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Autonomous Underwater Vehicles resurvey Bonaire: a new tool for coral reef management

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Abstract. Bonaire's reefs are among the most pristine in the Caribbean. Creation of the Bonaire National Marine Park in 1979 set an important precedent for Marine Protected Areas. Van Duyl (1985) published an underwater atlas of the bottom type and benthic community to a depth of 10 m, but there have been few surveys of the deeper (>65 m) reef. In 2008, Bonaire's reefs were remapped using three Autonomous Underwater Vehicles (AUVs), Nitrox, and Trimix SCUBA. The AUVs carried high frequency side scan and multibeam sonar, cameras, and water column sensors (CTD, pH, dissolved oxygen). Divers ground-truthed AUV data on bottom-type and biota present. AUVs were used because they can survey deeper, cover more area over shorter time periods, and simultaneously collect multiple datasets compared to surveys by ship or SCUBA. A preliminary examination of expedition data shows higher diversity (H') and coral percent cover as one proceeds from south to north. The AUVs successfully mapped the bathymetry, and collected data on bottom type, fishes, coral cover and community type at locations along the entire leeward coastline. Our work shows the potential for AUVs working in conjunction with divers to provide a new tool for reef assessment at the landscape level.

Key words: Autonomous Underwater Vehicle (AUV), Bonaire, multibeam sonar, side scan sonar, reef atlas

Introduction

Bonaire (Fig. 1A), Netherlands Antilles, is arguably among the most pristine coral reef environment in the Caribbean (Steneck and McClanahan 2004). Percent coral cover is the highest and percent algal cover the lowest compared to other Caribbean reefs (Kramer 2003) and thus it represents a baseline *sensu* Jackson (2001), with herbivory implicated in its health (den Haan et al. 2008). Bonaire's economy depends mainly on tourism with almost 30,000 SCUBA divers entering its waters in 2006 (DEZA 2006). Bonaire's reefs are among the best protected in the Caribbean with no collections of any kind allowed, with the exception of a hook and line fishery. The Bonaire Marine Park Authority oversees the administration and protection of this unique underwater resource with help from STINAPA (Stichting Nationale Parken) Bonaire, a not-for-profit foundation. Although the shallow environment near Bonaire has been extensively visited by tourists and scientists, little to no survey work has been conducted on the deeper reef (60-100 m) on into deeper water (100-300 m) (R de Leon, STINAPA, pers comm.). A recent meeting of the International Coral Reef Initiative, an effort of the United Nations Environmental Program, identified mapping of the reefs of Bonaire as a top priority (ICRI 2005).

Bonaire's reefs were extensively mapped in the early 1980s by van Duyl (1985). The resulting atlas (Fig. 1B) was compiled from high-resolution aerial photography, ground-truthed by extensive SCUBA diving. It provides a snapshot of reef cover, substrate type, and geomorphology around the time that full protection for Bonaire's waters was enacted. Long-term monitoring of Bonaire and Curaçao's reefs has been ongoing at specific locations since the 1970s (Bak 1977). Bak et al. (2005) analyzed a 30-year time series of permanent quadrats and found that while there has been some degradation of reefs in Bonaire in shallow water, corals deeper on the reef have remained at similar population levels over several decades. However, a large scale synoptic mapping effort of the scale of van Duyl (1985) has not been attempted.

AUVs are free-swimming robots that act as taxicabs for sensors. They can cover many km per day in close proximity to the seabed, providing enhanced resolution for multibeam (bathymetric) and side scan imaging sonars. AUVs can simultaneously acquire video imagery and water quality data (Patterson and Sias 1998; Hayes et al. 2007). They can also use advanced pattern recognition techniques to classify water column targets in the nekton seen on side scan or multibeam sonar down to the species level (Patterson et al. 2007). Diver video survey strategies (e.g. Aronson et al. 1994) can thus be complemented by AUVs, as AUVs can dive deeper and longer than humans, and gather more data types concurrently.

The goals of our expedition were to (1) test the efficacy of using AUV technology to conduct

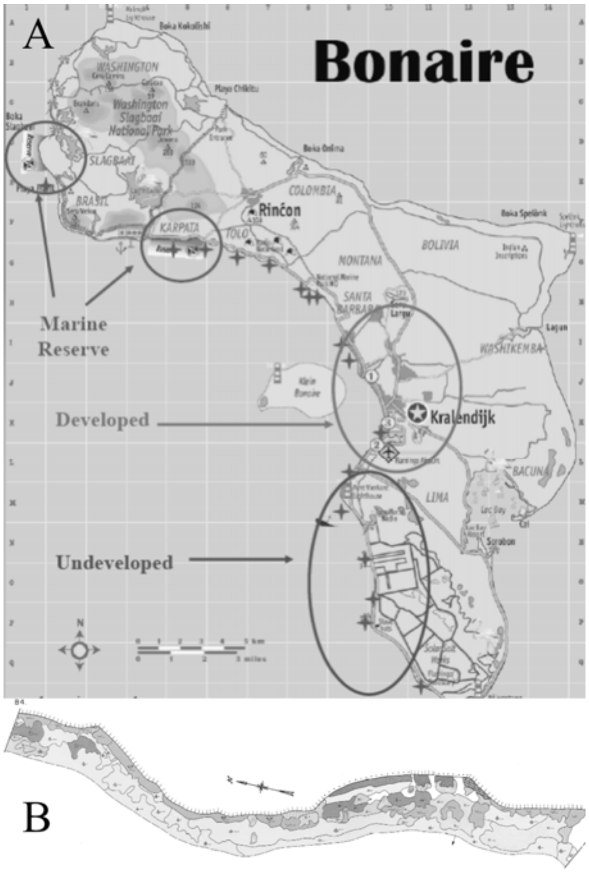

Figure 1: A. Areas targeted for diver and AUV surveys per recommendations of Bonaire government officials. Crosses represent locations where shore-perpendicular diver transects and AUV operations occurred. B. Example of a map created by van Duyl (1985). Eight community types from a set of 22 defined for Bonaire are represented in this view of the coast near Slagbaai.

bathymetric and side scan sonar surveys and video mapping in a coral reef setting, (2) concurrently characterize the physical and chemical oceanography, and (3) ground-truth the AUV data using diver surveys both shallow (Nitrox) and deep (Trimix). The long-term goal is to compare our maps with the previous survey of van Duyl (1985) to discern trends in the status of Bonaire's reefs.

Materials and Methods

Three AUVs (Fig. 2) were deployed from small boats or from shore at or near the locations shown (Fig. 1A). AUV payloads and characteristics are shown in Table 1. AUVs were operated in terrain-following and depth-holding mode. Each AUV was operated by a team of two to three people. Each of the Gavia AUVs logged about 120 dives ranging in length from 10 min to 2 hrs and depths from 2 to 220 m. The VIMS Fetch1 AUV completed 100 dives of 3 to 20 min duration over depths of 2 to 70 m.

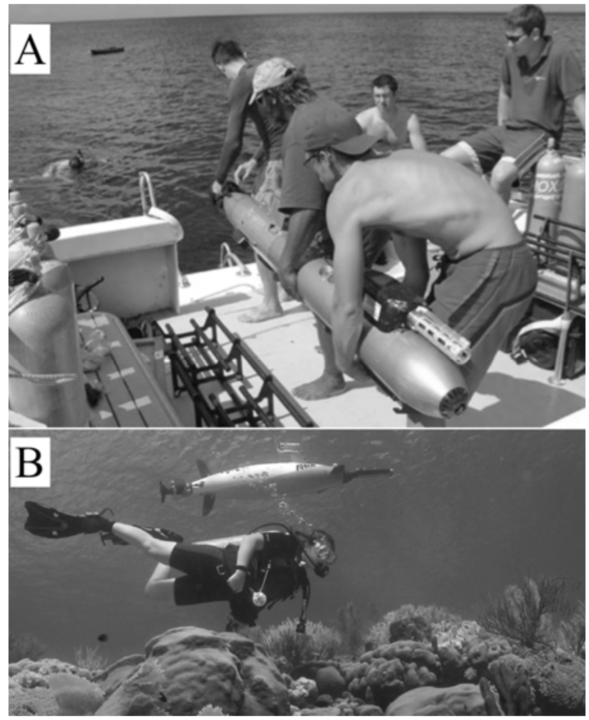

Figure 2: AUV technology used to map Bonaire's reefs. A. Two Gavia-class AUVs were deployed from boats and the shore on the leeward side of Bonaire. B. The VIMS Fetch1 AUV above a diver.

Diver video surveys were conducted using Nitrox SCUBA in a shore-perpendicular direction to a depth of 25 m, to allow ground-truthing of shallow-water AUV surveys. One diver towed a surface float containing a GPS (Garmin eTrex) set to logging mode. A second diver swam directly behind the first, and recorded video from an altitude of 2 m using a Canon Powershot SD950 IS digital camera in an underwater housing, on video setting with a resolution of 1024 x 768 pixels, shooting fifteen frames per second with no additional lighting. Trimix dive operations were conducted at a subset of the 17 areas noted in Fig. 1A, and gave us valuable phototransect data at depths as great as 81 m. Phototransects were also conducted at 40, 30, and 20 m. Video imagery was collected at several levels of resolution (Figs. 3 & 4). Video data were analyzed using Coral Point Count with Excel extensions (Kohler and Gill 2006), using 200 random points per video frame (Fig. 3C).

Results

The expedition successfully collected sonar, video, water quality, and still images over a substantial depth range. These data were used to generate percent cover, Shannon index (H'), and community composition, for comparison of deep vs. shallow reefs and sites along the coast. A full analysis comparing our data to van Duyl (1985) will be presented elsewhere. However, preliminary analysis of the diver

Table 1: AUV parameters. Abbreviations: VIMS = Virginia Institute of Marine Science; UBC = University of British Columbia; SLA = sealed lead acid; MSTL = Marine Sonic Technology Ltd.; CTD = Conductivity, Temperature, Depth; ADCP = Acoustic Doppler Current Profiler; DVL = Doppler Velocity Log; INS = Inertial Navigation System.

AUV / **Param.**	***VIMS Fetch1***	***UBC Gavia***	***Hafmynd Gavia***
Length	2.3 m	2.4 m	2.7 m
Weight	91 kg	55 kg	78 kg
Swim time	4 hrs	6 hrs	6 hrs
Batteries	SLA	Li-ion	Li-ion
Depth	100 m	500 m	250 m
Side scan sonar	MSTL 600 kHz	Imagenex 220/990 kHz	MSTL 900/1800 kHz
Multibeam sonar	None	None	GeoSwath Plus 500 kHz
Other payloads	CTD, pH, O_2, analog video	CTD, ADCP/ DVL, digital camera + strobe, fluorescence	Kearfott INS, digital camera + strobe, sound velocity

video data shows higher diversity (Shannon index H') and coral cover proceeding from south to north (Tukey multiple comparison, $p < 0.005$), and that deep reefs at all three sites are more diverse than their shallow reef counterparts. Percent cover is also higher with depth for these three sites (Table 2).

Landscape-level patterns can be discerned from photomosaics constructed from AUV datasets (Fig. 4). The fore-reef slope image shown was created from data gathered during a terrain-following dive by Fetch1. The resolution is sufficient for identification of coral genera, percent cover, and community type *sensu* van Duyl (1985). Individual camera frames were automatically adjusted for illumination and color balance. The mosaic was created in ptMac (Kerkus) using four to six control points per frame. Coral bleaching and coral mortality, overgrowth of corals by nuisance species like the tunicate *Trididemnum solidum*, and cyanobacterial tufts are detectable in AUV videos from Bonaire.

The deeper reef below 60 m, and the surrounding sand and rubble bottom in even deeper water, are virtually unexplored. The photo imagery gathered from these deeper dives will be the subject of a future publication. The expedition proved that AUVs gathering video provide a new tool for rapid reef assessment down into the twilight zone, where surface irradiance is less than 1% of that at the surface.

High frequency sonar data provided interesting insights into the geomorphology, reef structure, and even habitat utilization by fishes (Fig. 5). Relict reefs, spur and groove formation, double reefs, and bottom type changes can be discerned. Sonar swath widths are much larger than those obtained using video and thus allow the rapid survey and mapping of much larger areas. For example, a 400 m x 400 m area was

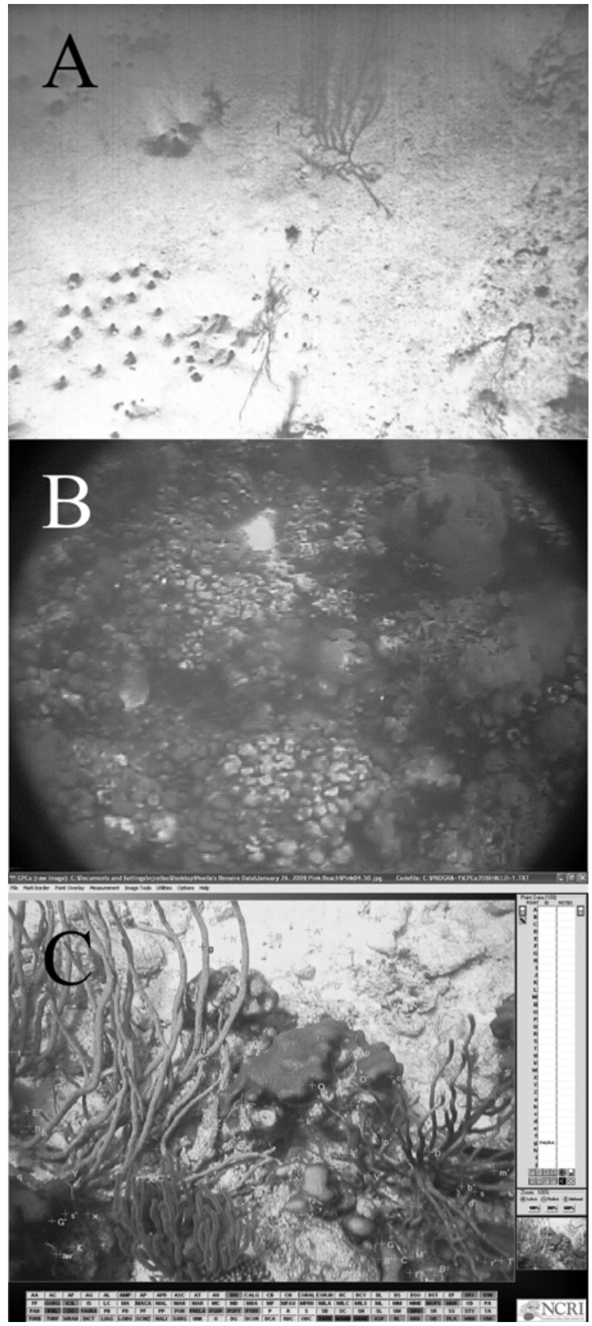

Figure 3: Examples of video imagery collected during the expedition. A. Twilight zone (65 - 200 m) of the reef was imaged by the Gavia AUV. This image is from 147 m. B. Shallow-water landscapes were imaged by the VIMS Fetch1, flying at an altitude of four m. C. Shore perpendicular and parallel transects were conducted by Nitrox and Trimix SCUBA, and were analyzed using Coral Point Count with Excel extensions, shown here in a screenshot (Kohler and Gill 2006).

completely surveyed at cm level resolution during a single dive by Gavia, using the GeoSwath Plus multibeam module. One of the key features of the GeoSwath Plus is that it collects simultaneous true digital side scan data. The side scan resolution of the 500 kHz system discerns structure down around 3-10 cm depending on survey speed, giving highly detailed images of the seafloor, corals and even fishes in the water column. Using backscatter data, an expert could discern bottom type over the survey area, which was then verified by diver ground-truthing.

Table 2: Mean coral cover and Shannon index (H') at 3 sites surveyed via SCUBA. Sites A, B, C are undeveloped, developed, and marine reserve, respectively. Percent cover (mean) was arc sine transformed for t-test of depth effect, and back-transformed for mean shown above. N is number of video frames.

Site, Latitude Longitude, Depth	**N**	**H'**	**Coral (%)**	**Sig. depth?**
A, 12° 3.8634' N 68° 16.9236' W, < 5 m	103	0.04	0.5	H', % p = .05
A, 12° 3.8634' N 68° 16.9236' W, > 5 m	70	0.82	13.4	
B, 12° 8.2884' N 68° 16.6050' W, < 5 m	30	0.42	5.5	H', % p = .05
B, 12° 8.2884' N 68° 16.6050' W, > 5 m	26	1.23	23.9	
C, 12° 12.6265' N 68° 19.2892' W, < 5 m	106	1.08	18.4	H', % p = .05
C, 12° 12.6265' N 68° 19.2892' W, > 5 m	28	1.48	47.0	

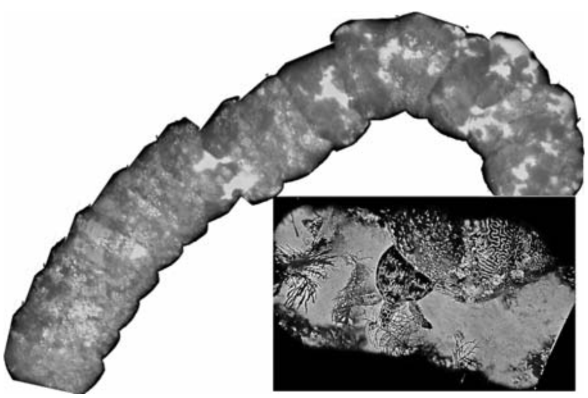

Figure 4: Seascape mosaics can be gathered in a cost-effective manner by AUV technology. VIMS Fetch1 AUV mosaic of fore-reef slope in marine reserve of Bonaire, deeper reef at lower left. Width of frame is 6 m. *Inset:* VIMS Fetch1 AUV image of turtle hiding under brain coral in FL Keys. Flying at lower altitudes allows identification to species level at the cost of reduced swath width (1.5 m), and strong possibility of collision with the bottom.

Discussion

AUV technology can reduce the cost per datum for seafloor mapping, by reducing or even eliminating the need for a ship, which can cost many thousands of dollars per day. AUV surveys also have the potential

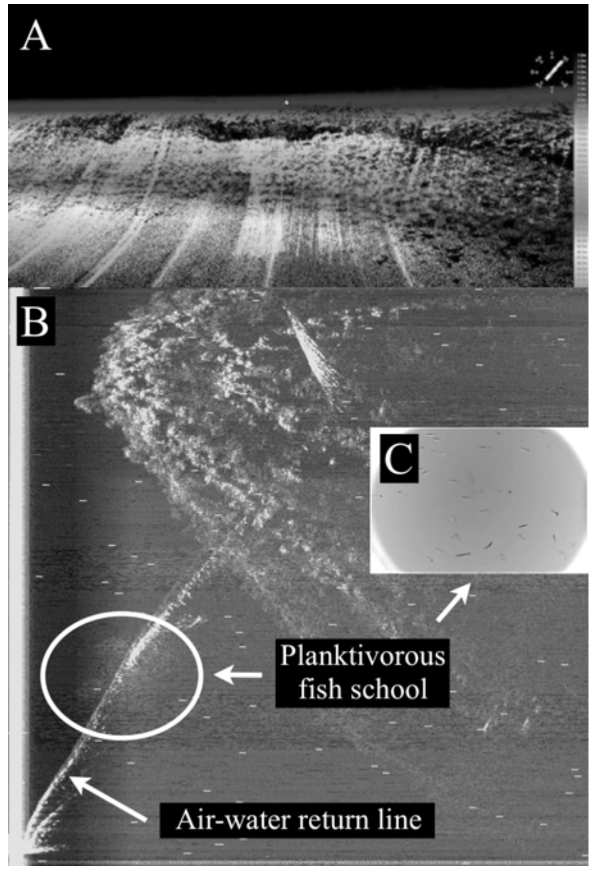

Figure 5: Sonar imagery of Bonaire´s reefs. A. GeoSwath Plus multibeam sonar view of reef, reef slope, and sand channel leading to Klein Bonaire, north of Kralendijk, perspective view facing east, collected by the Hafmynd Gavia AUV. B. MSTL side scan sonar image of fore reef, and water column biota, collected by VIMS Fetch1 AUV. Bright line is sonar return from the air-water interface, and shows AUV turning to begin depth holding. During the dive, Fetch1 passed through a school of planktivorous fishes (*Clepticus parrae*, *Chromis* spp.), verified by imagery from the onboard video camera (Inset C).

to allow rapid mapping of coral reefs at the landscape level complementing aerial or satellite remote sensing (cf. Andréfouët et al. 2003). When combined with diver ground-truthing, AUV surveys provide a synoptic view of coral reefs at scales from cm to 10s of km, and include depth ranges not easily attained by diving.

The high capital cost of AUV acquisition (US $80,000-600,000) depending on manufacturer and payloads) needs to be weighed relative to the 15 year working lifetime per vehicle currently used by insurers (AC Trembanis, Univ. Del., pers. comm.). AUV reliability for this emerging technology is also a concern with new risk assessment methods for operators under development (Griffiths and Trembanis 2007). Use of AUV mission control software that follows a strict state-machine architecture, used on interplanetary spacecraft where human intervention is not feasible, increases reliability, and was used on the Fetch1 AUV (Patterson 1998; Patterson and Sias 1999).

The seafloor survey rate of an AUV (32,400 m^2/hr) is about 12x that of the divers, based on swath width (6 m for AUV vs. 1.5 m for diver) and swimming speed (1.5 m/s for AUV vs. 0.5 m/s for diver). The AUVs also gathered two kinds of sonar data and water column data concurrently. Using identical personnel and boat costs, straight line amortizations for one $500,000 AUV (15 years) and $4,000 dive gear (4 years) for two people, the above coverage rate, and assuming the AUV gathers five sets of equally spaced data (two types sonar and water quality, video) vs. video only for the diver, the ratio of cost per datum acquired by AUV compared to a dive team is 0.56. Presently, diver surveys using photo-quadrats and handheld video remain the best choice for detailed survey work where identification to the species level is required. Soon AUVs will be able to terrain-follow at altitudes of 1-2 m required for such work (A Steingrimsson, Hafmynd ehf, pers. comm.).

AUV surveys could pinpoint nuisance species outbreaks so that divers could more efficiently remove them. Diver removal of a tunicate has recently been proposed for Bonaire's reefs (McGrath and Peachey 2008). AUVs could provide quick landscape level resurveys after storm disturbance or coral bleaching events. AUVs are emerging as the tool of choice for bathymetric mapping, assessing fish utilization on reefs, and conducting video surveys of the twilight zone. Their use promises to make the interval between valuable snapshots like that taken by van Duyl (1985) and our survey much shorter in the future. AUV surveys can thus help mitigate against shifting baselines by providing timely, cost-effective data acquisition.

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