Using panchromatic imagery in place of multispectral imagery for kelp detection in water

Angela M. Kim, R. Chris Olsen, Krista Lee, David Jablonski
Naval Postgraduate School, 1 University Circle, Monterey, CA 93943

ABSTRACT

Multispectral imagery (MSI) taken with high-spatial resolution systems provides a powerful tool for mapping kelp in water. MSI are not always available, however, and there are systems which provide only panchromatic imagery which would be useful to exploit for the purpose of mapping kelp. Kelp mapping with MSI is generally done by use of the standard Normalized Difference Vegetation Index (NDVI). In broadband panchromatic imagery, the kelp appears brighter than the water because of the strong response of vegetation in the NIR, and can be reliably detected by means of a simple threshold; overall brightness is generally proportional to the NDVI. Confusion is caused by other bright pixels in the image, including sun glint. This research seeks to find ways of mitigating the number of false alarms using spatial image processing techniques. Methods developed in this research can be applied to other water target detection tasks.

Keywords: Panchromatic imagery, remote sensing, *Macrocystis pyrifera*, Giant Kelp, sun glint removal

1. MOTIVATION AND BACKGROUND

The goal of this research is to determine if panchromatic imagery can be used in cases where multispectral imagery may not be available for the purposes of mapping kelp in water. In the typical spectral range for panchromatic imagery, kelp will appear bright as compared to the water surrounding it, and so is separable by means of a simple threshold. Problems with false indications occur due to sun glint, clouds, or other bright objects in the water.

1.1 *Macrocystis pyrifera* (Giant Kelp)

Macrocystis pyrifera, also called Giant Kelp, is a species of seaweed that has high economic and ecologic importance. *M. pyrifera* is the world's largest alga, and it grows in temperate seas of the Pacific and Southern Oceans (Reed, 2009). Kelp forests form one of the most biologically productive marine environments, and these areas have a large impact on oceanographic processes. The health of kelp forests can be used as an indicator of global environmental change. Kelp is also important economically, having a wide variety of applications, including pharmaceutical, cosmetic, and paper and textile manufacturing uses.

On average, one plant can live between 3 and 5 years, and growth rates are as high as 0.5 meters per day. Growth and mortality are regulated by water temperature, nutrients, ocean bottom type, predation, and wave action (Cavanaugh, 2008). The life cycle of *M. pyrifera* is shown in Figure 1.

As *M. pyrifera* grows to maturity, it forms a surface canopy, which can extend horizontally up to twenty feet on the sea surface. The canopy itself may reach 1 to 2 cm above the surface (Jensen, 1980). This large canopy enables detection and mapping by means of remote sensing.

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14. ABSTRACT
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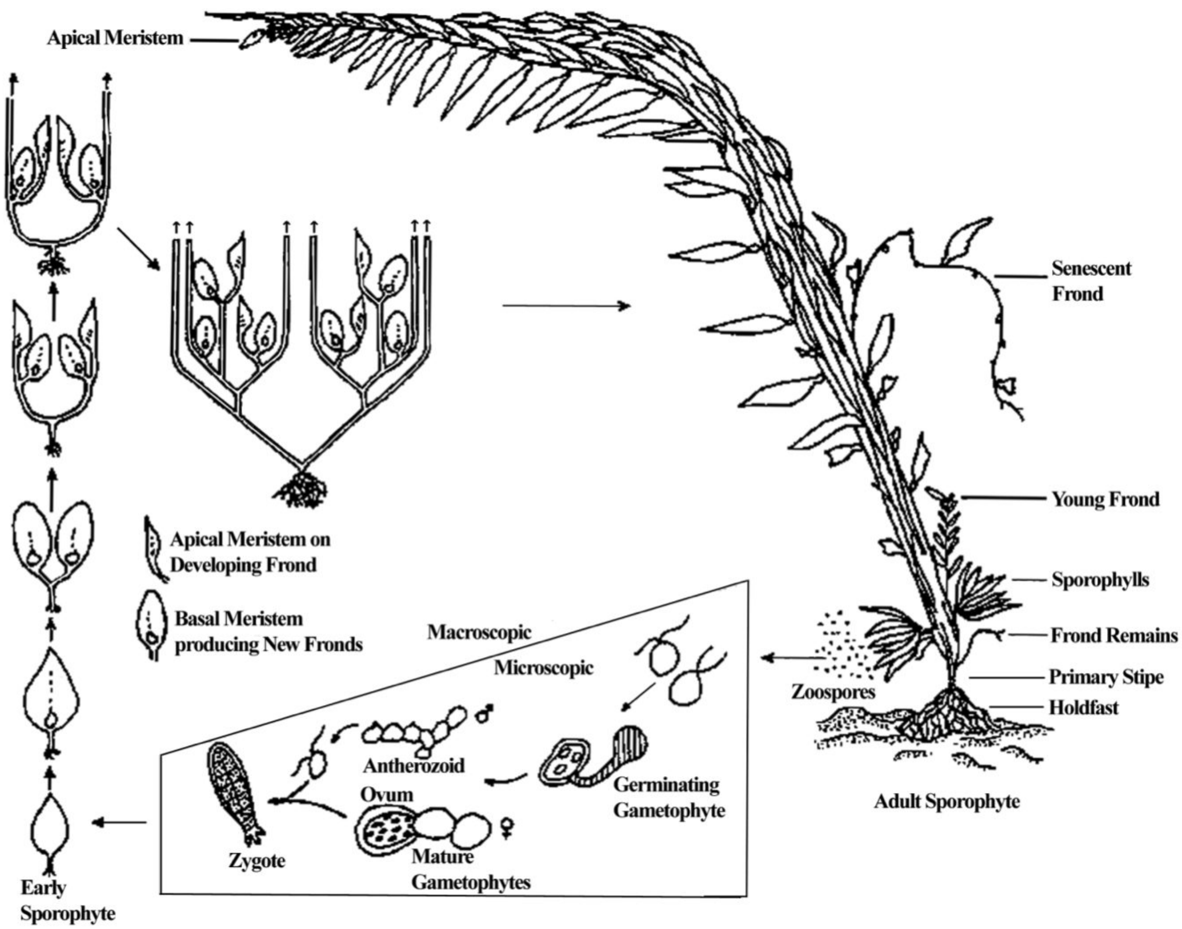

Figure 1. Life cycle of *Macrocystis pyrifera*; reproduced from (Doty, 1987).

1.2 Monitoring Kelp

Photographs and maps of kelp canopies have been collected along the coast of the state of California for over a century. Canopies were used in the 1800s as features for coastal navigation and were included on hydrographic charts. Captain William Crandall took on the first comprehensive survey of kelp resources in 1911, mapping beds as a possible source for potash (potassium carbonate) production. Aerial photographs of kelp canopies were first taken in the 1930s. KELCO, a major harvester of kelp beds in southern California, and the California Department of Fish and Game conducted surveys in the 1950s and 1960s. Satellite imagery from both Landsat (MSS and TM) and SPOT have also proven to be useful in mapping *M. pyrifera* resources (Deysher, 1993).

In situ spectroradiometer measurements have shown that *M. pyrifera* has a spectral signature that is similar to terrestrial orange-brown vegetation. Chlorophyll absorption in the green is apparent with somewhat greater reflectance in the blue and red. This feature makes the mapping of kelp via the standard Normalized Difference Vegetation Index (NDVI) very straightforward. In the range from 700 to 1000 nm, *M. pyrifera* reflects 60% to 70% of the incident radiant flux, while water absorbs the majority of energy in this region (Jensen, 1980). This explains why the kelp appears bright in panchromatic imagery with silicon sensors.

2. METHODS

The study area is located at the southern coast of Santa Cruz Island, south of Santa Barbara, CA. Imagery was collected on December 17, 2006 by DigitalGlobe's QuickBird satellite. The QuickBird sensor has 4 channels of spectral data (blue, green, red, and near-infrared (NIR)) with a spatial resolution of 2.4 m, and a high-resolution panchromatic channel capable of collecting data with 61 cm spatial resolution (DigitalGlobe website).

Figure 2. Research Area – The southern coast of Santa Cruz Island (QuickBird image from December 17, 2006). Land areas are masked.

2.1 Create Kelp Map using Multispectral Imagery

Multispectral imaging has been proven to be an effective technology for mapping kelp locations, and is used here to create a 'truth' map of kelp locations in the water. To create the kelp map, the land areas are masked, and a standard NDVI transform is applied to the data. The NDVI transform is calculated using the Red and NIR spectral data as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR - Red}}{\mathrm{NIR + Red}}$$

Because chlorophyll is highly absorptive in the red channel, and highly reflective in the NIR channel, positive NDVI values are indicative of vegetation. A threshold is applied to the NDVI result, and any pixels having a value greater than 0 are classified as kelp.

2.2 Create Kelp Map using Panchromatic Imagery

Kelp is highly reflective as compared to water, so a simple threshold can be used to separate the two in the panchromatic imagery. Initially, a threshold value was chosen to create a result most similar to the MSI result. This kelp map represents the best possible result achievable from the panchromatic data using a simple threshold, and illustrates the utility of panchromatic imagery for mapping kelp in water. Figures 3 and 4 show a comparison of the NDVI-derived kelp map, and the panchromatic threshold result. Comparisons to results achieved using alternate threshold levels are presented in Section 2.5. A method for semi-automatically determining the threshold value is examined in Section 2.6.

2.3 Compare MSI and Pan Results

An advantage of panchromatic over multispectral imagery is the much higher spatial resolution that is typically achieved. In order to compare the panchromatic and the multispectral results, the NDVI image result was geographically warped and spatially resampled to match the resolution of the panchromatic imagery. While this process creates a much larger dataset without the benefit of any additional information, it enables a direct pixel-by-pixel comparison between the datasets while maintaining the high spatial resolution of the panchromatic data.

Two methods of comparing results are employed: first, a comparison of the overall area classified as kelp, and second, a pixel-by-pixel analysis of false indications and missed detection locations.

Two subsets of the study area were chosen to demonstrate the feasibility and challenges of utilizing panchromatic imagery for the purpose of mapping kelp in water. The subsets are shown in Figures 3 and 4. In the first subset, false indications are found in the panchromatic result due to sun glint. The analysis of the second subset illustrates the problem with clouds in the image. In Section 2.4, methods for refining the panchromatic results are introduced, and results are again compared to the 'true' MSI kelp map.

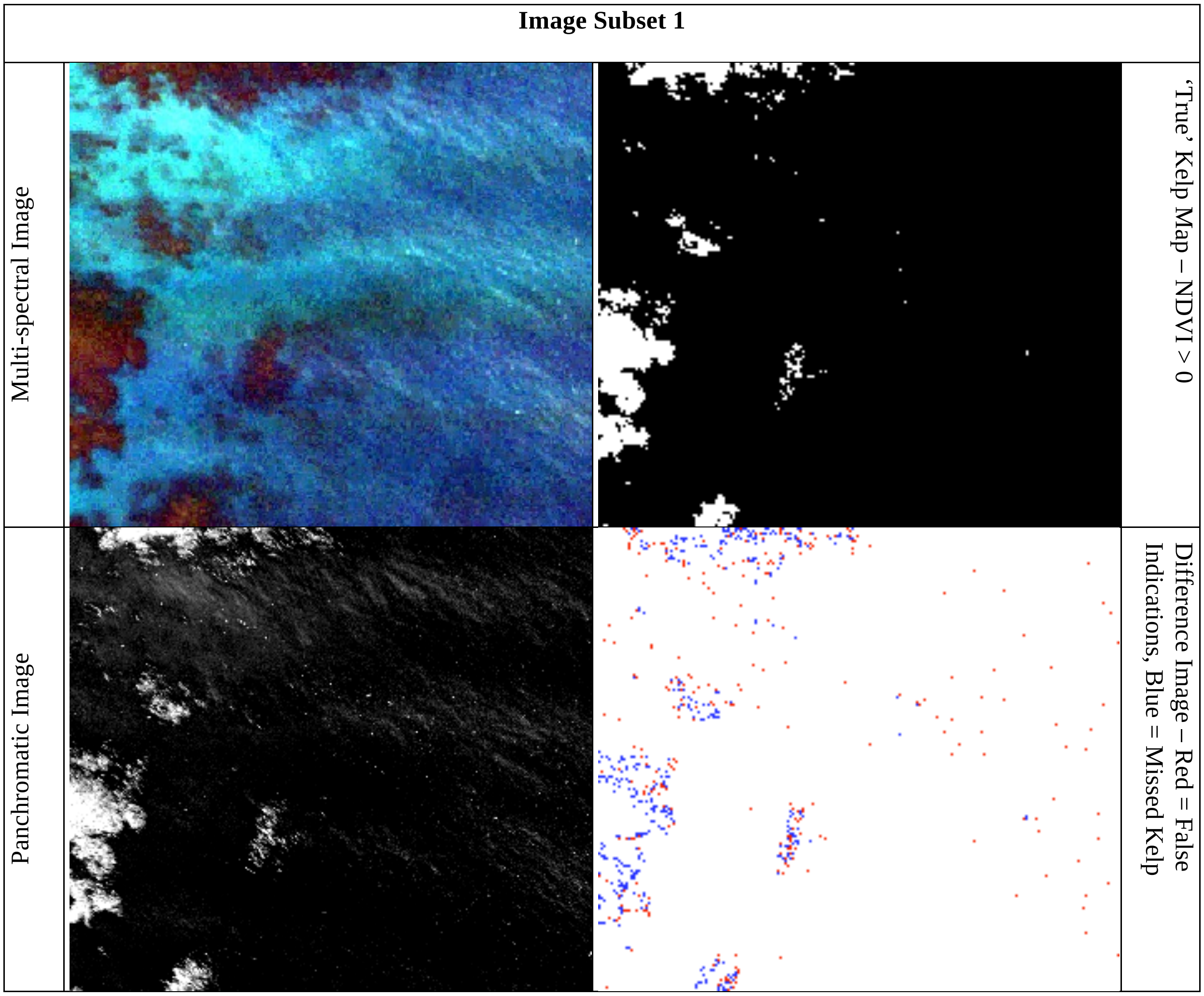

Figure 3. Image subset area 1. The bottom-right image shows the difference between the NDVI result and the panchromatic threshold result; Red represents areas where the panchromatic data creates false indications of kelp, and blue represents areas of missed kelp detections.

The bottom-right image is a comparison of the 'true' kelp map and the result created by applying a threshold to the panchromatic data. The occurrence of false indications in the panchromatic image result due to sun glint is demonstrated. Red areas represent regions where false indications in the panchromatic image occur. Evidence of missing kelp detections, shown in blue, can be seen around the edges of the kelp beds.

As illustrated by this example, remote sensing can be seriously impeded by the effect of wave-induced sun glint. When the surface of the water is not flat, direct radiance from the sun can be reflected on the crests or slopes of waves. This reflected radiance does not contain any useful information about what is on the water's surface or below. Sun glint may be reduced by flying the sensor at a different angle or time of day, but this is not always an option. This makes the ability to identify and remove such features a requirement. A method for reducing the effect of sun glint on panchromatic imagery is presented in Section 2.4 – Refining Panchromatic Results.

The second subset area (Figure 4) illustrates the problem caused by clouds in the panchromatic image. Clouds are a problem no matter what type of imagery is being used, because the ground beneath them is hidden. When using MSI data, clouds will be masked because the NDVI score will not be greater than 0 in these areas. In the panchromatic imagery, clouds have brightness values very similar to kelp, and so will cause false indications of kelp when a threshold is applied.

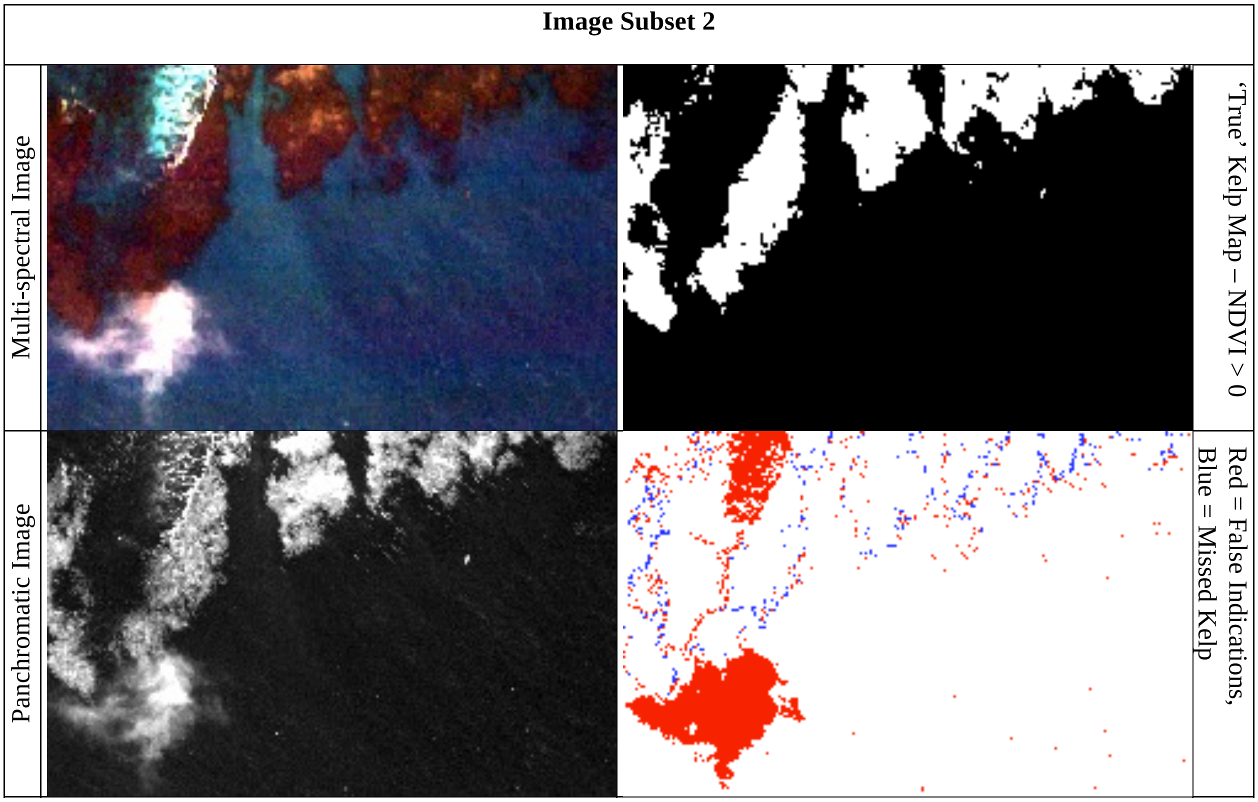

Figure 4. Image subset area 2. The bottom-right image shows the difference between the NDVI result and the panchromatic threshold result; Red represents areas where the panchromatic data creates false indications of kelp, and blue represents areas of missed kelp detections.

2.4 Refining Panchromatic Results

Applying a simple threshold to the panchromatic data provides a good initial approximation of the kelp locations. There are several areas where the resulting kelp map differs from the MSI 'truth' result. False indications occur due to sun glint, other bright objects on the water, and clouds. Missed detections, especially around the edges of the kelp beds, occur because some of the kelp is darker than the chosen threshold. Spatial imaging techniques can be used to mitigate some of these problems.

2.4.1 Morphological Filtering to Remove Sun Glint

Sun glint has brightness values that can be very similar to kelp, so it is impossible to eliminate by means of a threshold. It is easy to identify visually because it occurs as small bright points on the water. The kelp, on the other hand, tends to occur in much larger patches. This difference can by exploited to eliminate the sun glint areas by means of morphological filtering.

Morphological filtering is a spatial imaging processing technique. In this paper, the filtering kernel is defined as a 3x3-pixel square. The morphological erosion filter causes "image details smaller than the structuring element [to be] filtered (removed) from the image" (Gonzalez, 2008). The dilation operation has the complementary effect of growing or thickening elements in an image. Erosion followed by dilation using the same filtering kernel is referred to as 'opening'. A morphological opening filter is employed to reduce the effects of sun glint and other speckle-type false indications.

Results of applying the morphological opening filter to the first image subset are shown in Figure 5. The process appears to effectively eliminate most of the false indications due to sun glint, while maintaining most of the kelp areas.

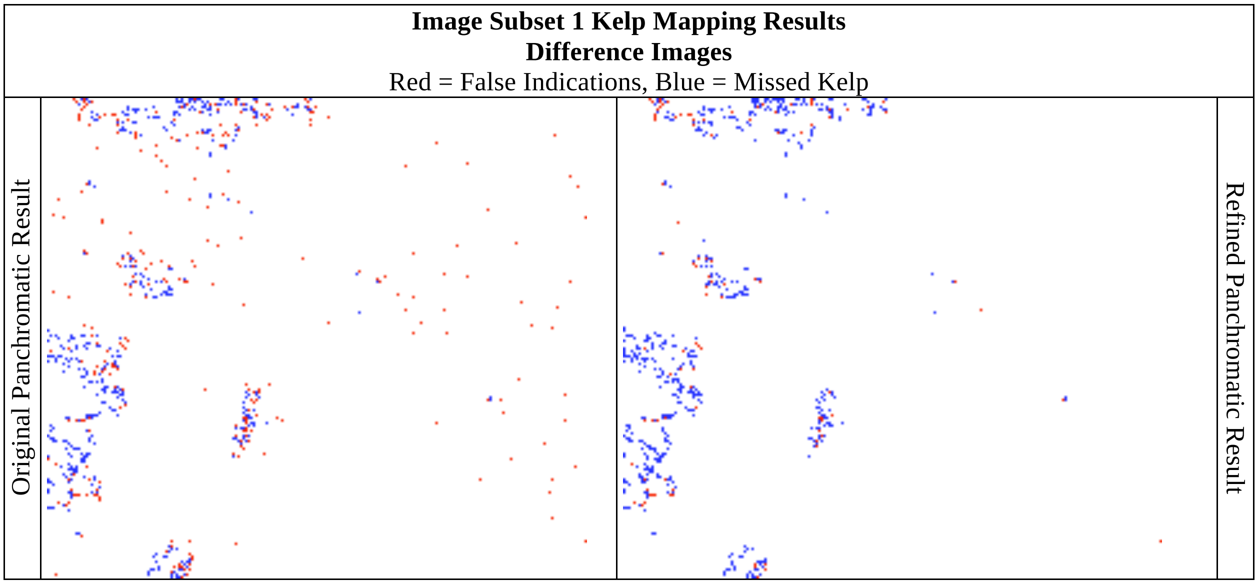

Figure 5. Comparison of kelp map created from the panchromatic data. The initial result was created by applying a threshold to the panchromatic data; the refined result has had a morphological opening filter applied. False indications of kelp areas are shown in red, and missing kelp areas are shown in blue.

The 'true' kelp map is created by applying a greater-than-0 threshold to the NDVI transformed MSI data. This 'true' result maps 46,439 pixels as kelp. The best result achieved by applying a threshold to the panchromatic data created a kelp map containing 43,423 – an underestimation by 6.5% of the total kelp area. By applying the morphological opening filter, the rate of false indications is lowered by about 0.5%. The total kelp area with the morphological opening filter applied underestimates the total kelp area by 21%.

Confusion matrices for the original and refined panchromatic kelp are given in Table 1.

Table 1. Confusion matrices for panchromatic kelp maps for Image subset area 2.

Original Panchromatic Result			
Class	Water	Kelp	Total
Water	99.3	20.48	95.57
Kelp	0.7	79.52	4.43
Total	100	100	100

Refined Panchromatic Result			
Class	Water	Kelp	Total
Water	99.77	25.25	96.24
Kelp	0.23	74.75	3.76
Total	100	100	100

In the second image subset, a total of 142,872 pixels are mapped as kelp using the NDVI transform applied to the MSI data. Because of the cloud in the image, the panchromatic threshold kelp map overestimates the total kelp area by 41% (201,586 pixels). Applying the morphological opening filter reduces the amount of overestimation to 35% (192,451 pixels). The false indications of kelp are reduced by 1% by the morphological opening filter.

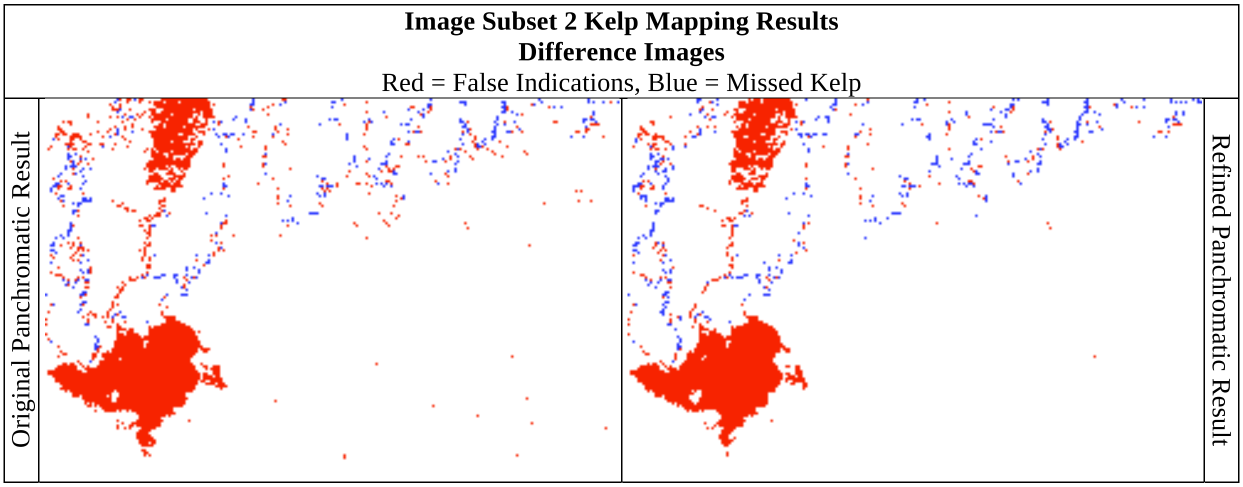

Figure 6. Comparison of kelp map created from the panchromatic data. The original result (L) was created by applying a threshold to the panchromatic data; the refined result (R) had a morphological opening filter applied. False indications of kelp areas are shown in red, and missing kelp areas are shown in blue.

Table 2. Confusion matrices for panchromatic kelp maps for Image subset area 1.

Original Panchromatic Result			
Class	Water	Kelp	Total
Water	90.5	6.73	76.64
Kelp	9.5	93.27	23.36
Total	100	100	100

Refined Panchromatic Result			
Class	Water	Kelp	Total
Water	91.54	7.89	77.7
Kelp	8.46	92.11	22.3
Total	100	100	100

2.4.2 Texture Analysis of Clouds

Clouds are similar in size and shape to the kelp beds, and so morphological filtering cannot be used to separate them. The brightness values are also very similar, and so a threshold cannot be used to discriminate them. Visually, the kelp is distinguishable from the cloud areas because clouds seem to have a different 'texture' than kelp.

It may be possible to use texture features to mask clouds in the panchromatic imagery, but more research is needed to find an effective way of using this information. An illustration of the different 'texture' of clouds and kelp is shown in Figure 7.

Two types of texture filters are employed; occurrence and co-occurrence features. An introduction to texture filters and their utility for classifying panchromatic imagery is given in the thesis by Humphrey (2003).

Occurrence features use the number of occurrences of each gray level within a user-defined processing window for texture calculations (ENVI Help). The Data Range and Variance texture filters provided the most visible distinction between the kelp and cloud (see Figure 7).

Co-occurrence texture features are defined based on 'gray-tone spatial dependencies,' and provide a way to mathematically describe the spatial relationships of tonal variations in an image (Haralick, 1973). To do so, Haralick makes use of a gray-level co-occurrence matrix (GLCM). The GLCM is a matrix P, in which $P_{i,j}$, is the number of times two neighboring pixels separated by distance d occur in the processing window, one with gray tone i and the other with gray tone j. P is a square matrix with dimension equal to the number of gray levels. The processing window size is user-defined, and depends upon the 'scale' of the texture being analyzed.

The definition of 'neighboring pixels' depends both upon a distance, d, and an angle. Figure 7, taken from Haralick's 1973 paper, illustrates the 8 nearest neighbors of a pixel at a distance of $d = 1$.

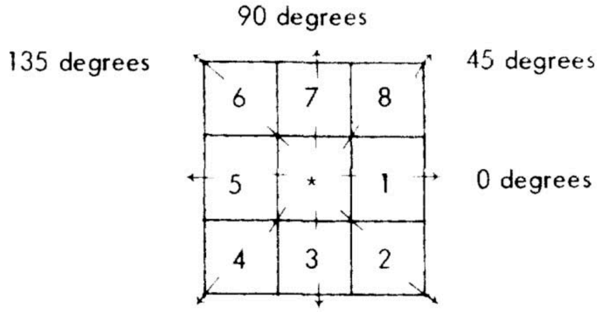

Figure 7. Illustration of neighboring pixels (Haralick, 1973).

Of the various co-occurrence texture features defined in Haralick 1973, the 'homogeneity' and 'contrast' features seem to provide the most distinction between the clouds and kelp.

They are defined as follows (Haralick, 1973):

Homogeneity $f_1 = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} \left(\frac{P(i,j)}{R} \right)^2$ Contrast $f_2 = \sum_{n=0}^{N_g - 1} n^2 \left\{ \sum_{|i-j|=n} \left(\frac{P(i,j)}{R} \right) \right\}$

The GLCM is given by $P_{i,j}$, where i,j and n are indices for the number of gray levels N_g; R is a normalizing constant.

In the texture feature images presented in Figure 7, a distance of 1 pixel and an angle of 0 degrees were used for the co-occurence measures. A 3x3-pixel processing window was used for both the occurrence and co-occurrence measures.

Image Subset 2 – Texture Filters

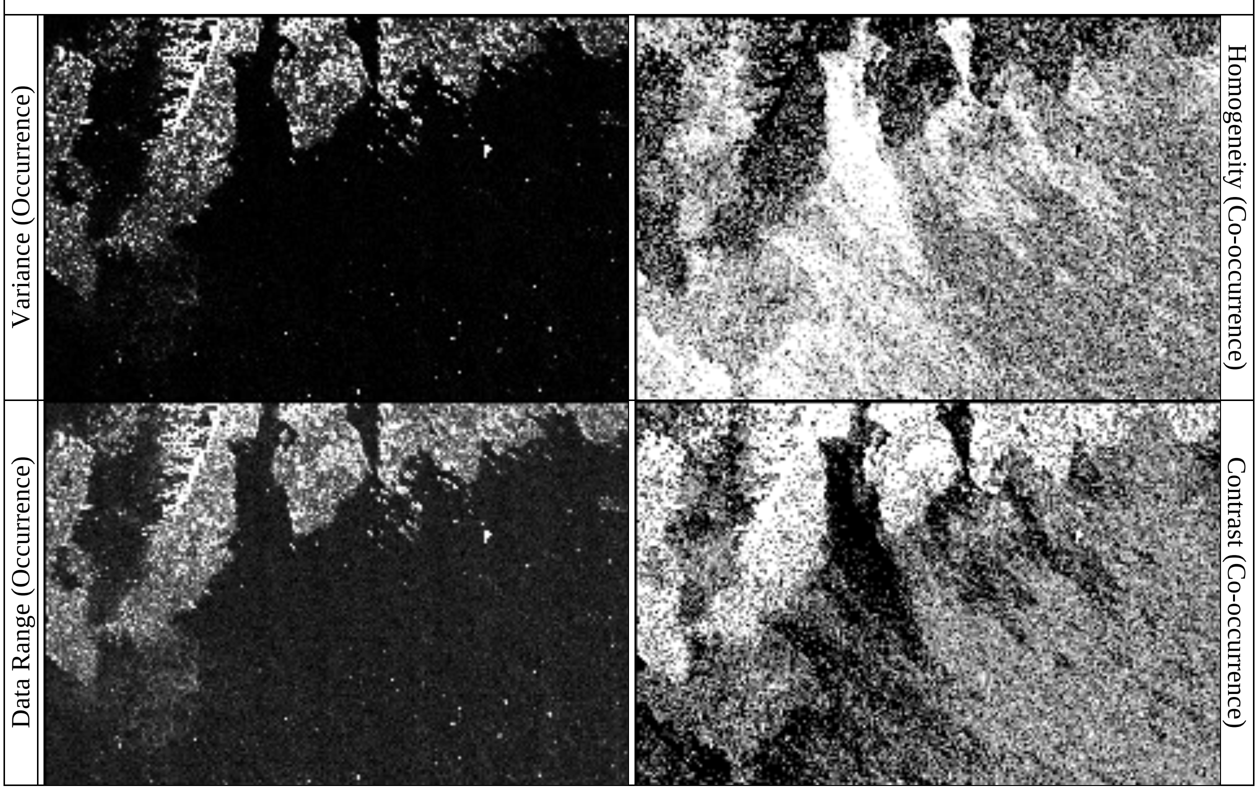

Figure 8. Texture features applied to the image subset 2 area, showing the textural differences between the kelp and cloud areas.

2.5 Effect of Threshold Level

In the examples presented so far, the threshold value for the panchromatic data was chosen so that the resulting kelp map most closely resembles the 'true' kelp map created using the NDVI transform of the MSI data. In order for panchromatic data to serve as a substitute for MSI data, the threshold value has to be determined from the panchromatic information itself. The best threshold to use depends upon the desired outcome – a trade-off exists between the number of false indications and missing areas.

The effect the threshold level has on the kelp map was analyzed by creating kelp maps using multiple threshold levels. The kelp map created using the NDVI transform of the MSI data was used as the 'truth' map, and confusion matrices were calculated for the multiple threshold levels. Figures 9 and 10 show the effect of changing the panchromatic threshold value. The solid lines indicate results created by applying a simple threshold to the panchromatic data; the dashed lines represent the results of the morphologically opened kelp maps. The overall correct quantity is the average correct value for the two classes.

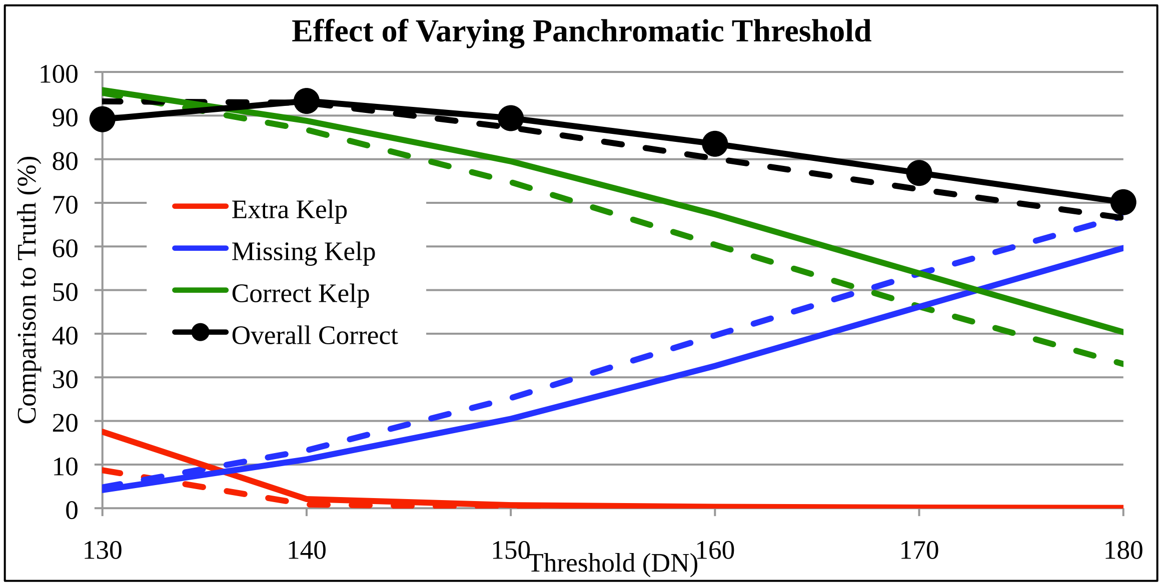

Figure 9. Effect of varying the panchromatic threshold value for the Subset 1 image area.

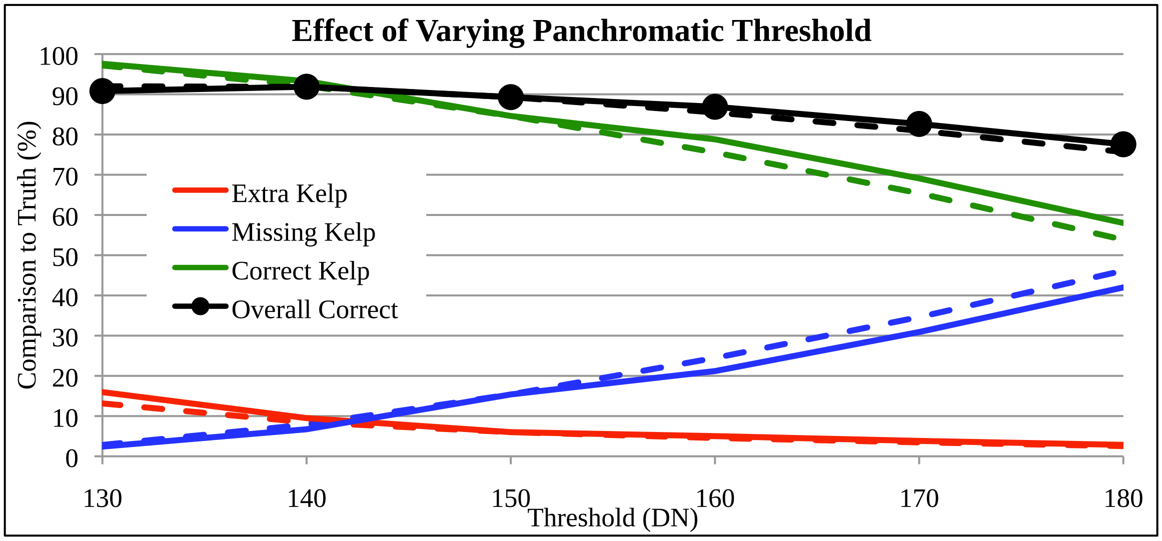

Figure 10. Effect of varying the panchromatic threshold value for the Subset 2 image area.

The cloud in the Subset 2 image area causes a significant amount of extra kelp to be detected even as the threshold is raised.

2.6 Semi-automatic Threshold Determination

An attempt was made to automate the threshold determination process, but more research is needed in this area. To automate the threshold determination process, the following assumptions were made about the data:

1) A land mask already exists, or is created using some other means; creation of the land mask is not dependant on panchromatic information.
2) Kelp areas to be mapped occur in 'large' contiguous spatial areas.
3) False alarms occur in 'small' spatial areas.

Under these assumptions, it was hypothesized that a threshold can be automatically determined by examining the change between the kelp maps created by applying a threshold to the original panchromatic data and the 'opened' panchromatic data. The correct threshold is assumed to be the point at which the difference between the two images is minimized.

When the threshold is too low, a large amount of 'speckle' will occur in the kelp map due to water being mapped as kelp. These speckle areas will be removed by the morphological opening process, and the amount of change between the original and the 'opened' kelp maps will be large.

As the threshold gets closer to the correct value, the returns from the water will be minimized, and only speckle due to sun glint will remain. The opening process will cause the sun glint areas to be removed, but the kelp areas will be maintained. The amount of change between the original and the opened kelp map should be very small.

As the threshold becomes too high, the contiguous areas of kelp will start to break apart into separate areas, and the 'opening' process will cause some of these kelp areas to be removed. The amount of change caused by the 'opening' process will start to grow.

The semi-automatic threshold determination process was applied to each of the subset areas and the entire study area. See Figure 11.

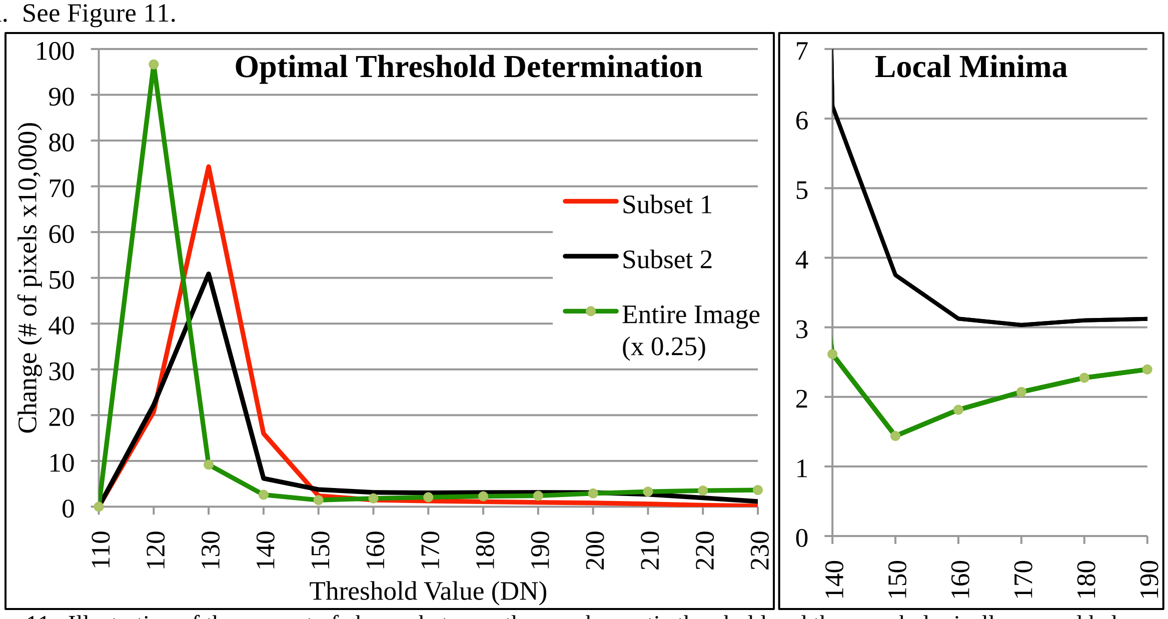

Figure 11. Illustration of the amount of change between the panchromatic threshold and the morphologically opened kelp maps as a function of threshold value. Local minima exist for the Subset 2 image area and the entire image area, but not for Subset 1.

The semi-automatic threshold determination process gives mixed results. For the first subset area, the expected local minimum does not occur. The amount of change between the panchromatic threshold map and the 'opened' result continually decreases as the threshold increases.

For the second subset area, a local minimum occurs at a threshold value of 170. As illustrated in Figure 10, however, the threshold value that gives the result that most closely matches the ‘true’ kelp map is closer to 140. Using a threshold value of 170, the amount of kelp is underestimated as compared to the ‘true’ NDVI result – this may be due to an overestimation of kelp areas in the ‘true’ kelp map for this subset area, or, may be an indication that further work is needed to develop a method for automatically determining the optimal panchromatic threshold.

For the entire scene area, the automatic threshold process causes the amount of kelp to be overestimated. Using the automated process, a threshold of 150 should be appropriate. Analysis of a range of threshold values near 150, however, illustrates that this threshold causes an overestimation of the amount of kelp as compared to the ‘true’ NDVI-derived kelp map. Setting the threshold at 140, 150 and 160 causes the kelp area to be overestimated by 122%, 67% and 33% respectively. A threshold value of 173 creates a result most similar to the NDVI-derived result.

3. CONCLUSIONS AND FUTURE WORK

Panchromatic imagery may provide an alternative or complementary technology to multispectral imagery for the purposes of mapping kelp in water. Because kelp is highly reflective as compared to water, a simple threshold can be used to map the kelp areas. Significant challenges to using panchromatic imagery include false indications due to sun glint, clouds, or other bright objects in the scene. Spatial image processing techniques such as morphological filtering and texture features may provide a means of dealing with false indications due to sun glint or clouds, but further research needs to be done to find effective ways of using this information.

In this paper, any area with an NDVI result greater than 0 was assumed to be kelp. The validity of this assumption should be tested, and results of the panchromatic threshold method should be compared with established ground truth. Other factors to study include the effects of sea surface roughness and natural oil seeps.

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