Based on the previous discussion, the following specific research questions are proposed:

1. Can the time window of opportunity for image acquisition, particularly via aerial photography, be extended and/or more accurately predicted?

2. Is Secchi disk depth ($Z_{sd}$) a useful measurement of water clarity when preparing to acquire imagery for the purpose of observing the deep edge of seagrass beds?

3. What are the limiting factors on the detection of the deeper edge of seagrass beds in digital aerial photography?

4. Can \textit{Heterozostera tasmanica} be distinguished from \textit{Halophila australis} at the deeper edge of seagrass beds in digital aerial photography?

5. Does image classification of digital aerial photography produce accurate spatially explicit measurements of seagrass condition or epiphyte abundance?
6. Is the discrimination of seagrass condition or epiphyte abundance in digital aerial photography improved with a depth correction of the imagery?

7. Does a visual fuzzy c-means image classifier perform better than a maximum likelihood image classifier in discriminating seagrass classes in digital aerial photography?

While no research questions directly address the issues of data accuracy and uncertainty in shallow water marine environments, most of the answers to the questions that are posed depend on a close understanding of these issues.

According with the overarching aim of the thesis, the imagery and mapping outputs of the applied image interpretation and analysis methods must be able to produce results that will provide input to mesoscale analyses of seagrass extent, condition, patchiness and fragmentation, that is, at scales in the tens and hundreds of metres. The hope, and intention, of this work is that the results will be relevant to the actual management of these extraordinarily rich and beautiful environments.

1.4.1 Thesis structure

This thesis seeks to draw on the knowledge of the spatial sciences, especially remote sensing, to produce new methods applicable to mapping and monitoring seagrass habitats. As such, the quintessentially spatial process of map production informs the structure of the thesis. The three key stages in the production of maps based on optical remote sensing are: data acquisition, image preparation and processing, and image interpretation (Lillesand and Kiefer, 2000).

The first chapter provides the background both to the ecological context and to the spatial science and remote sensing involved and defines the problems that underpin the research aims and questions.

The current methodological foundations of remote sensing work relevant to seagrass mapping are presented in Chapter 2, which provides a basis for method selection in response to the research questions. For example, the significant effects created at the air/water interface, including refraction and particularly sun glitter (Finkbeiner et al., 2001), are addressed in detail in Chapter 2. The result of research into these issues is presented in Chapter 3, including development of simple new methods that enable mission planners to precisely forecast sun glitter and subsurface illumination in imagery.
In a second example, Chapter 2 provides an assessment of the critical air and water column effects on the attenuation of light, and methods for reducing their influence on image capture, and then Chapter 4 reports on a study designed to, among other goals, discover the critical measurements of water clarity required to detect the deeper edges of seagrass beds in imagery. Chapter 4 is mainly focussed on the question of how well optical remote sensing can detect the deeper edge of seagrass beds, which provides a research vehicle for determining the controlling factors at the extreme limits of detectability.

Partially in response to the call by Malthus and Mumby (2003), Chapter 2 outlines a series of image transformations applicable to digital aerial photography, such as atmospheric and depth corrections, and then Chapter 5 reports on their efficacy in assisting image classification. Another issue that receives little attention in the recent image processing literature is that of geometric corrections for refraction. Chapter 2 provides a review and description of the techniques applied in later chapters.

Chapter 5 mainly presents the results of a study that applies standard remote sensing image classification techniques, as described in Chapter 2, to digital aerial photography to discriminate submerged aquatic vegetation habitat surfaces and classes.

The overall discussion and conclusions presented in Chapter 6, draw together the findings of the individual chapters and assess them, firstly, with respect to the field of remote sensing and spatial science and then, finally, in relation to the monitoring and mapping of seagrass in temperate shallow marine waters.

While there is a clear focus for the thesis, many of the issues, and solutions, are broadly applicable to other aquatic environments such as freshwater systems as well as saltmarshes and wetlands.
Chapter 2

The foundations of map production with digital aerial photography for seagrass monitoring

2.1 Introduction

This chapter addresses the essential qualities required of maps that are to be used for the purpose of mapping and monitoring seagrass and then reviews and discusses relevant map production methodologies to provide the foundations for the research that follows in later chapters. The chapter is considered necessary, as there are a very large number of possible methods for each stage of map production and, it follows, innumerable possible combinations that could be used for the process as a whole. An attempt is made to select the methods most able to support the identified purpose. A distinctive characteristic of the approach taken is the application of remote sensing techniques that were developed for multispectral and hyperspectral imagery to digital aerial photography.

The challenges to optical remote sensing when producing maps or spatial metrics are optimising the spatial and spectral resolution of the imagery to best match the habitat characteristics and the mapping outputs required, and the incorporation of any supporting data such as benthic video, spectral libraries, acoustics and sediment sampling. There is a complex interaction between the often-heterogenous structure of the habitats and the map-making approach taken. The available solutions range from sophisticated inverse modelling of hyperspectral remote sensing signals using analytical or radiative transfer approaches to subjective airphoto interpretation. The second part of this review outlines current airborne

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and satellite remote sensing techniques used for benthic habitat mapping and monitoring and assesses their limitations and capabilities, particularly regarding digital aerial photography – the selected platform for this thesis (see Chapter 1 Section 1.3.1.1). Techniques for small-format and standard aerial photography using film and digital cameras are presented as well as a brief review of digital multispectral and hyperspectral satellite sensors such as Landsat, Quickbird, IKONOS and airborne sensors such as the Compact Airborne Spectrographic Imager (CASI) and the HyMap.

2.2 Multispectral and hyperspectral remote sensing

While aerial photography primarily makes use of radiometric contrast for discriminating seabed habitats, multispectral and hyperspectral optical remote sensing mostly rely on spectral reflectance. Both satellite and airborne multispectral systems have been used to map seagrass habitat (e.g., Malthus and George, 1997; Pasqualini et al., 2001) and over the last decade, satellite sensors have made considerable progress, particularly in terms of spatial resolution (see Table 2-1). For example, the IKONOS and Quickbird satellites produce imagery with 0.6 to 1.0 m ground resolution in greyscale (panchromatic) and 2.4 to 4.0 m in the multispectral (that is, blue, green, red and infrared bands). Similarly, the Landsat and SPOT satellite programs have improved spectral and radiometric resolutions. While sensors with higher spatial resolutions do not necessarily provide better discrimination of the boundaries of broad scale seagrass beds (that is, tens to hundreds of square kilometres) (e.g., Mumby and Edwards, 2002; Malthus and Karpouzli, 2003), they do provide opportunities for improved delineation of patchy and narrow linear beds (tens of metres across). It also means that it is easier to obtain the resolutions needed to meet the mapping requirements determined by the habitat characteristics and map purpose (Phinn et al., 2000). Improved spectral resolution also allows more seagrass and algal species to be discriminated and optically active components of the water column and water column depth to be determined (e.g., Dekker, Anstee et al., 2005).

Mumby and Edwards (2002) compare multispectral satellite imagery (IKONOS, Landsat and SPOT) to a hyperspectral airborne sensor (Compact Airborne Spectrographic Imager, or CASI) and make recommendations for the best use of the various combinations of spectral and spatial resolutions. They suggest that, for coral reef mapping in clear waters over smaller areas, CASI is the best sensor for detailed accurate mapping though IKONOS data can compete if the requirements are for assessing change in patch shape and structure rather than discriminating specific habitat types. For coarse mapping over areas larger than 500 km², Landsat was clearly the most cost effective platform, though within-reef textural
information was lost due to the lower resolution of the data compared to the size of the structures within the target habitat.

Table 2-1. Characteristics of commonly used airborne and satellite sensors (from Dekker et al., 2003).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Spectral resolution</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airborne photography</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photography</td>
<td>Panchromatic, colour, and colour infra-red</td>
<td>EF to F</td>
<td>User and weather dependent</td>
</tr>
<tr>
<td><strong>Airborne multispectral</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital Video</td>
<td>Spectral filters</td>
<td>EF to F</td>
<td>User and weather dependent</td>
</tr>
<tr>
<td>Daedalus 1268</td>
<td>12 bands: 7 VIS/NIR, 3 SWIR and 2 TIR</td>
<td>EF to F</td>
<td>User and weather dependent</td>
</tr>
<tr>
<td>ADAR</td>
<td>Spectral filters</td>
<td>EF to F</td>
<td>User and weather dependent</td>
</tr>
<tr>
<td><strong>Airborne hyperspectral</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CASI-spatial mode</td>
<td>Up to 20 bands: VIS-NIR</td>
<td>EF to F</td>
<td>User and weather dependent</td>
</tr>
<tr>
<td>CASI-spectral mode</td>
<td>Up to 256 bands VIS-NIR</td>
<td>Spectral rake</td>
<td>User and weather dependent</td>
</tr>
<tr>
<td>HYMAP</td>
<td>126 bands: VIS-SWIR</td>
<td>EF to F</td>
<td>User and weather dependent</td>
</tr>
<tr>
<td><strong>Satellite multispectral</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat TM 7+</td>
<td>8 bands: 1 Pan, 4VNIR, 2 SWIR, 1TIR</td>
<td>30m multispectral, 15m panchromatic</td>
<td>16 days</td>
</tr>
<tr>
<td>SPOT 4</td>
<td>4 bands</td>
<td>20m multispectral, 10m panchromatic</td>
<td>26 days</td>
</tr>
<tr>
<td>SPOT 5</td>
<td>5 Bands: 3VNIR, 1SWIR+, 1 Pan</td>
<td>EF (2.5m panchromatic), F (10m VNIR)</td>
<td>26 days</td>
</tr>
<tr>
<td>ASTER</td>
<td>14: 3VNIR, 3SWIR, 5TIR</td>
<td>15m VIS, 90m TIR, 250m</td>
<td>16 days Needs request</td>
</tr>
<tr>
<td>MODIS</td>
<td>36</td>
<td>500m land, 1000m water</td>
<td>Twice daily, or every other day</td>
</tr>
<tr>
<td>Ikonos</td>
<td>4 VNIR</td>
<td>1m pan, 4m multispectral</td>
<td>3 days, pointable sensor</td>
</tr>
<tr>
<td>Quickbird</td>
<td>4 VNIR</td>
<td>0.61m panchromatic, 2.5m multi-spectral</td>
<td>1-3.5 days depending on the latitude, pointable sensor</td>
</tr>
<tr>
<td><strong>Satellite hyperspectral</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperion</td>
<td>224 bands</td>
<td>30m</td>
<td>16 days (near TM)</td>
</tr>
<tr>
<td>ALI</td>
<td>10 bands: 1 Pan, 6 VNIR, 3 SWIR</td>
<td>15m panchromatic, 30m multi-spectral</td>
<td>16 days (near TM) Pointable sensor</td>
</tr>
</tbody>
</table>

Table interpretation notes:

**Spatial (pixel) resolution**

EF = Extremely fine <5m; F = Fine 5-20m; M = Medium 20-250m; C = Coarse 250 - >1000m

Spectral Rake is a collection mode where a limited number of points are collected across the scene.

**Spectral resolution**

Low = panchromatic or analogue images; Medium = multi spectral, 3-20 spectral discrete bands; High = hyper spectral, contiguous spectral bands (typically between 20 and 300 bands); User dependent = sensor deployment should occur according to the user’s specifications (date, time & location); Weather dependent = sensor deployment should occur under optimal weather conditions.
The development of hyperspectral airborne sensors such as CASI and the HyMap, has also allowed the development of sophisticated quantitative modelling methods for seagrass mapping (e.g., Clark et al., 1997; Alberotanza et al., 1999) and biomass estimation (Mumby et al., 1997). The high signal to noise ratios and the very narrow spectral bandwidths of these sensors enable the discrimination of seagrass species via their differing pigments (Fyfe, 2003). Improved methods of direct georeferencing (see Section 2.3.2.5) and radiometric calibration (Edirisingshe, 2004) have allowed increased repeatability and accuracy. Comparison studies between multispectral satellite and hyperspectral airborne sensors show that the airborne sensors produce substantially more environmental information (e.g., Mumby et al., 1997; 1998; Jakubauskas et al., 2000) and are found to be competitive with aerial photography on a cost basis, particularly on a per indicator basis (Mumby et al., 1997; Dekker, Brando et al., 2005). This is also partly explained by a reduced number of geometric and radiometric issues such as sun glitter due to the line scanner technology used by these sensors.

Processing of the imagery can be based on empirical methods, which typically relies upon image classification techniques that make use of auxiliary data collected in the field, such as video imagery or quadrat observations, to train and assess the classifications. The method typically does not account for air and water column attenuation and generally depends on expert interpretation skills and local knowledge, resulting in a lack of transferability to other geographic areas.

Inverse modelling of the seabed reflectance with multispectral or hyperspectral data requires three main informational inputs to parameterise the model, including; the upwelling water leaving radiance (that is, the atmospherically corrected image pixel values), the vertical attenuation coefficients of the optically active water constituents (that is, both upwelling and downwelling), and the reflectance properties of the target habitats (Dekker et al., 2001). Reflectance properties are increasingly available from spectral libraries or published results (e.g., Malthus and George, 1997; Alberotanza et al., 1999; Myers et al., 1999; Hochberg and Atkinson, 2000; Kutser et al., 2003; Lubin et al., 2001; Fyfe, 2003; Karpouzli et al., 2004; Anstee et al., 2004). The advantages of the inverse modelling approach include; increased levels of repeatability; transferability of the model to other sensors; exact sensitivity and error analyses; and providing for the ready inclusion of new information inputs as they become available. The advantages of the method are realised most strongly with the examination of temporal changes in seagrass parameters, particularly as the temporal coverage of the satellite sensors is increasing.
In spite of these advances, there are a number of limitations of multispectral and hyperspectral imaging. In coastal environments, a higher signal-to-noise ratio is needed due to the high attenuation of light in water. The target habitats often intergrade with each other and the incorrect attribution of habitat types is relatively common, particularly where the seagrass is sparse or there is reduced contrast between the seagrass and the substrate (Mumby et al., 1997). Other limitations relate to the relatively high initial costs of operating the systems and the complex and sophisticated infrastructure required to process the imagery.

### 2.3 Remote sensing for seagrass monitoring: digital aerial photography

The primary source of optical remote sensing for most shallow marine resource management agencies remains aerial photography (e.g., Thomas et al., 1999; Kendrick et al., 2000, 2002; Orth et al., 2004; Lathrop et al., 2004). However, much of the aerial photography used for seabed mapping is captured for assessing terrestrial landscapes so optimum conditions for shallow water mapping are not considered, including atmospheric and water column conditions, and often much of the shallow water coverage is of poor quality. Methods for acquiring vertical, or nadir-looking aerial photography over shallow marine waters were first described by Lee (1922) and detailed developments are summarised by Slama et al. (1980). Most photogrammetry literature focuses on broad scale mapping programs of the coastline and/or near shore bathymetry (Lillesand and Kiefer, 2000; Wolf and Dewitt, 2000). Recently, comprehensive manuals detailing methodologies for mapping seagrass habitats were produced by large agencies such as NOAA Coastal Services Center, UNESCO and the Joint Nature Conservation Committee (JNCC) (e.g., Finkbeiner et al., 2001; Waddington and Hart, 2003; Davies et al., 2001; Green et al., 2000). At the same time small format aerial photography (SFAP) has seen renewed interest and technique development (Warner et al., 1996; Phinn et al., 2001; Mills et al., 2003) as it is well suited to low cost, specialised remote sensing for resource management purposes that target limited areas, with a particular focus on temporal monitoring.

The key developments taking place in aerial photography for habitat mapping in shallow coastal waters include; sensor advances and improved availability of small format digital cameras; development of image capture methods including a reduced need for ground control; improving image interpretation and analysis, such as object oriented classifications; and an increasing range of applications – such as, fine-scale spatial metric studies. These are addressed in turn in the following sections.
2.3.1 Sensor developments

Large format digital cameras with high quality metric lenses are now available and the rate of uptake is accelerating (Malthus and Mumby, 2003), partially driven by significant savings as a result of no longer requiring film processing and scanning (e.g., Lathrop et al., 2004). The image spatial resolution, radiometric response and quality of the colour response is regarded by some as sufficient for topographic and habitat mapping (Malthus and Mumby, 2003). The spatial resolution of digital images is also often higher when compared to typical scanned film imagery (Leberl et al., 2002). Radiometric resolution is considered to be superior, which has advantages for shallow water photo interpretation where contrast is important, though some parts of the image may be more likely to be over or underexposed. However, at present, the high cost of the new large format digital systems means that relatively few are operational and the costs are beyond the reach of many.

Small format high resolution digital cameras of six mega-pixels or more with the option of good quality non-metric lenses have rapidly reduced in cost in recent years. The often-quoted advantages of the digital cameras are the rapid availability of images following acquisition (even in real time) and the avoidance of the issues associated with scanning in large format aerial photography, such as Newton Rings and spectral or spatial artefacts (Mills et al., 2003; Coburn et al., 2001). Phinn et al. (2001) document a small format system based on the Positive Systems ADAR-1000 with a Kodak DCS460 that is regularly deployed for quantitative monitoring of environmental health and change.

Despite the recent advances, standard film aerial photography remains the media of choice for most. The advantages of film include the vast amount of work over the decades to establish highly dependable standards for every aspect of the process – from film quality, to image capture to processing and interpretation (Slama et al., 1980; Wolf and Dewitt, 2000). The media archives well, while archiving of digital media, including digital photography, is still under development (e.g., Lavoie, 2004).

Technological developments enable the use of aerial photographic techniques by relatively small organisations particularly with the increased availability of cheaper photogrammetric software and much increased computing power and storage. This is creating opportunities for specialised applications of remote sensing, such as small-format aerial photography, where cameras with image sizes smaller than the standard 230 x 230 mm aerial film negatives are used to capture smaller, specific targets – often from lower altitudes (Goba and Senese, 1992; Warner, 1994; King, 1995; Warner, 1996; Warner et al., 1996; Abd-Elrahman et al., 2001; Mills et al., 2002; Sandmann and Lertzman, 2003).
Multi-sensor platforms, such as the Airborne Integrated Mapping System (AIMS) (Grejner-Brzezinska and Toth, 1999) and the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system, offer considerable advantages to seabed mapping. Both systems have GPS with its high positional accuracy and inertial navigation systems (INS) coupled with high-resolution digital imagery, while CHARTS also incorporates LIDAR (light detection and ranging) to enable the collection of bathymetric survey measurements. These systems are very similar to the ideal integrated sensor system outlined by Ackerman (1996). In another approach to multi-sensor systems, airborne optics and waterborne acoustics have also been used, with an integration of the results to determine habitat extent and distribution across the boundary between optically shallow and deep waters (Malthus and Mumby, 2003).

### 2.3.2 Capturing imagery over shallow waters

A systematic approach to planning the acquisition of imagery is essential to achieve successful coastal remote sensing projects and a generic framework is presented in Phinn et al. (2000). It is designed to produce imagery suitable for mapping, monitoring and modelling while taking into account scale and resolution issues. Components of the planning framework are adapted and summarised as follows: information required; target characteristics; environmental conditions including atmosphere, surface interactions and water column conditions; minimal spatial, temporal, spectral and radiometric dimensions; positional and thematic accuracy; sensor and sensor platform choice; and logistics.

In order to maximise the information available from aerial photography and to increase the accuracy of mapping it is important to define the information required of the imagery, such as seagrass extent and density; spatial metrics including fragmentation; or epiphyte abundances. The target characteristics could include the known species types; physical structure (or architecture) of the habitat (see Figure 3-11); patchiness and growth habits of those species; spectral signatures of the targets; and expected depth ranges and water clarity.

Generally, the most critical environmental conditions are the high variability of light absorption and scattering in and over coastal marine waters (that is, water clarity; see section 1.2.2) and the reflection of light by the water surface, which is further complicated by wave slopes (see section 3.2). Typical standards set for an aerial photography flight could be: sun angle (that is, the angle of the sun above the horizon or sun elevation angle) greater than 20° and below 40°; wind speed below 2.5 ms⁻¹ (~5 knots) at the surface; low tide; better than average water clarity; low atmospheric haze; and no cloud. Finally, while a
systematic approach is critical, the data acquisition planning process is iterative and requires shuffling back and forth between what is ideally required and what can be achieved (Warner et al., 1996). Further aspects of mission planning and image capture are presented in the following subsections.

2.3.2.1 Image capture – sun glitter

Aerial photography image acquisition methods are largely established and documented in guidelines and manuals (see above), however there are a number of aspects where more detailed information could assist the process. For example, the existing literature make only general recommendations about suitable sun angles, apart from Fleming (1968) who published detailed sun glitter nomograms under “worst case” rough water conditions. Refined methods for forecasting the amount of glitter on an image are presented in Chapter 3 that more accurately account for wave slope reflections.

The acceptability of glitter on imagery will depend on criteria including the location of the areas of interest with respect to the glitter. For stereo photogrammetry, when sun glitter is a problem, it is common to increase the end overlap to 80%, though at increased cost for image acquisition and processing. Large photogrammetric quality digital cameras enable increased end overlap at less cost than film and, with automated mosaic or “fan” processing, open another avenue to glitter-free orthophotos. An alternative strategy is to use a narrower FOV lens (Mount, 2004) with added benefits of reducing the effects of refraction (see below) as well as variability in the sea floor reflectance with illumination and viewing angles (that is, the bidirectional reflectance distribution function (BRDF)) (Voss et al., 2003), which are both dependent on the incident angle of light rays from the target into the sensor. A disadvantage of a narrower FOV lens is that it necessitates a higher flying height for the same coverage, which often results in an increase in atmospheric haze effects.

Sun glitter avoidance places a severe restriction on the time available for image collection and new methods to overcome the problem are needed. Methods for the removal of sun glitter from captured imagery using a simultaneously collected near infrared (NIR) band are now published for multispectral imagery (Hochberg et al., 2003), with the distinct possibility that the methodology could be applied to aerial photography. The implications for aerial photography could be substantial, as it could mean much larger windows of opportunity for data collection in any one day, higher levels of subsurface illumination and reduced BRDF and shadowing effects. Multispectral and hyperspectral line scanners can
avoid many of these sun glitter issues and also allow a greater range of sun angles (30° to 60°) during image capture.

2.3.2.2 Image capture – subsurface illumination and shadowing

Subsurface illumination is related to the problem of sun glitter as the low sun angles required to ensure low levels of glitter rapidly reduce the available light below the water surface. For aerial photography over the land, sun angles close to 45° are generally recommended with a caution of excess shadowing and low illumination levels below 25° (Brew and Neyland, 1980). Over water, research presented in Chapter 3 shows that sun glitter sets the upper limit but that the lower limit is not yet established. Absolute levels of sunlight and skylight illumination available at the surface are also presented and discussed in Chapter 3.

![Figure 2-1. Snell’s Cone illustrating that the minimum subsurface sun angle is about 42°. The lower image is taken looking straight upwards with the horizon appearing as a circle (from Apel, 1987).](image)

Another related issue requiring further research is that of the amount and variation in shadowing within submerged vegetation target habitats with changing sun angles. The amount of shadowing will clearly affect the signal received by a camera, depending on the structure (architecture) of the target (see Figure 3-11) and the effective subsurface sun
angle. The subsurface sun angle is accurately described by Snell’s law and gives rise to an effect known as Snell’s Cone (Figure 2-1). Chapter 3 presents a detailed exploration of the issues and findings.

2.3.2.3 Image capture – temporal resolution

The issues associated with obtaining appropriate temporal resolution are illustrated with the mapping of macroalgal surface canopies (e.g., Giant kelp *Macrocystis pyrifera* (Linnaeus) C. Agardh) with infrared photography. Deysher et al. (1995) describe the methods used to capture the maximum canopy cover extent each year over a 25-year monitoring period by North et al. (1993). Approximately monthly missions were flown with the largest extent found in any one month used for that year. The variability in mapped extents caused by storms and the high unpredictability in the plant’s growing cycle due to irregular environmental conditions showed that regularly timed image collection dates (e.g., seasonal) would have failed to capture an optimal distribution (see also Jensen et al., 1980). Seagrass is generally much more stable in its distribution than *M. pyrifera*, though the results of quarterly monitoring in North West Bay and Norfolk Bay in southeastern Tasmania (Crawford et al., 2005) show that the target species for the thesis does not appear to have a regular seasonal pattern of biomass growth. This means that targeting optimal temporal resolution is made more challenging. A further issue is the limitations placed on obtaining the imagery by the weather and water column environmental conditions. For example, Jupp (1985, 1988) notes the numbers of days available, when the environmental conditions are optimal for image capture over the Great Barrier Reef, are a serious constraint.

2.3.2.4 Image capture – positional accuracy

An estimate of required positional accuracy must be made to ensure adequate positional control is implemented. Many sensors, both satellite and airborne, are now fully modelled and accurate across the whole image, for example, Ikonos to within 1 m (Fraser and Yamakawa, 2004). For satellites, this is achieved through accurate knowledge of the satellite’s position and orientation coupled with models of the sensor itself. Airborne systems can use direct georeferencing (see next subsection) to achieve geometric correction and positioning of the imagery, often without any ground control at all (e.g., Skaloud, 2002). Given the scarcity of well-surveyed stable geographic features in subtidal environments compared to the land, such advances are welcome.

However, in general terms, aerial photography still needs ground control to assist with obtaining a precise location and orientation of the camera, thus allowing the removal of tilt,
roll and yaw distortions and the absolute positioning of the image in geographic space. Ground control takes the form of well defined objects visible in the image that have a known geographic position (including height) and are distributed around the image – ideally not clustered or in straight lines (Wolf and Dewitt, 2000). In the absence of such objects, it is common to place artificial targets, or “premarks”, in the target area prior to flying the mission (Burnside, 1985).

2.3.2.5  **Direct georeferencing**

Operational direct georeferencing (Skaloud, 2002) systems are available which locate the precise orientation and position of the camera in space providing a direct solution for the position of the image and the creation of an orthophoto. The systems make use of high quality inertial movement units (IMUs) and GPS to locate the camera at the precise moment of image capture. Some ground control may still be required as check points. The systems are becoming more common operationally and are used on multiple sensor platforms, such as Scanning Hydrographic Operations Airborne Lidar Survey (SHOALS) and CHARTS, as a way of integrating sensor outputs and are essential on airborne LIDAR systems.

2.3.3  **Image preparation and processing**

The methods used for preparing film-based imagery are well documented and are generally not covered here, rather the focus is on remote sensing techniques that can be applied to digital aerial photography – that is, imagery either scanned from film or captured directly with a digital sensor. Several radiometric and spectral corrections can be used including vignetting, illumination, atmospheric, BRDF and depth corrections. Vignetting is well documented (e.g., Phinn et al., 2001), whereas illumination corrections are not well documented at all (though see Carder et al., 2003), and attention is given later in this section to BRDF, atmospheric and depth corrections. Typically, when preparing imagery, the first stage is to remove geometric distortions, including lens distortions, relief displacement and refraction effects. Most of these geometric distortions are well understood by photogrammetrists; therefore this section begins with a focus on the issue of refraction correction. For shallow water applications, the amount of distortion introduced by refraction, in addition to that caused by relief displacement, needs to be assessed. There are different solutions to distortion removal depending on whether stereo photogrammetry or a single image approach is used.
2.3.3.1  **Stereo photogrammetry and refraction**

Image displacements caused by refraction have been addressed since the middle of last century (Rinner, 1969; Tewinkel, 1963; Harris and Umbach, 1972). For stereo photogrammetry there is negligible horizontal displacement but measured subsurface depths are systematically shallower than actuality and correction factors should be used. Waves have little effect on horizontal position though they do have a detrimental effect on image sharpness (Fryer, 1985).

2.3.3.2  **Single image orthophotos and refraction**

For single images with a digital elevation model (DEM) available, an orthophoto can be produced, though displacements due to refraction are present in the horizontal position of image objects, particularly in the corners of the image. This is caused by the higher angle of incidence of the light rays passing from the sea floor up through the water column and refracting at the surface into the sensor as radial distance increases from the centre of the image. Correction formulas are available with the potential to be incorporated into orthophoto production systems (Rinner, 1969; Harris and Umbach, 1972). The magnitude of distortion varies strongly with the angle of incidence and water depth, which means that wide-angle aerial photography (approximate FOV of 90°) is more affected than normal angle photography (approximate FOV of 60°). Rinner’s formula (1969) is used to derive a surface plot (Figure 2-2) and then a nomogram (Figure 2-3) of displacement as a function of distance from the image centre and depth.

Some indicative displacement values are as follows: in 10 m of water, an image captured with a wide angle lens (half angle FOV of 45°) can retain displacements of up to 6 m in the image corners while, in 5 m of water, the displacement is about 3 m. At the same depths, imagery obtained with a normal angle camera (half angle FOV of 30°) would have displacements in the corners of about 4 m and 2 m, respectively.

2.3.3.3  **Simple atmospheric correction – dark subtraction**

The strength of the light signal arriving at the sensor (film or digital) has significant components added and subtracted by the atmosphere (haze) and the water surface (skylight reflections). In the absence of a complete atmospheric correction, Green *et al.* (2000) recommend the use of a method called “dark subtraction” to account for light arriving at the camera that is added in from sources such as atmospheric scattering and skylight reflected from the water surface. In the environmental noise approach of Dekker and Peters (1993),
further developed in Wettle et al. (2004), sources of noise are explicitly taken into account and an estimation of the noise in each image is calculated.

Figure 2-2. A surface plot of the modelled combined refraction and relief displacement (displacement_r) in metres as a function of distance from the image centre (radius_degrees) in degrees and depth in metres.

Figure 2-3. Nomogram of the modelled combined relief and refraction displacement for depth (m) and radial distance (°). The radial distance can be directly related to lens FOV (that is, FOV/2). The displacement is radial with the displaced position closer to the image centre than the orthometric, or true, position, that is, the image features “lean in” below the image datum.
2.3.3.4 Bidirectional effects correction

The bidirectional reflectance distribution function (BRDF) (Schowengerdt, 1997; Martonchik et al., 2000) describes the effect of variable reflectance of the target surface caused by a changing relationship between viewing and illumination angles. This means that identical surfaces will register more strongly or weakly at the sensor depending on a combination of the sun angle or their position in the image. While significant progress has been made in identifying and correcting BRDF in aerial photography for land cover types (Tuominen and Pekkarinen, 2004), progress is less advanced for aquatic vegetation (Valta-Hulkkonen et al., 2004). However, theoretical and practical advances in the multispectral and hyperspectral fields (Ackelson, 2003; Mobley et al., 2003) lay the groundwork for further progress in aerial photographic processing.

2.3.3.5 Depth corrections

A number of methods developed for multispectral and hyperspectral images are increasingly being applied (Malthus and Mumby, 2003), some of which could possibly be applied to aerial photography. Where a DEM is unavailable, Lyzenga’s (1978, 1981) depth invariant method has been applied and has improved the classification accuracy of multispectral imagery (Mumby et al., 1998), though results are inconsistent for areas with suspended matter and changing substrates (Lyzenga, 1978). Other models available include: Jupp’s (1985, 1988) Depth of Penetration; Bierwirth’s (1993) Bottom Reflectance model; Tassan’s (1996) modification of Lyzenga’s method and Hedley and Mumby’s (2003) matrix method.

Where a DEM is available, a simple depth correction based on regression can be developed (e.g., Chavez et al., 2000). Authors such as Jupp et al., (1985) and Dekker, Anstee et al., (2005) suggest that unless spectral readings are collected with spectroradiometers in the field at the time of image capture, more accurate methods (e.g., Bierwirth et al., 1993) cannot be applied as, for example, by Malthus and Karpouzli (2003). Newman and LeDrew (2001) identify further issues for depth corrections when they found that, the light field as described by Beer’s Law of Logarithmic Decay is subject to significant variability within the bottom 5 m of water, particularly over bright substrates, such as sand.

In spite of its shortcomings, the regression method can lead to improvements in image interpretation in circumstances where the water clarity is high and the bottom features are relatively uniform (Chavez et al., 2000). In general terms, the method is applied by fitting a model to the decay in pixel brightness with depth for a bottom type that is, ideally, consistent across the depth range (see section 5.2.3.2 and equation 5-2 for details). Decay is
usually exponential, though variations in inherent and apparent optical properties of the water will alter the rate of attenuation and produce non-standard curves (Apel, 1987). Usually sand is selected for the bottom type, as it is reasonably easy to identify, though high levels of variability in pixel brightness can be found over sand – particularly shallower than 2 m (see Chapter 5). This is consistent with Newman and LeDrew’s (2001) findings and the BRDF study of Voss et al. (2003). Submerged aquatic vegetation pixel samples from similar bottom types should also be fitted. Finally, each pixel is then standardised to the brightness of a selected depth by adding the residuals of the fitted model to the selected depth. To obtain the brightest reflectivity, the depth selected should ideally be the shallowest depth that has water coverage at low water.

2.3.4 Image interpretation and mapping

2.3.4.1 Discrimination of submerged aquatic vegetation

Methods for discriminating seabed habitats in aerial photography are largely dependent on the contrast between adjacent substrates, such as the darker submerged aquatic vegetation and a brighter adjacent substrate – typically sand. Tone, texture and colour play a much lesser role as the water highly attenuates these components. The customary approach is to scan in the aerial photographs and then manually digitise around darker areas of the substrate in a GIS based on the assumption that these areas are homogenous areas of submerged aquatic vegetation (e.g., Robbins, 1997), though practitioners also make use of stable base overlays and zoom transfer scopes (Ferguson et al., 1993).

Mapping rules are used to maintain a standardised result across time and between operators (e.g., Robbins, 1997; Green et al., 2000; Kendrick et al., 2002). The rules identify minimum discernible objects, minimum mapping units and the size and spacings for grouping patches. Rules can also be set to define the scale at which digitising takes place and the classes for habitat types, with some software able to facilitate the implementation of these rules (e.g., NOAA, 2002). While humans are reasonably good at perceiving contrast, computer-aided techniques are often confounded by variable illumination across images caused by, for example, depth differences or BRDF effects. However, Kendrick et al. (2002) presents a local thresholding methodology designed to differentiate between seagrass and sand in small subsections of an image using a semi-automated quadtree moving window approach.

The level of discrimination achievable with aerial photography is dependent on a large variety of factors including sun and skylight reflections (Chapter 3), turbidity, depth and
contrast of the substrate with submerged aquatic vegetation (Chapter 4). For example, most literature reports that aerial photography is reasonably accurate at depicting seagrass beds and some density classes, though generally unable to differentiate between seagrass species or between very sparse seagrass species and the substrate (e.g., Finkbeiner et al., 2001; Waddington and Hart, 2003; Davies et al., 2001; Green et al., 2000). Ekebom and Erkkila (2003) report on differences in operator interpretation error when identifying a variety of marine and coastal habitats in aerial photography.

### 2.3.4.2 Classification of aerial photographs

Some difficulties in interpreting underwater signatures through spectral differences have been identified (McKenzie et al., 2001), although standard remote sensing unsupervised and supervised classification techniques with accuracy assessments have indicated useful results (e.g., Pasqualini, 1998; Chauvard et al., 1998; Pasqualini et al., 1999, 2001; Beanish et al., 2002; Agostini et al., 2003; Calvo et al., 2003). Lathrop et al., (2001, 2004) applied more sophisticated object-orientated segmentation and classification techniques with good results – particularly in determining seagrass density – with possible extensions to that technique identified by Lobo et al., (1998). Fuzzy set mapping (Matsakis et al., 2000; Urbanski and Szymelfenig, 2003) and decision tree classifications (e.g., Franklin et al., 2001; Puestow et al., 2001; Dartnell and Gardner, 2004) have good classification potential for further work.

### 2.3.5 Applications development

There are a large number of applications for the products of aerial photography including mapping and monitoring shallow marine habitats as well as providing a basis for accuracy assessments of satellite and hyperspectral image classifications (e.g., Calvo et al., 2003; Williams et al., 2003). Some key areas for further application development are: refining the ability to discriminate differences within habitat types – for example, between seagrass densities or determining epiphyte abundance (Lathrop et al., 2004); identifying opportunities to improve image capture – for example, with more precision about water quality, target characteristics and sun glitter; matching temporal resolution with habitat dynamics – perhaps by using small-format digital cameras (Phinn et al., 2001; Mills et al., 2003); the production of robust spatial metrics (Manson et al., 2003); the use of landscape scale studies to take advantage of the broad spatial coverage of imagery (Fonseca and Bell, 1998; Kendrick et al., 1999); the use of aerial photography as a sampling method (e.g., double sampling) similar to terrestrial land cover applications (Kalkhan et al., 1998; Kohl et
With regard to scale, Duarte (1999) and Thomas et al. (1999), found that the bulk of seagrass monitoring work is conducted either at the local scale – typically focusing on the 1 m² quadrat – or the broad area mapping and resource inventory style studies covering 10’s to 1000’s of km². Thomas et al. (1999) found that the local studies had relatively weak statistical power while the broad area work had high levels of uncertainty and error. Fine scale image capture platforms include: cliff top photography (e.g., Ducrotay and Simpson, 2001); micro lights (e.g., Mills et al., 2003); and balloon or blimp photography (e.g., Guichard and Bourget, 2000; Yamamuro et al., 2003).

2.4 Conclusion

A number of avenues for methodological development are raised in this review and discussion of the map production process for seagrass monitoring. Progress can be achieved through improvements at any stage of the map production chain, and by aligning the research effort adequately to the requirements of seagrass monitoring. A key barrier to image acquisition is the major limitation on the time window available for image capture imposed by the effect of sun glitter on aerial photography. Other barriers to acquisition include the cost of stereo photogrammetry and the clear specification of the environmental conditions necessary for optimal image quality such as water clarity and wind speeds. Barriers to the use of small format digital aerial photography include the non-metric quality of the lenses, the reduced quality of ground control partly due to the small areal coverage of the imagery, and the low spectral resolution of the sensor.

The emerging approaches and advancing technologies in the multispectral and hyperspectral domains are promising to provide many benefits to all stages of map production including improving cost-benefit ratios, increased repeatability, and powerful multi-temporal analyses (Malthus and Mumby, 2003; Dekker, Anstee et al., 2005). It is proposed here that some of the advances can be applied to digital aerial photography at both the image preparation and processing as well as the image interpretation and analysis stages in an effort to obtain improvements to the approaches generally used with this simpler form of imagery. Identified methods that might produce improvements are depth corrections, band ratios, surface modelling, and image mapping (classification, segmentation and unmixing).
Overall, methods that enable flexible image acquisition with the use of low cost equipment and aircraft and fast image processing would facilitate monitoring of seagrass at landscape scales with high temporal resolution by sampling a large number of small locations from widely dispersed areas.
Chapter 3

Acquisition of through-water aerial survey images: Surface effects and the prediction of sun glitter and subsurface illumination

3.1 Introduction

Methods for acquiring vertical, or nadir-looking, aerial photography over shallow marine waters have a long history (Lee, 1922) and Slama et al. (1980) describe many of the more recent developments. In the last 10 years, more attention has focussed on seabed, or benthic, habitat mapping with comprehensive manuals detailing methods, for example, Finkbeiner et al. (2001). Phinn et al. (2000) developed a useful framework for planning remote sensing missions in the coastal environment designed to produce data suitable for mapping, monitoring and modelling. However, while useful developments are taking place, the published methods typically offer “rules of thumb” for some components of mission planning, including minimising the amount of sun glitter on the imagery. The reliance on “rules of thumb” is partially explained by the complex and challenging nature of remote sensing in the shallow marine environment (see Chapters 1 and 2). While these complexities create barriers to obtaining clear observations of subsurface features, the focus of this chapter is on enhancing the image quality through the application of more precise understanding of the behaviour of light at the air/water interface to image capture.

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3 This chapter is a slightly adapted version of: Mount, R.E. (2005). “Acquisition of through-water aerial survey images: Surface effects and the prediction of sun glitter and subsurface illumination.” Photogrammetric Engineering and Remote Sensing Vol 71 Issue 12, Pp 1407-1415.
Knowledge of light behaviour at the water surface was significantly progressed by workers in the field of hydrological optics such as, Hulbert (1934), Cox and Munk (1954), Duntley (1963), Goodell (1971), Plass et al., (1977), Preisendorfer and Mobley (1986) and Minnaert (1993). Researchers are continuing to find ways of reducing the effects of sun glitter on imagery (Wang and Bailey, 2001; Mobley, 1999). However, many of the models and functions developed by these researchers are too complex and provide more detail than that required by most aerial survey practitioners. This chapter aims to simplify the models while maintaining sufficient accuracy to be useful.

In shallow waters, surface interactions affect both downwelling and upwelling light incident to the air/water interface – that is, both “air-incident” or “water-incident” light. The effects are mainly created by reflection and refraction, which are dependent on the geometry of the light path and the surface, which, in turn, are strongly influenced by the magnitude and slope of the surface waves. Of primary interest for image quality are: sun glitter (reflections of the direct beams of the sun), and subsurface illumination and shadowing, which are dependent amongst other factors on the quantity and geometry of the light transmitted through the water surface. Surface glare, which is the reflection of diffuse light from sources such as skylight and clouds, also affects image quality but is not treated here other than to indicate that clouds and atmospheric haze both increase glare, and should be avoided during image capture whenever possible.

### 3.2 Sun glitter

The position of the sun above the horizon is critical to image quality because the sun can create sun glitter in the image by the specular reflection of the direct solar beam from the water surface into the sensor. Sun glitter is also known as solar flaring or sun glint. Figure 3-1 is an example of how severe sun glitter obscures subsurface features in an image.

Generally, on land, if the sun angle is low during image acquisition, there is an increase in the amount of shadowing in the imagery and a reduction of illumination on the target. If the sun angle is high, problems are created by “hotspots”, which are areas with a lack of detail caused by a lack of shadow and increased backscatter from the atmosphere and the ground at specific angles described by BRDF (Apel, 1987; Fleming, 1968). For aerial photography over the land then, sun angles close to 45° are generally recommended with a caution of excess shadowing and low illumination levels below 25° (Brew and Neyland, 1980).
Figure 3-1. Sun glitter obscuring sub-surface features at Lime Bay, southeast Tasmania. Aerial photograph captured on 25/2/1990 at 1:42,000 and the portion shown here is orientated with north up and is 9.5 by 5 km.

However, over water, the forward scattering of the direct beam of the sun by the water surface causes an added problem in the form of sun glitter. In principle, sun glitter can be avoided by capturing imagery when the sun angle is low enough for the reflected light of the direct beam to pass under the field of view (FOV), or cone angle, of the vertical, nadir-looking camera (Strandberg, 1967). Yet, empirical evidence from imagery shows that low sun angles in combination with surface waves can create very large areas of sun glitter.

### 3.2.1 Sun glitter model definition

In the simple case of vertical, nadir-looking photography over a perfectly flat water surface, the specular reflection of the sun subtends an angle of 0.54° from one edge of the solar disk to the other (Gardashov and Barla, 2001). This specular reflection will become visible in an image when, as the sun climbs in the sky, the solar zenith angle ($\theta_z$) reduces to become equal to or less than half the sensor’s angular field of view (FOV) (see Figure 3-2) –

$$\theta_z \leq \text{FOV}/2$$ (3-1)

Note that $90 - \theta_z$ is the sun angle or solar elevation ($\alpha$) and that the angular FOV of an image is measured into the corners and not the sides of an image (Wolf and Dewitt, 2000). Standard aerial photography specifications for angular FOV are given in Table 3-1.
Figure 3-2. The angle ($S_{sp}$) at the focal point between the image centre ($O$) and the solar specular point ($SP$) is equal to the solar zenith angle ($\theta_z$). $\theta_z$ is complementary to sun angle ($a$) (that is, $a = 90 - \theta_z$) and $\text{FOV}_{saz}$ is the image field of view in the direction of the solar azimuth. Distance in image units ($d$) can be calculated with the camera focal length ($f$) and $\theta_z$. Distance at the water surface is $d'$.

Table 3-1. Standard names and angles for camera lens angular fields of view used in aerial photography.

<table>
<thead>
<tr>
<th>Lens Angle</th>
<th>Angular FOV</th>
<th>Half Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Normal”</td>
<td>~60°</td>
<td>~30°</td>
</tr>
<tr>
<td>“Wide”</td>
<td>~90°</td>
<td>~45°</td>
</tr>
<tr>
<td>“Super Wide”</td>
<td>~120°</td>
<td>~60°</td>
</tr>
</tbody>
</table>

The shape and orientation of the image relative to solar azimuth ($S_{sa}$) is significant (Figure 3-3). As any image has a wider diameter (or FOV) from corner to corner than side-to-side, reflections become visible at lower sun angles if a corner is orientated towards the sun (that is, at the solar azimuth). The difference is even more marked for rectangular images – such as those used for small format aerial surveys – where the sides of the shortest width will be the last to be affected by reflections as sun angle increases.
Equation 1 can be amended by using the angle of the FOV in the direction of the solar azimuth (FOV\textsubscript{saz}) in place of the angular FOV to find when the sun will become visible in an image at any orientation for a flat-water surface (see Figure 3-3):

\[
\theta_z \leq \text{FOV}_{saz}/2 \text{ or, therefore, } \text{FOV}_{saz} \geq 2\theta_z \tag{3-2}
\]

In the image, the angle (S\textsubscript{sp}) measured at the focal point of the camera lens between the principle point – nominally the centre of the image, O – and the centre of the solar specular reflection, or solar specular point, (SP) is equal to the solar zenith angle (see Figure 3-2):

\[
S_{sp} = \theta_z \tag{3-3}
\]

Figure 3-3. The egg-shaped oval of sun glitter is shown in the northeast corner of a standard 23 by 23 cm aerial photograph. The following terms are illustrated: the image centre (O), solar azimuth angle relative to north (S\textsubscript{az}), solar specular point (SP), image field of view in the direction of the solar azimuth (FOV\textsubscript{saz}), the long diameter of the glitter (G\textsubscript{az}), the widest diameter of the glitter normal to G\textsubscript{az} (G\textsubscript{w}), and the radial distances from SP to the edge of the glitter in the direction of S\textsubscript{az}, which are G\textsubscript{azro} (towards O) and G\textsubscript{azrh} (away from O).
The distance on the image, \( d \), is dependent on the focal length of the camera, \( f \), and is found by:

\[
d = f \tan \theta_z
\]

(3-4)

Given the sun angle and FOV and using equations 1 to 4, a flight plan can be checked to see whether or not SP will fall on an image at the angle of the solar azimuth. If \( \text{FOV}_{saz} \) is used, a more precise estimate can be obtained.

3.2.1.1 Perturbed water surface

However, in reality the sea is seldom still and any wave on its surface acts as a mirror that both raises and lowers the effective sun angle for the sensor at the position of that wave (Apel, 1987; Gardashov and Barla, 2001). The result is a greatly enlarged area of glitter, generally in the form of an egg-shaped oval around \( SP \) (see Figure 3-3), which can spread into the image even when the sun angle would – if the surface were perfectly flat – be low enough for the reflected direct beam of the sun to miss the sensor (that is, \( \theta_z > \text{FOV}_{saz}/2 \)). The dimensions of the glitter-affected area vary mainly with sun angle and wave slope (Preisendorfer and Mobley, 1986), though various authors define the shape differently. Fleming’s (1968) definition is at odds to that described by Minnaert (1993) and both are different to that proposed by Preisendorfer and Mobley (1986). Fleming’s approach will be shown to be inaccurate, while the latter authors each make useful contributions.

Fleming (1968) claims empirical (though undocumented) evidence from the U.S. Coast and Geodetic Survey shows that, under “worst case” conditions – that is, rough seas – the angle subtended by the long axis of the oval of glitter varies from 30° at a sun angle of 90° to almost 90° at a sun angle of 20°. The relationship between sun angle and the size of the glitter-affected area measured directly from Fleming’s nomographs (that is, in the image plane) is described by the following formula:

\[
G_{az} = G_{zen} / \cos \theta_z
\]

(3-5)

where \( G_{az} \) is the diameter of the long axis of the glitter oval (that is, in the direction of the solar azimuth – see Figure 3-3) in degrees, \( \theta_z \) is the solar zenith angle, and \( G_{zen} \) is the observed diameter of the glitter oval with the sun at the zenith under worst-case wave conditions. \( G_{zen} \) is estimated from empirical data and Apel (1987) and Fleming (1968) give values of 20° to 30° for rough conditions. Equation 5 actually describes the long diameter of the oval of incident light on a flat specular surface when a parallel beam of light circular in cross section (like the sun) is used. The shape of the area varies from a disk – when the
incident angle is normal to the surface – to an oval for other incident angles. The resultant function (Figure 3-4) shows that as sun angle increases (i.e. as $\theta_z$ tends to 0), the area of glitter reduces to a minimum area of spread when the sun is directly overhead.

![Figure 3-4. Long diameter of the sun glitter oval ($G_{az}$) in degrees by sun angle, after Fleming (1968). The diameter of the glitter oval is set to 30°, that is, rough conditions, when the sun is at its zenith ($G_{zen}$).](image)

In contradiction to Fleming, Minnaert (1993) clearly argues that, though the width of the glitter ($G_w$) is dependent on the sun angle, the long axis of the glitter ($G_{az}$) varies only with the slope, or tilt, of the surface waves ($\beta$). Minnaert offers the following equations:

$$G_{az} = 4\beta_m \text{ and } (3-6)$$

$$G_w = 4\beta_m \sin a \text{ (3-7)}$$

where $\beta_m$ is the maximum wave tilt, and $a$ is sun angle. Preisendorfer and Mobley (1986) agree with Minnaert’s arguments in principle, however, the results of their modelling reveal some significant differences in the shape of the glitter-affected area. Preisendorfer and Mobley provide convincing theoretical and experimental evidence to support their case, drawing from previous work by Hulbert (1934), Cox and Munk (1954) and Duntley (1963). The key elements of this work are the linear relationship between wind speed and wave slopes and the almost Gaussian distribution of the wave slopes (see next section). Preisendorfer and Mobley present both a Monte Carlo procedure for generating reflected glitter patterns as a function of wind speed and sun position and an analytical first-order
model. The shape of their modelled glitter pattern (approximated in Figure 3-3) generally takes the form of an egg-shaped oval that is distended towards the observer with the widest part of the oval closer to the observer than the solar specular point (SP), though, as for Fleming and Minnaert, when the sun is directly overhead, the oval becomes a disk (i.e. circular). For a given wind speed, and thus wave slope distribution, they found the radius of the glitter oval closest to the image centre ($G_{azc}$) is approximately $2\beta_m$ whatever the sun angle – agreeing with Minnaert (Equation 6). However, at that same given wind speed, the radius of the glitter oval towards the horizon ($G_{azh}$) and the diameter at the widest point normal to $G_{ae}$ ($G_w$) reduces with decreasing sun angle, until, when the sun finally touches the horizon, $G_{azh}$ becomes non-existent and $G_w$ becomes the width of the widest part of the sun still visible. At this stage the glitter is known as the “Pathway to Heaven” (Lynch and Livingstone, 1995).

![Image of glitter at horizon]

Figure 3-5. The “Pathway to Heaven”, illustrating the narrow width of the glitter-affected area. (Lynch and Livingstone, 1995).

The direction of the wind also influences the shape of the glitter pattern with cross winds tending to give wider but shorter ovals and winds parallel to the long axis making it longer and more narrow. Recent work by Ebuchi and Kizu (2002) indicates a weaker relationship between wind direction and wave slopes than that found by Cox and Munk (1954). Further, for Preisendorfer and Mobley’s (1986) model, the winds are assumed to be consistent...
enough in direction and speed to allow the development of mature waves. These steady wind conditions are not typically encountered in aerial photography over shallow waters as the photography often takes place early in the morning with variable wind speeds near to shore. There are potentially some problems associated with waves that are not fully mature or are altered in shape by water currents or energy interactions with the seabed or shore, as it changes the relatively straightforward relationship between wave slope probabilities and light reflection angles. However, while the issue of wave shape stability is noted here, it is highly complex and beyond the scope of this discussion to address, other than to speculate that because forming waves are likely to have a wider range of slopes than mature waves, the model presented here is likely to underestimate the extent of glitter.

A further unresolved issue is the problem associated with multiple reflections, or scattering, from the sea surface. This is where each beam of light is reflected more than once by the waves, thus changing the simple geometry of a single reflection into a highly complex one. The multiple reflections are thought to give rise to a wider glitter oval when the maximum wave slopes are greater than half the sun angle (Cox and Munk, 1954; Preisendorfer and Mobley, 1986). For example, if the sun angle is 30° (an angle typically used for image capture), wave slopes of 15° or greater can cause multiple reflections. Further work is required to assess this effect, though Preisendorfer and Mobley (1986) indicate that only a few percent of incident light rays are affected by multiple scattering at wind speeds of less than 5 m/sec and with sun angles relevant to optical remote sensing.

Waves spread the range of angles at which the sun may be perceived in the image – effectively raising the sun angle at the edge of the glitter closest to the image centre (O), and lowering the sun angle at the edge of the glitter furthest from O. The location of the edge of the glitter closest to O (G_{eo}) is taken to be the critical measurement (see Figure 3-3), as it is the first part of the glitter to appear on the image and also represents the maximum extent of glitter on an image. The number, size and intensity of glints per unit area relate to the probability density function of wave slopes described by Cox and Munk (1954) (Plass et al., 1977; Guinn et al., 1979). However, the complexity of Cox and Munk’s and Preisendorfer and Mobley’s equations make them unwieldy to use in practise, so following the previous discussion, a simplified equation is proposed for finding the location of G_{eo} under single scattering conditions. It is based on the assumption that G_{aero} = 2\beta_m, and is measured at the focal point of the lens as an angle from the image centre (O) and is dependent on the solar zenith angle (\theta_z) and the maximum wave tilt (\beta_m):

\[ G_{eo} \approx \theta_z - 2\beta_m \]  

(3-8)
\( \theta_i \) may be readily calculated using local time and position and \( \beta_m \), which is linearly related to wind speed, is either calculated directly or obtained from previously published work (see next section). The resulting angle is positive when \( G_{eo} \) is found in the direction of the solar azimuth (\( S_{az} \)) from the image centre (\( O \)). A negative value indicates that the glitter has extended across more than half the image and covers \( O \). This occurs when the sun angle is particularly high and/or the wave tilts are large.

From the preceding discussion, the maximum penetration of glitter onto the image (\( G_i \)) can be predicted. This measurement refers to the same point on the edge of the glitter oval as \( G_{eo} \) but is measured from the edge of the image instead of the image centre. It is defined as the angle subtended at the lens focal point from the edge of the image in the direction of the sun to the edge of the glitter oval closest to the image centre (\( O \)). It is calculated in degrees by subtracting \( G_{eo} \) from half the FOV \( S_{az} \), as follows (see Figure 3-3):

\[
G_i = \frac{\text{FOV}_{S_{az}}}{2} - G_{eo}
\]  (3-9)

When \( G_i \) is negative, the image will be glitter free and when it is positive there will be glitter on the image. Equation 9 will also work in image units instead of degrees by using camera focal length to convert distances from degrees to image units with Equation 4 (though care should be taken to convert both \( \text{FOV}_{S_{az}} \) and \( G_{eo} \) to image units first, and then use these as inputs to Equation 9, because a degree at the edge of an image is larger in image units than a degree at the centre of the image). \( G_i \) can also be expressed, perhaps most usefully, as a percentage of the image, in either degrees or image units.

### 3.2.1.2 Wind speed and wave tilt estimates

Preisendorfer and Mobley (1986) state that it is the distribution of the capillary waves that primarily determines the glitter patterns, even in the presence of gravity waves. To obtain estimates of capillary wave slopes for a given wind speed Cox and Munk’s (1954) Gram Charlier series is used. The distribution of wave slopes essentially takes the form of a normal Gaussian probability distribution function in both crosswind and alongwind directions with small variations to account for skewness and peakedness provided by the addition of Hermite polynomials and coefficients derived empirically. While there are some differences in crosswind and alongwind slope distributions, the downwind slope of the wave has the maximum tilt (\( \beta_m \)) and thus it is the probability distribution of the maximum wave slopes that is used in this study. In lieu of implementing the full Cox and Munk formula, a reasonable approximation of \( \beta_m \) at the inflexion point of the wave slope distribution (corresponding to first standard deviation (1\( \sigma \)) for the normal distribution), for
wind speeds between 0 and 10 m/sec at 12.5 m above sea level \((u_{12.5})\), can be obtained by the following function, derived by fitting a curve to published data (Preisendorfer, 1976):

\[
\beta_m \, (1\sigma) = (-0.1004 \, u_{12.5}^2) + (2.0043 \, u_{12.5}) \tag{3-10}
\]

It can be seen that, for a wind speed of 3 m s\(^{-1}\) (about 6 knots), the maximum wave slope at 68\% probability \((1\sigma)\) is about 5\(^\circ\) and at 99.7\% probability \((3\sigma)\) it is about 15\(^\circ\). In other words, 68\% of the waves have a probability of having slopes of about 5\(^\circ\) or less, while only 0.3\% of waves are likely to have slopes steeper than 15\(^\circ\) or more.

In summary, with the inputs of sun angle and azimuth, camera FOV and wind speed, the practitioner can estimate the amount of glitter likely to appear on the image with equations 8, 9 and 10. The amount of glitter on an image \((G_i)\) is presented in Figure 3-6, expressed as a percentage of the width of the image subject to sun glitter, measured in the direction of the solar azimuth, that is, the FOV\(_{saz}\) (see Figure 3-3). Percentages less than zero indicate that all the sun glitter is off the image, while percentages greater than one hundred indicate complete coverage of the image in sun glitter. The figure shows the relationship of the sensor FOV to the amount of glitter present in an image, with the wider FOVs subject to greater glitter.

Figure 3-6a shows that for a maximum wave tilt of 15\(^\circ\) (that is, at 99.7\% probability \((3\sigma)\) for a wind speed of 3 m s\(^{-1}\), or about 6 knots), a nadir-looking camera fitted with a standard wide angle lens will begin to have glitter on its images in the direction of the solar azimuth when the sun angle reaches between 14 to 23\(^\circ\) (depending on image rotation) while a normal angle lens on the same camera will begin to be affected with sun angles between 32 to 39\(^\circ\) (depending on image rotation). Figure 3-6b shows that in virtually calm conditions with maximum wave tilts of 7.5\(^\circ\) (that is, at 99.7\% probability \((3\sigma)\) for a wind speed of 1.34 m s\(^{-1}\) or about 2.6 knots), the ranges are 28 to 39\(^\circ\) and 47 to 55\(^\circ\) respectively. A small format digital SLR camera – a Canon EOS D30 with a focal length of 24 mm in this example – gives even better results of around 58\(^\circ\) sun angle with a “best case” rotation, that is, with the shortest image radius orientated towards the sun.
Figure 3-6. Amount of glitter on nadir-looking images ($G_i$). $G_i$ is expressed, for any given sun angle, as the percentage of the width of the image in the direction of the solar azimuth (FOV$_{saz}$) (see Figure 3-3) that has sun glitter. For a), the wind speed is 3 m s$^{-1}$ giving a maximum wave tilt of 15° at 3$\sigma$ and b), 1.34 m s$^{-1}$ giving a maximum wave tilt of 7.5° at 3$\sigma$. Negative $G_i$ values indicate a glitter-free image and positive values indicate glitter on the image. The solid black line is a Zeiss RMK/A standard wide-angle metric aerial photography camera (Cam1), with the image orientated at its “worst case” rotation with respect to the solar azimuth, that is, with the corner oriented towards the sun (FOV$_{saz}$ 94°). The solid black circles are the same camera under “best case” rotation conditions, that is, the image side towards the sun (FOV$_{saz}$ 74°). The solid black triangles and the solid black squares are the same camera with a normal angle lens under “worst case” and “best case” rotations respectively (FOV$_{saz}$ 56° and 41°). The dashed black line is a Canon EOS D30 digital SLR camera (Cam2) with a 24 mm focal length lens (that is, about normal angle), orientated at “best case” rotation (FOV$_{saz}$ 35°). The figure illustrates how changes in sensor FOV affect the amount of glitter in an image.
3.2.2 Sun glitter test case – methods

In a test case, a comparison is made between the predicted edge of the sun glitter oval closest to the image centre \((G_{eo})\) and that subjectively measured in a small sample of archival aerial photography collected over the last two decades. A second comparison is made between the predicted edge of the continuous highest density sun glitter closest to the image centre \((G_{deo})\) and that measured in actual photographs. The 16 images were captured on film using a Zeiss RMK/A metric 23 cm format camera at a range of scales near Eddystone Point on the east coast of Tasmania (40.9933° S, 148.3467° E, Australian Geodetic Datum 1966). The sample included both 152 mm and 305 mm focal length photography. The site was chosen for its close proximity to a weather station positioned near to the tip of a long promontory (see Figure 3-7), so as to minimise the land effects on the recorded wind speeds and to make use of the large expanse of surrounding shallow marine waters visible in the imagery. The wind speed for each image was obtained from a Synchrotac cup anemometer 30 m above sea level at automatic weather station 92045.

To enable their use in the Cox and Munk (1954) wave slope equations, the collected wind speeds were adjusted to the height of 12.5 m above sea level using the formula (Linacre, 1992):

\[
u_z = u_s \ln \left(\frac{(z-d)}{z_o}\right) / \ln \left(\frac{(z_s-d)}{z_o}\right)
\]  

(3-11)

where \(u_z\) is the wind speed at the height \(z\) above the ground in m s\(^{-1}\), \(u_s\) is the wind at the fixed constant height \(z_s\), \(d\) is a zero-plane displacement constant for a given surface, and \(z_o\) is the surface roughness or roughness length. Values of 30 m for \(z_s\), 0.66 m for \(d\) and 0.125 for \(z_o\) are used – the latter two based on a wave height of 1 m (Linacre, 1992).

There are issues with identifying the position of the edge of the glitter in the image, as the number of glints per unit area (glitter density) reduces with distance from \(S_g\) until the individual glints are spaced a long way apart. As the density of the glints is related to the probability density function of wave slope, visual determination of the glitter boundary requires the observer to conduct the seemingly difficult task of defining a boundary between areas with a low number of glints and areas with very low, or no, glints. The approach taken in the test case is to define two boundaries in each image (see Figure 3-7): the first around the outward boundary of the glitter oval (thus including \(G_{eo}\)) defining the area where the glitter would, if subsurface features were present, interfere with their interpretation and, the second, around the outward boundary of the central area of continuous high density sun glitter (thus including \(G_{deo}\)). The first boundary is defined this way because the desired outcome of this work is to obtain a clear view of the bottom.
Figure 3-7. An illustrative graphic of sun glitter measurements in the north-east quarter of a sample aerial photo. It shows: Eddystone Point on the East Coast of Tasmania; the location of the weather station; some fiducial marks; image centre \( O \); the solar azimuth angle \( S_{az} \); the edge of the glitter oval closest to the image centre \( G_{geo} \); the edge of the dense glitter closest to the image centre \( G_{geo} \); and the solar specular point \( S_{sp} \). The 23 x 23 cm photo was captured at 10:35 Australian Eastern Standard Time, 3/3/2003 at 1:42,000 and the portion shown here is orientated with north up and is 5.25 by 5.25 km.

The predictions of sun glitter extent for each image are based on the geometry of the sun angle and azimuth, wave slopes and camera as described in the previous section, with wave slopes calculated for the 68%, 95% and 99.7% probability levels using the Cox and Munk analytical formula with the wind speeds recorded at Eddystone Point. The wind speed closest to when each image was captured was used in the analysis.

### 3.2.3 Sun glitter test case – results

Using 16 images, the relationship between the measured and predicted edge of the glitter oval closest to the image centre \( G_{geo} \) is illustrated in Figure 3-8a. It shows that, while there are large variations in both solar zenith angle (19.9° to 49°) and wind speed (1.9 to 7.5 m s\(^{-1}\)), the differences between the predicted and measured location of \( G_{geo} \) are, on average, 5.2° with a standard deviation of 3.9°. The chart shows that, while the predicted and measured
values vary in a very similar manner, that level of correlation is not found with either variation in solar zenith angle or wind speed alone. The negative values of $G_{eo}$ were measured in images where the wind speed and sun angle had caused the sun glitter oval to include the image centre ($O$), in other words, the glitter had spread more than half way across the image. This occurred more often with high sun angles, that is, with $\theta_z$ of 20° to 25°, or 35° and higher wind speed. Part b of the figure shows the strong linear relationship between the predicted and measured $G_{eo}$, with a coefficient of determination $r^2$ value of 0.9554. The predicted location is based on the 99.7% probability of wave slopes, that is, the
waves slopes with a probability of occurring of 0.3% or more and it was predicted with equations 8, 9 and 10.

The results in Figure 3-9a show that the predicted edge of the denser central area of glitter closest to the image centre ($G_{deo}$) is also in good agreement with the measured location. It is, on average, within 2.8° of the measured location with a standard deviation of 1.9°. Part b of the figure shows a strong linear relationship between the measured and predicted with $r^2 = 0.925$.

![Figure 3-9](image.png)

Figure 3-9. a) The difference between the measured and predicted edge of the central area of densest sun glitter closest to the image centre ($G_{deo}$). The average difference is 2.8°. All values are in degrees, measured as the angle at the focal point of the lens between the centre of the image (O) and edge of the glitter, except for wind speed (dashed line), which is in m/sec. Note that the solar zenith angle is also the angle ($S_{sp}$) to the solar specular point. b) Shows measured $G_{deo}$ plotted directly against predicted $G_{deo}$ in degrees.

Chapter 3
This high correlation is obtained with predictions based on the 68% probability of wave slopes calculated for the recorded wind speed. There are fewer images (14) used because the $G_{deo}$ was not present on two images. No relationship was found between the amount of error in the results and any other variable including: scale, solar azimuth, solar zenith angle and wind speed.

3.2.4 Sun glitter – discussion

The high level of agreement between the predicted amount of sun glitter in nadir-looking imagery with that measured in the test case samples lends strong support to the proposition that enough of the factors contributing to sun glitter have been accounted for and that, given sun angle, camera field of view and wind speed, a reasonable estimate of sun glitter extent can be made. More precise predictions of glitter extent can be made if solar azimuth and image orientation are included. The methods of Cox and Munk (1954), Preisendorfer and Mobley (1986) and Minnaert (1993) have been adapted, simplified and tested – with favourable results. For many practitioners, implementing the full set of equations presented by Cox and Munk and Preisendorfer and Mobley is unwieldy and overly complex. The finding that boundaries subjectively drawn around, firstly, the densest central part of glitter and, secondly, the outer edge of the glitter-affected area, so closely matched the 68% ($1\sigma$) and 99.7% ($3\sigma$) probability of the wave slopes is notable. The issues of wind direction, multiple scattering and immature wave formation do not seem to have affected the results, indicating they did not have a large influence in the test case, possibly as the measured sun glitter is an integration over the whole area and thus averages the contributing processes well.

While this chapter is focussed on vertical, or nadir-pointing, image acquisition, it is worth noting that if it is appropriate to capture imagery at other angles, pointing the sensor away from the solar specular point will greatly increase the times available for acquisition missions. Pointing satellite sensors, such as Quickbird, are frequently acquiring glitter free imagery. Mobley (1999), for example, recommends a pointing angle of 40° from nadir and 135° from the solar azimuth to minimise reflections into the sensor. Also, work is progressing on removing glitter from imagery after acquisition using a simultaneously captured near-infrared signal. The papers by Hochberg et al. (2003) and Hedley et al. (2005) provide details.
3.3 Subsurface illumination

In keeping with the focus on the interactions at the air/water interface, subsurface illumination is discussed here only in terms of the effects on the light path that take place at the surface – the effects of light attenuation by the water column itself are explicitly excluded (see Chapters 1, 2, 4 and 5). Subsurface illumination is affected by the surface interactions created by sun angle, reflection and refraction. Sun angle affects the amount of energy delivered to a given square metre of the earth’s surface because the virtually parallel solar rays are spread over a greater surface area as the sun angle becomes more acute. Paltridge and Proctor (1976) provide a model that is sufficiently accurate for calculating global irradiance (K) (i.e. direct and diffuse irradiance) at the surface for the full range of sun angles (90 – $\theta$). It is adapted here for clear skies:

\[ K = I_o (1 - \phi_w - a) \cos \theta_z \quad \text{(W/m}^2) \]  

where $I_o$ is the solar constant (1416 W/m\(^2\)) adjusted for the variation in the solar distance to day number 3 (Jan. 3\(^{rd}\)) (that is, perihelion and summer in the southern hemisphere), $\theta_z$ is solar zenith angle, $\phi_w$ is atmospheric absorption (0.18) and $a$ is the atmospheric albedo for clear skies given by (Paltridge and Proctor, 1976):

\[ a = \frac{0.28}{1+6.43 \cos \theta_z}. \]  

Note that while both $\phi_w$ and $a$ are not constant in place and time, the primary purpose here is to identify the variation of $K$ due to sun angle. Also note that $K$ is made up of direct solar irradiance (sunlight) and diffuse irradiance (skylight). A stacked bar chart of $K$ by sun angle is shown in Figure 3-10, with $K$ subdivided into reflected and transmitted light to illustrate their relationship. The proportion of reflected to transmitted light is found by the Fresnel equations, in this case for flat water. The direct solar component (sunlight) is unpolarised, so the effective reflectance for sunlight is an average of the values found by the Fresnel equations for the two forms of polarised light (Apel, 1987). An average value of 6% was used to quantify the amount of reflected skylight (Apel, 1987). The chart shows the rapid decline in $K$ at the water surface as the sun angle reduces. For example, when the sun angle is 35°, $K$ is 617 W/m\(^2\) while for a 25° sun angle it is 446 W/m\(^2\), which is 72% of the amount at 35°.

The chart also shows that, as the sun angle reduces, there is surprisingly little change in the absolute amount of reflected light in spite of the very rapid increases in the reflection coefficients for sun angles below about 35° (Apel, 1987). This can be readily explained by
the simultaneous rapid reduction in absolute $K$ with sun angles below 35°. The net result is that the absolute amount of reflected irradiance remains fairly constant between about 25 to 30 W/m$^2$, increasing to a peak of 41 W/m$^2$ at about 20° but then rapidly falling away as the sun angle approaches 0°. For sun angles useful for downward-looking remote sensing (say, 25 to 40°) the amount of reflected light ranges from 9 to 4% of $K$. This means that losses to reflection have a negligible effect on subsurface illumination.

![Figure 3-10. Global irradiance ($K$) at the sea surface for varying sun angles (i.e. sun elevation angle) divided into reflected irradiance (black portions) and transmitted irradiance (grey portions) at a smooth water surface in W/m$^2$. Reflectivity coefficients are obtained using Fresnel’s equations (Apel, 1987) and global irradiance ($K$) following Paltridge and Proctor (1976). Note that diffuse irradiance (skylight) provides a significant proportion of irradiance at very low sun angles.](image)

The implications of the reduction in illumination with sun angle is that eventually there will not be enough light to obtain a clear response from the sea floor. The limiting sun angle cannot be estimated precisely, however, due to local variation in both the properties of the target habitats (including patch boundary contrast (Mount, 2003; Chapter 4)) and light attenuation by the water column. Coastal waters attenuate light via the processes of absorption and backscatter, which are driven by the interaction of variables such as depth, turbidity, plankton and CDOM. Therefore, the lower limit to sun angle is dependent on both the light attenuation characteristics of the water column in any particular target area and the properties of the target habitat.
3.3.1 Subsurface shadowing

Sun angle, refraction and surface waves interact to affect the amount of subsurface shadowing. Figure 3-11 shows an image taken just above the surface of a typical seagrass bed of *Heterozostera tasmanica* in 0.5 m of sunlit water (Note the banding pattern of bright light – often seen on a sandy bottom – which is a result of the lensing effect of the surface waves (Lynch and Livingstone, 1995)).

It is noticeable that, while the upper surfaces of the seagrass leaves are quite bright in the image, there is a considerable amount of shadowing in the underlying part of the bed. A remote sensing instrument will integrate the spectral signal over the image resolution unit (that is, a pixel or a film granule) and record an average spectral and radiometric value. The degree of blending of the bright and dark signals is critical to the interpretation of the final image. Clearly, the physical structures of the subsurface features interact with the sun angle and the lensing effect of waves to produce greater or lesser amounts of shadowing. A detailed study of habitat structure is not the focus of this section, however, brief observations and calculations are made to clarify the geometry of the subsurface illumination.

![Figure 3-11. Subsurface illumination and shadowing of seagrass plants (*Heterozostera tasmanica*) at 0.5 m depth (Note the patterning of focussed bands of bright light).](image)

The key air/water surface interaction here is between sun angle and refraction. When applied to seawater, Snell’s Law of refraction results in the function shown in Figure 3-12. When the sun angle is 0° the function gives a minimum refracted, or transmitted, angle of 41.73°. Further, the rate of change is clearly quite flat at the lower sun angles. The implications are that the minimum possible subsurface sun angle is relatively high (41.73°).
and that shadowing within a target habitat does not change significantly even with quite large changes in sun angles (see also Figure 2-1 for an illustration of the effects).

Figure 3-12. Refraction of light across the air/seawater interface – the subsurface sun angle (i.e. sun elevation angle) versus the actual sun angle. Refractive Index is 1.34 – an average value for seawater in the middle of the visible spectrum. The 1:1 line is shown for reference.

3.4 Conclusions

Generally, even with cloudless, low haze atmospheric conditions, the window of opportunity for downward-looking aerial surveys over shallow waters is often limited because of the effects created at the surface of the water by the sun angle, reflection and refraction. These limitations mean that surveys can often only take place for a short period in the morning – that is, before the sun angle is too high and the sea breeze starts for the day. This study has found that different processes determine the starting and ending times of this window of opportunity. The ending time is clearly set by the amount of sun glitter on the imagery, which, given the strength of the results of the test case, can be approximated with knowledge of the camera field of view, sun angle and the wind speed. There is added
accuracy to the predictions if solar azimuth and image orientation are included. In particular, the amount of glitter (in degrees from the edge of the image) may be predicted with equations 8, 9 and 10. Lenses with a normal field of view (that is approximately 60°) are subject to less glitter, though there are trade-offs with increased haze as a result of the greater flying heights. It is possible to obtain glitter-free images with standard wide-angle lenses (that is, approximately 90°), though the window of opportunity is reduced as these lenses are more strongly limited by sun angle. In general, images captured with sun angles greater than about 30 – 35° are likely to have glitter in the direction of the solar azimuth. When more than a single image is required, the ability to calculate the amount of glitter on an image will assist with setting the degree of image end-lap and side-lap.

Wind speeds greater than 2.5 to 5 m/sec (about 5 to 10 knots) are increasingly problematic due to greatly increased glitter diameters and, possibly, increased multiple scattering. The variable wind speeds found in the early morning and the short fetches around the shoreline can create waves with slopes that do not fit the normal distribution found for mature waves, especially when combined with nearshore currents and shallow water bathymetries. These variations can result in unexpected glitter patches in imagery, which are not addressed by the simplified model applied in this chapter. Significant changes to the ending time for the window of opportunity are becoming possible through the careful application of sun glitter removal techniques making use of near infrared reflections – though this requires the simultaneous capture of NIR as well as the visible bands. Where downward pointing imagery is not required, pointing the sensor away from the sun can also increase the available acquisition times.

The starting time for the window of opportunity is largely determined by the absolute amount of illumination of the subsurface features rather than too much shadowing (as on land). The adequacy of subsurface illumination is controlled by sun angle and locally varying factors including light attenuation by the water column and the characteristics of the target subsurface features. This means the start time must be determined by a combination of sun angle and local conditions. When sun angles are lower than about 20 to 25°, the strong reduction in the absolute quantity of light transmitted into the water are likely to create limiting illumination conditions. Losses to reflection at low sun angles have little net effect on illumination levels, as the absolute amount reflected is small.

Subsurface feature shadowing does not significantly change at the lower sun angles – the minimum possible subsurface sun angle is still quite elevated at 41.73° – and is generally not a limiting factor.
Table 3-2. Summary of controls on image acquisition quality and optimal ranges.

<table>
<thead>
<tr>
<th>Controls</th>
<th>Optimal range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acquisition start time:</strong></td>
<td></td>
</tr>
<tr>
<td>Determined by absolute</td>
<td>1. Sun angle ( (\alpha) )</td>
</tr>
<tr>
<td>amount of illumination of subsurface features</td>
<td>1. ( \alpha &gt; 20^\circ-25^\circ )</td>
</tr>
<tr>
<td></td>
<td>2. Light attenuation by local water column</td>
</tr>
<tr>
<td></td>
<td>2. Low as possible</td>
</tr>
<tr>
<td></td>
<td>3. Subsurface feature characteristics (reflectivity, shadowing)</td>
</tr>
<tr>
<td></td>
<td>4. NO significant losses to surface reflections</td>
</tr>
<tr>
<td></td>
<td>4. Any sun angle ( \alpha )</td>
</tr>
<tr>
<td><strong>Subsurface shadowing:</strong></td>
<td></td>
</tr>
<tr>
<td>Determined by sun angle and subsurface feature characteristics</td>
<td>1. NO significant change with sun angle as minimum subsurface ( \alpha ) is 41.73°</td>
</tr>
<tr>
<td></td>
<td>2. Subsurface feature characteristics (architecture)</td>
</tr>
<tr>
<td><strong>Acquisition end time:</strong></td>
<td></td>
</tr>
<tr>
<td>Determined by amount of sun glitter on imagery</td>
<td>1. Camera FOV</td>
</tr>
<tr>
<td></td>
<td>1. 60° FOV - less glitter, more haze;</td>
</tr>
<tr>
<td></td>
<td>90° FOV - more glitter, less haze</td>
</tr>
<tr>
<td></td>
<td>2. 20° &lt; ( \alpha ) &lt; 35°</td>
</tr>
<tr>
<td></td>
<td>3. ( u &lt; 2.5 ) m/sec (about 5 knots)</td>
</tr>
<tr>
<td></td>
<td>4. Shortest image radius towards ( \text{saz} ), i.e. a side, NOT a corner.</td>
</tr>
<tr>
<td><strong>Other environmental conditions:</strong></td>
<td></td>
</tr>
<tr>
<td>Surface glare and haze</td>
<td>1. Minimal or nil cloud cover</td>
</tr>
<tr>
<td></td>
<td>2. Good to excellent visibility</td>
</tr>
</tbody>
</table>
Water clarity, depth and seagrass visibility: Observing the deep edge of seagrass beds along a water clarity gradient using digital aerial photography

4.1 Introduction

Seagrass is regarded as an important indicator species for measuring the “health” of coastal and estuarine ecosystems, both in terms of biodiversity and water quality (Ward et al., 2000; Saunders et al., 1998). Monitoring changes in the position of the deep boundary, or maximum depth limit (MDL), of a seagrass bed through time are a useful measurement for monitoring seagrass condition (Dennison & Abal, 1999). The MDL can also, in certain circumstances, be used to obtain the water quality measurement of average annual water clarity, which is usually measured with Secchi depth (Abal and Dennison, 1996; Carruthers et al., 2001). The depth to which sebed habitat boundaries can be detected is a critical issue when assessing the potential use of optical remote sensing for mapping such habitats. Pasqualini et al. (1998) present a list of 18 seabed-mapping studies in which aerial photographic techniques manage to detect seagrass to depths of between 2 and 15 m, which in many cases did not represent the maximum depth of the beds. Norris et al. (1997) and Pasqualini et al. (2001) among others have rejected the use of optical remote sensing in certain circumstances because of its failure to detect the deeper boundaries of seagrass beds.

4 This chapter is a slightly adapted version of: Mount, R.E. (2003). The application of digital aerial photography to shallow water seabed mapping and monitoring - how deep can you see? Coastal GIS 2003, 7th - 8th July 2003, Wollongong, University of Wollongong. (Full review by 2 unknown peers and editor).
Others, such as Thomas et al. (1999) and McKenzie et al. (2001), identify some of the complications and limitations of optical remote sensing and suggest that it is not useful in turbid waters or where access is not available to a combination of “highly developed expertise in remote sensing with equivalent knowledge of the ecology and environmental characteristics of the target site” (Thomas et al., 1999). Some mapping and monitoring efforts have misinterpreted the deeper boundaries of the beds leading to substantial errors in estimating distribution and extent, therefore reducing the value of the resulting maps for monitoring purposes (e.g., Edyvane et al., 2000; Rees, 1995). Yet, many programs and researchers continue to make use of remote sensing to gain insight into long-term trends (Dekker, Anstee et al., 2005; Kendrick et al., 2000; Blake and Ball, 2001; Jordan et al., 2002; Armstrong, 1993; Mumby et al., 1997; Beanish et al., 2002; Cuevas-Jimenez et al., 2002).

This pattern of use suggests that optical remote sensing is being used at its limits and that there are a large number of variables influencing successful image acquisition through water. These variables include the characteristics of the target habitats, the range of water and atmospheric environmental conditions and the type of methods used to acquire the imagery (Phinn et al., 2000; see Chapters 1 and 2 for details). Improved detection of the deep edges of seagrass beds can increase the precision of monitoring the extent and patchiness of seagrass beds through time, through more accurate delineation of patch boundaries (McKenzie et al., 2001). Short-term events, such as severe flooding, can impact on local seagrass distribution patterns (Campbell and McKenzie, 2004), as can a range of other abiotic and biotic factors (Moore and Wetzel, 2000; Dennison and Abal, 1999), however, the position of the deeper edges of most aquatic macrophytes is primarily a response to the average light conditions, as light is a limiting factor for seagrass growth (Carruthers et al., 2001). Therefore, chronic decreases in water quality, and thus clarity, are likely to result in a loss of habitat on the deeper boundary. The average light conditions are shown to be often determined by the average annual water clarity conditions (Duarte, 1991; Dennison et al., 1993; Dennison and Abal, 1999). This means that the deeper edges of the seagrass beds are most likely to be detected in remotely sensed imagery when the water is clearer than usual.

The characteristics of the deep edge boundary will influence its observability. Generally, seagrass beds are delineated in aerial photography primarily on the basis of contrast (see section 2.3.4), so a measurement designed to characterise the contrast of the boundary is proposed to assist in the interpretation of the results. Seagrass also often becomes sparser and patchier as it approaches the MDL (personal observation; Carruthers et al., 2001), so
another measurement characterising the type boundary in terms of the gradient across the 
boundary is also proposed. This measurement of gradient assesses whether the boundary is 
“abrupt”, “well defined”, “patchy” or “gradual”.

A case study is conducted in temperate shallow estuarine waters using practical, readily 
available technologies such as Secchi disks and digital cameras. The primary aim of this 
chapter is to determine whether it is possible to detect the deeper edge of seagrass beds 
using digital aerial photography when the water is clearer than the annual average clarity.

4.1.1 Study Area

Please refer to Section 1.1 for details of the study site. The estuary (see Figure 1-1) was 
selected to cover seagrass beds growing under a range of typical estuarine water clarity 
conditions. There is a strong north-south water clarity gradient, with clearer waters in the 
southern end of the estuary away from the fluvial inputs in the north (Jordan et al. 2002)(see Figure 4-1).

4.2 Methods

The general approach was to capture airborne digital imagery and water clarity 
measurements over the study sites and determine seagrass detection depths. An independent 
measurement of the location of the deep edges of the seagrass beds was also obtained via 
benthic videography. The two data sets were then compared taking into account depth, 
water clarity, habitat type, and two proposed measurements for characterising boundary 
types: boundary contrast and boundary gradient.

4.2.1 Data capture

Existing water turbidity and clarity measurements for North West Bay were assessed to 
obtain approximate average water clarity conditions (Jordan et al., 2002). Secchi disk 
readings are a simple, though effective, visual index of water clarity (Preisendorfer, 1986). 
Secchi depths were collected pre-flight at weekly intervals, to determine when water clarity 
was close to the average annual maximum, and during the flight to obtain measurements of 
water clarity in each image. These readings were spatially consistent with the historic 
measurements as presented in Figure 4-1. Turbidity readings were also taken in situ during 
the overflight at 1 m depth with a Hach 2100P turbidity meter, with three replicates at each 
site. Each water sample site was located where it was both definitely visible in an image.
and in waters deeper than the Secchi depth yet as close as possible to the deep edge of a seagrass bed.

Figure 4-1. Water clarity gradient – north to south. a). Indicative distribution of Secchi depths in North West Bay from single sampling event in February 2002. b). Indicative distribution of turbidity levels (mean Nephelometric Turbidity Units, or NTUs) in North West Bay from single sampling event in November 2001 (Jordan et al., 2002).

Imagery was acquired from a light plane through a port in the floor using a fixed Canon EOS D30 digital camera with a high quality 24 mm lens. Image size is 2160 x 1440 pixels, which at 720 m (2,360 ft) gives a ground resolution of 0.3 m per pixel and an extent of 681 x 453 m. This means that the minimum discernible object is, depending on its shape and contrast, about 1 m across. The imagery has standard red, green and blue bands with 8 bit resolution. Imagery was captured under a clear sky and a sun elevation between 25° and 30°. This sun angle, combined with the windless conditions, ensured no surface glint and, due to the effects of refraction, gave an effective sun elevation underwater of 48° to 50°, thus limiting the effects of shadowing (Chapter 3). A mix of stable geographic features and temporary floating tarpaulins that were 1.8 x 2.4 m (6 x 8 pixels) in size and anchored securely in 3 directions provided ground control.
Benthic video footage was collected using a submersible MorphCam single CCD digital video camera with images recorded on a Sony TRV900 digital handycam. The MorphCam was attached to a weighted tow frame at a 45° angle to the horizontal. The frame was suspended approximately 1 m from the sea floor, and maintained at this height by a winch operator on deck while viewing the live video footage, giving a field of view (FOV) that varied between 0.5 to 2 m wide. Tow speed was kept to less than 0.5 m s\(^{-1}\) (1 knot) to maintain the camera position below the GPS antenna. A single frequency Garmin Map 135 GPS Sounder was used with a Landstar differential unit providing real-time corrections. Estimated horizontal positional error is 3-5 m 90% of the time with most of the error due to the long baseline to the base station – approximately 350 km. Differential GPS location, time, date and water depth were overlayed onto the video from the GPS sounder using a genlock device and logged for use in the analysis.

The sampling path of the video transects were targeted at the deeper edges of seagrass beds. The general locations were selected by using pre-existing seagrass maps of the study area and, in the field, a path was taken which zigzagged across the mapped boundary. The interaction of winds and currents and navigational imprecision meant that the exact location of each path was randomised to some extent along any one edge. The procedure adopted was to continue a run into deeper water until a combination of the live video footage and knowledge of the maximum depth to which seagrass grows in the area clearly indicated that the deep edge of the seagrass beds had been passed.

Digital aerial photography was collected on 12th January 2003 along with \textit{in situ} measurements of water quality. Videographic data of the deep boundaries of seagrass beds were collected on the 7th February and 5th March 2003, that is, mid to late summer.

### 4.2.2 Data analysis

Five sites distributed across the study area where chosen for analysis (see Figure 4-2). The aerial imagery was geo-referenced in ArcGIS 8.1 (ESRI, 2001) using an average of \(~25\) ground control points and then contrast enhanced using a simple stretch (Pasqualini \textit{et al.}, 1998). Apparent boundaries of the seagrass beds were digitised on screen. Estimated positional error potentially present in the imagery is around 3.6 to 5.8 m – mainly due to DGPS error in locating ground control (3-5 m) and image capture geometry, including lens distortion (2-3 m).

The benthic video footage was viewed and coded according to a coding protocol (see Appendix 4 Benthic video coding protocol). As each habitat boundary was crossed, the
new habitat type was characterised using classes “sand”, “H. tasmanica” and “H. australis” (adapted from Barrett et al., 2001). A further class of “epiphyte” was added. These classes were modified with subjective estimates of “substrate brightness” on a scale of 1 to 5, “vegetation density” (1 to 4) and “epiphytic abundance” (1 to 5). Two variables were developed to characterise the boundary itself – “gradient” and “contrast”. Gradient is a subjective measurement of the rate of change between habitat classes with categories consisting of “abrupt”, “well defined”, “patchy” and “gradual”. Contrast is a subjective measurement of the difference in overall brightness between the old habitat and the new, with categories consisting of “none”, “low”, “moderate” and “high”.

Figure 4-2. Sites where digital aerial photography and benthic video were collected for the study.

All of the resulting video footage codes, the sounder depths and the DGPS position of the video camera were loaded into a GIS as a point layer. Estimated positional error potentially present in the boundary point locations is around 3.2 to 5.4 m – mainly due to DGPS error (3-5 m) and differences in the video camera location relative to the GPS antenna (1-2 m). When overlaying layers in a GIS, the positional error propagates (Burrough and
McDonnell, 1998) and so, the overall potential positional error of the combined GIS point layer and the geo-referenced imagery was calculated to be 4.8 to 7.9 m (for details see section 5.3.2.2, equations 5-6, 5-7 and 5-8)

To determine whether the video boundary was matched by a boundary visible in the imagery, the position and depth of the GIS point boundary markers were visually compared to the position of the digitised seagrass bed boundaries visible in the imagery, particularly noting the deepest edges. Any potential matches were evaluated and the optimal match identified. Potential matches were identified as those digitised bed boundaries within a radial distance defined by the overall potential positional error (i.e. <10 m). The optimal match was usually the closest boundary (shortest distance). Attributes relating to the best match were recorded against each boundary defined in the video footage, including the presence or absence of a matching boundary in the polygon layer digitised from the imagery, the distance and direction to that boundary and the classes either side of the boundary. An example of a contrast-stretched image with a video transect and bathymetric contours overlaid can be seen in Figure 4-3. Further examples are depicted in Appendix 9, showing imagery with benthic video transects overlaid for four of the five study locations within the Bay.

A comparison of the maximum seagrass detection depths obtained in the video footage with those from the aerial imagery was conducted in each of the 5 study sites. Whereas the previous methods rely on the video footage as the standard, this method compares the two sets of data against each other. Firstly, the imagery was placed over a pre-existing high-resolution digital elevation model (DEM) in the GIS. The DEM was generated from previous single beam sounder surveys (Jordan et al., 2002) and is estimated to be accurate to within 0.5 m depth (z) and 3.5 m location (x, y). At each of the 5 sites, an average of four or five depths at which seagrass was clearly discernable in the imagery was obtained from the DEM and compared with the average of the deep edge boundary point depths obtained directly from the sounder readings recorded in the video log file. A limitation of this method is that the video footage was not necessarily captured over the deepest part of any one seagrass bed.

Finally, for illustrative purposes, the integrated mean annual attenuation coefficient (Kz) was calculated from the maximum depth limits of the seagrass in each part of the bay and an estimate of the minimum light requirement (MLR) for H. tasmanica based on the published MLR for Zoster marina of 18.6% (Carruthers et al., 2001). The formula is an adaptation of the Beer-Lambert equation for light attenuation in water:
\[ K_z = -\ln \left( \frac{MLR}{100} \right) / z \]  

(4-1)

Where \( MLR \) is 18.6% and \( z \) is the maximum depth penetration of the seagrass. The \( MLR \) can be also calculated if the amount of light just under the surface (\( I_o \)) and the light at the maximum seagrass depth (\( I_z \)) is known, as follows:

\[ MLR = \left( \frac{I_z}{I_o} \right) \times 100 \] 

(4-2)

Figure 4-3. Boundary locations from benthic video transect and depth contours in metres, Snug Beach, North West Bay, Tasmania. Numbers = depths in metres, small green circles = video transect, squares = deep edge boundaries, triangles = other boundaries.

4.3 Results

In total, 105 boundaries were identified in the video footage – 71 inter-class boundaries and 34 intra-class boundaries. Of the inter-class boundaries, 58 were sand/seagrass boundaries – 27 of which were matched in the imagery and 31 missed. \( H. tasmanica \) to sand boundaries are relatively easy to match, whereas any boundary involving \( H. australis \) is missed more often than matched. Of the 15 deep edge boundaries, 9 were picked in the imagery, 4 were missed and 2 were uncertain (Table 4-1).
The results for match rate by contrast for the sand/seagrass boundary points (n=58) show that boundaries are missed in the aerial imagery much more often as boundary contrast reduces, and vice versa for matched points (Figure 4-4a). A chi-squared test for independence between the matches and the misses confirmed that there is an extremely low probability ($\chi^2 > 28.5$; df = 3; $p<< 0.0001$) that the differences are due to the chance effects of random sampling and they are, therefore, highly likely to come from different populations. For depth, there is a similarly strong relationship (Figure 4-4b).

Table 4-1. Summary of deep edge boundary match results between video footage and digitised boundaries from aerial imagery, North West Bay, Tasmania, Jan-Mar, 2003. Percentages in brackets.

<table>
<thead>
<tr>
<th>Boundary grouping</th>
<th>Match</th>
<th>Miss</th>
<th>Uncertain</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>(%)</td>
<td>n</td>
<td>(%)</td>
</tr>
<tr>
<td>All</td>
<td>39</td>
<td>(37)</td>
<td>64</td>
<td>(61)</td>
</tr>
<tr>
<td>Intra-class</td>
<td>9</td>
<td>(26)</td>
<td>23</td>
<td>(68)</td>
</tr>
<tr>
<td>Inter-class</td>
<td>30</td>
<td>(42)</td>
<td>41</td>
<td>(58)</td>
</tr>
<tr>
<td>Sand/seagrass</td>
<td>27</td>
<td>(47)</td>
<td>31</td>
<td>(53)</td>
</tr>
<tr>
<td>Ha/all</td>
<td>6</td>
<td>(22)</td>
<td>19</td>
<td>(70)</td>
</tr>
<tr>
<td>Ht/sand</td>
<td>13</td>
<td>(62)</td>
<td>8</td>
<td>(38)</td>
</tr>
<tr>
<td>Deep edge</td>
<td>9</td>
<td>(60)</td>
<td>4</td>
<td>(27)</td>
</tr>
</tbody>
</table>

Note: Ha = *H. australis* and Ht = *H. tasmanica*.

There is a dependency between perceived contrast and depth as illustrated in Figure 4-4c, with a $\chi^2 > 25$ (df = 4; $p<< 0.0001$) showing that different depth classes have independent distributions of contrast classes. Note that the chi-squared test required grouping of classes due to missing values in some classes. Conversely, there is no difference between the matches and the misses in regard to the gradient variable, with a $\chi^2 > 2.26$ (df = 3; $p = 0.52$) (Figure 4-4d).

For each of the 5 study sites, the mean maximum depth at which seagrass was positively visible in the aerial imagery was compared with the mean maximum seagrass detection depth of the video footage (Figure 4-5a). The depths were derived from a pre-existing high resolution DEM and are independent of the benthic video depth data. The results show the depths at which seagrass are visible over broader areas in the imagery are very similar to the detection depths of the video. They are also clearly related to Secchi depth, and are, on average, about 60% shallower (Figure 4-5b). There was an inconclusive relationship of detection depth with turbidity and errors in measurement are suspected.

The integrated mean annual attenuation coefficient ($K_z$) was calculated using Equation 4-1 and is presented in Table 4-2. There is a definite trend from the north of the bay, with consistently lower water clarity, to the south, where water clarity is consistently higher (see Figure 4-2).

Chapter 4
Figure 4-4. Results of match rates by contrast, depth and gradient for seagrass/sand habitat boundaries (n=58) in North West Bay, Tasmania, Jan-Mar 2003: a) Number of matched boundaries in each “contrast” category. b) Number of matched boundaries in each “depth” category. c) Number of boundaries in each “depth” category subdivided into “contrast” categories. d) Number of matched boundaries in each “gradient” category. Note: squares = matches, triangles = misses.
Figure 4-5. Comparison of the maximum perceived seagrass detection depths in the aerial imagery at 5 sites in North West Bay, Tasmania, Jan – Mar 2003 with a) the maximum measured seagrass detection depths in the benthic video footage, and b) Secchi depths (depths in metres). One-to-one ratio lines are also shown.

Table 4-2. The integrated mean annual attenuation coefficient \( K_z \) calculated from the maximum depth limits of \( H. \) tasmanica observed in the imagery \( (z) \) based on an estimate of minimum light requirement from \( Z. \) marina (Carruthers et al., 2001) and listed from north to south. The Secchi Disk values \( (Z_{sd}) \) listed are from the day of image capture.

<table>
<thead>
<tr>
<th>Image detection depth ((z)) (m)</th>
<th>( K_z ) (m(^{-1}))</th>
<th>( Z_{sd} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.84</td>
<td>4</td>
</tr>
<tr>
<td>3.2</td>
<td>0.53</td>
<td>5.5</td>
</tr>
<tr>
<td>4.4</td>
<td>0.38</td>
<td>8</td>
</tr>
<tr>
<td>4.0</td>
<td>0.42</td>
<td>8</td>
</tr>
<tr>
<td>5.6</td>
<td>0.3</td>
<td>7</td>
</tr>
</tbody>
</table>
4.4 Discussion

Airborne optical remote sensing is an established technique for mapping and monitoring seagrass beds (Thomas et al., 1999). This work seeks to extend these techniques by specifically evaluating the detection of the deeper edge boundaries of seagrass in a temperate estuary along a water clarity gradient. The water clarity measurements collected on the day of image capture show that conditions were at the higher end of the average conditions, but not exceptionally clear.

4.4.1 Boundary match rates and contrast

Results of the video-to-image matching contain a number of useful insights. The intra-class match rates are much lower than inter-class match rates, indicating that changes in density within classes are difficult to discern. There is a clear difference in the value of the
“contrast” and “gradient” boundary characterisation variables for this study. Contrast performed well and, while it could potentially be improved by using a ratio of measurements based on the net greyscale values of the video images before and after a boundary, it has proved to be useful for characterising sand/seagrass boundaries. The variable could also be used to assess specific areas to determine whether aerial photography would be a suitable method for mapping and monitoring.

“Contrast” also has a relationship with depth, where perceived contrast decreases as depth increases. This is possibly because there is less water turbulence at depth and thus both the organic and inorganic particle composition is different from the sediments in shallow water with a smaller, siltier particle size range. These differences could explain a net reduction in reflectance of the substrate and thus reduced contrast. Clearly, the absorption properties of the water itself will eventually make even high contrast boundaries undetectable at greater depths. This observation is relevant to the deeper growing species of seagrass such as *Posidonia oceanica*, with a maximum depth limit of 35 m (Carruthers et al., 2001), though *Heterozostera tasmanica* has been recorded at 18 m (Barrett et al., 2001). While “gradient” is not useful for identifying boundaries in imagery, it may still be useful for other forms of boundary work including landscape ecology patchiness metrics (see below).

Within the classes, *Halophila australis* was the most difficult boundary to match (22%), which may be partially explained by the large amount of substrate visible between its very short, sparse growth habit. It also tends to occur on the deeper, darker fringes of the *H. tasmanica* beds. This means it is difficult for optical remote sensing to clearly identify the deep edge boundaries when *H. australis* is present. A more promising result was evident for the *H. tasmanica* boundaries, which were matched more often than not, particularly at a sand boundary (62%).

### 4.4.2 Benthic video versus airborne imagery detection depths

The results of the more general comparison between benthic video and imagery show similar seagrass detection depths were derived from the two data sources at all 5 sites (Figure 4-5). Also, the deeper edges of the seagrass beds were located at greater depth as the Secchi depths increased. Imagery seagrass detection depths for *H. tasmanica* were about 60% of *in situ* Secchi depths. These findings are consistent with those of others that show that seagrass is limited by average light conditions and that the seagrass maximum depth limit (MDL) is often similar to the average annual Secchi depth (Duarte, 1991; Dennison et al., 1993; Kenworthy and Fonseca, 1996; Gallegos and Kenworthy, 1996; Carruthers and Walker, 1999; Carruthers et al., 2001). The results show that, within the limitations of this
study, aerial photography is able to detect the deeper edges of seagrass beds when the water clarity is higher than the annual average. Given that the MDL was about 60% of the $Z_{sd}$ on the day of image capture, there may also be extra capacity in the imagery to detect seagrass deep edges down to 80 or 90% of the Secchi depth at the time of image capture.

The imagery and benthic videography have similar seagrass detection depths, which probably means that, at these depths and for these species, water column attenuation is not as much a limiting factor on boundary detection as the contrast between the habitat classes. It is a key finding of this study that contrast, rather than water column attenuation, is the limiting factor to deep edge seagrass boundary detection when water clarity is clearer than usual. No other references to this issue currently appear in the published literature.

The relatively clear turbidity readings were not related to detection depth, which suggests that absorption and scattering factors other than turbidity – such as CDOM or plankton – may be more influential in this case. A number of studies (Dunton, 1994; Onuf, 1994; Kenworthy and Fonseca, 1996; Gallegos and Kenworthy, 1996) have differentiated between the water column constituents that are driving the maximum depth range. For example, while Gallegos and Kenworthy (1996) identified turbidity as the primary controlling constituent at their study site, the MDL was also influenced by fluctuations in CDOM (colour) levels. However, for the purposes of this study, the Secchi depth usefully integrates these other factors and the turbidity into a single apparent optical measurement (Preisendorfer, 1986). Further, even though the method depends on the human eye, the wavelengths detected optically are very similar to those required for growth by seagrass. Carruthers et al. (2001) provide a detailed discussion of the relationship between the Secchi disk, average annual light availability and maximum seagrass depth limits, in which they also report that seagrass maximum depth limits are broadly similar to Secchi depths.

The calculation of the annual average attenuation coefficient ($K_z$) from the depth of the deep edges of the seagrass beds produced results consistent with the historical Secchi depth record and replicated the north-south water clarity gradient (see Table 4-2 and Figure 4-6), however, the absolute values are unable to be independently verified. It is important to note that the MDL of seagrass is not necessarily related to average annual water clarity as underwater irradiance (and thus photosynthetically available radiation, or PAR) is known to fluctuate strongly and rapidly in response to short term variations in the level of turbidity and phytoplankton (Zimmerman et al., 1991; Dunton, 1994; Banas et al., 2005). The fluctuations in irradiance have implications for seagrass growth and mortality and the study by Moore et al. (1997) showed that pulses of turbidity may have differing effects on seagrass growth dependent on the season and the length of the pulse. The degree of
variability in the factors that influence seagrass depth limits was studied by Greve and Krause-Jensen (2005) across an eutrophication gradient (inner estuaries to open coast). They found considerable variability in the factors with the key factors related to seagrass MDL being Secchi depth ($z_{sd}$) and ammonium ($\text{NH}_4^+$). In spite of the high local temporal and spatial variability, they also found resilience and long term persistence in MDL at habitat scales.

### 4.4.3 Complementarity of benthic video and airborne imagery

The imagery offers the benefit of superior spatial coverage of the deeper boundary than the video transect. The latter has the drawbacks of a very limited field of view and a much smaller chance of capturing the spatial variation in the deep edge position at any one time. The imagery has the drawback of increased uncertainty at the deeper edges. The two data sources complement each other well, as the imagery can provide a much more synoptic view of the deeper edge than that provided by the video, and the video greatly increases the confidence of locating the deeper edge in the imagery as well as improving habitat identification generally (Figure 4-3). Pasqualini et al. (1998) argue that aerial photography also complements side scan sonar when mapping the deeper edges of seagrass habitats that grow to depths of 30 m, such as *Posidonia oceanica* in the Mediterranean Sea. Estimates of seagrass areas by Rees (1993) and Edyvane et al. (2000) – that were largely based on pre-existing optical remote sensing alone – both suffered from an inaccurate location of the deeper boundaries. For example, Edyvane et al. (2002) estimated only 15% of the seagrass mapped by a later, much more accurate, study of the Bruny Bioregion of southeastern Tasmania (Barrett et al., 2001).

### 4.4.4 Landscape ecology metrics

Improved detection of deep edge boundaries with imagery should have benefits for analyses of spatial pattern and structure using methods such as landscape ecology metrics. Fonseca and Bell (1998) extracted perimeter/area ratios for seagrass beds from 50 x 50 m fieldsampled study sites and related them to the physical variables of wave exposure, surface tidal current speed and depth. There is considerable scope for image-based landscape ecology work as the raster structure of the imagery and broad spatial coverage suit this type of analysis. It should be noted, though, that many landscape ecology metrics rely on ratios of perimeter to area of mapped polygons (McGarigal and Marks, 1995). The trimming of polygons to a particular depth when the deep boundary is unknown significantly reduces the value of such measurements, particularly when seeking to understand the patch dynamics of the deep boundary.
4.4.5 Limitations

With regard to limitations, there is a scaling problem between the field data and the aerial image data when attempting to match the boundaries perceived in the benthic videography with those in the imagery. This is because the video field of view is about the size of the smallest discernible object in the imagery, that is, about 1-2 m. This means that, if the video camera was crossing sand and entered a narrow sand channel about a metre wide between two seagrass beds, no boundary would be apparent. In the imagery, however, a sand/seagrass boundary is likely to be drawn across the start of the channel as the narrow sand channel itself may be blurred by the resolution of the pixels (Figure 4-3).

Finally, the study area represents only one set of environmental conditions and results may not hold for different seagrass species, substrates, water clarity conditions and wave exposure levels, though initial observations in estuaries with similar species, water clarity and depth ranges (Georges Bay and Little Swanport on the east coast of Tasmania) indicate that the findings are valid (Mount, 2005 unpub. work). The methods outlined in this chapter, specifically including those using benthic video to provide independent reference data for aerial imagery interpretation, need to be refined and formally applied in other locations to test for transferability and repeatability of the approach.

4.5 Conclusions

While this is a small study, the results indicate that purpose-flown digital aerial photography coupled with vessel-based benthic videography offer good opportunities for monitoring and mapping the deeper edges of seagrass beds. The two technologies complement each other well – video for its precise boundary detection and more accurate classification of habitat types and aerial photos for its extensive spatial coverage.

The maximum detection depth of seagrass in aerial imagery is not an absolute measurement – rather, it is a relative measurement largely determined by the same factors that control seagrass growth. It was found that the deeper edges of the seagrass were located at greater depth as the Secchi depth increased. The seagrass detection depth of the imagery also increased with Secchi depth, and at a similar rate. Seagrass detection depths for *H. tasmanica* in the imagery were about 60% of *in situ* Secchi depths. The overall detection depths of the imagery were similar to that of the benthic video, indicating a close match between the deep edges of the seagrass and the maximum detection depths of the aerial photography. Once water attenuation factors were optimised, the contrast of the boundaries was found to be an important factor in boundary detection. Given that the imagery was
acquired when water clarity was good but not exceptionally high, these results are promising.

This study indicates that the critical components for optimising detection of the deep boundaries of seagrass beds to approximately 15 m are, firstly, a pre-flight evaluation of the contrast of the deep boundaries of the target habitat and, secondly, to fly when water clarity is higher than the annual average. Further, benefits are obtained by maximising the field of view when using benthic videography, yet retaining enough detail to classify the bottom accurately, and combining aerial imagery and *in situ* data.

Future developments could include, in order of preference; an increase in the positional accuracy of data collection to better than 1-2 m in horizontal position through improved GPS methods such as shorter baselines, the use of dual frequency GPS, post-processing or direct georeferencing techniques (Skaloud, 2002); the comparison of simple contrast stretching and hand digitising methods applied in this study with more sophisticated image processing including depth corrections, image classification and image segmentation (see Chapter 5); and the development of more objective measurements of the “contrast” and “gradient” boundary characterisation variables.