High-resolution imagery applications in the littorals

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ABSTRACT

We focus on three applications of high-resolution imagery in the littorals: mapping bathymetry, monitoring the health of coral reefs, and taking censuses of marine mammals. All three applications show the importance and potential benefits of higher-resolution imagery. Increased radiometric sensitivity and the simultaneous collection of panchromatic and multispectral imagery are also important. An Ikonos image of Maui is used to demonstrate these applications. We also briefly explain some important differences between multispectral remote sensing over water and land.

1. INTRODUCTION

For the past 12 years my colleagues at SRI International and I have investigated multispectral remote sensing over oceans and littorals. Among the applications we have studied are the detection of mines and small obstacles,[1,2] search and rescue at sea,[3] and bathymetry and coral reefs.[4] All of these studies have been limited to airborne systems; but we are now starting to look at the possibility of using commercial high-resolution satellites. Our experience with satellite data is still limited; however, thanks to the interest and efforts of Ms. Tish Williams (the chair of this session) we have been provided with several samples of Ikonos[†] imagery for evaluation and an invitation to report the initial results to this conference. The analysis is continuing as this paper is being written, so we may have more results to present at the conference than are available before the manuscript deadline.

The focus of this paper is on three specific applications: bathymetry, monitoring the health of coral reefs, and census of marine mammals. In all three applications the subjects are underwater, which, as explained in the next section, introduces complications and requires the use of techniques different from those used for subjects on land.

These applications also benefit greatly from several Ikonos system features other than high resolution: Ikonos' increased dynamic range (11 bits) helps to overcome the attenuation of light by water; simultaneous panchromatic and multispectral imaging provides target identification by both spectral and shape characteristics; and off-nadir pointing provides a sun-ocean-sensor angle that is optimum for the application. This angle is more critical over water than over land, especially because of sunglint on water.

We show results we obtained from an image of Maui, Hawaii collected by Ikonos on 25 January 2001 (Figure 1). This particular image was chosen because it can be used to illustrate all three applications. Bathymetry is available in United States Geological Survey (USGS) topographic maps for comparison with the image; there is a famous and well studied coral reef in the Molokini crater lagoon; and the image covers part of the Hawaiian Islands Humpback National Marine Sanctuary (the humpback population at the sanctuary peaks in late February and March, but data from 25 January can be used to investigate the detection of marine mammals). Marine mammal detection is a subject of immediate interest for a research project we are conducting for the Office of Naval Research (ONR). Possible first detections of marine mammals from space are presented here in Subsection 3.3.1).

Before we discuss applications, we present a brief introduction to some considerations and issues specific to remote imaging over water. In Section 2 we briefly describe the physics, radiometric calibration, and uses of multispectral bands. Readers already familiar with over-water multispectral techniques may wish to skip to Section 3.

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† The Ikonos satellite is a product of Space Imaging, LLC.

Figure 1: Panchromatic Ikonos image of Maui, Hawaii (left) and zoom-in on Molokini crater (center). Right: Aerial photograph of the crater.

2. SPECIAL CONSIDERATIONS FOR MULTISPECTRAL IMAGING OVER WATER

2.1 Radiance of underwater subjects

For land objects the radiance at a remote sensor is

$$L_{sensor} = L_{path} + t\, L_b \quad , \tag{1}$$

where L_{path} is path radiance, t is the atmosphere transmission, and L_b is the radiance from the surface object. The radiance of objects below the ocean surface is more complicated because there are additional contributions from skylight reflected from the ocean surface, L_{sky}; light scattered from the water volume, L_{vol}, the water equivalent of L_{path}; and water attenuation, a, the water equivalent of t. In other words, there are two transmission media and an intervening layer of clutter. The modified form of Equation 1 is

$$L_{sensor} = L_{path} + t\, [L_{sky} + e^{-2\,a\,z}\, L_b + (1 - e^{-2\,a\,z})L_{vol}] \quad , \tag{2}$$

where z is the depth of the target.[5,6] It is easy to see that Equation 2 reduces to Equation 1 with the target at $z = 0$, and water terms are eliminated. The wavelength dependence is suppressed, for notational simplicity, but it is important to remember that everything except z depends on wavelength.

Path radiance is an unavoidable nuisance in both land and water applications. The other factors, L_{sky}, L_{vol}, and a, are a nuisance or benefit, depending on the application. For example, L_{sky} is modulated by wave slope, which makes waves visible. Wave visibility is desirable in studies of ocean waves, but reduces the visibility of objects below the surface.

2.2 Sunglint and whitecaps

Sunglint and whitecaps are not included in Equation 2 because we assume that they are either avoided or eliminated in advance. Sunglint can be removed by special spectral processing, as described in References 2 and 3, but can also be easily avoided by pointing at least 30^{o} from the solar specular. This is one of the advantages of a satellite's re-pointing capability.

Whitecaps are much brighter than the background ocean (10 × in the blue band, > 50 × in the near infrared [IR] band,) and have been a problem with previous low-resolution imagery because they mix in and contaminate the spectral radiance of undisturbed water. With high-resolution imagery we have a simple solution. Individual whitecaps are now resolved; pixels with whitecaps are flagged as "bad pixels" and eliminated in further processing, which usually leads to a loss of 1–10% of the image area.

2.3 The implication of water attenuation

Water attenuation is a mixed blessing. The radiance from objects below the surface falls exponentially with depth. In shallow water, then, the bottom depth is linearly proportional to the log of radiance. This relationship is used to measure depth.[5,6,7]

On the other hand, very slight depths cause radiance to fall below the sensor threshold. One-half meter of water attenuates red light as much as twenty kilometers of atmosphere. Figure 2 shows the radiance-depth relationship of an object with 10% Lambertian reflectivity and water with a chlorophyll concentration of 2 mg m^{-3}. Radiance fall-off in the red and blue bands is shown. Fall-off in the near-IR band is much steeper than in the red band. (Near-IR depth penetration is nil for all practical purposes.) Fall-off in the green band is similar to that in the blue band at this chlorophyll concentration.

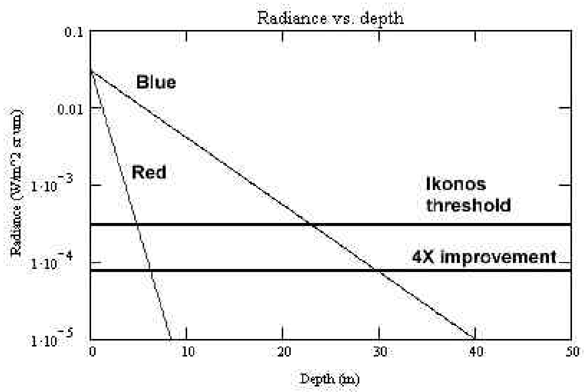


Figure 2: Water-leaving radiance of an object with 10% Lambertian reflectivity.

Figure 2 shows that the depth range is limited and depends very much on the radiometric sensitivity of the sensor. The upper radiometric threshold level plotted in the figure corresponds to that of the Ikonos sensor. (The threshold varies slightly for different bands, but we used a constant to simplify the plot.) The lower threshold is achieved with a $4 \times$ improvement in sensitivity. The $4 \times$ threshold provides a 30% increase in depth penetration, or, alternatively, a 12 dB improvement in the signal-to-noise ratio (SNR) at a fixed depth.

2.4 Atmosphere correction

In the littorals there are a several new considerations for atmosphere correction. The radiance from water (the sum of L_{sky} and L_{vol}) and objects in the water is small compared with the path radiance. In fact, most over-water radiance is atmospheric scattering: 90% in the blue band, > 99% in the near IR. In a raw satellite image (not atmosphere corrected) the ocean is blue, but that blue derives from the atmosphere, not the ocean. Thus, a small error in atmosphere correction can translate into a very large misinterpretation of the target spectrum.

It is a common practice to assume that there is no ocean radiance and use the over-water radiance as an estimate of L_{path}. This is a simple atmosphere-correction procedure for land features. When this procedure is used for water applications, the radiance measured for the target is relative to the deep-water radiance rather than absolute. This is fine for some applications.

Absolute atmosphere correction requires several objects with known reflectance spectra in the image. Besides the usual land features (e.g., vegetation), littoral scenes also provide sandy beaches and white water (foam from braking waves, surf, and ship wakes). White water is almost always present.

Foam is a Lambertian reflector, with reflectivity that is near constant 55% across the visible bands and slightly less in the near-IR band.[8] Foam can thus be used as a surrogate calibration reflector. It is important to resolve the foam features. As mentioned before, the new high-resolution imagery resolves whitecaps, so this use of foam is now practical. Several foam patches in the Maui image were examined and found to have nearly identical spectral reflectance curves.

Still another consideration is the adjacency effect, i.e., photons from a bright area leaking into dark pixels. This is especially relevant in the near IR band, where the contrast between land and water radiance is ~400. A colleague, William Snyder, detected the adjacency effect to a distance of 1 km from the coast in one of the images we studied earlier.[9]

2.5 Utility of multispectral images

A few points can be made about the special utility of multispectral images in the littorals. Objects below the surface are visible in the blue and green bands. The blue band has the greatest water penetration in clear water, and the green band is better in more turbid coastal waters. The blue-green ratio can be used for material classification, as in land features, although the interpretation is complicated by a combination of errors in both the atmosphere and water path corrections.

The near-IR band has virtually no water penetration, and very little IR is scattered from the water volume. This makes near-IR images useful as data masks. Any pixel with an IR value slightly above the mean water radiance represents land, whitecaps or foam, or a hard target on the ocean surface (e.g., a boat or buoy). Near IR is also excellent for detecting surface oil slicks.[3]

A very small fraction of the light that falls on the ocean is modulated by wave slope. The surface reflectance is color neutral. The modulation is the same at all wavelengths. The modulation in the near-IR band can thus be used to subtract the sky reflectance in the other spectral bands. This technique is useful if wave patterns obstruct the visibility of objects below the surface, as will be illustrated in our discussion of coral reefs (Subsection 3.2).

The usefulness of the red band is somewhere between those of the near-IR and green bands. If the target is very close to the surface (< 2 m), the red radiance may be useful for classifying targets with band ratios. At greater depths, where there is no red signal, the red band can be used in place of or in addition to the IR band to flag whitecaps or subtract surface reflections.

The red and near-IR bands are also used for estimating water turbidity. However, such estimates do not require a great deal of resolution and can be done equally well with other satellites, e.g., LANDSAT 7.

With these preliminaries over, we can discuss three littoral applications of high-resolution imagery.

3. APPLICATIONS

3.1 Bathymetry

Coastal bathymetry is constantly changing, due to the action of storm waves. It is thus the case that most nautical charts must be frequently updated. Unfortunately, existing technology is not up to the task. The traditional method of bathymetric charting with ship sonars is slow and expensive. The newer technology, airborne laser bathymetry, is orders of magnitude faster than ships and is continuing to improve. Meanwhile, many researchers have been studying the use of multispectral imaging from satellites, which is potentially the fastest and most economical approach.

Hydrographic charting standards are very rigorous, especially for charts to be used in navigating shallow waters. International Hydrographic Organization (IHO) “order-1” standards are: 2-sigma depth accurate to 50 cm + 0.013 $\times$ depth, and resolution of 2-m cube objects. These requirements are difficult to meet with remote sensing. Older commercial satellites are far from able to resolve 2-m objects, but Ikonos, with 4-m resolution in the multispectral band, is approaching that capability. The next generation of high-resolution satellites will have 2-m multispectral resolution. It may also become possible to combine multispectral resolution with higher-resolution panchromatic.

3.1.1 Comparing Ikonos Maui image with USGS map

Figure 3 compares a blue-band image of Maui (right panel) with a USGS topographic chart of the Kalepolepo area of Maui (left panel). The bathymetry structure is very clear to a depth of about 30 ft. Note the similarity between the features in the Ikonos image and the chart contour lines nearest to shore. The bottom structure is less clear at depths greater than 30 ft, but we can detect features in the Kihei Shoals, which according to the charts are at a depth of 60 ft. The features are more obvious with a histogram stretch to emphasize the features, as shown in the bottom panel of Figure 3. Column noise becomes apparent with this stretch, so 60 ft is close to the detection limit in these waters.

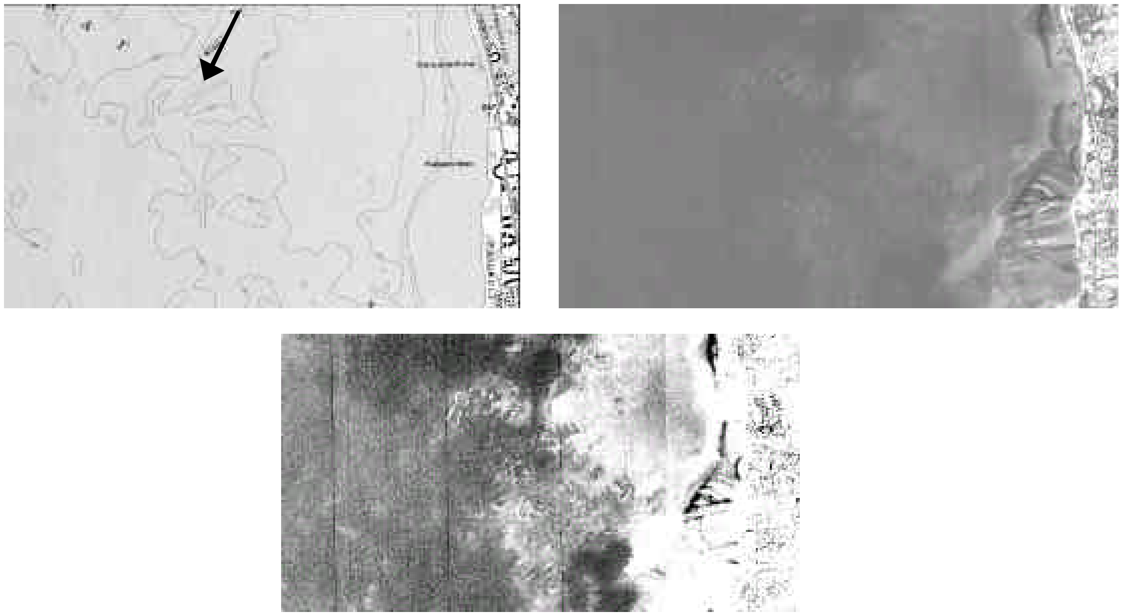


Figure 3: Bathymetry off Kalepolepo. The arrow points to the Kihei Shoals, which are 1.5 km from shore and 60 ft deep. Top: USGS topographic map and corresponding Ikonos blue-band image; bottom: image with histogram stretch.

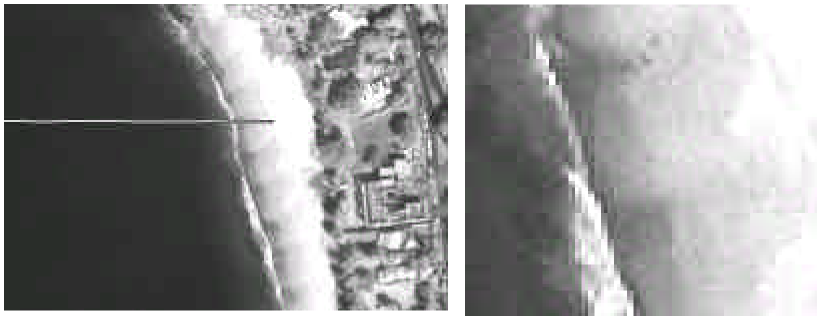
3.1.2 Measuring depth

We have established that the bottom structure is visible to a depth of at least 30 ft. Can we estimate the depth of the structure? Equation 2 can be solved for depth, z. However, we must consider a few complications such as the need to know the reflectivity of the material on the ocean bottom. The reflectivities of sand, vegetation, and rock are different. Various techniques are used to classify the bottom material and determine the depth and the optical properties of the water. A full discussion of these techniques is beyond the scope of the paper, but one in particular is worth mentioning because it illustrates another benefit of higher resolution.

One can assume that the beach sand extends underwater some distance from the water line so the radiance measured on sand above water can be used as a reference for the radiance from the surface object, L_b. This removes one of the unknowns in Equation 2. However, the solution is not quite that simple. Wet and dry sand have different reflectivities, so if we are to use sand as a depth reference we must be able to differentiate the wet sand from the dry sand in the wave runup area of the beach.

Figure 4, left, shows the Keawakapu Beach area in panchromatic. At right, is a close-up showing that the runup region is resolved into 5–10 pixels. Figure 5 shows the radiance profile in the blue band along a transect from the beach out to 400 m from shore. Radiance is plotted on a log scale, which is linear with depth, assuming a constant substrate reflectivity. At a location +24 m from the water line, the surface is dry and very bright sand. The peak, at –8 m from the water line, is due to whitewater surf. The point at 0 m is probably the first pixel with some water cover. The pixel at either 0 m or +4 m would then be used as the wet sand reference radiance.

The radiance profile is in agreement with the USGS topographic map depth contours. The depth increases out from the beach to a plateau at 18 ft depth, then drops off again to 40–50 ft at the furthest point from shore. The radiance at that point is only slightly above the Ikonos detection limit.



Source: Space Imaging, LLC.

Figure 4: Keawakapu Beach, from the panchromatic image of Figure 1. Left: the transect line used for the radiance profile in Figure 5. Right: zoom-in showing pixel-level resolution of the beach surf and of the wet and dry sand.

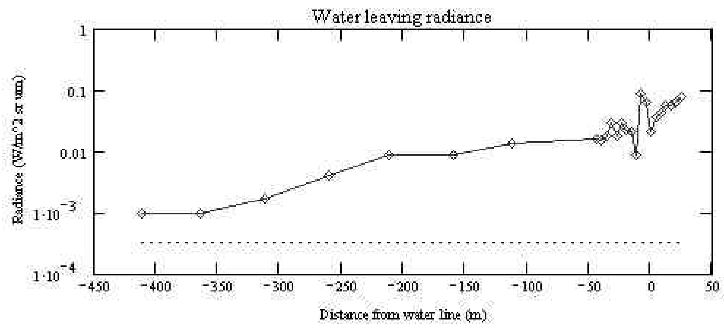


Figure 5: Profile of the blue-band radiance in the Figure 4 image, from a point 400 m from the water line to the dry sand. The diamonds signify the locations of actual measurements. The dashed line is the Ikonos detection limit.

3.2 Coral health

Coral bleaching is a worldwide and increasingly serious environmental concern. It would be desirable to monitor coral health at regular intervals. Due to the geographic remoteness and large areas of coral habitats, satellite monitoring is an attractive approach. Coral needs sunlight, so by definition the water in coral habitats is clear enough for coral to be detected by remote sensing. Roahman[10] gives an excellent summary of the coral health situation and the possibilities for satellite monitoring.

The main requirements for remote sensing are high spectral and pixel resolution. Spectral resolution provides discrimination between healthy, bleached, and dead coral, but hyperspectral resolution may be required to detect all the subtle spectral nuances that differentiate degrees of bleaching. High spatial resolution is also essential because areas of healthy, unhealthy, and dead coral are in close proximity to one another.

However, no space-based system provides both high spatial and hyperspectral resolution. A fusion of two imaging systems, one with high resolution and the other hyperspectral, may be required. This may be a real option in the near future, when moderate-resolution hyperspectral systems (Orbital Imaging Corporation's OrbView 4 or the Naval Earth Map Observer [NEMO]) go into service and can be combined with Ikonos and similar high-resolution imagers.

3.2.1 Band ratio anomaly in Molokini coral

Let us see what we can do with Ikonos resolution alone. The coral structure in the Molokini lagoon is revealed in the blue band image shown in Figure 6 (left). The structure is similar to that seen in the aerial photograph in Figure 1. The accompanying blue-green ratio map (center) shows small patches within the overall coral area where the ratio is significantly greater than the average value. The right panel is a zoom-in on a 120 m ×120 m area showing one anomaly in more detail. More analysis is needed to interpret the meaning and significance of this result.

The anomalies are small and would not be detected from space without the higher resolution provided by Ikonos. LANDSAT 7 and SPOT 4 resolution would not be adequate to resolve these features.

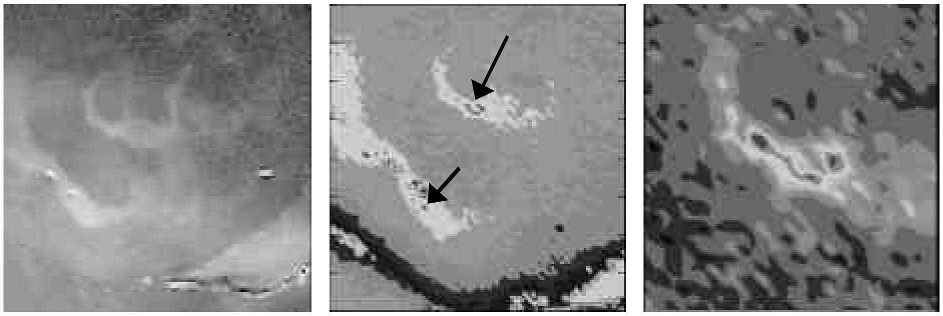


Figure 6: Study of Molokini coral reef. Left: view in the blue band showing coral reef and part of crater rim. Center: blue-green band ratio. Right: zoom-in and rescaled view of a 120 m × 120 m area showing details of the anomaly. Arrows point to anomalous high ratios in coral.

3.2.2 Surface reflection removal

The radiance levels can be stretched to reveal more coral structure, usually at lower depths, as shown in Figure 7, a view of a select area of the Molokini coral. However, not all the structure revealed in this way is real. Stretching the radiometric levels also exaggerates clutter from ocean surface waves and results in an inaccurate depiction of the coral.

The wave conditions during the time of the Ikonos image is similar to that in the aerial photo (Figure 1). The crater walls protect the lagoon but some waves do enter, especially into the area shown in Figure 7.

As mentioned earlier, the ocean surface clutter is coherent across all spectral bands. The near IR band, which has virtually no signal from below the surface, is thus a good reference for the coherent subtraction of surface-wave-modulated radiance. This was done to produce the cleaner image in the right panel. Note that the two "fingers" in the unprocessed image which are actually surface reflections from ocean waves, have disappeared. Waves-like features in the lower left are also removed. Note that other features of low intensity remain after near-IR subtraction and are presumably real.

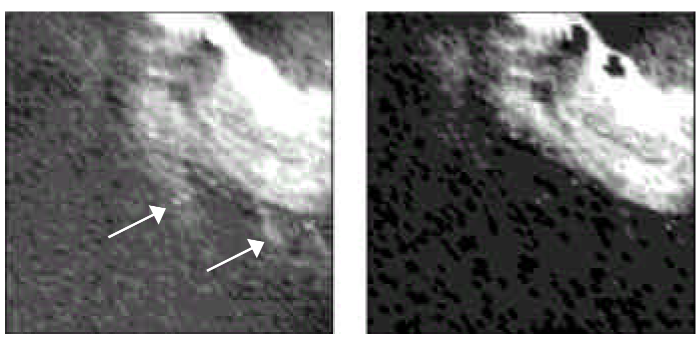


Figure 7: Blue-band image of a section of the lagoon coral structure. Left: unprocessed image. Arrows point to "fingers" that will be removed by coherent subtraction of surface reflections. Right: image after coherent subtraction of surface reflections.

3.3 Marine Mammals

Aerial surveys are routinely used to census marine mammals.[11,12] Aside from the scientific interest in their migration patterns, such surveys are increasingly needed for compliance with the Marine Mammals Protection Act (MMPA). The most effective way to comply with MMPA is to avoid, if possible, maritime activities in areas with animal concentrations. On the U.S. Atlantic coast, aerial surveys are used to monitor the movements of the critically endangered right whale for dissemination to the maritime community. There are already encouraging signs that this practice is reducing ship strikes. The Navy is also using aerial surveys to "clear" an area for naval exercises, as reported by Carretta et al.[13] and others. There is also continuing interest in the effects of the U.S. Navy's Low Frequency Active (LFA) sonar on marine mammals, which also can be investigated by aerial surveys.

High-resolution satellite imagery can now be used to count the number of cars parked on city streets, so why not use such imagery to census marine mammals? The answer to this question is of course not that simple, for all the reasons already mentioned above: the targets have a low radiance, diminishing with depth; ocean clutter (waves and whitecaps) is present, and very large geographical areas must be covered. SRI, in collaboration with Fulcrum, Inc., Hampton University, and the University of California at Santa Cruz is engaged in a Phase I study for ONR on using satellite surveillance. The theory is that satellite imagery can now resolve images of animals to at least a few pixels. Satellite surveys can be initiated and completed faster than aerial survey campaigns, and satellites can cover remote regions that are difficult for aerial surveys. The ONR research has just started, so there is little to report at this time. However, the Maui image was a wonderful opportunity for an initial evaluation.

3.3.1 Search for marine mammals in the Maui image

Our search for marine mammals in the data exploited the best features of multispectral (4 m resolution) and panchromatic (1 m resolution) imagery. We assumed that marine mammals would stand out best in the blue band (assuming that marine mammals are usually below the surface). The entire water area was scanned for small objects with significant blue radiance levels above background. The candidate detections were then examined with panchromatic images, where shape and size are more discernable and yield more information for identifying the targets.

By this technique we found many small objects, most of which turned out to be pleasure boats. These were generally obvious from the shape, size, and presence of wakes. A few objects, however, appeared distinctly different and could be marine mammals. The left panel in Figure 8 shows one of these unidentified objects. This object is about 1 m $\times$ 4 m long and is one of a group of four similar objects with similar orientation. The group has the general appearance of a pod of animals swimming in formation. The middle panel shows two faint targets, 12 m and 5 m in length, from another area of the image. These objects may be a humpback female and calf. The third panel shows a typical pleasure craft, for comparison.

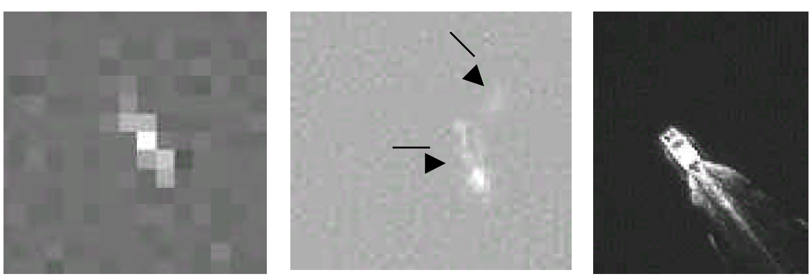


Figure 8: Unidentified objects in the Maui image (Figure 1). Left: unidentified object, 4 m in length. Center: unidentified pair, 12 m and 5 m in length. Right: catamaran and wake.

None of the unidentified objects we detected can definitely be identified as a marine mammal. On the other hand, what else could they be? Whitecaps have a similar appearance, but the two examples shown here and others are in a calm, wind-sheltered area several kilometers from the nearest area of rough seas and whitecaps. They might be smaller pleasure boats, but they lack the wakes that boats would be expected to have, and no similar-size objects appear in and around the harbors along the coast. That is all we can say at this point: more conclusive verification will require ground truth. Further improvements in detection and discrimination will be needed to make satellite imagery useful for marine mammal studies. The investigation is continuing.

4. SUMMARY

Higher resolution is making possible several new applications of imagery from satellites. Three applications have been demonstrated with Ikonos 1-m panchromatic and 4-m multispectral imagery. In bathymetry, for example, space-based imaging systems such as Ikonos are just reaching the point of meeting international standards for resolving navigational hazards. In coral health monitoring, higher resolution is needed to detect unhealthy coral. In marine mammal censuses, higher resolution is essential for classifying detections. In the near future, commercial satellites will provide 0.5 m panchromatic and 2 m multispectral resolution, which will make all three applications even more attractive.

The imagery we studied also showed that marine subjects are one or two orders of magnitude fainter than land objects and near the threshold of radiometric sensitivity. It would be worthwhile to explore ways to increase the radiometric sensitivity of future imaging systems.

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