Exploring Coral Reef Sustainability

with New Technologies

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The Island of Bonaire in the Southwest Caribbean, a Marine Protected Areas since 1979, has one of the most pristine coral reefs in the region. The last synoptic survey of the leeward coast was by the Dutch scientist Dr. Fleur van Duyl in the 1980s and parts of the deeper reef have never been mapped. In January 2008, the US National Oceanographic and Atmospheric Administration (NOAA) funded a unique expedition to Bonaire, deploying 3 compact Autonomous Underwater Vehicles (AUVs) carrying various oceanographic instrumentation packages and a swath bathymetry sonar.

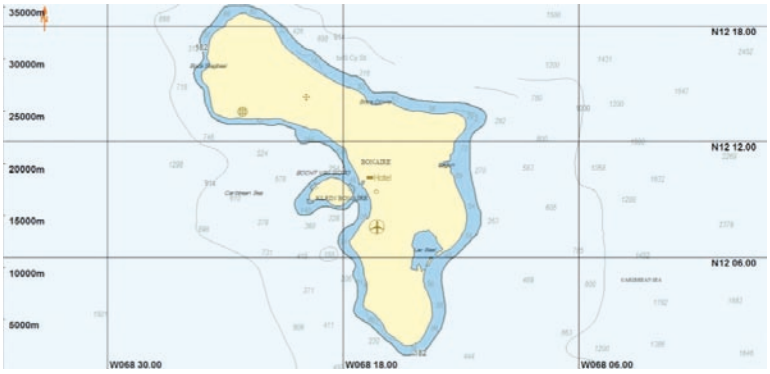

Figure 1: Bathymetric Site Map of Bonaire, Netherlands Antilles. Contours are in intervals of X m. Thumbtack markers indicate locations of AUV operation.

THE CRYSTAL CLEAR WATERS and schools of reef fish made an enchanting setting for the first NOAA Ocean Explorer Signature Exploration Expedition of 2008. An international team of scientists and engineers from academia, government, and industry gathered on Bonaire in the Netherlands Antilles, a 35 km long island about 90 km north of Venezuela (12°10'N 68°15'W) (Figure 1- Nautical Site Map of Bonaire). Their mission was to use new technology to look at the coral reefs and ocean environment around the island. Accompanying them were 16 undergraduate students from the University of Delaware, participating in a new science study abroad program to learn about and engage in cutting-edge oceanographic exploration.

At a recent meeting of the International Coral Reef Initiative (ICRI), delegates identified mapping the reefs of Bonaire as a top priority. Bonaire's reefs are unique in a regional context and in 2004 were proposed for United Nations World Heritage Status. In this context the NOAA expedition Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies was proposed by Mark Patterson of the Virginia Institute of Marine Science (VIMS), along with co-Principal Investigators Arthur Trembanis (University of Delaware), and Jim Leichter and Dale Stokes (Scripps Institution of Oceanography).

The goals of the expedition were to:

- Produce comprehensive maps of the sea bottom environment of Bonaire over a substantial depth range (i.e. shore to twilight zone);
- Describe physical and chemical conditions near healthy bottom ecosystems (e.g. currents, temperature, and dissolved oxygen levels); and
- Investigate biodiversity of "deep" (twilight zone and beyond) bottom ecosystems, with particular

Figure 2: A) Preparing to launch the UBC Gavia from the diver platform of the D/V Green Flash. Nukove Bonaire.
B) Fetch1 AUV in the background while VIMS graduate fellow Noelle Relles conducts a visual survey of the reef
Images courtesy of Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies.

Figure 3: A) Fetch1 AUV gliding over a dense shallow water field of Elkhorn coral (Acropora palmata)
B) Gavia AUV (Hafmynd ehf) with GeoSwath bathy sonar module preparing to set off on a reef survey mission.
Images courtesy of Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies.

attention to new types of communities and new invertebrate species.

The Bonaire reefs have largely escaped the recent coral reef crisis seen worldwide. A 2005 survey of the state of Bonaire's reefs by Steneck and McClanahan (2005) found that they were among the healthiest reefs in the Caribbean. This makes Bonaire's reefs uniquely important as baselines for comparison with other Caribbean coral reef ecosystems. Detailed mapping of Bonaire's shallow- and deep-water coral reefs is a top priority for protecting these ecosystems, as well as for defining a baseline for investigating and possibly restoring other coral reef systems. The expedition's findings will also help the Island Government of Bonaire continue to protect this unique ecosystem and manage their marine reserves.

Advance teams from the Virginia Institute of Marine Science and University of Delaware arrived in Bonaire at the end of December 2007 to meet with local government officials and start the process of mobilizing the infrastructure and equipment required for the project. During the first full week of January dive locations and AUV launch sites were scouted and the rest of the team arrived, including the 16 undergraduate students from the University of Delaware. Next, the three AUVs were assembled and tested and diving operations using Nitrox SCUBA were started (Figure 2).

The Autonomous Underwater Vehicles (AUVs) were the technological centerpiece of the Bonaire 2008 Expedition (Figure 3). Two kinds of small AUVs were used, one Fetch1 vehicle (Figure 3A) and two Gavia AUVs (Figure 3B) each with slightly different but complimentary payload sensor configurations. The Fetch1 AUV was developed by Mark Patterson and Jim Sias (described in Hydro International, October 1998, Turn-Key Autonomous Underwater Vehicles: A New Option for Seabed Exploration and Imaging) and carried sensors to measure dissolved oxygen, pH, CTD, underwater video camera, and high frequency side-scan sonar. Hafmynd ehf, a company based in Iceland, developed the Gavia AUV. As well as the standard range of sensors (e.g. pressure, GPS, altimeter, camera) each Gavia carried a special payload: the Gavia from the University of British Columbia carried a sensitive CTD while the other Gavia carried a GeoSwath wide swath bathymetric sonar from GeoAcoustics Ltd. The

Table 1

AUV	Fetch 1	Gavia-UBC	Gavia-Hafmynd
Length/weight	2 m / 70 kg	2.4 / 55 kg	2.7 m / 78 kg
Depth rating	300 m	500 m	250 m
Endurance/batteries	4 hrs / Lead-acid	6 hrs / Lithium-ion	6 hrs / Lithium-ion
Side-scan sonar	Marine Sonic 600 kHz	Imagenex 220/990 kHz	Marine Sonic 900/1800 kHz
Bathymetry Sonar	None	None	GeoSwath-Plus 500 kHz
Other payloads	pH; Oxygen; CTD; video	CTD; Up/down ADCP; DVL; camera/strobe; optical sensor; acoustic modem	INS; DVL; camera/strobe; sound velocity sensor

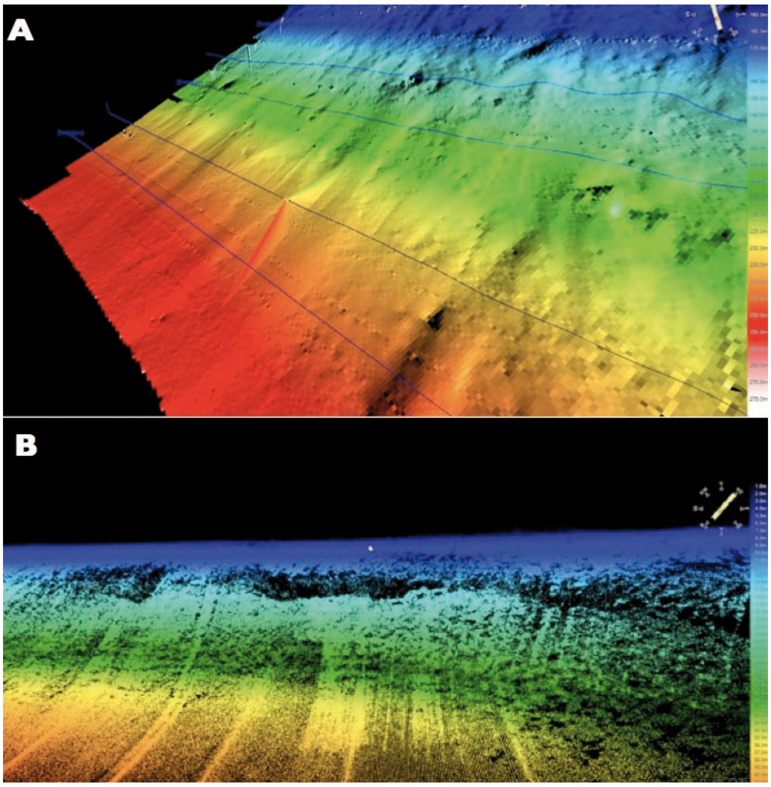

Figure 4: A) The deeper end of a Gavia survey pattern to the south of Klein Bonaire, showing the vehicle run-lines (in blue) and GeoSwath sonar bathymetry. The survey was run at 15 m fly height with 30 m & 60 m line spacing (see text). Depths shown in this image are from 150 m to 250 m and no vertical exageration has been applied. Note the sonar swath extending from above the vehicle due to the steep slope.

B) The bathymetric sonar onboard the Gavia AUV provides an incredibly dense map of the reef structure. Each colored dot represents a sonar depth measurement with the colors indicating depth (dark blues are shallow < 5 m and yellows are depths around 35 m). Black areas are shadow zones where the reef drops off steeply. You can see the overhanging coral on the crest of the reef and the steep sheer face, which is why this dive site is called "Cliffs". Each AUV mapping survey generates millions of bathymetric soundings.

Images courtesy of Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies.

Gavia is one of the smallest AUVs capable of carrying such a wide range of sensors.

A typical operational day saw the three AUVs in the water (Figure 4) early in the morning until lunch then a break for battery recharge and data download, and transit to a new survey site for an afternoon mission. The Fetch1 AUV (Figure 3B and Figure 4A) ran linear transects from shallow to deep water at many of Dr. van Duyl's sites surveyed in the 1980s but this time in place of aerial photos and spot SCUBA dives the team utilized high frequency side scan sonar (600 kHz), underwater video, and water quality sensors (i.e. Oxygen, CTD). The two Gavia AUVs (Figure 3A and Figure 4B) ran lawnmower patterns at select locations along the leeward side of Bonaire and Klein Bonaire, including sites of special interest to the territorial government of Bonaire. Multiple missions were completed from various beaches and jetties around the island, with both shoreline missions and deep dive missions down to beyond the 200 m depth contour. Operations included several beach-launch and boat-launch missions where all three AUVs were simultaneously collecting data in the same area.

Because AUVs can fly through the water column or in close proximity to the bottom (in terrain-following mode) they provided a superior method of carrying sensitive sensors right to the survey site compared to using a surface boat (Figure 4). Operating up to 220 m deep the Gavia AUV with the GeoSwath flew survey patterns at a constant 15 m altitude to collected high-resolution 500 kHz simultaneous side-scan and bathymetry data. Both the Fetch1 vehicle and the UBC Gavia carried side-scan sonar systems (see Table 1). The UBC Gavia also measured water currents near the bottom, chlorophyll, conductivity, and temperature while the Fetch1 vehicle measured dissolved oxygen, pH, conductivity, and temperature. The expedition team also deployed fixed bottom instruments to measure temperature fluctuations and water currents. The robot mapping effort was ground-truthed at selected spots by compressed air and trimix SCUBA divers using underwater video, and hand-held instruments. The VIMS team used a diver-deployed profiling instrument that used the same sensors carried by the Fetch1 AUV.

The GeoSwath payload unit was built by GeoAcoustics Ltd of Great Yarmouth (UK), and is a miniaturised version of the popular boat-mounted GeoSwath Plus interferometric sonar. The GeoSwath sonar uses sound to remotely sense the properties of the seafloor. It sends out a ping of sound more than 15 times per second. This sound scatters (echoes) from the sand, coral, and rocks that it hits and the GeoSwath uses these echoes to measure the range to the seafloor and its acoustic scattering properties. From one ping the GeoSwath can measure a line of up to 5000 points extending 40 meters or more to either side of the AUV (Figure 5). As the AUV swims over the reef at about 4 knots (2 m/s) the GeoSwath is continually mapping what lies beneath. After each survey was complete the AUV returned to the beach and the data was

Figure 5: Bathymetric charts overlaid on top of a satellite photo of the island. Collecting sonar data in the field is only the step of post-processing the data aimed at producing bathymetry charts. Each rectangular shaped patch represents a single survey mission lasting between 1 - 2 hours of robot swim time. Colors indicate depths from shallow (dark blue) to depths of 170-180 m below the surface (red). The thick and thin black lines represent isobath contours. Charts like this helped to identify target areas for deep trimix diving and helped the marine park managers inventory the shallow and deep reef areas of Bonaire.
Image courtesy of Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies.

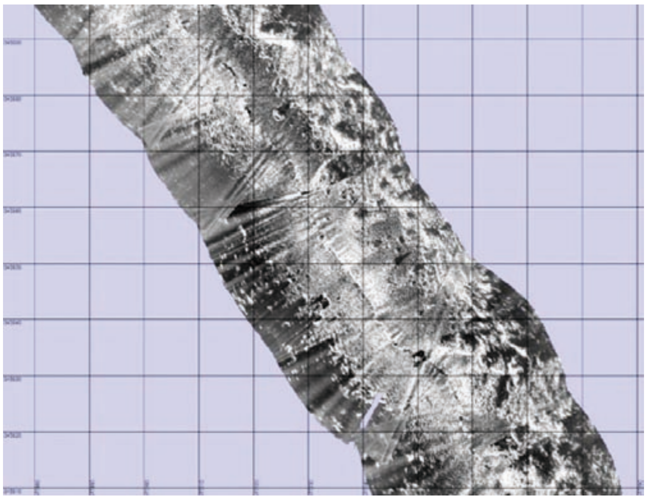

Figure 6: 500 kHz digital side-scan sonar mosaic created from survey data collected by the GeoSwath sonar on the Gavia AUV. Bright areas indicate high backscatter return energy associated with coral fragments or scattered rocks while dark patches represent shadow zones or patches of soft sand and/or mud that absorb more sound than rocks or corals. In this image the beach is towards the right and each grid cell is a 10 m x 10 m square. The total swath width is 40 m (in less than 5 m of water) and the line length from tip to tip is approximately 100 m. Image courtesy of Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies.

downloaded to the processing computer. In the case of the GeoSwath-enabled Gavia the data was used to make the depth (bathymetry) and scattering intensity (side-scan) maps of the survey area.

The Gavia carrying the GeoSwath sonar alone ran a total of 40 km of trackline survey over 8 days of missions. The AUV surveyed from the beach to 220 m deep, which is the maximum depth rating of this model of Gavia (a 1000 m version is also available). The maximum bottom depth seen was over 250 m.
Typically the missions were run at 15 m terrain following height with the GeoSwath sonar set to achieve 70 m swath width. The surveys were run using the 'side-scan search pattern' with parallel lines up to 1.2 km long spaced at 30 m & 60 m – this ensured that every object ensonified had a side scan shadow in at least one line (Figure 6). Typically the GeoSwath data was inspected as scrolling waterfalls and processed to a 0.5 m grid: the Kearfott T24 inertial navigation system (INS), when aided by the RDI Doppler velocity log (DVL), gave a position error with less than 0.5 m drift per hour, so the missions were kept fairly short (typically 2-3 hours) to ensure that high-resolution binning could be used.
One of the key features of the GeoSwath is that it collects simultaneous true digital side-scan data with the bathymetry. The side-scan resolution of the 500 kHz system is 0.5 degree along track and 3 cm across track, giving highly detailed images of the sea floor, corals and even the fish in the water column (Figure 7). The backscatter data was also effective in mapping and classifying the seafloor bottom type over the survey area, and the resulting classification was matched to diver ground-truthing.

Coral reefs have interesting geology as well as biology. Sediment movement and location are important to measure around coral reefs. Land-use practices onshore can affect sediment distribution and abundance on the reef, and many reef organisms can be harmed if there is too much sediment present. The government of Bonaire is especially interested in investigating these processes at several locations where there is some concern about the effects of land development. The sand-filled grooves between coral spur formations, and the sand plains in deeper water are also of interest. Understanding sediment movement can help predict whether an ancient shipwreck, or a modern-day mine, might be visible on the seafloor. The effects of currents and waves on the appearance of the seafloor in and around coral reefs is not well known and is one of the focus areas of this research project.

Finally, in cooperation with the US Geological Survey (USGS), the AUVs were used to map geological features and find evidence of how Bonaire fared during a suggested series of tsunamis that may have struck the island about 4,000 years ago. The USGS wants to understand how past tsunamis affected low-lying areas and islands so they can better assess current tsunami risks. The ability of the AUVs to gather high-resolution, precisely located bathymetry and backscatter data from the shore down to several hundred meters is a

Table 2
Extracts from the Survey log of one of the Gavia AUVs: 8 days of GeoSwath survey missions.

Date	Start (UTC)	End (UTC)	No. of lines	Line length	Max depth	Notes
12th Jan	13:00	14:00	4 lines	00 m	80 m	Jetty launch / beach recovery
	15:00	15:40	7 lines	500 m	90 m	Jetty launch at Dive & Adventure
	21:50	23:10	4 lines	250 m	30 m	Beach launch at science camp
13th Jan	14:00	16:00	8 lines	350 m	30 m	Pink Beach - beach launch
	23:20	00:10	4 lines	400 m	1 m	Very shallow survey 2m-10m near science camp
14th Jan	14:40	15:20	1 line	1200 m	160 m	From science camp across channel to Klein Bonaire
	23:50	01:12	4 lines	280 m	5 m	
15th Jan	18:30	19:00	4 lines	500 m	50 m	
	19:50	20:30	1 line	600 m	150 m	A single cross-line
16th Jan	16:10	17:00	8 lines	550 m	220 m	Klein Bonaire, beach to max depth
17th Jan	15:20	17:30	11 lines	350 m	220 m	New Cove, beach to max depth
18th Jan	15:00	15:50	6 lines	500 m	195 m	National park, beach to deep
	16:40	16:50	1 line	200 m	80 m	
19th Jan	15:10	15:50	8 lines	400 m	200 m	Klein Bonaire (boat launch)
	17:00	19:00	6 lines	1050 m	180 m	Longer survey at depth

valuable asset in the investigation of tsunami impacts.

Many gigabytes of environmental and seabed mapping data were collected for analysis and publication in the scientific journals over the coming months. After the success of this mission future AUV expeditions to Bonaire are already being planned. This will include surveys of the windward side of the Island, where it is too dangerous to take small dive boats. This expedition was a great example of the unique abilities of small AUVs such as the Fetch and Gavia to carry high-resolution sonar payloads like the GeoSwath into areas where other survey technologies cannot reach. The Coastal Sediment Hydrodynamics and Engineering Lab at the University of Delaware has now taken delivery of a Gavia AUV with a GeoSwath sonar and is working together with researchers at the Center for Coastal and Ocean Mapping at the University of New Hampshire to develop new techniques for bathymetric sonar data interpretation. VIMS researchers are exploring neural network algorithms to classify water column targets like fishes and jellies from side-scan sonar to enhance the value of these unique datasets (US Patent 7221621). Seafloor mapping and ecosystem analysis can now occur simultaneously when AUVs are utilized.

Bonaire 2008: The Explorers

Mark Patterson of the Virginia Institute of Marine Science (VIMS) led the Bonaire 2008 Expedition, along with co-Principal Investigators Arthur Trembanis of the University of Delaware, with Jim Leichter and Dale Stokes from Scripps Institution of Oceanography. Scientists also assisted the mission from NOAA's Undersea Research Center (Otto Rutten), the University of British Columbia (Bernard Laval and Alex Forrest), Northeastern University (Sal Genovese), and the National Oceanography Centre Southampton (Ken Collins, Jenny Mallinson). The Island Government of Bonaire, the Bonaire Marine Park Authority (special thanks go to Ramon de Leon, the Marine Park Manager) and STINAPA, a management advisory body, provided local support to the project. Technology specialists from Iceland (Richard Yeo and Eggert J. Magnússon from Hafmynd Ehf) and England (Tom Hiller and James Baxter from GeoAcoustics Ltd) helped run the survey equipment. On hand to help with the AUV deployment, data collection and, most importantly, to learn from the unique collection of expertise present were 16 students from the 2008 Study Abroad Program of the University of Delaware.

The full list of the Bonaire 2008 'explorers' can be found on the expedition website (1)

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Tom Hiller received his BSc and PhD degrees in Physics from Bristol University, UK. Dr Hiller has worked in application engineering and product management for several UK sonar manufacturers as well as for his own company, Anka Ltd. At GeoAcoustics Ltd he has been involved in the development of a range of new technologies, including the GeoSwath interferometric multibeam, digital side-scan sonars, synthetic aperture sonar and 3D sub-bottom imaging systems.
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1. http://oceanexplorer.noaa.gov/explorations/08bonaire/