Integrating dual frequency side scan sonar and high spatial resolution satellite imagery for monitoring coral reef benthic communities

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Abstract—In this study, the characteristics of both optical and acoustic data types were compared to determine if synergistic use of both methods improved the accuracy of classification of benthic reefs and associated habitats. IKONOS imagery and dual frequency side scan sonar data were acquired in the western Caribbean encompassing coral, seagrass, algal and sediment habitats. Both data types were analysed in isolation and in combination at both habitat and community classification levels. The accuracies achieved with the combined dataset (61% and 52% for the coarse and medium classification levels, respectively) were significantly higher than what was achieved on the basis of the two datasets used in isolation, demonstrating the synergy of the acoustic and optical datasets. The greater accuracy improvements were attributed to the higher spatial resolution of the sonar data, its greater depth penetration, and information contained in the sonograms regarding structural organisation of the habitats. Misclassifications using the combined datasets could be attributed to spectral and textural similarities between different classes, quantity and classification of the ground truth sites, and uncertainties in the co-registration of the two datasets.

Keywords- IKONOS, side scan sonar, coral reefs, seagrass, classification, biotope mapping

I. INTRODUCTION

The mapping of both temperate and tropical marine benthic habitats using medium and high spatial resolution optical satellite systems shows that generally only a few classes can be discriminated on the basis of spectral signatures alone [1,2], owing to limited spectral information available in conventional optical instruments and similarities in reflectance of many species and habitats [1,3,5]. Recently, high spatial resolution data from commercial satellites such as IKONOS and QuickBird has shown to be well suited for mapping coral reef systems [5,6].

A major challenge to optical remote sensing in both temperate and tropics regions is cloud cover which reduces the number of images available over a period of time over an area of interest. The attenuation of light by water also significantly limits the technique in deeper and more turbid waters [1]. These limitations have been drivers to develop and use active remote sensing systems for imaging the seabed such as acoustic systems. However, in comparison to satellite or airborne optical sensors, acoustic systems have rarely been used to map and monitor tropical marine habitats [7,8] and their potential is still in need of evaluation [9]. Acoustic systems may offer further advantages over optical systems such as the provision of structural information on different habitat types, and geomorphological zonation. This additional information may improve the discrimination of spectrally similar but structurally different bottom types.

Despite increasing evidence of the benefits to be gained, there is presently a lack of studies on the synergistic use of alternative remote sensing approaches for mapping shallow water marine near shore habitats [10]. The most obvious advantage of using acoustic and optical methods in combination is the different depth ranges that each of the systems operate; optical systems perform best in shallow waters, while sonar systems can be used to depths of hundreds of metres. Few studies have attempted to integrate side scan sonar data with optical data to exploit the complementarity of the two systems [e.g. 11]. These studies used mainly visual photo-interpretation methods to classify the optical imagery, and to establish the upper boundary limits, whilst the sonograms were used to detect lower depth limits. The present study represents a first attempt to test the discrimination of coral reef habitats based on textural and spectral parameters derived from both side scan sonar (SSS) and IKONOS datasets, to evaluate optical and acoustic remote sensing in discriminating reef benthic communities both in isolation and in combination.

II. METHODS

Study area - The study site, selected for its conservation importance and for the availability of ancillary data, focused on the littoral habitats of San Andres island (12° 34’ N; 81° 43’ W, land area 24 km²), Colombia, situated within the San Andres, Old Providence and Santa Catalina Archipelago in the western Caribbean Sea. The Archipelago comprises a series of oceanic islands, atolls and coral shoals, and was designated a UNESCO Biosphere Reserve in 2000.

Optical imagery - IKONOS multispectral satellite imagery (4 m spatial resolution) were acquired (9th September 2000) to coincide with SSS and ground-truthing biological surveys. An independent geometric correction, atmospheric correction using the empirical line method [12] and water column
correction based on the semi-analytical approach of [13] were undertaken before classification [14].

**Acoustic dataset** - Dual frequency (100 and 500 kHz) Side Scan Sonar (SSS) backscatter and bathymetric data were acquired in the coastal waters of San Andres using a towed GeoAcoustics system. The survey overlapped with parts of the IKONOS image and encompassed the full range of marine habitats found in the area (coral, seagrass, algal and sediment habitats). Anamorphic and slant-range corrections were applied to the raw data in real time, to eliminate lateral and longitudinal distortions, as were corrections using an affine model to geo-correct the sonograms using image to image registration to the optical IKONOS dataset.

The sonograms acquired were used to extract a number of acoustic parameters on the basis of which the discrimination of a number of habitat classes was tested. These included the mean signal intensity of the 2 original sonar bands (at 100 and 500 kHz frequencies: I$_{100}$ and I$_{500}$) and two statistical models of texture which created four extra data layers for the sonograms, two for each frequency available. Full details are given in [14].

**Biological surveys** were undertaken to groundtruth the satellite and SSS images. The survey employed a combination of transects and quadrats [14]. Each survey station was classified depending on its percentage cover of lifeforms according to the hierarchical habitat classification system of [15], with some amendments in the thresholds of different classes to account for regional differences. In total, 4 coarse habitats were identified (coral, algal dominated, bare substratum, and seagrass dominated classes), and 10 bottom types in the medium descriptive resolution (Table 1).

**Discriminant function analysis (DFA)** was used to test the discrimination of the sub-littoral habitat types found around San Andres, based on the optical and acoustic data in isolation and in combination. Water column corrected spectral and SSS acoustic backscatter and textural signatures for 125 of the detailed, ground-truthing sites were extracted. The DFA analysis was performed at both the coarse and medium descriptive habitat classification levels. To build a model of discrimination, individual bands or sonogram layers were chosen as independent variables within the DFA by a forward stepwise selection process. Confusion matrices were produced to assess the accuracy of the classifications at each level and to identify misclassifications, and overall accuracy rates and user’s accuracy for the individual classes were calculated to compare the results based on the acoustic, optical, and combined datasets, as well as between the classifications at the two descriptive resolutions.

**III. RESULTS AND DISCUSSION**

**A. Optical results**

The DFA results (Table 1) from the extracted IKONOS signature data yielded an overall accuracy of 29% at the medium level (10 classes) and 40% for the coarse level of descriptive resolution (4 classes). The greater accuracy at the coarser level is in agreement with findings of classification accuracies of similar habitats from optical imagery [16]. Individual class (user’s) accuracies ranged from 12-100% at the medium level, and 0-58% at the coarse level. At the medium descriptive level, the highest user’s accuracy was achieved for dense seagrass (100%). An overall accuracy of 40% at the coarse level is still poor for scientific or management applications. The best discrimination was achieved for the bare substratum class (58%), in agreement with other IKONOS case studies [6]. The next best discriminated class was seagrass (53%) with the main confusion of this class being with algae. This is not surprising as the algal classes were dominated by green algae which are spectrally similar to the seagrasses. The algal and coral classes failed to be discriminated.

**B. Acoustic results**

The DFA results for the acoustic data (Table 1) yielded higher accuracies compared with the optical data (medium

### Table I. Individual Class User’s Accuracies and Overall Accuracies (%) from the Discriminant Function Analysis of the Optical, Acoustic, and Combined Datasets at the Medium and Coarse Descriptive Levels.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Optical</th>
<th>Acoustic</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Medium resolution classification</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 Sheet corals (mainly Agaricia) ≥1%</td>
<td>16</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>1.4 Massive and encrusting corals</td>
<td>45</td>
<td>40</td>
<td>64</td>
</tr>
<tr>
<td>1.5 Dead coral (Dead &gt; live coral cover)</td>
<td>12</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2.1 Green algae (≥ 50% algal cover)</td>
<td>17</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>3.1 Bedrock and rubble with dense gorgonians (&gt;50% bare)</td>
<td>23</td>
<td>40</td>
<td>33</td>
</tr>
<tr>
<td>3.3 Sand &amp; rubble with some algae (&gt;50% bare)</td>
<td>25</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>3.4 Sand with some algae (&gt;50% bare)</td>
<td>50</td>
<td>40</td>
<td>78</td>
</tr>
<tr>
<td>4.1 Sparse seagrass and algae (&gt;50%)</td>
<td>43</td>
<td>29</td>
<td>53</td>
</tr>
<tr>
<td>4.2 Medium density seagrass and algae (&lt;50%)</td>
<td>18</td>
<td>26</td>
<td>38</td>
</tr>
<tr>
<td>4.3 Dense seagrass and algae (&lt;50%)</td>
<td>100</td>
<td>22</td>
<td>38</td>
</tr>
<tr>
<td>Overall accuracy (%)</td>
<td>29</td>
<td>34</td>
<td>52</td>
</tr>
<tr>
<td><strong>Coarse resolution classification</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Coral classes</td>
<td>0</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>2. Algal dominated</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>3. Bare substratum</td>
<td>58</td>
<td>52</td>
<td>76</td>
</tr>
<tr>
<td>4. Seagrass dominated</td>
<td>53</td>
<td>46</td>
<td>65</td>
</tr>
<tr>
<td>Overall accuracy (%)</td>
<td>40</td>
<td>50</td>
<td>61</td>
</tr>
</tbody>
</table>

Key factors which contributed to the poor classification are similarity in spectral signatures between many habitat classes and the limited number of IKONOS wavebands. Seagrasses, algae and reef habitats are dominated by photosynthetic organisms resulting in similar spectral signatures. Differences between classes are often subtle and require high spectral resolution and often spectral derivative analysis for segregation [2, 3, 4]. IKONOS spectral bands are too broad and poorly placed to detect subtle differences needed to discriminate between such classes.
level 34%, coarse level 50%), in agreement with studies of similar habitats from acoustical single beam data [7].

Individual class user’s accuracies ranged from 22-50% at the medium descriptive level, and 5-78% at the coarse level. Hard coral classes were best discriminated with user accuracies ranging from 40 – 50%, followed by dense gorgonian habitats (40%), the sand and rubble classes (40%), and the sand classes (40%). Seagrass classes and green algae were poorly classified, being confused mainly with each other and with sand and algae or sand and rubble. With the exception of the latter, the rest of the classes showed a similar coarseness in texture in the sonograms, especially the seagrass and algal habitats which may partly explain their poor discrimination. The typical green algal habitats found around San Andres were on sandy substrate and most often mixed with seagrass species which may explain their apparently similar acoustic responses. Coarse sand and seagrass also had similar textures with the main difference being in the intensity of the backscatter and their different responses in the two frequencies.

At the coarse level accuracies of all classes increased except for the algal class which was reduced to 5% from 25% and was largely misclassified as seagrass. Seagrass classification was improved over the medium level, demonstrating the potential for seagrass discrimination using acoustic data at a coarser level where subclasses of different densities are not considered. The bare substratum class also showed an increase of accuracy to 52%. The class best discriminated was coral with a user’s accuracy of 78%. Many of the processes that drive coral reef dynamics such as recruitment processes or hurricane damage result in patchy distributions which, together with variable three dimensional structures, contribute to this class showing the greatest variance measures [16], apparent in the acoustic data.

Whilst the results this study are not strictly comparable with those obtained using AGDS by [7] and [8], their single beam acoustic signatures measured parameters of “roughness” and “hardness” of the habitats under investigation. [7] reported similarly poor (28%) overall accuracies for a 10 class level of resolution and a higher overall accuracy (60%) at a coarser level of four classes. At the coarse level coral was the best discriminated class with a user’s accuracy of 68%, comparable to the results of this study. [8] presented similar classification accuracies of 56% when attempting to classify 4 classes (coral, rock, algae and sand) on the basis of two signal frequencies, 50 and 200 kHz.

The SSS survey had a number of limitations which may have contributed to the misclassifications of some of the classes. Positional and locational errors are in general greater for acoustic data compared with satellite data [10] and may have been introduced from a variety of sources including inadequate positioning of the towfish in relation to the survey boat, and the approximate nature of the manual georectification of the sonograms.

C. Optical and acoustic synergy results

With the inclusion of both optical and acoustic signatures in the DFA classification accuracy improved significantly compared to either method used in isolation, at both levels of descriptive resolution. The overall accuracy of the classifications improved to 52% at the medium level (10 classes) and to 61% at the coarse level (4 classes, Table 1).

At the medium classification level the most effective classification was achieved on the basis of the Blue IKONOS band and the four acoustically-derived textural parameters derived from the SSS data. At the coarse classification level a best classification was achieved on the basis of the three acoustically derived texture bands and the Blue IKONOS optical band. The textural information derived from the SSS data made a significant improvement to the user’s accuracies of each class at both discrimination levels compared to the original spectral discrimination (Table 1); all except one habitat class, showed an increase of at least 10% from their optical classification accuracy when the acoustic data were included in the DFA. The classes that benefited most from the inclusion of the textural acoustic data were the three coral classes, the green algae class and the sand class where % increases ranged from 19% to 38%. Even though the overall accuracy at this level is still low (52%) and probably inadequate for management purposes, some individual classes were well discriminated.

The better discrimination achieved at the coarse classification level was demonstrated, with the exception of the algal class, by high class user’s accuracy values close to or over 70% (Table 1). Similar to the medium level classification, the coral class exhibited the greatest improvement in accuracy from 0% to 78%. This was followed by the bare substratum class (58% to 76%), and by the seagrass class (53% to 65%). The only classes which did not benefit from the inclusion of the textural acoustic information in the DFA were dense seagrass class (medium classification level) and the algal class (coarse level). Dense seagrasses, along with the other seagrass classes, showed relatively poor discrimination based on their acoustic properties alone. At the coarse level, when all seagrass subclasses were amalgamated into one class, the sonar classification accuracy was higher (46%) which had the overall effect of improving the classification accuracy to 65% for the combined dataset. These results may indicate the inability of sonar data to differentiate between different seagrass densities, and demonstrates that if a class has very good discrimination on the basis of one dataset but low discrimination on the basis of the other, then it is best classified only on the basis of the single dataset that gives the best results.

The discrimination achieved when both datasets were used in combination was equal to or greater than the best discrimination achieved on the basis of each dataset in isolation. This was the case for eight out of ten classes at the medium level and for all classes at the coarse level. The improvement in the discrimination of the dead coral class with the inclusion of the acoustic textural data is particularly significant for monitoring coral health. Clearly, diseased coral cannot be discriminated spectrally on the basis of IKONOS bands alone as, due to their rapid colonization by macroalgae, they are spectrally indistinguishable from macroalgal beds. Even after the inclusion of the sonar data the accuracy of this class is still not high (50%), but the combination of the two datasets shows potential for improving the discrimination of diseased or dead coral. This is attributed to the acoustic signatures of algae overlying dead coral mounds; it still
identifies the distinct texture of coral, even though spectrally the signature is similar to algal or seagrass classes.

IV. CONCLUSION

This study showed that only a few classes can be discriminated by their IKONOS spectral signatures alone, and the incorporation of spatial information, in the form of fine scale, acoustically-derived texture, greatly improved the accurate classification of reef habitats. The combined use of both techniques provides a means by which the rich diversity of tropical reef ecosystems can be mapped and monitored with significantly greater accuracy than with either technique alone. The improvements brought about by the acoustic data were to classes which were spectrally similar but had contrasting textural characteristics, or of classes whose distribution could not be resolved by the spatial resolution of the IKONOS imagery. Textural (spatial) information was of particular benefit for discriminating classes characterized by a complex spatial pattern, represented by heterogeneous acoustic response, and even though the overall classification accuracies were still not high (at 52% for the detailed level and 61% at the coarser level), the improvements from the optical classification (23% and 21%) was very encouraging. Significant increases in accuracies occurred for the highly textured coral classes in particular, where individual class accuracy levels as high as 78% were very satisfactory. The improvement in the discrimination of the dead coral class, has significant implications for monitoring coral health.

The results highlight the limited capacity of high and medium spatial resolution terrestrial satellite sensors to discriminate reef bottom types compared to higher spectral resolution systems [5, 9]. Sensors with wavebands different to those used by conventional terrestrial satellites are required for detailed mapping of reef biotic systems. It can be expected that higher spectral resolution data would further improve the classification accuracies obtained when optical and acoustic data are combined.

Overall, the results of this study demonstrate the benefits to be gained from the synergistic use of optical and acoustic data. This is due to the combination of texture and morphological information (acoustic data) and ‘colour’ (satellite data) which facilitate the improved discrimination of different habitats than on the basis of colour alone. Discrimination of the habitats could be further improved with the use of contextual editing and the use of complementary data such as bathymetry. Few studies have used spectral and textural variables in conjunction to improve the classification of high spatial resolution images fewer still have derived textural parameters from high spatial resolution SSS data. The results presented here highlight the need for significant development in the synergistic use of optical remote sensing and acoustic data.

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