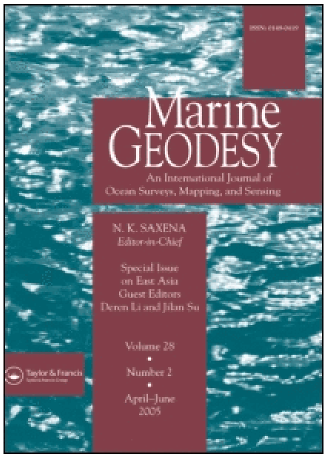

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Low-Cost Bathymetric Mapping for Tropical Marine Conservation—A Focus on Reef Fish Spawning Aggregation Sites

WILLIAM D. HEYMAN,[1] JEAN-LOUIS B. ECOCHARD,[2] AND FRANK B. BIASI[3]

[1]Department of Geography, Texas A&M University, College Station, USA
[2]Technology and Information Systems, The Nature Conservancy, Arlington, Virginia, USA
[3]National Geographic Maps, Washington, DC, USA

Marine conservation scientists and managers working in the tropics need bathymetric data, yet there exists no relatively simple and inexpensive system to derive them. We designed a system to produce bathymetric maps in 0–1,000 m water depth in less time, with less cost, and with less effort than any other system available. The system uses Landsat TM imagery to guide the collection and visualization of depth soundings obtained with a commercially available fish finder/GPS on a small boat. ArcGIS is used for interpolation and data display. The system was used to map two reef fish spawning aggregation sites in Belize and may be useful for shelf-edge mapping in other tropical locations.

Keywords bathymetric mapping, marine conservation, spawning aggregation

Introduction

Tropical marine environments harbor high biodiversity and are therefore attractive and extremely valuable for tourism and fishing. These delicate environments are under increasing threat from unregulated fishing, marine pollution, and climate change, and their conservation is critically important (NRC 1999). Marine Reserves and zoning plans can aid marine conservation. To be most useful, reserve plans should incorporate an understanding of the life cycles and habitat requirements of target species, particularly during vulnerable life history stages (Koenig et al. 2000). To guide the placement and zoning of reserves in order to maximize their effectiveness, detailed maps are needed that illustrate critical habitats for key species (Franklin et al. 2003; NRC 2000).

Through the efforts of the National Oceanic Atmospheric Administration (NOAA) and other organizations, detailed bathymetric data are available for most navigable U.S. waters and for important ports and navigable waterways around the world. For deep waters, the ETOPO5 data set can be used as a general guide for global bathymetry. This data set has horizontal accuracy of, at best, 5 minutes of latitude and longitude and vertical accuracy of 1 m at best, and 250 m for large areas; and data for areas shallower than

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Address correspondence to William D. Heyman, Department of Geography, Texas A&M University, College Station, TX 77843-3147. E-mail: wheyman@tamu.edu

200 m are sparse (NOAA 1988). Smith and Sandwell (1977) improved on ETOPO5, using satellite altimeter data to map seafloor gravity anomalies and additional shipboard soundings to create an updated global seafloor map with 1–12 km horizontal resolution. Using these innovative techniques, they revealed many previously undiscovered seamounts and dramatically improved our understanding of global seafloor bathymetry (Smith and Sandwell 2004).

Priority areas for state or federally funded hydrographic surveys include harbors, harbor channels, and navigation ways and are generally less than 100 m in depth (NOAA 2006). Most areas of interest for marine conservation, however, are generally more remote, less developed, and less important for navigation, and have been a lower priority for previously funded bathymetric mapping. This is particularly true for tropical areas, where existing nautical charts for areas outside of intensive navigation ways and harbors are based on only limited, often lead-line soundings, and are thus insufficiently detailed for use in habitat delineation and conservation planning. Therefore, there remains a great need for bathymetric data for most remote areas, particularly those that provide critical habitat for commercially or biologically important marine species.

Coral reef ecosystems range from the sea surface to waters deeper than 500 m. In many cases, the underlying geology of reef systems provides the broad-scale basis for critical fish habitat, e.g., spawning areas (Scanlon et al. 2003). The location and shape of the shelf edge can be critical for feeding and reproduction of many important tropical marine species. Johannes (1978) noted that many reef fish spawning aggregations occur at reef promontories that jut into deep water. Additional reef promontories that harbor multispecies spawning aggregations were found in Belize at the 25–35 m shelf edge (Heyman et al. 2005; Heyman and Requena 2002). The job of scientists and managers would be much easier if they had accurate bathymetry. Biotic habitat could be identified and depicted on such maps as well as shelf edges and major features in 20–500 m deep water.

Remote sensing techniques have advanced rapidly in recent years and have proven valuable for tropical benthic habitat mapping in shallow water (Andréfouët et al. 2003; Green et al. 1996). Landsat TM, for example, has been used to create benthic habitat maps for shallow (<10 m) coral reef environments with 30 m horizontal resolution (Mumby et al. 1998). More recent satellite-based sensors, such as those used in IKONOS imagery, provide multi-spectral horizontal resolution of 4 m or less and have been used to map bathymetry and habitat type in coral reef environments to 25 m depth (Andréfouët et al. 2003; Stumpf et al. 2003). Airborne multispectral and hyperspectral sensors can provide 1 m horizontal resolution and thus increase the resolution and the number of distinct habitat types that can be reliably mapped (e.g., Mumby et al. 1998).

For bathymetric mapping in shallow waters, airborne bathymetric LIDAR may offer comparable accuracy but a reduction in the cost of acquisition for shallow water bathymetric data as compared to hydrographic surveys. LIDAR data are collected by aircraft rather than by ship, and data to 70 m depth can be collected (MacDonald 2005). Most studies consider 50 m the maximum and typically do not report data below 25–30 m. In an ideal world, bathymetric LIDAR would be used to map bathymetry out to its maximum depth of about 20–50 m (depending on water clarity), and these data would overlap hydrographic data collected with multibeam and side-scan sonar (Tripsanas et al. 2004) that would extend from about 20 m to the abyssal plane (Intelmann 2006). However, these surveys are prohibitively expensive, equipment intensive, and time consuming to create. They are thus beyond the scope of marine conservationists in tropical developing countries (Kvernevik et al. 2002).

Suitably accurate and affordable techniques for bathymetric mapping in coral reef areas in developing nations would be valuable for fishery managers and marine conservationists.

This study describes a low-cost system that uses remotely sensed data (Landsat TM) to guide the collection and visualization of field-collected, gridded, single-beam bathymetric data, and the creation of updatable geo-referenced, 3-D bathymetric maps of tropical reef environments in waters from 0–1,000 m. We evaluated the system's utility in two case studies mapping reef fish spawning aggregations in Belize.

Materials and Methods

Equipment Selection

Bathymetric data were collected with a LCX-15 MT fish finder from Lowrance Electronics Inc. (hereafter referred to as Lowrance; http://www.lowrance.com/Marine/) mounted on a 7.5 m Mexican-style skiff with twin outboard engines. The fish finder had an integrated 12-channel GPS and was equipped with an external GPS antenna (Figure 1). The sounder head was equipped with either a standard dual frequency (50 and 200 kHz) transducer or a more powerful Airmar TM 260 transducer (hereafter called Airmar) mounted at the stern of the boat. The unit recorded latitude, longitude, and depth points to a removable medium (a Multi-Media flash card, or MMC), which was downloaded to a computer (Figure 1). The unit produced pulses of sound with a particular frequency whose beam lobes were approximated by a cone. An echo was produced by the first depth encountered by the sound beam. The return time (calibrated for temperature and salinity) was used to calculate the depth. Soundings were often less than the actual depth, particularly in steeply sloping areas (Figure 2A).

The LCX-15 MT sounder produces a 1 kW RMS (root mean square) output (the DC voltage equal to 0.707 times the peak of an AC voltage) and comes with a standard

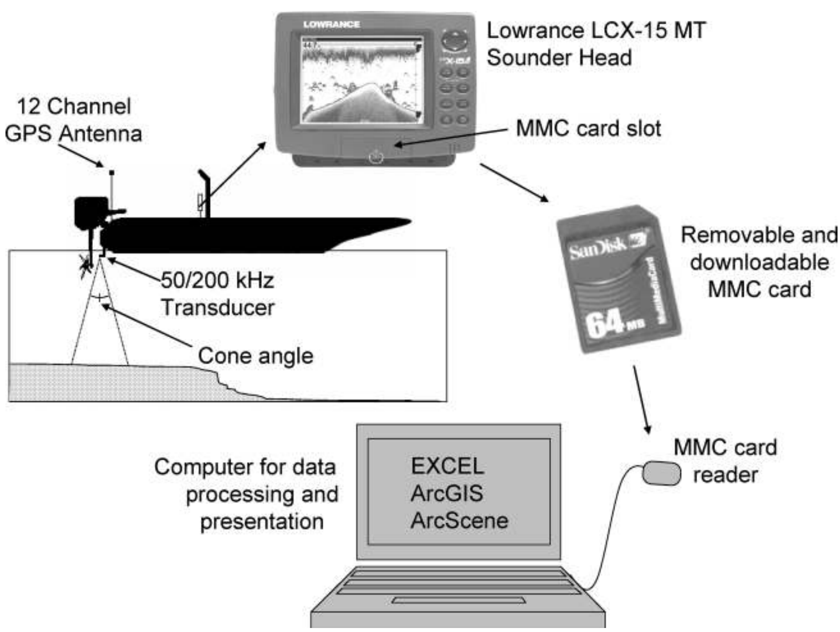

Figure 1. Low-cost bathymetric mapping system components and their relationships. Note that placing the GPS antenna directly above the transducer reduces one source of error.

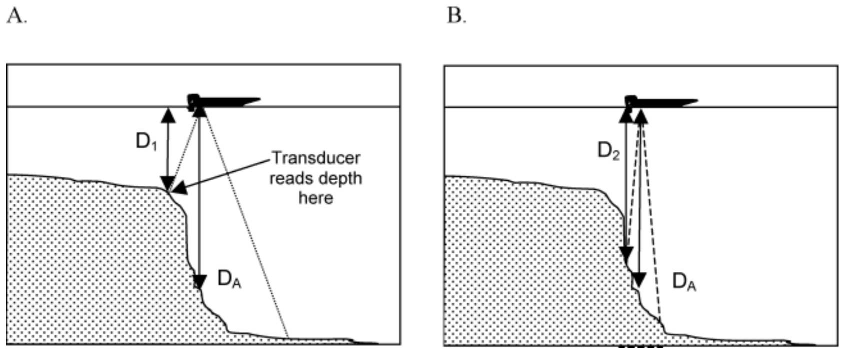

Figure 2. Sources and magnitudes of error introduced in bathymetric surveys where D_A is the actual depth, and D_1 and D_2 are the depths recorded using a Lowrance transducer and an Airmar transducer, both at 200 kHz. **A** The standard Lowrance transducer produces a 12° cone angle. The shallowest point encountered within any sonar cone delivers the depth reading D_1 which is generally less than the actual depth, D_A. **B** A 200 kHz Airmar transducer, however, uses a smaller (6°) cone angle, which encounters a reduced area of seabed and therefore delivers more accurate readings, D_2 in deeper waters, particularly on steep slopes.

dual frequency transducer that emanates from a single piezoelectric element. The 200 kHz transducer (with a 12° cone angle) can penetrate down to a maximum of 150 m and the 50 kHz (with a 37° cone angle) to a maximum depth of about 600 m. For deeper waters with steeper slopes, we used an Airmar transducer. It has an array of seven dedicated 50 kHz elements and a single, large diameter 200 kHz element. The Airmar produces a beam with a 19° cone angle at 50 kHz and a 6° cone angle at 200 kHz and is rated for a maximum depth of about 1,000 m.

Planning and Adapting Field Surveys

Sketches of the survey were made using geo-referenced, remotely sensed images of the target survey areas prior to field work. Surveys were designed to capture a high density of points on areas of rapidly changing slope and low density elsewhere. Survey grids were constructed and uploaded into the sounder using MapCreate™ software from Lowrance. Field data were logged (latitude, longitude, and depth) into the Lowrance while running transect lines at 3–20 knots along the predesigned grid. Additional survey data were gathered for areas that required increased detail.

Data Processing and Map Creation

Data gathered using the Lowrance depth sounder were recorded on a removable MMC and downloaded to a computer. Data were transformed to .csv file format, parsed, and loaded into a spreadsheet. Irrelevant data (e.g., altitude) columns were removed and all individual transect data were combined into a single file. These data were then filtered to remove invalid points using sort functions within Excel Points that did not have both a depth and position were removed. Points that repeated previously reported depths more than twice consecutively were removed. Points with depths shallower than the minimum or deeper than the maximum survey depth were removed.

Data were collected using proprietary Lowrance Mercator coordinates. These data were transformed to standard Universal Transverse Mercator (UTM) coordinates to be analyzed by ArcGIS. Lowrance Mercator Eastings (LME) were translated to UTM X coordinates using the following coordinate system conversions that were kindly provided by Luke Morris at Lowrance (lmorris@lowrance.com):

$$\text{UTM X} = 180/\text{Pi} * \text{LME}/6356752.3142$$

Lowrance Mercator Northings (LMN) were translated to UTM Y coordinates using the formula:

$$\text{UTM Y} = 180/\text{Pi} * (2 * \text{ATAN}(\text{EXP}(\text{LMN}/6356752.3142)) - \text{Pi}/2)$$

Depth in feet were translated to meters using the formula:

$$\text{D} = -\text{Depth} * 0.3048$$

Given that the study area has a tidal range of less than 30 cm (Kjerfve 1981), depth data were not corrected to mean low, low water; this was considered an insignificant error compared to that introduced by the cone footprint (Figure 2). The data (X, Y, and Z for each point) were saved into a DBF file, which was uploaded directly into ArcGIS. Inverse Distance Weighted (IDW) interpolation was used to produce a digital elevation model. The data were displayed in three dimensions (with a 2× vertical exaggeration) using ArcScene. Final data filtering was conducted visually after creating the 3-D scene. For example, when spires appeared to jut vertically from deep waters to the surface, they were considered artifacts and removed.

Results

Equipment Accuracy and Sources of Error

We evaluated the depth range and error introduced by both the GPS and two transducers. The horizontal position accuracy is dependent on the accuracy of the GPS, the cone angle, and a percentage of the depth. Horizontal accuracy of GPS is 10 m without differential correction, and ±3 m with WAAS (Wide Area Augmentation System, generally available only in North America). Depth readings are recorded as the shallowest point within the roughly circular footprint approximated by the sounder cone intersecting the bottom. The radius of the footprint is a function of cone angle and depth. At 50 m depth, for example, the standard transducer has a footprint radius of 17 m or 5 m at 50 and 200 kHz, respectively, while the Airmar has a radius of 8 or 3 m at 50 and 200 kHz, respectively (Table 1). The Airmar is twice as precise in the horizontal plane as the standard transducer at both frequencies. Vertical (depth) accuracy depends on the speed of sound in water, which ranges between 1,400 and 1,570 m sec^{-1} at the surface and varies by 4 m sec^{-1} per degree Celsius. Standard 50–200 kHz frequency vertical soundings are accurate to within ±3 cm. More error is introduced as a result of wide cone angle soundings on steep slopes (Figure 2). These errors can be dramatically reduced by selecting the appropriate transducer and frequency for a given depth following Table 1. For depths less than 500 m, the Airmar at

Table 1

Sounder footprint radius is shown for two transducers at two frequencies. Accuracy decreases with increasing depth and with increasing cone angle. For each combination of equipment and frequency there is a depth range that can be used with confidence; below which readings are not usable (NA). Values in italics are usable but not always obtainable depending on water clarity and salinity

	Airmar M260		Lowrance	
Transducer frequency (kHz)	50	200	50	200
Cone angle	19	6	35	12
Water depth (m)	Radius of coverage at depth (m)			
10	2	1	3	1
20	3	1	7	2
30	5	2	10	3
40	7	2	13	4
50	8	3	17	5
100	17	5	33	*11*
150	25	8	50	*16*
200	33	10	67	*21*
250	42	13	84	*26*
300	50	16	100	*32*
350	59	18	117	*37*
400	67	21	134	*42*
450	75	24	151	*47*
500	84	26	167	*53*
550	92	*29*	184	*N/A*
600	100	*31*	201	*N/A*
650	109	*34*	217	*N/A*
700	117	*37*	234	*N/A*
750	126	*39*	251	*N/A*
800	134	*42*	268	*N/A*
850	142	*45*	284	*N/A*
900	151	*47*	301	*N/A*
950	159	*50*	*318*	*N/A*
1,000	167	*52*	*335*	*N/A*
1,050	176	*N/A*	*351*	*N/A*
1,100	184	*N/A*	*368*	*N/A*
1,150	192	*N/A*	*385*	*N/A*
1,200	201	*N/A*	*402*	*N/A*
1,250	209	*N/A*	*418*	*N/A*
1,300	218	*N/A*	*435*	*N/A*
1,350	226	*N/A*	*452*	*N/A*
1,400	234	*N/A*	*468*	*N/A*
1,450	243	*N/A*	*485*	*N/A*
1,500	251	*N/A*	*502*	*N/A*
1,550	259	*N/A*	*N/A*	*N/A*
1,600	*268*	*N/A*	*N/A*	*N/A*
1,650	*276*	*N/A*	*N/A*	*N/A*
1,700	*284*	*N/A*	*N/A*	*N/A*
1,750	*293*	*N/A*	*N/A*	*N/A*
1,800	*301*	*N/A*	*N/A*	*N/A*
1,850	*310*	*N/A*	*N/A*	*N/A*
1,900	*318*	*N/A*	*N/A*	*N/A*
1,950	*326*	*N/A*	*N/A*	*N/A*
2,000	*335*	*N/A*	*N/A*	*N/A*

200 kHz is preferred, while the 50 kHz Airmar is favored between 500 and 1000 m. All of the horizontal and vertical errors in the survey data are rendered relatively insignificant, however, after interpolation from a 50 m grid to create the bathymetric surface.

During field surveys of steep slopes, we found that the Lowrance unit did not always detect the bottom. This was particularly common when traveling from shallow into deep water. When this occurred, depth readings first stayed constant and blinking, and then gradually rose to the surface. Plotted data appeared like thin spires arising vertically from the deep edges of the reef. We found two solutions for this problem:

1. manually adjusting the depth range, and
2. recording data on transects from deep to shallow water, and/or on angles to the fall of the shelf break.

Another possible source of uncorrected error is the heave, pitch, and roll of the vessel while collecting the data in choppy seas. Of these, only heave is relevant to single beam surveys such as this (NOAA 2006). We minimized the effect of heave by choosing calm days for depth surveys.

Case Study 1: Reef Fish Spawning Aggregation Site—Half Moon Caye, Belize

During September 2003, the system was used to map the reef fish spawning aggregation site at Half Moon Caye, Belize (see also Ecochard et al. 2003b). The aggregation site is located at the southeastern end of Lighthouse Reef Atoll (17° 12′N, 87° 31′W) (Figure 3). Local managers were aware that the aggregation occurred at the tip of a reef promontory that drops into deep water, as visible on hydrographic charts showing rough bathymetry.

Landsat TM imagery of the area illustrated the location of the reef in relation to the aggregation site and the shelf edge and allowed for a detailed survey design, prior to field work (Figure 4A). We selected the Airmar transducer because of the steep drop-off and deep (>1,000 m) waters. Two initial depth transects were recorded, downloaded, and integrated with Landsat TM data to produce an initial map of the area (Figure 4A). A standard survey grid was developed and plotted using 50 m intervals. A modified grid was developed to obtain maximum resolution where needed and to save time sampling areas of low relief (Figure 4B). A 59% reduction in sampling effort was achieved without a corresponding loss in accuracy. Field surveys were conducted over a three-day period. Data were downloaded, filtered, and incorporated into the model at the end of each survey day. The survey path was modified adaptively each day to account for new findings and focus on the most needed data. For example, survey data collected on day one revealed depths exceeding 650 m on a steeply inclined wall on the fore reef. The survey area was expanded to capture (rather than truncate) the shape of the promontory feature.

Field surveys produced 34,955 data points with GPS coordinates, which were reduced by filtering and cleaning to 27,965 points that were used to create the final graphics (Figure 5A). The bathymetric surface model data was georeferenced and could therefore be integrated with semi-transparent Landsat TM satellite imagery data to provide a more realistic view (Figure 5A) of the bathymetry in relation to surface features of the atoll.

The total cost of the process was US $2,810, broken down as follows:

- Initial Grid Preparation: $140 (4 hours of a GIS analyst @$35/hr)
- Field Survey: Staff: $450 (2 surveyors @ $75/day for 3 days). Equipment: $2,080 (boat $200/day for 3 days + 100 gallons @$3.80 + Lowrance LCX-15 MT @$1,100)
- Data Processing: $140 (4 hours of a GIS analyst @$35/hr)

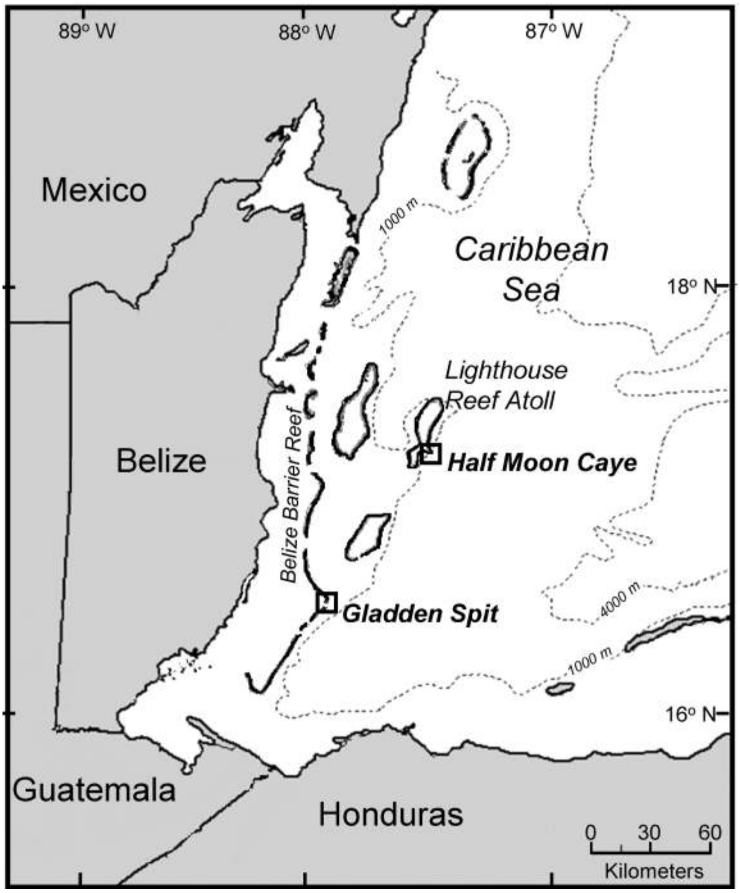

Figure 3. The location of the case study sites, **1** Half Moon Caye on Lighthouse Reef Atoll and **2** Gladden Spit on the Belize Barrier Reef, both close to the 1,000 m isobath off the coast of Belize.

These costs are conservative and include the entire cost of the sounder and four hours of a GIS analyst (in practice the process takes less than an hour). The Airmar transducer, required for depth beyond 500 m and up to 1,000 m, was kindly donated by Airmar but retails for less than $800. The process took less than four days from start to finish. This was the first field test of the system, and the team had to learn the equipment in the process.

Case Study 2: Reef Fish Spawning Aggregation Site—Gladden Spit, Belize

Gladden Spit reef promontory (16° 30′ N 88°W) is known to harbor reef fish spawning aggregations for several commercially important reef fish species (Heyman et al. 2005). We developed a 3-D map showing the relationship between the shelf edge and the location of spawning for each species to help guide conservation and monitoring efforts. Using Landsat TM imagery to create a base map, we developed a 6.54 km^2 grid, centered on the tip of the promontory and including the steep shelf edge to the north and south. A total

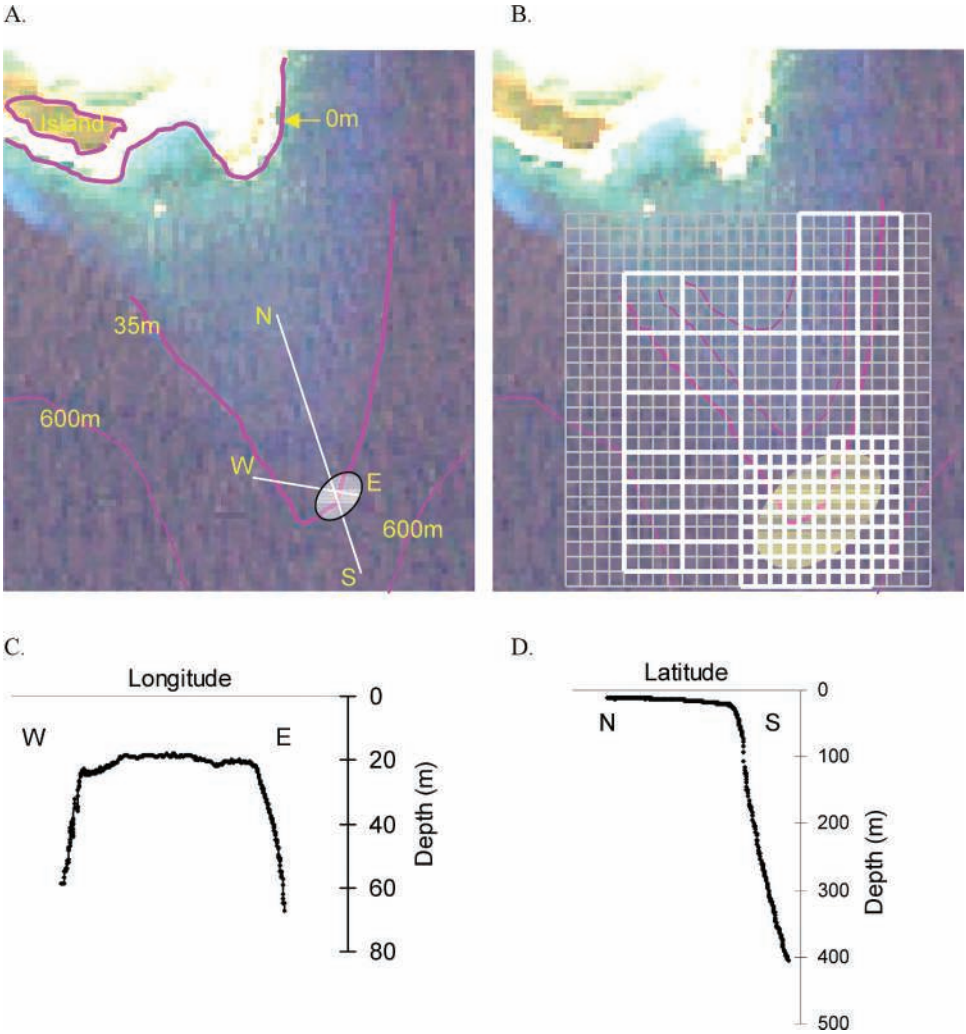

Figure 4. Bathymetric survey planning maps for Half Moon Caye, Belize. **A**. Initial map showing the location of a known spawning aggregation site, oval, in relation to the Caye and to initial observations of depth based on two transects and Landsat TM imagery. **B**. The full grid (grey) of the area of interest (50 m squares) and the adaptive grid (white) which concentrates sampling effort on the areas of interest and high slope, and reduces sampling density in areas of low relief. **C.** Depth transect between points W and E, and D) Depth transect between points N and S.

of 17,253 points were collected on September 19, 2003, with the Lowrance GPS/sounder, concentrating on the shelf dropoff. These data were downloaded, filtered, and visually cleaned leaving a total of 10,961 points that were used for the graphic interpolation and presentation (Figure 5B). The locations of reef fish spawning aggregations were collected with a handheld Garmin GPS 12 from a boat, while divers located the aggregations below (Heyman et al. 2005). The spawning locations were integrated with the bathymetric map and Landsat TM image using ArcGIS.

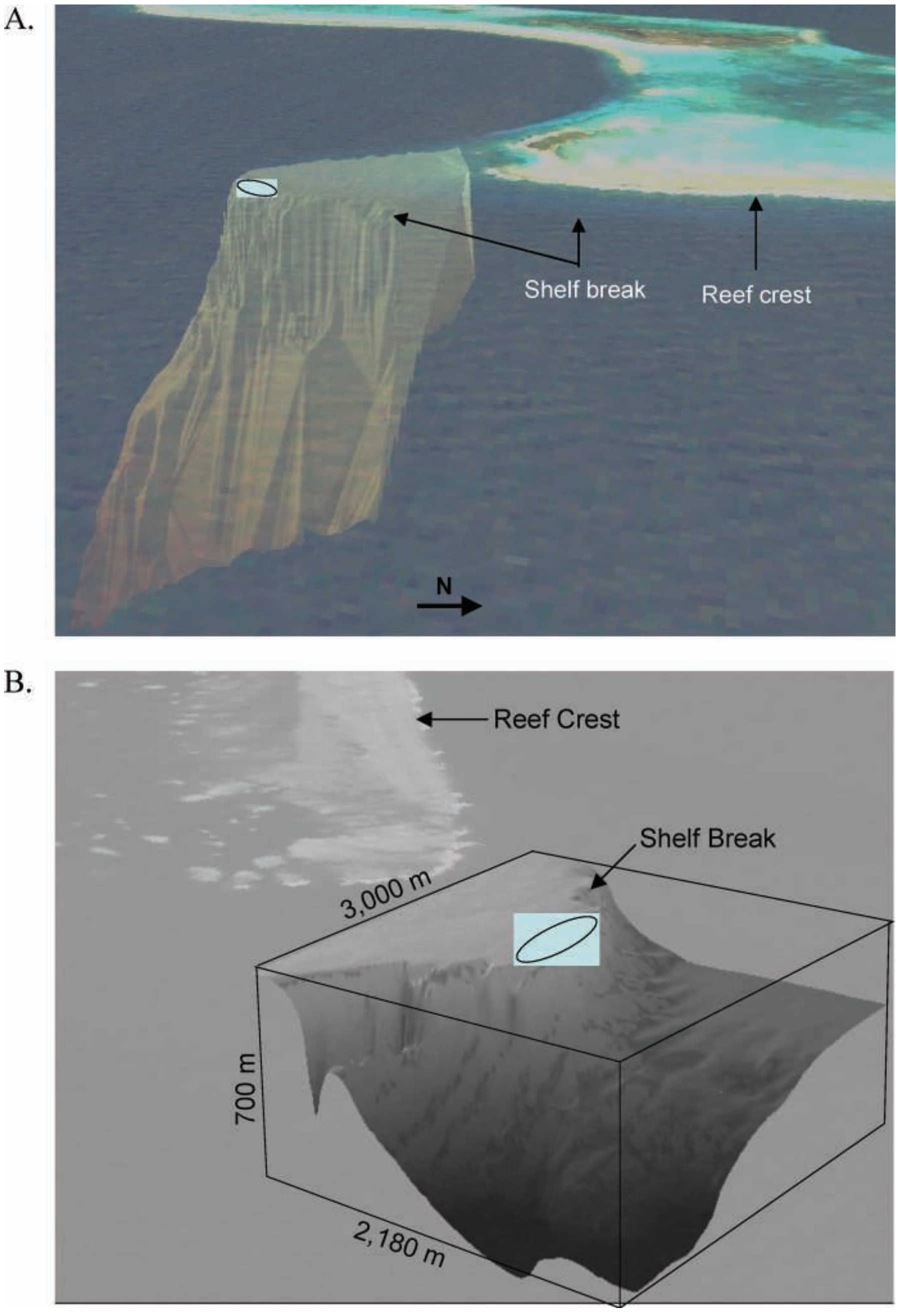

Figure 5. **A** Half Moon Caye multi-species spawning aggregation site is mapped using ArcScene along with a semi-transparent Landsat TM satellite image. The spawning site (oval) occurs close to the tip of the promontory along the 35 m deep shelf edge, adjacent to a very steep drop of over 1,000 m. **B** Gladden Spit, Belize, illustrating the location of the multi-species spawning aggregation site (oval) in relation to the reef crest and shelf break (30 m depth), as created using a distance weighted interpolation and overlay of Landsat TM imagery. Both sites are shown with 2× vertical exaggeration.

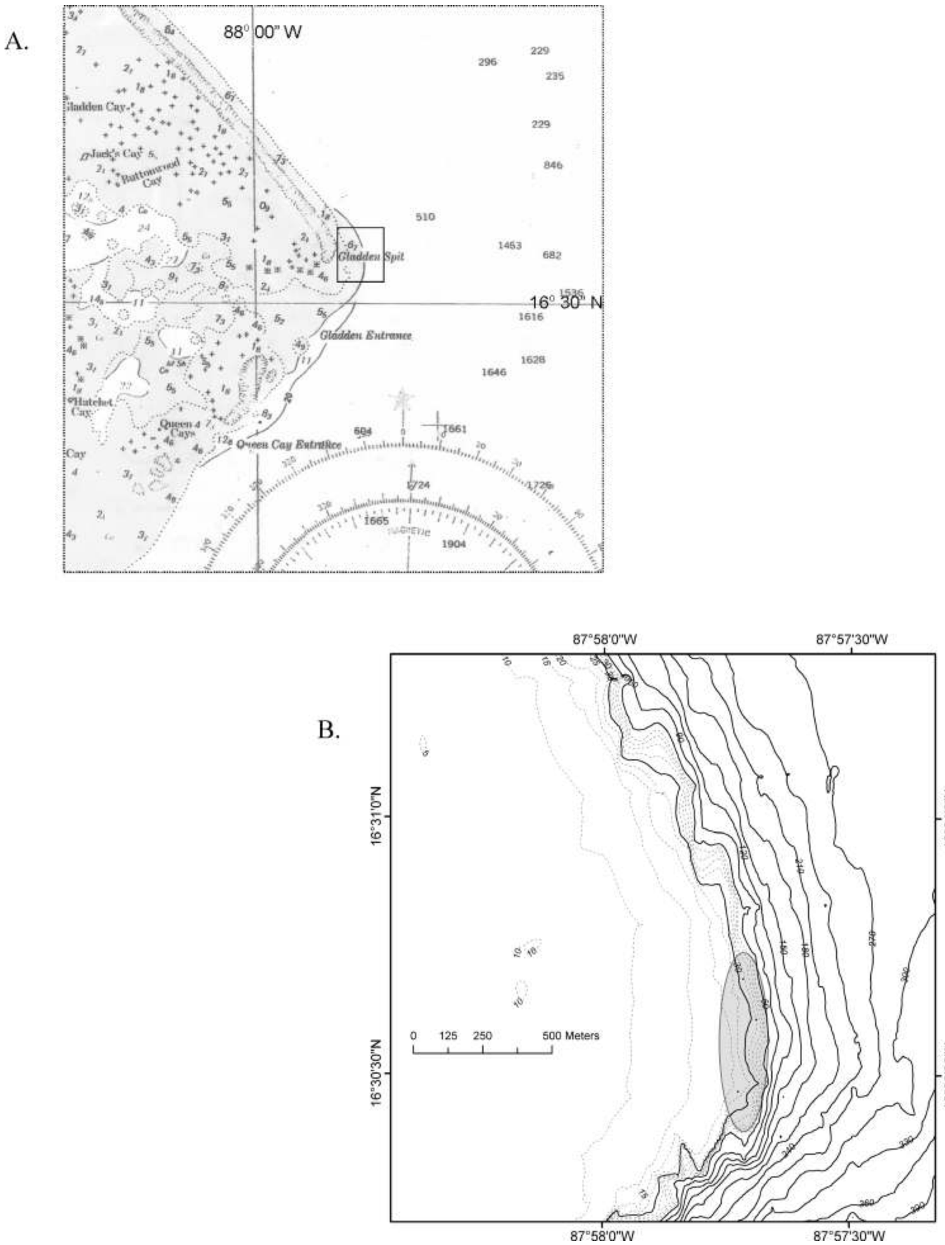

Figure 6. A The best existing hydrographic chart for the Gladden Spit area (British Admiralty Chart # 1797, 1996) showing the location of the low-cost survey area in a rectangle, and soundings in meters. **B** Bathymetric map view of Gladden Spit showing 5 m contour lines (dotted) and 30 m contour lines (solid). The general location of the spawning area is marked with a grey oval.

Discussion

The system presented herein provides marine scientists and conservationists with low-cost, spatially explicit bathymetric maps. The cost of the Half Moon Caye bathymetric mapping case study presented here was $2,810 (including equipment purchase) and was completed in four days. A commercial estimate for the same job was $30,000 and required a minimum of two weeks of data collection and processing.

We have described the sources of error in the low-cost bathymetric technique, including vessel heave, GPS accuracy, cone angle, sea water properties, and interpolation. We recognize that this tool is not designed to develop navigational quality charts with stringent standards (NOAA 2006). Instead, this low-cost technique is offered as a tool that can provide spatially explicit models of reef bathymetry and far higher resolution than existing nautical charts for some areas. Figure 6, for example, compares the best available bathymetric data for Gladden Spit, Belize, along with the increased detail provided with this technique.

Kvernevik et al. (2002) and Colin et al. (2003) present similar systems for mapping areas of up to 100 m depth. These systems use a laptop within a protective box on the boat and manual wiring for the integration of sensors. Free Windmill software is used for data integration and Surfer is used to present the data. Though the principles are the same, our system uses downloadable media from a waterproof integrated sounder and GPS, and industry-standard ArcGIS software. This platform is robust for operations in rough waters with a small boat, easier to set up, and flexible enough to incorporate geo-referenced data from other sources and/or adaptively increase resolution. It isolates the easy skills required for the operation of the fish finder from the more complex skills needed for the use of the computer and GIS system. This allows data collection to be performed by most fishermen, even if they do not have computer skills.

Most important, the system allows for relatively accurate bathymetric mapping to depths up to 1,000 m. The standard dual frequency transducer is a reasonable option for depths less than 100 m and with low ($<10^\circ$) slope. The more powerful Airmar transducer is more appropriate for steeper slopes and deeper waters (Table 1).

The techniques described here can aid conservation planning exercises and, as demonstrated in this case, illustrate the location of reef fish spawning aggregations in relation to reef geomorphology. The technique can be used to predict the locations of spawning aggregation sites and to verify their position with field observation and bathymetric mapping. More generally, this technique can help model the shape and location of reef edges and general bathymetry in uncharted areas when more expensive options are not available.

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