Improving cloud detection in satellite images of coral reef environments using Space Shuttle photographs and High-Definition Television

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Introduction

Coral reefs worldwide are suffering from severe and rapid degradation (Bryant et al., 1998; Hoegh-Guldberg, 1999). Quick, consistent, large-scale assessment is required to assess and monitor their status (e.g., USDOC/NOAA/NESDIS et al., 1999). On-going systematic collection of high resolution digital satellite data will exhaustively complement the relatively small number of SPOT, Landsat 4-5, and IRS scenes acquired for coral reefs the last 20 years (e.g., Andr fou t et al. 1999 **different citation??). The workhorse for current image acquisition is the Landsat 7 ETM+ Long Term Acquisition Plan (Gasch et al. 2000).

Coral reefs are encountered in tropical areas and cloud contamination in satellite images is frequently a problem (Benner and Curry 1998), despite new automated techniques of cloud cover avoidance (Gasch and Campana 2000). Fusion of multidate acquisitions is a classical solution to solve the cloud problems. Though elegant, this solution is costly since multiple images must be purchased for one location; the cost may be prohibitive for institutions in developing countries. The are other difficulties associated with fusing multidate images as well. For example, water quality or surface state can significantly change through time in coral reef areas making the bathymetric processing of a mosaicked image strenuous. Therefore, another strategy must be selected to detect clouds and improve coral reefs mapping. Other supplemental data could be helpful and cost-effective for distinguishing clouds and generating the best possible reef maps in the shortest amount of time.

Photographs taken from the 1960s to the present from the Space Shuttle and other human-occupied spacecraft are one under-used source of alternative multitemporal data (Lulla et al. 1996). Nearly 400,000 photographs have been acquired during this period, an estimated 28,000 of these taken to date are of potential value for reef remote sensing (Robinson et al. 2000a). The photographic images can be digitized into three bands (red, green and blue) and processed for various applications (e.g., Benner and Curry 1998, Nedeltchev 1999, Glasser and Lulla 2000, Robinson et al. 2000c, Webb et al, in press).

From this unique database, several applications to studies of coral reefs have been made. Georeferenced astronaut photographs have been used as surrogates to simple shoreline base maps for pilot coral reef studies (Robinson et al. 2000a). The photographs have been used as a source of opportunistic observations of phytoplankton blooms in coral reef regions (Kuchler and Jupp, 1988). Recent tests of High Definition Television (HDTV) technology on the Space Shuttle extended the kinds of Earth observation images that can be acquired (Robinson et al. 2000b).

Astronaut photography is distributed at cost of reproduction; images for scientific research are digitized on request; and digital images are made available for free search and download via the Internet (http://eol.jsc.nasa.gov/sseop). However, there are a number of challenges to using the data for remote sensing including variability in look angle, sun elevation angle, altitude, variety of lenses used, and film processing (e.g., Webb et al. in press, Robinson et al. 2000b). Both digitized Space Shuttle photographs and HDTV suffer from the lack of accurate systematic geometric corrections from which georeferenced products could be derived automatically (Zheng et al. 1997). For this, existing maps must be used as a reference. This is a severe limitation for mapping and inventory applications in areas such as coral reefs where reliable, updated maps at the right scale seldom exist, and where independent geographic features to use as tie points can be limited. Therefore, for this reason, Landsat or SPOT products must be favored as a primary source of data for reef mapping.

Here, we illustrate the complementarity of satellite images and astronaut photography. We used astronaut photography and HDTV for cost-effective detection and removal of clouds from remote sensing classifications based on satellite data.

Study Area and Methods

In the atolls of French Polynesia specific geomorphological features (coral pinnacles) make the presence of small clouds a critical hindrance to accurate reef mapping. Even with clear sky, occurrence of small clouds is common and they look extremely similar to the top of coral pinnacles rising vertically from the bottom of atoll lagoons (figure1). The top of a pinnacle may reach the surface and provide a strong optical signal or the top may be submerged deeper, providing only an attenuated signal.

Although pinnacles represent only a fraction of the surface of an atoll, they cannot be neglected for several reasons. First, from a human-use point of view, they are navigation hazards and must appear on maps. Second, from a biological point of view, pinnacles are a center of biodiversity and species abundance, and their presence or absence may explain the differences between atolls in the population structure of benthic communities (Adjeroud et al. 2000). Third, from a geochemical point of view, the fluxes of carbon, carbonate and nutrients around pinnacles are not negligible in the budget of an atoll lagoon (Charpy et al. 1998).

Depending on the depth of the pinnacles, and the density and size of the cloud, it may be possible to readily discriminate pinnacles from clouds. However, there is no single rule and processing for automatic cloud filtering (e.g., classification, segmentation, ratios, ISH transformation, shadow matching, etc.) that may perform well on one image may fail on another (Loubersac et al. 1990). Multidate data becomes a necessity for distinguishing pinnacles from small clouds.

**Paragraph on SPOT data acquisiton and coverage to date.

The database of astronaut photography reveals extensive coverage of French Polynesian atolls with a number of high-quality images available; almost all the 84 atolls of this oceanic region have been photographed multiple times. We searched the database to identify images acquired in the past, and digitized them at 2400 ppi (10.6 μm / pixel). We also obtained digital still images extracted from HDTV video acquired during tests on Space Shuttle mission STS-93 (see details on the projects and on still image deinterlacing in Robinson et al. 2000b).

Processing of the Space Shuttle images for cloud-filtering began with geometric rectification of the Shuttle image using the satellite image as a reference (a tutorial for this process is provided by McRay et al. 2000). The spatial resolutions are similar (table 1) and control points along the rim of the atoll were easy to select as illustrated on several types of atoll rims in figure 2 (rim typology in Andr fou t et al. in press). This stage was made more effective by using images with high spatial resolution (low altitude and long lens) and low distortion due to oblique look angle, as the image in figure 3.

Next, the near infra-red bands in the satellite image (XS3 in SPOT XS data or TM4 in Landsat TM/ETM+ data) and the red channel of the digitized photograph or

HDTV were stretched and thresholded, to produce two binary images featuring the background/lagoon in white (255) and the clouds/pinnacles in black (0. The final stage was to inspect simultaneously the two binary images. A cloud-flag was set for any pixel that was black in both images. Since the geometric correction may not be perfect, a tolerance factor, N, can also be set to allow inspection in a $N \times N$ window instead of per pixel (N can be estimated using the RMS error of the geometric correction). Note that once the presence of pinnacles is confirmed, they may be used as new control points to refine the geometric rectification, by providing references not only along the rim of the atoll, but also in the lagoon.

Results and conclusions

Illustrations of the technique presented here will focus on two SPOT images acquired 5 November and 17 September 1989. These data were combined with a deinterlaced HDTV still image of Amanu atoll acquired 25 July 1999 (STS093-HDTV-5166), from 285 km, with a spatial resolution of 27.7 m / pixel. Figure 3 shows where coral pinnacles and clouds were detected on Amanu atoll.

Figure 4 illustrates cloud/pinnacle discrimination on Takaroa atoll using a Landsat 7 ETM+ image acquired **ZZ/ZZ/ZZ and a digitized photograph (STS093-717-?? **Serge add number of the image used 73, 74 or 75) acquired from the Space Shuttle on 25 July 1999. The complementarity of the two sources of information, satellite and Shuttle, for cloud detection is well demonstrated by these two examples.

This method has served well for distinction of clouds and pinnacles in a number of cases. One condition for its success is that both images be relatively cloud-free (as in figures 3 and 4). If clouds were very abundant, they could occur simultaneously on same locations on the two images and be interpreted as pinnacles. However, this event is unlikely using images with very low cloud cover. It is also possibile to use a third astronaut photograph for further refinement.

We found that identifying deep pinnacles could be a problem since their signatures in the astronaut photographs and satellites images could be weak. In this case, the processing can be applied also to the XS2 (SPOT-HRV), TM3 (Landsat TM/ETM+) and Green (astronaut photographs/HDTV) channels of the images to have a better signal.

Finally, for small clouds occurring on satellite images such as this in figure 4 and 5, the information may be interpolated from the neighborhood to construct a cloud-free image, although this is not recommended when clouds get bigger. Even if pinnacles are obviously absent, there may exist other deeper structures with smooth bathymetric variation (e.g., sand dunes) and it would be preferable to simply indicate the area as pinnacle-free .

In the cases presented here, adequate maps are not available, ground-truthing is problematic in such remote areas, and a quantitative accuracy assessment of this process is difficult. However, we feel extremely confident with such simple techniques. The key is to have access to multidate relatively cloud-free images. This study demonstrates that with simple methodology, astronaut photographs serve as complementary supplemental data that can improve mapping based on satellite data. The cost-effectiveness of this approach is an important factor for tropical developing countries eager to map their vital coral reef environments.

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Table 1. Best possible digital spatial resolution (pixel width in m) for the most common cameras used to acquire images of French Polynesia from the Space Shuttle. The spatial resolution given is for an image taken looking directly toward spacecraft nadir with values representing different lenses and spacecraft altitudes. (after Robinson et al. 2000b, unpublished data).

{**Note to Serge this table has been removed from the Webb et al. paper because a larger more complete version is going to be in the big resolution paper which is due to be submitted ASAP. I ve edited it so that it doesn t conflict with that publishing, but does provide supplemental information needed here.}

		Minimum ground distance represented by 1 pixel (m) as a function of altitude		
Camera	Lens focal length (mm)	Minimum (222 km)	Median (326 km)	Maximum (611 km)
Hassleblad [a]	100	23.5	34.5	64.7
	250	9.4	13.8	25.9
Sony HDW-700	15 ×, zoom to 8 mm	218	320	601
	15 ×, zoom to 120 mm	14.5	21.3	40.1

[a] Film camera with 55 × 55 mm original image size, digitized at 2400 ppi (10.6μm/pixel) to 5198 x 5198 pixels.

[b] Digital HDTV camera with 14.8 × 8.31 mm (1920 × 1035 pixel) original image size.

Figures

Figure 1: Top: the picture, taken from a commercial airplane, illustrates small low altitude clouds (C) and coral pinnacles (P1 in subsurface and P2 deeper) in the lagoon of Apataki atoll. Bottom: a typical coral pinnacle, photographed in Raroia atoll lagoon.

Figure 2: Comparisons of atoll rims view. Top: a section of the rim of Amanu atoll viewed by SPOT-HRV (XS3-1) and Space Shuttle HDTV (deinterlaced still image, STS093-HDTV-5166). Bottom: a section of the rim of Rangiroa atoll viewed by Landsat ETM+ Bands 4,3,1 and Space Shuttle photograph RGB (Hasselblad camera, STS080-750-76).

Figure 3: Pinnacles (1) and clouds (2) in HDTV (deinterlaced still STS093-HDTV-5166), and SPOT-HRV images of Amanu atoll. Images have been stretched to highlight the pinnacles and clouds. The letter A marks the very large pinnacle with an arrowhead shape. Note that on the mosaicked SPOT images, the shadows of clouds are visible on the western part of the image, providing an indirect control of the accuracy of the processing.

Figure 4: Pinnacles (1) and clouds (2) in digitized Shuttle photographs (Hasselblad STS093-717-?? **Serge add number of the image used 73, 74 or 75) and Landsat ETM+ Bands 4,3,2 images of Takaroa atoll.

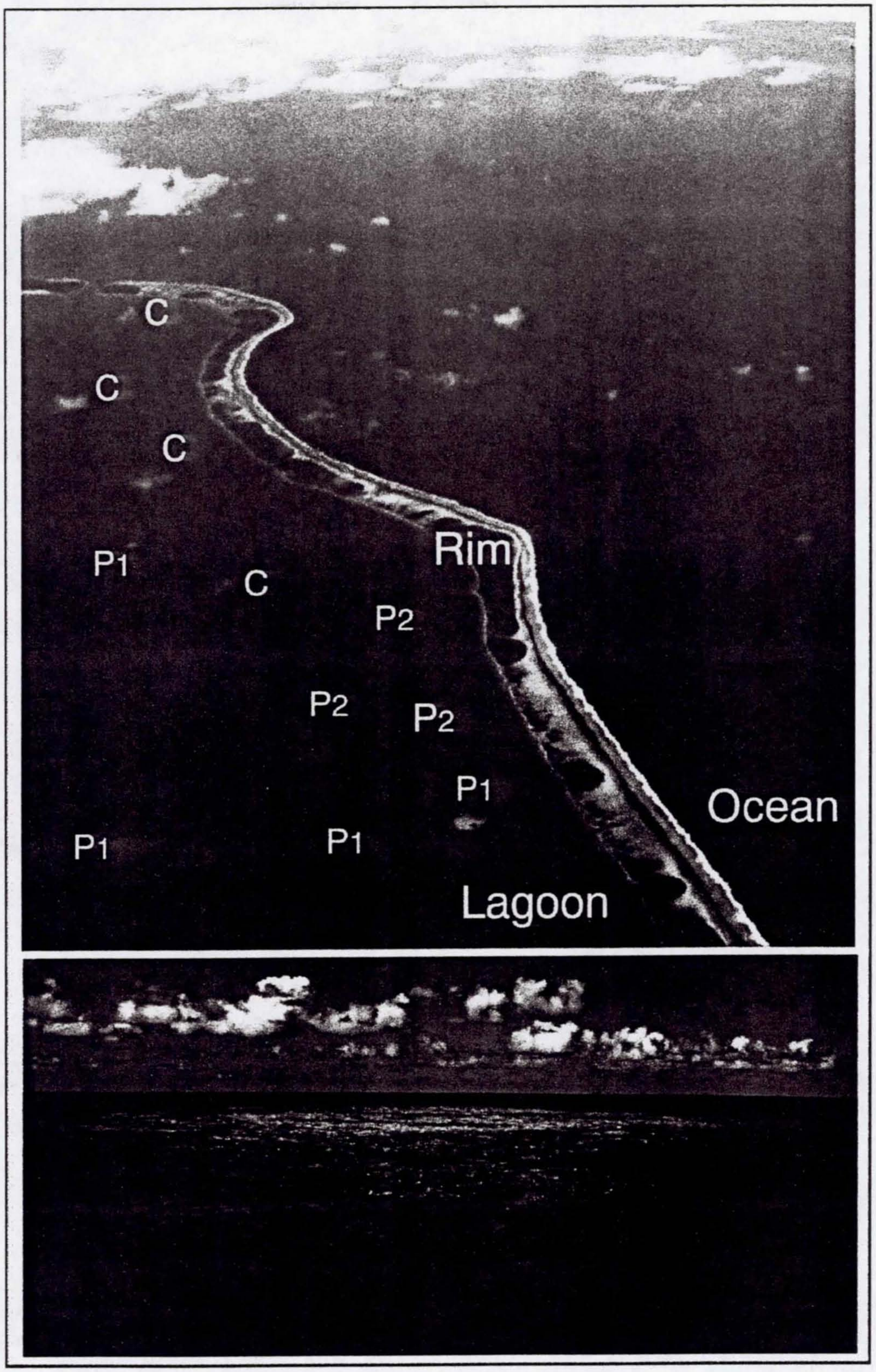

Figure 1

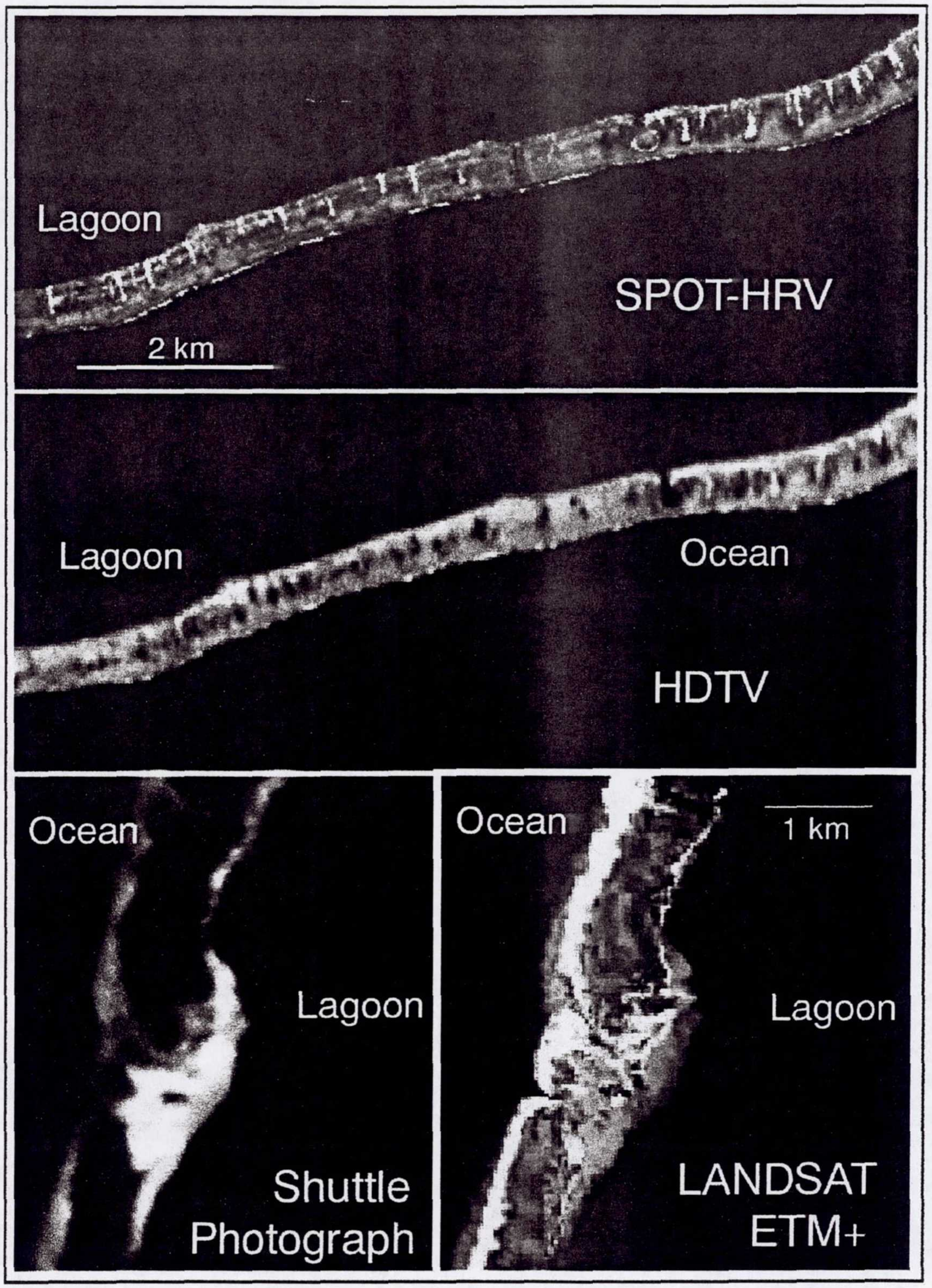
Lagoon
SPOT-HRV
2 km
Lagoon
Ocean
HDTV
Ocean
Lagoon
Shuttle
Photograph
Ocean
1 km
Lagoon
LANDSAT
ETM+

Figure 2

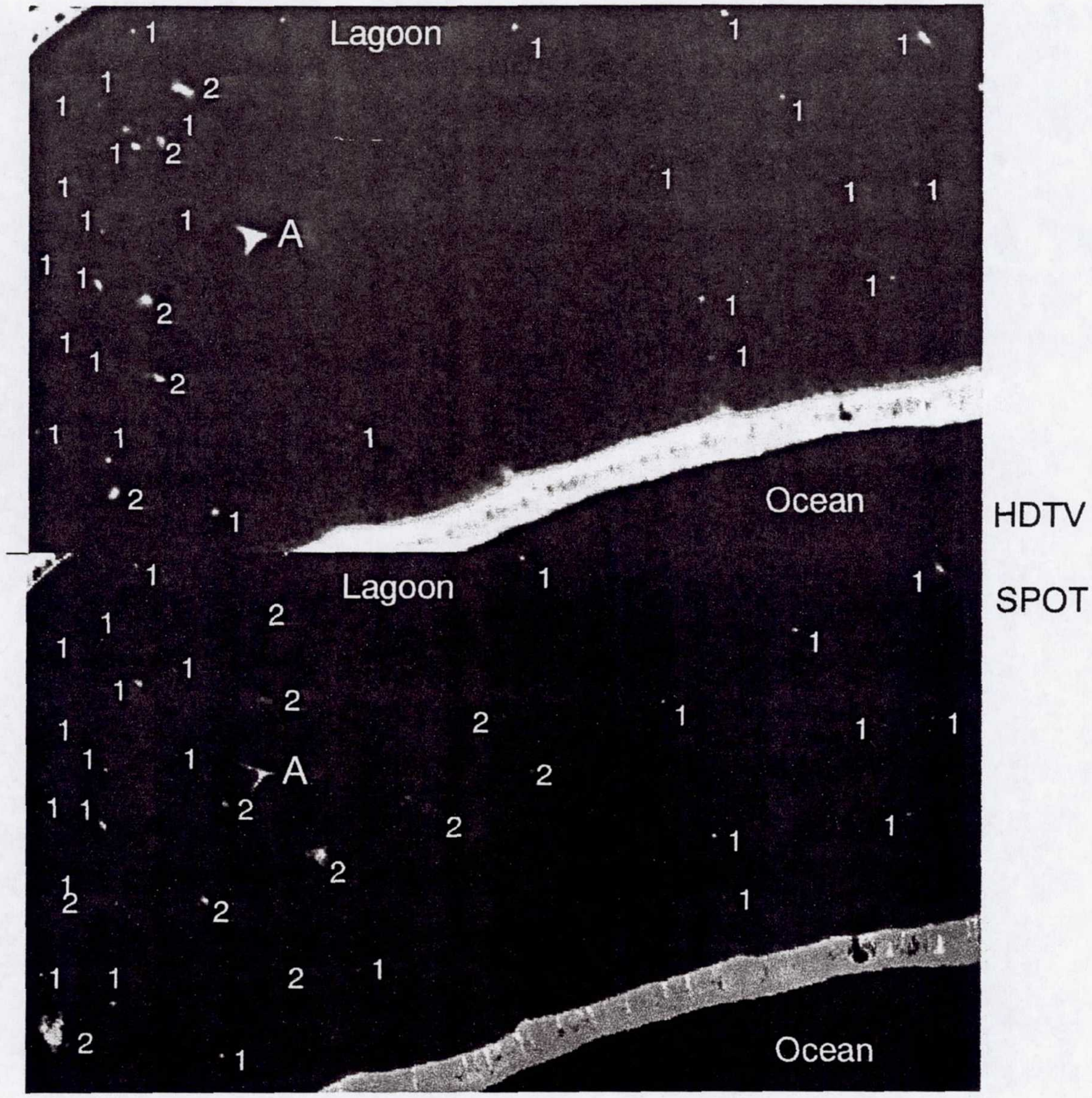

Figure 3

Figure 4