Damage Assessment of Vessel Grounding Injuries on Coral Reef Habitats Using Underwater Landscape Mosaics

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ABSTRACT

Vessel groundings are a source of disturbance to coral reefs worldwide. Documenting the extent of damage caused by groundings is a crucial first step in the reef restoration process. Underwater landscape mosaics, created by merging thousands of downward-looking images, combine quantitative and qualitative aspects of damage assessment and provide a georeferenced, high-resolution, spatially accurate, permanent record of an injury. We present a landscape mosaic from a scar along the south coast of Puerto Rico created by a 289 m (920 ft) long liquefied natural gas tanker. This mosaic is contrasted with an earlier one acquired in the Florida Keys where a 15 m (49 ft) long vessel impacted 150 m^2 of reef. In both cases mosaics enabled observations at a new spatial scale, had spatial accuracy comparable to GPS, and provided context for traditional, smaller scale observations. The technical challenges addressed during the creation of these two mosaics were, first, combining individual mosaics to cover larger areas, second, removing wave-focused light artifacts, and third, color correcting multiple image sets.

KEY WORDS: Reef restoration, Evening Star, Suez Matthew

Evaluación de Daños del Buque a Tierra Lesiones en los Hábitats de Arrecifes de Coral don Mosaicos Submarino Paisaje

Encallamientos de buques son una fuente de perturbación para los arrecifes de coral en todo el mundo. Documentar la magnitud del daño causado por encallamientos es un primer paso crucial en el proceso de restauración de los arrecifes. Mosaicos del paisaje submarino, creado por la fusión de miles de imágenes a la baja de aspectos, se combinan los aspectos cuantitativos y cualitativos de evaluación de daños y proporcionar un georeferenciados, de alta resolución espacial precisa, y registro permanente de una lesión. Se presenta un mosaico de paisajes de una cicatriz a lo largo de la costa sur de Puerto Rico creado por unos 289 m (920 pies) de largo de cisterna de gas natural licuado. Este mosaico se contrasta con una anterior adquirida en los Cayos de la Florida, donde un buque de 15 m (49 pies) de largo afecto 150 m^2 de arrecife. En ambos casos mosaicos habilitado observaciones en una escala espacial nueva, había precisión espacial similar al GPS, y proporcionó el contexto para las observaciones tradicionales, de menor escala. Los desafíos técnicos abordados en la creación de estos dos mosaicos fueron, en primer lugar, la combinación de los mosaicos individuales para cubrir áreas más grandes, en segundo lugar, la eliminación de luz enfocada por las olas, y tercer, corrección de color de imágenes múltiples.

PALABRAS CLAVE: Mosaicos del paisaje submarine, Evening Star, Suez Matthew

L'Evaluation des Dommages d'un Navire à la Terre de Blessés sur les Récifs de Corail Utilisation Mosaïque Paysage Sous-Marin

Échouements de navires sont une source de perturbation pour les récifs coralliens dans le monde entier. Documenter l'ampleur des dommages causés par les échouements est une première étape cruciale dans le processus de restauration des récifs. Mosaïques des paysages sous-marins, créé par des milliers d'images, de combiner les aspects quantitatifs et qualitatifs d'évaluation des dommages et de fournir un géoréférencées, haute résolution, record permanente d'une blessure. Nous présentons une mosaïque de paysages d'une cicatrice le long de la côte sud de Puerto Rico créé par un m 289 (920 pi) de long-citerne de gaz naturel liquéfié. Cette mosaïque est contrastée avec une version antérieure acquise dans les Keys de Floride, où un navire de 15 m (49 pi) de long touché 150 m^2 de récifs. Dans les deux cas mosaïques permis des observations à une nouvelle échelle spatiale, avait précision spatiale comparable au GPS, et a fourni un contexte pour les traditionnels, les observations à plus petite échelle. Les défis techniques abordés lors de la création de ces deux mosaïques ont été, en premier lieu, associant mosaïques individuels pour couvrir les grandes régions, la deuxieme, la suppression d'artefacts d'image de la lumière réfractée par les vagues, et la troisième, la correction des couleurs des ensembles multiples d'images.

MOTS CLÉS: Mosaïques des paysages sous-marins, Evening Star, Suez Matthew

INTRODUCTION

Vessel groundings on coral reefs, and other tropical habitats such as seagrass, are common, can be destructive, and expensive to repair. Some groundings, such as the *Columbus Iselin*, which ran aground on Looe Key in 1994, or the USS *Port Royal*, which ran aground exiting Pearl Harbor in 2009, are large, dramatic, and publicized. Most groundings, on the other hand, are much smaller, cause less damage per event, and likely go unreported. Large groundings can result in substantial settlements and extensive restoration projects. For example, the *Iselin* event was settled for $3.76 million in 1997 (NOAA 1997) and the US Navy had already paid $7 million by June of 2009 for *Port Royal* restoration efforts (Star-Bulletin Staff 2009). Small groundings are not necessarily less important than the larger events, however, because numerous small injuries, in aggregate, can cause substantial damage (Lutz 2006, SFNRC 2008).

Regardless of the size of the grounding, a Natural Resource Damage Assessment needs to be conducted prior to any restoration activities in order to determine the proper amount of restoration required (Symons et al. 2006). Typical methods of damage assessment involve diver-based measurements of the size of any scar and comparative inventories of the benthic community inside and outside of the affected area (Hudson and Goodwin 2001). Typical diver-based methods, however, are labor-intensive and therefore relatively expensive. Furthermore, diver-based maps of large areas are usually restricted to outlines for areal calculations (e.g. the fishbone system of Hudson and Goodwin 2001). Although outlines of the scar are useful, they are limited in the information they can convey to anyone not intimately familiar with the site. Underwater photographs provide outstanding detail of small areas and therefore complement outline maps of damaged areas. The overall scale of damage is difficult to assess from individual underwater photographs, however, due to the attenuation of water, which forces images to be acquired close to the seabed thereby limiting the size of the area that can be included in a single frame.

Lirman et al. (2010) described a technique of mosaicing underwater images that provides numerous advantages for the purpose of assessing grounding damages. Underwater mosaics are spatially accurate and provide a “landscape view” of the seabed that facilitates assessment by specialists focused on restoration In addition, landscape mosaic images can facilitate communication with other parties involved with assessment, restoration, and liability of a grounding event. Data for underwater landscape mosaics are more rapidly collected than diver-based mapping with tape measures and provide more detailed benthic information for future change-detection purposes. Mosaics can be easily geo-referenced by the use of surface-based GPS, if the depth is not too great at the site (Lirman et al. 2010). A series of mosaics taken over time at one site, whether or not they are georeferenced in an absolute sense, can be easily mapped to one another in a relative sense to facilitate change detection, thereby not only assisting the initial damage assessment but also monitoring trends of recovery. Finally, comparative inventories of the benthic community inside and outside of the affected area, which are a separate step when divers make maps of the scar by hand, can be performed directly from the image mosaics themselves, thereby further reducing dive time.

Lirman et al. (2010) used underwater landscape mosaics to map the 150 m^2 scar created by the 15 m (49 ft) long vessel *Evening Star*, off the northern end of Key Largo, FL. Two mosaics of the *Evening Star* scar were created, one in 2005 and the other in 2006, in order to evaluate the potential of landscape mosaics for change detection. In this paper, we present the results of mapping a much larger scar created by the liquefied natural gas tanker *Suez Matthew* off the southern coast of Puerto Rico in December 2009. Assessment of the damage caused by the *Matthew* grounding and negotiation of a restoration settlement is still pending, so the focus of this paper will be to highlight novel mosaicing techniques used to create large area mosaics rather than describing the damage itself. In particular, we will present results of:

i) Combining multiple individual landscape mosaics to create a single image map of large affected areas,
ii) Wave-refracted sunlight corrections for shallow-water data, and
iii) Color correction procedures to create a seamless image from overlapping mosaics acquired during different times and water conditions.

METHODS

The underlying method used to create both the *Evening Star* and the *Suez Matthew* landscape mosaics was described by Lirman et al. (2007). Briefly, the mosaicing technique involved three general steps. First, a sufficient number of nadir-view images were collected to cover the areas of interest with high (~75%) overlap between adjacent frames. Second, the images were automatically matched to determine their relative locations. Finally, the images were blended together to produce a single mosaic. The basic technique does not require any inputs from auxiliary navigation sensors (Lirman et al. 2007). As used for both the *Evening Star* and the *Suez Matthew* surveys, however, the method was extended to incorporate the GPS coordinates of a few prominent landmarks within each mosaic (Lirman et al. 2010).

Three refinements to the mosaicing method described by Lirman et al. (2007, 2010) were developed to adapt the technique to challenges encountered during the *Evening Star* and *Suez Matthew* surveys. First, the large areas of the groundings required partitioning these two surveys into multiple subsections. Second, a correction for wave-refracted sunlight was applied to the *Evening Star* data, which had been acquired in shallow water on a clear day.

Third, the component mosaics of the *Suez Matthew* survey were color-matched to correct for different cameras used and changing conditions at the site during the course of the survey.

The data acquisition for both surveys was subdivided into sections. In 2005 - 2006, when the *Evening Star* surveys were performed, computer constraints limited the size of a single mosaic to approximately 15 x 15 m. Thus, the 2005 *Evening Star* survey consisted of three individual mosaics and the 2006 survey, which covered more area, consisted of six individual mosaics. By 2008, advances to computers and the mosaicking technique including larger memory, parallel processing, and integration with GPS-derived control points enabled reprocessing all sections of the *Evening Star* surveys together as one mosaic (Lirman et al. 2010).

The *Suez Matthew* data were also acquired by segmenting the survey into multiple individual mosaics, but in this case, it was not a result of a computer limitation, but rather a diver limitation. Due to improvements in memory, processing, and GPS integration, dive time had become the primary limit on the size of an individual mosaic by 2008 (i.e. basically anything that a diver could cover in one dive could be mosaiced). Estimates of the *Suez Matthew* scar, however, indicated that the impacted area might be as large as 100 x 50 m, which is much too large for a diver to swim in a single dive given the requirement for highly overlapping imagery. An outline of the scar created by GPS was used to lay out boxes for individual mosaics 20 x 10 m in size. Previous work had shown that divers could comfortably acquire sufficient imagery over a 20 x 10 m area in approximately 45 minutes. Three divers simultaneously acquired data, each swimming over one 20 x 10 m box per dive. Thus, three different cameras were used: a Nikon D200 with Nikon 12-24mm f/4 AF-S DX lens set to 24 mm, a Nikon D200 with Nikon 18-70mm f/3.5-4.5 AF-S DX lens set to 18 mm, and a Sony TRV-900 video camera with a Kenko KNW-05 HI 0.5X wide angle conversion lens. The D200s were set to acquire one image per second. A pair of two divers worked ahead of the imaging team, laying out 4 x 4 inch tiles at 5 m intervals to serve as reference points along the borders of the survey boxes. After laying out all the survey boxes, coordinates of the tiles were acquired by a snorkeler at the surface using a GPS strapped to a buoy and guided by a diver at the seabed who placed a line from the buoy on each tile. When the line was pulled taut, the snorkeler marked each point. Each of the individual sections of the *Suez Matthew* data was mosaicked using the "image plus GCP method" as described by Lirman et al. (2010). The individual sections were then hand-composited using ENVI software to create a single mosaic of the entire site.

The *Evening Star* data, acquired in 2 m water depth on a clear day, exhibited strong patterns of refracted sunlight. These did not affect the mosaicking algorithm, but did result in distracting patterns in the final mosaic that enhanced the visibility of seams between images. A pre-processing technique was used to filter these patterns of refracted light to improve the final appearance of the mosaic (Gracias et al. 2008).

The *Suez Matthew* data exhibited strong differences in overall color balance among the various individual mosaics due to using more than one camera for the survey and by changing conditions during the survey. In order to match the colors between the individual component mosaics, one of the mosaics was chosen as a standard. Histograms of red, green, and blue intensities were generated by randomly sampling 10,000 pixels from 20 randomly selected images that were part of this standard mosaic. All of the images from the other mosaics were matched to the standard histogram using histogram equalization (the MATLAB "histeq" function).

RESULTS

Two divers acquired the *Evening Star* data in approximately 1 hour during both the original survey on 23 May 2005 and during the follow-up survey on 19 July 2006 (Lirman et al. 2010). One diver swam with the camera and the other worked ahead of the camera operator laying out markers on the seabed to delineate the survey area. In contrast, five divers completed 45 person-dives on March 11, 12, and 13, 2010 to acquire the data for the *Suez Matthew* survey.

Nineteen individual mosaics were constructed to cover the *Suez Matthew* site. These individual mosaics were processed into GeoTIFF files during the month following data collection and delivered as they were completed to divers working on the restoration. All 19 individual sections were complete on April 9, and the first version of the entire mosaic, with all sections tiled together in a single image, was delivered on 13 April 2010 (Figure 1).

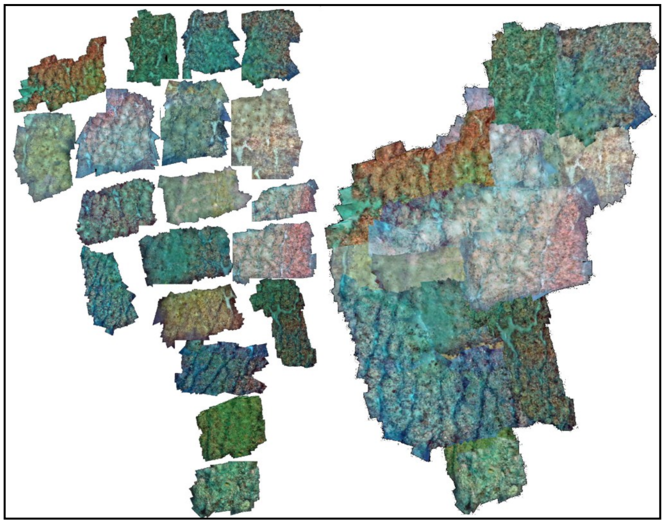

Figure 1. All 19 individual mosaics (left) and the first version of the entire mosaic, with all sections tiled together in a single image (right). Images are not presented at the same scale in this figure.

Spatial resolution, area mapped, and consequently the number of input images varied among the 19 individual mosaics. The variance in these factors was primarily due to the different cameras used and adjustments to the planned 20 x 10 m survey boxes that were made in the field. Spatial resolution is a function of the camera, lens, and distance of the camera off the seabed. In the *Suez Matthew* survey, the difference in spatial resolution between the video camera (720 x 480 pixels) and the still cameras (3872 x 2592 pixels) was much larger than differences of camera-seabed distance among divers. Four of the planned 20 x 10 m survey boxes were adjusted as the survey progressed. Two areas were extended to cover approximately 30 x 10 m areas, one area was truncated to cover only 10 x 10 m, and one area was truncated to cover only 10 x 5 m. In the end, the largest and smallest individual mosaics consisted of 2815 and 358 images, respectively. The complete mosaic was constructed from 16114 individual images. All of the individual component mosaics were resampled to a common resolution of 1 x 1 cm when the final, single mosaic was made.

Pre-processing the *Evening Star* data with the Gracias et al. (2008) algorithm effectively removed the patterns of refracted sunlight, greatly improving the appearance of the final mosaics (Figure 2). The *Evening Star* data were all acquired with one camera and over a short enough time that the overall lighting and water conditions did not change appreciably. Therefore, the colors were not noticeably different among the sections of the *Evening Star* survey.

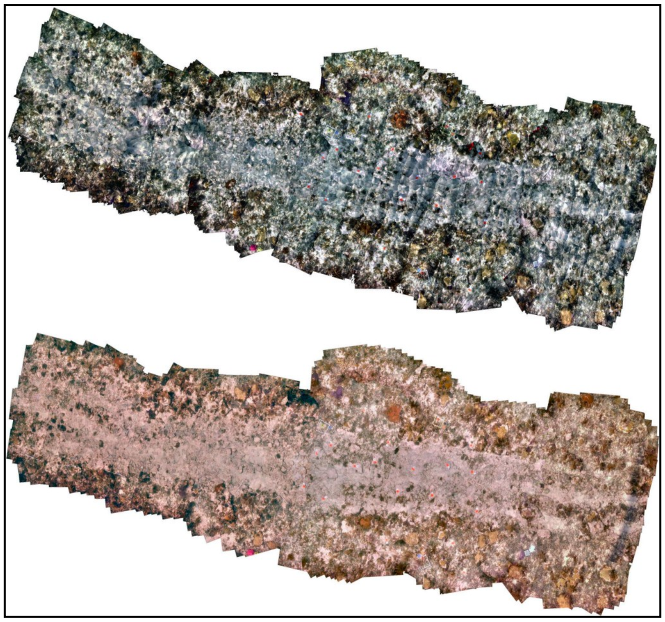

Figure 2. *Evening Star* mosaic from 2005 before (top) and after (bottom) removing wave-refracted sunlight patterns from the original video imagery.

The *Suez Matthew* data, acquired in 8 - 12 m of moderately turbid water, did not contain any distracting patterns of refracted sunlight. Large differences in overall color balance were apparent among the various individual mosaics comprising the overall *Suez Matthew* survey, however. Camera-to-camera differences were largest between the TRV-900 and either D200. Colors between the two D200s were not obviously different for images acquired under the same water conditions. Conditions changed significantly during the survey, however, due to tides and wind. At the Puerto Rico insular shelf edge, where the *Matthew* grounding occurred, flood tides brought relatively clear, blue water to the survey site and ebb tides brought relatively green, lower visibility conditions. Each afternoon sea breeze-generated waves resuspended sediment, increasing turbidity. Thus, colors between the two D200s, and even for the same camera at different times, did vary considerably (Figure 1). Histogram equalization between each image and the reference mosaic effectively balanced the colors across the entire survey area (Figure 3).

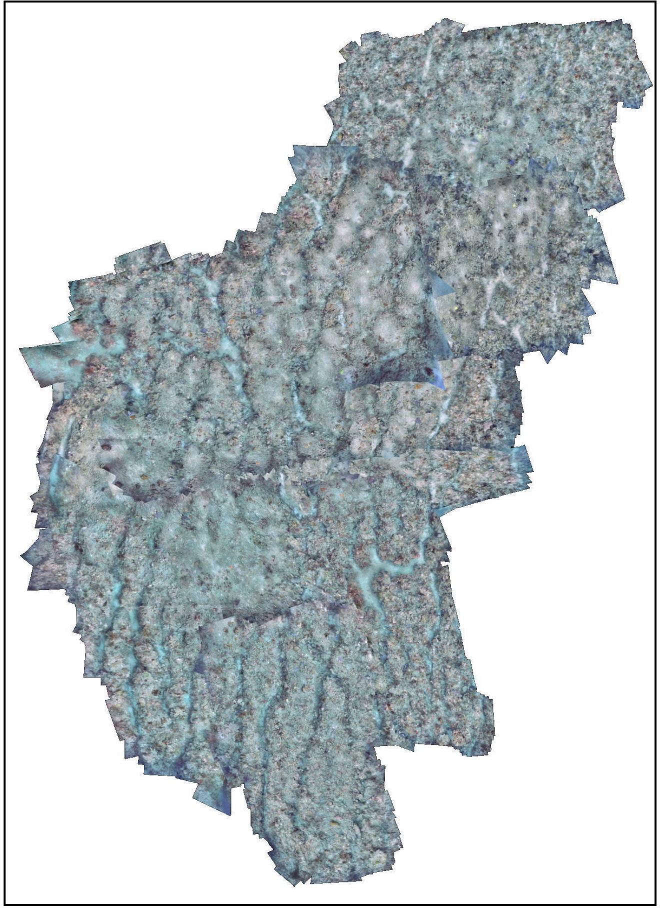

Figure 3. The *Suez Matthew* mosaic after color matching the individual component mosaics. Image is oriented North up, and covers 76 m from East to West and 117 m from North to South. The full mosaic has 1 x 1 cm pixels, so is presented here at much less than full resolution.

DISCUSSION

The *Suez Matthew* mosaic is by far the largest dataset assembled with the Lirman et al. (2007) technique to date. The methodological improvements that enabled this milestone are the use of multiple divers and cameras to simultaneously acquire several portions of the survey and the use of color matching to improve the appearance of the final mosaic. Previous landscape mosaics have used a single camera to document even large areas of interest such as the *Evening Star* survey. Because there are no standard underwater cameras used by monitoring or damage assessment teams, the ability to combine information from multiple systems increases the applicability of the mosaic mapping technique. The ability to use multiple camera types for a single survey can increase the number of diver + camera surveying systems in the water at a single time, thereby decreasing total survey time relative to using a single diver-imaging system. From a technological standpoint, these are incremental improvements, but from a practical standpoint, they have a substantial impact on the use of this mosaicing technology for ship grounding restoration work.

The significance of being able to subset a survey into small blocks, which can be acquired in parallel by multiple cameras and divers over the course of a few days, is that very large areas can be mapped using a technique that has minimal hardware requirements. Minimal hardware requirements facilitate a rapid deployment, which is essential if a mapping method is to be useful for grounding restoration efforts. In this case, all the required equipment was flown to Puerto Rico on a commercial flight with no extra baggage charges. A standard commercial dive boat was chartered, which was possible because there were no special power or weight requirements (i.e. no A-frame or crane needed). An added benefit of the image-based mosaicing approach is that the same software could use imagery acquired by a remotely operated or autonomous underwater vehicle (ROV/AUV) if the deployment of such tools is possible in a given situation.

The ability to remove strong light attenuation and provide color correction over multiple mosaic image sets increases the capability to provide a single, seamless, image map of affected areas even when portions of the data are acquired under variable conditions. Data for previous mosaics have all been acquired in a single day, in fact most were acquired in a single dive, thereby limiting the changes of in-water conditions. The ability to remove some of the variability in images using pre and post-processing techniques will allow damage assessment teams the flexibility to:

i) Conduct surveys over larger time scales (in this case over several days),
ii) Use multiple cameras for image acquisition, and
iii) Acquire images under a variety of in-water conditions.

Our future plans for the *Suez Matthew* grounding are to acquire a second mosaic once restoration activities are completed. Analysis of this future mosaic relative to the baseline image presented here will enable documentation of the restoration efforts. Ideally, additional mosaics could be acquired at regular intervals to quantify recovery from this grounding event.

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