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Evaluation of remote sensing techniques for monitoring giant kelp populations

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Abstract

Photographs and maps of the floating canopy of the giant kelp, *Macrocystis pyrifera*, provide an important data source to monitor nearshore water quality in southern California. Declines in water quality related to turbidity from coastal development, ocean discharges, and non-point source runoff have caused reductions in the areal extent of these kelp beds. Historically the kelp beds have been monitored by a variety of methods including small format infrared and color photography. New digital remote sensing instruments combined with geographical information system (GIS) databases offer an efficient method for collecting and analyzing data on changes in kelp bed size and location. SPOT satellite imagery has been found to provide adequate resolution for mapping the larger beds of giant kelp along the California coast. Beds smaller than 10 ha are not resolved well with SPOT imagery and need to be mapped with a resolution greater than the 20 m pixel size provided by the SPOT multispectral imagery. Imagery from a prototype of the Positive Systems ADAR system, an airplane mounted multispectral video sensor, provided a spatial resolution of 2.3 m in 4 spectral bands. ADAR imagery taken on 2 October 1991 of the San Onofre Kelp Bed in northern San Diego County showed 39% more kelp than small format color infrared photography made during the same time period.

Introduction

The floating canopies of the giant kelp, *Macrocystis pyrifera*, have been mapped along the California coast for over a century. During the 1800s these canopies were important features for coastal navigation and were included on hydrographic charts of the period. The first comprehensive survey of kelp resources in California was in 1911 when Captain William Crandall (1912) mapped the beds as a potential source for potash production. The maps at this time were made with a sextant and triangulation to shore points.

Aerial photographs of the kelp canopies began to be taken in the 1930s. KELCO, the major harvester of the kelp beds in southern California, began to take systematic aerial surveys in the early 1950s. These surveys included black and white infrared photographs. It is difficult to generate charts from these photographs, however, because most were taken at oblique angles (North, 1991). The California Department of Fish and Game conducted annual aerial photographic surveys from 1955 to 1961. Wheeler North of the California Institute of Technology began a series of annual aerial photographic surveys in 1967 that has continued to the present time. From 1967 to 1971 the surveys were made with black and white infrared film and from 1972 onward they were made with infrared color film (North, 1991). Satellite imagery from both Landsat (MSS and TM) (Jensen *et al.*, 1980) and SPOT (Augenstein, 1989; Augenstein *et al.*, 1991) have also been shown to be useful in mapping *Macrocystis* resources in California.

The objective of this study was to evaluate the resolution of various multispectral digital sensor systems for mapping the distribution and abundance of *Macrocystis* populations along the southern California coastline. The compatibility of data from these systems with geographical information system (GIS) databases was also assessed. Multispectral images from the SPOT satellite and from an airborne video system were compared with surveys made with 35 mm color infrared photographs. The results of other kelp mapping studies using SPOT imagery are also compared.

Table 1. Canopy areas for kelp beds in southern California covered by the SPOT satellite images compared in this study. Areas are the maximum areas during 1987. All areas are in hectares.

Kelp Bed	Canopy Area
North Laguna Beach	0.3
South Laguna Beach	0.9
Dana Point	1.7
San Mateo	2.0
San Onofre	0.8
Barn	0.1
La Jolla	23.7
Pt. Loma	36.8

Materials and methods

Study site

The kelp beds mapped in this study are located offshore of the San Onofre Nuclear Generating Station (SONGS) in northern San Diego County, California (33° 21′ N, 117° 33′ W). The San Onofre Kelp Bed is located 2.5 km directly offshore of the nuclear power plant in an average depth of 15 m. The San Mateo Kelp Bed is located 5 km upcoast of the San Onofre Bed. The area of these kelp beds fluctuates from year to year and the average size during 1987 was approximately 0.8 ha (Table 1). These fluctuations are caused by a number of factors including sea urchin grazing, winter storms, and increases of sea water temperatures caused by El Niño events.

SPOT satellite imagery

Multispectral SPOT satellite images for the offshore region at San Onofre were acquired for 16 March 1987 and 22 March 1987. The image on 16 March coincided with a photographic survey conducted by Dr Wheeler North using color infrared film. This image included the coastline from Newport Bay (33° 36′ N, 117° 53′ W) to Oceanside, California (33° 11′ N, 117° 23′ W). The times and tidal conditions for the SPOT images and aerial survey are summarized in Table 2.

The SPOT images were analyzed using ERDAS image analysis software. A 512 by 512 pixel subscene of the San Onofre area was first subsetted from the full SPOT scene. The effects of atmospheric scattering on the reflectance values (DN) for each spectral band were removed by normalizing the histograms of each band. This normalization was accomplished by shifting the spectral histograms so that the lowest DN values were 1. The kelp canopy areas were classified using both the ratio of the near-infrared band (XS3) to the green band (XS1) and an unsupervised clustering algorithm. Each band was also contrast enhanced for visual evaluation of the imagery.

Table 2. Summary of data collection conditions for SPOT satellite images at San Onofre and the color infrared photography overflight used for comparison.

Survey	Date	Time	Tide
San Onofre SPOT	16 Mar 87	1045 (PST)	+ 1.5 m
W. North CIR photos	16 Mar 87	1500 (PST)	+ 0.1 m
San Onofre SPOT	22 Mar 87	1029 (PST)	+ 0.4 m

ADAR multispectral video imagery

Multispectral digital video images of the San Onofre kelp bed were made using the ADAR (Airborne Data Acquisition and Registration) SYSTEM 5000 developed by Positive Systems, Inc. of Kalispell, Montana. This system was developed to provide multispectral digital images intermediate in resolution between satellite images and scanned aerial photography. The ADAR SYSTEM 5000 consists of 4 digital format video cameras, each using a CCD image sensor. The panchromatic response of the sensor ranges from 200 to 1000 nanometers, providing full coverage of the visible spectrum as well as the near UV and near-infrared spectra. The active imaging area of the sensor is 739 horizontal and 484 vertical pixels with a light sensitivity as low as 0.4 lux. GPS navigation is also available for logging the position of the aircraft at the time each image is acquired.

A flight of the ADAR SYSTEM 5000 over the San Onofre kelp bed was made on 2 October 1991. Table 3 summarizes the tide level during this flight and the times of other surveys used for comparisons with the ADAR data. On this flight the SYSTEM 5000 video cameras were fitted with filters in the blue (410–490 nm), green (510–590 nm), red (610–690 nm), and near-infrared (810–890 nm). The data were collected at an altitude of 4175 m that provided a spatial resolution of 2.3 m per pixel.

Post flight processing of the data included the registration of the 4 spectral bands and the georeferencing of the registered image to known ground control points. Polystyrene floats (1.28 × 2.86 m) that were deployed prior to the flight were used as registration marks for both of these processes. The floats were attached to permanent buoys in the San Onofre nearshore region and their positions were surveyed with a Mini-Ranger transponder system at the time of deployment and on retrieval at the end of the survey. The positions of prominent kelp canopy features were surveyed with the Mini-Ranger system on 24 September and these features were also used to georeference the ADAR imagery. GPS navigation for the ADAR system was not available for this survey.

Classification of the ADAR imagery was conducted with ERDAS image processing software. The image was classified with the CLUSTR algorithm into 10 classes which were then recoded into open water, subsurface kelp, and canopy classes.

Color infrared color photography and charts

Dr Wheeler North of the California Institute of Technology has been mapping the kelp beds of southern California since 1967. His survey methodology is described in his historical summary of the kelp beds of San Diego and Orange Counties (North, 1991). His kelp canopy photographs were taken with hand-held Exacta 35 mm cameras with both Kodachrome KX and Ektachrome IE (infrared sensitive) 35 mm film. A 50 mm focal length lens with a 25A Wratten filter was used with the infrared film, and a 21 or 24 mm focal length lens was used with the Kodachrome film. The infrared photographs were used to detect the surface kelp tissue and the color photographs made with the wide angle lens were used to detect subsurface kelp biomass. The wide angle photo was also used to locate the kelp beds with respect to the shoreline usually not included in the infrared photography.

Table 3. Summary of data collection conditions for ADAR and color infrared photography overflights.

Survey	Date	Time	Tide
San Onofre Kelp ADAR	2 Oct 91	1355 (PDT)	+ 1.20 m
Wheeler North CIR photos	4 Oct 91	1450 (PDT)	+ 0.55 m
Boat Canopy Survey	24 Sep 91	1700 (PDT)	+ 0.13 m

Table 4. Comparison of kelp canopy areas mapped by SPOT and CIR photography for the San Onofre and San Mateo Kelp beds. All areas are in hectares.

Kelp Bed	SPOT 16 mar 87	SPOT 22 Mar 87	CIR photography 16 Mar 87
San Onofre Kelp	0.16	0.12	0.84
San Mateo Kelp	0.78	0.04	0.91

Photographic surveys of the San Onofre area kelp beds were made on 4 October 1991 and a kelp canopy map was produced from this photography.

The original 35 mm color slide from this survey was scanned into a digital raster format with a Howtek slide scanner (1200 dpi). This digital image was then processed with ERDAS image analysis software. The image was georeferenced using the same ground control points that were used to georeference the ADAR imagery. The photograph was then masked to show the identical area represented by the ADAR imagery. The image was then classified into classes representing open water and kelp canopy.

Results

The kelp canopy areas resolved by the SPOT imagery for both of the San Onofre area kelp beds were smaller than that determined by the color infrared photography (Table 4). The underestimation of canopy area was especially large for the San Mateo Kelp Bed on 22 March. The primary cause for the underestimation of canopy by the SPOT imagery was the lack of contrast between the canopy and the surrounding nearshore water. The nearshore waters were very turbid on these dates and the turbidity in the water was a strong reflector of near-infrared radiation. Table 5 summarizes the range of brightness values for the kelp canopy, nearshore water, and offshore water in the infrared band (XS3) in these images. Turbidity in the nearshore water produced reflectance values that overlapped the near-infrared reflectance of the kelp canopy. This was especially severe at San Mateo Point where a turbid plume was moving down the coast and eddying in the region of the San Mateo Kelp Bed.

In addition to the lack of contrast with the surrounding water, the kelp canopies in the San Onofre region showed a much smaller range of near-infrared reflectance than the canopies of other kelp beds seen in other studies using SPOT to map kelp resources. The range of the Pt. Loma and LaJolla beds off San Diego was twice as large as that for the San Onofre area beds. This is most likely related to the lower biomass of the canopies in the San Onofre area as indicated by the relationship of SPOT brightness values and canopy biomass shown by Mouchot & Belsher (1991). It is interesting that the range of near-infrared brightness values for kelp beds in Kerguelen Island is approximately twice as large as that for

Table 5. Range of brightness values (DN) for the near-infrared band (XS3) of SPOT scenes used to map *Macrocystis* canopies. All scenes from the California coastline have been histogram equalized to correct for atmospheric scattering.

Image	Kelp	Nearshore Ocean	Offshore Ocean
San Onofre – 16 Mar 87	3–7	3–14	1–3
San Onofre – 22 Mar 87	2–6	3–13	1–3
Pt. Loma – 25 Feb 92	4–12	4–58	1–3
LaJolla – 22 Nov 86[1]	4–20	3–24	1–3
LaJolla – 10 Oct 87[1]	4–22	2–24	1–3
Kerguelen – 1988[2]	6–35	5	–

[1] Augenstein (1989).
[2] Mouchot & Belsher (1991).

both the Pt. Loma and LaJolla beds. These beds have the highest canopy biomass of any kelp bed in southern California.

The kelp beds showed good contrast with the nearshore water in the green band (XS1) (Table 6), but this signal was lost when the beds were bordered by less turbid offshore water.

The entire SPOT image for 16 March was also used to see if the other kelp beds along the Orange County coast that are routinely mapped in Wheeler North's surveys (Table 1) could be detected. These beds averaged less than 1 hectare during 1987 and none could be distinguished in the image.

Initial analyses of the ADAR imagery showed that only the near-infrared and blue bands were necessary for delineating kelp biomass. The image in the green band provided poor contrast between the kelp tissue and water. The red band provided approximately the same information as the near-infrared band, but with less contrast between the kelp tissue and water. The red band may play some role in determining water turbidity in this region, but this research has not been completed. All classification of the ADAR imagery and the comparisons between the other survey methods, therefore, was conducted with a composite image of blue and near-infrared bands.

The kelp canopy areas for the San Onofre kelp bed on 2 October 1991 as determined by ADAR imagery and the survey conducted with color infrared photography are summarized in Table 7. The ADAR imagery disclosed 39% more kelp area than the classified color infrared photograph. Most of this kelp area, however, was reported as subsurface kelp. The total area of kelp canopy was actually less in the ADAR image than in the infrared photograph. This may have been due to the slightly higher tidal level when the ADAR imagery was taken (Table 3) or due to the 850 nm filter used on the near-infrared sensor. Wavelengths at 850 nm have little water penetration ability and kelp tissue even a few centimeters below the surface may have been missed with this sensor. A filter in the 750 nm range or a broader bandwidth near-infrared filter may be better for detecting the surface canopy of *Macrocystis*.

Table 7. Comparison of San Onofre Kelp canopy area in the region covered by the ADAR imagery for the 2 October 1991 survey. All areas are in hectares.

Survey method	Sub-surface	Total canopy	Total Kelp
ADAR	1.9	0.6	2.5
Infrared photography	–	1.8	1.8

Discussion

SPOT satellite imagery offers the ability to produce precisely georeferenced imagery that can be easily incorporated into geographical information system databases for analysis of changes in kelp canopy location and abundance. In addition, the radiometric characteristics of this sensor permit quantitative estimates of kelp canopy abundance. This system can adequately resolve kelp canopies with areas greater than 10 hectares and with surface biomass greater than approximately 4 kg

Table 6. Range of brightness values (DN) for the green band (XS1) of SPOT scenes used to map *Macrocystis* canopies. All scenes from the California coastline have been histogram equalized to correct for atmospheric scattering.

Image	Kelp	Nearshore Ocean	Offshore Ocean
San Onofre – 16 Mar 87	2–8	9–23	4–8
San Onofre – 22 Mar 87	2–6	7–17	1–6
Pt. Loma – 25 Feb 92	3–6	7–56	4–6
LaJolla – 22 Nov 86[1]	2–6	5–55	3–4
LaJolla – 10 Oct 87[1]	3–5	7–52	4–6

[1] Augenstein (1989).

m^{-2}. However, mapping of smaller and less dense beds, which is required to monitor water quality criteria in southern California, requires a sensor with greater spatial resolution than that obtained by SPOT imagery. This is especially true when turbid nearshore water interferes with the near-infrared signature of the kelp canopy.

Multispectral digital imagery with a spatial resolution of 1 to 2 m such as that provided by the ADAR SYSTEM 5000 will be an invaluable tool in future assessments of nearshore kelp resources. This instrument fills the resolution gap between satellite imagery and more detailed sonar and diver surveys. It has a distinct advantage over conventional color infrared photography in detecting subsurface kelp biomass. This instrumentation is currently sufficient for conducting surveys in localized areas where ground control points such as floats can be placed in the field to provide data for spectral band registration and georeferencing. Better integration of GPS navigation data to the imagery and automated spectral band registration will be necessary before this technology can be used for surveys covering large areas of coastline. Research on the optimum spectral bands for canopy resolution and calibration of the sensors for quantifying kelp canopy biomass also needs to be conducted.

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