Geomorphology 242 (2015) 21–28

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Measuring coral reef terrain roughness using 'Structure-from-Motion' close-range photogrammetry

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ARTICLE INFO

Article history:
Received 2 May 2014
Received in revised form 4 December 2014
Accepted 6 January 2015
Available online 3 February 2015

Keywords:
Structure-from-motion (SfM)
Agisoft photoscan
Rugosity
Fractal dimension
Coral reef
Heron Reef

ABSTRACT

Our understanding of Earth surface processes is rapidly advancing as new remote sensing technologies such as LiDAR and close-range digital photogrammetry become more accessible and affordable. A very-high spatial resolution digital terrain model (DTM) and orthophoto mosaic (mm scale) were produced using close-range digital photogrammetry based on 'Structure-from-Motion' (SfM) algorithms for a 250 m transect along a shallow coral reef flat on Heron Reef, Great Barrier Reef. The precise terrain data were used to characterise surface roughness, a critical factor affecting ecological and physical processes on the reef. Three roughness parameters, namely the root mean square height, tortuosity (or rugosity) and fractal dimension, were derived and compared in order to asses which one better characterises reef flat roughness. The typical relief across the shallow reef flat was 0.1 m with a maximum value of 0.42 m. Coral reef terrain roughness, as characterised by the three chosen parameters, generally increased towards the middle of the transect where live coral covers most of the reef flat and decreases towards the edges of the transect. The fractal dimension (values ranging from 2.2 to 2.59) best characterised reef roughness, as evidenced by a closer agreement with the distribution of known coral benthic substrates. This is the first study quantifying scale-independent roughness of a coral reef at benthic and biotope/patch levels (cm-m). The readily available and cost-effective methods presented are highly appropriate for data collection, processing and analysis to generate very-high spatial resolution DTMs and orthophoto mosaics of shallow and energetic coral reefs.

1. Introduction

Our understanding of Earth surface processes is rapidly advancing with the advent of new remote sensing technologies and geospatial techniques. Emerging technologies such as LiDAR (Light Detection and Ranging) (Höfle and Rutzinger, 2011) and close-range digital photogrammetry (Westoby et al., 2012; Fonstad et al., 2013) have become more accessible and affordable in the last decade. Metre and sub-metre scale terrain datasets have become more popular and provide unique opportunities to answer questions about the history and processes acting upon different geomorphic systems (Tarolli, 2014).

Coral reefs are complex geomorphic systems with some of the highest biodiversity on the planet, and are of great economic value, yet are very vulnerable to climate change (Hoegh-Guldberg et al., 2007). Most ecosystem services provided by reefs are related to the intricate structure/roughness of reefs (Perry et al., 2013). For example, at the whole-reef scale, roughness is an important factor in the net carbonate production and evolution of the 3-dimensional (3D) reef structure (Perry et al., 2008; Hamylton et al., 2013) which, in turn, provides wave sheltering for coastal ecosystems (Saunders et al., 2014) and shorelines (Sheppard et al., 2005; Storlazzi et al., 2011; Ruiz de Alegria-Arzaburu et al., 2013).

At smaller spatial extents (m^2), reef flat roughness modifies wave processes, which have important forcing functions on shallow reefs as they act upon the majority of ecological and biogeochemical processes by exerting direct physical stress, indirectly mixing water (temperature and nutrients) and transporting sediments, nutrients and plankton (Hopley et al., 2007; Hearn, 2011). Furthermore, reef flat roughness is a key ecological indicator as the physical structures contributing to roughness provide important benthic habitats and have been shown to strongly correlate with fish diversity (Harborne et al., 2012) and coral community composition (McCormick, 1994).

Although there is no standard method to characterise surface roughness, common parameters include calculating the root mean square (or standard deviation) of elevation or the ratio between the surface area and the area of its orthogonal projection onto a plane, also known as the tortuosity index or rugosity (Shepard et al., 2001). Coral reef roughness has been traditionally measured using the chain-method for ecological applications (McCormick, 1994). This technique measures rugosity at a fixed resolution (chain-link size) and is a labour-intensive

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http://dx.doi.org/10.1016/j.geomorph.2015.01.030
0169-555X/

and time-consuming task (see Dustan et al., 2013 for an improvement on the method). This opposes Hobson's (1972) view of a useful measurement of surface roughness which was characterised as easily measured and comparable across different scales. In the field of reef hydrodynamics, considerable improvements on modelling wave transformation over heterogeneous reefs have been observed when incorporating spatially-explicit bottom friction coefficients representing the variability of the reef roughness (Cialone and Smith, 2007; Hearn, 2011). However, roughness is usually obtained empirically from frictional dissipation calculations (Nielsen, 1992), as high-spatial resolution measurements of hydraulic roughness are challenging to acquire over scales relevant to reef processes (10^2 m).

Recent studies have attempted to use high-spatial resolution (metre scale) and very-high resolution (sub-metre scale) digital terrain models (DTMs) to characterise coral reef roughness from the rugosity parameter. For example, high-spatial resolution bathymetric LiDAR was used to measure coral reef rugosity at the landscape scale (up to 10^2 km^2) (Brock et al., 2004; Kuffner et al., 2007). Friedman et al. (2012) utilized georeferenced stereo imagery collected by an Autonomous Underwater Vehicle (AUV) to produce a very-high resolution DTM from which they derived multi-scale measures of rugosity, slope and aspect. However, the rugosity parameter does not contain measurements of surface roughness variation in multiple directions (Bretar et al., 2013) or represent surface roughness appropriately over large spatial extents (>10^2 m^2) (Zawada and Brock, 2009).

The use of auto-similarity, or scale-invariant parameters, such as the fractal dimension could be a more appropriate measure to characterise roughness (Mandelbrot, 1982). The advantage of using a fractal dimension parameter is that it relates complexity, spatial patterns and scale, making it a powerful and intuitive descriptor of change as a function of scale in any direction (Zawada and Brock, 2009; Bretar et al., 2013). Despite its potential, only few coral reef studies have employed it. For example, Knudby and LeDrew (2007) explored scale-dependencies on roughness of characteristic substrate types on coral reefs. Zawada and Brock (2009) computed the fractal dimension of a 880 × 880 m coral reef region as a proxy of reef roughness based on high-resolution LiDAR-derived bathymetry. Further, Zawada et al. (2010) mapped the fractal dimension of each pixel in order to visualize the spatial changes in roughness throughout an 880 × 800 m study region. Spatial patterns in the fractal dimension parameter were positively correlated with known distribution of coral reef benthic substrates.

The limited use of fractal analysis in coral reef roughness studies has been partly because of the limited availability of very high-spatial resolution bathymetric datasets covering relatively large spatial extent areas (>10 m^2). For this study, we elaborate a very-high spatial resolution DTM (mm pixel size) covering 100s of meters of an inter-tidal reef flat using close-range digital photogrammetry, derive one scale-invariant and two commonly used roughness parameters and compare which parameter better characterises the reef flat roughness.

2. Methods

2.1. Study site

Heron Reef (23°25′S, 151°55′E) is a platform reef (~28 km^2) located in the Capricorn Bunker Group on the southern Great Barrier Reef, Australia (Fig. 1). The platform emerges from water depths ~25 m below mean sea level (MSL) and is classified as a lagoonal reef type according to the geomorphological evolutionary scheme developed by Hopley (1982). It has a steep reef slope and is mostly surrounded by a narrow intertidal crest enclosing a shallow reef flat (~1 m below MSL) and a sheltered backreef environment that remains beneath water at all stages of the tide. The submerged lagoon (~4 m below MSL) is infilled by sand aprons and covered by relatively large coral patches (~20 m in diameter). A vegetated coral cay (~0.24 km^2) is located towards the west of the platform and has a maximum elevation of ~7 m above MSL (Phinn et al. 2012). A resort and a research station have been operating on Heron Island since the early 1940s.

The prevailing winds on Heron Reef are the south easterly trade winds during the austral winter months (April–September). From October to March winds are variable, with common strong north easterlies and cyclonic events (Flood, 1974). Waves and wind/wave-induced currents over the reef flat are strongly modulated by tide levels. Tidal range is 3.3 m (Gourlay and Jell, 1993).

2.2. Photo survey and generation of DTM

A 250 m transect running perpendicular from the reef crest and along the south-western exposed, shallow reef flat (Fig. 1) was surveyed on the 4th of November 2013. Close-range digital photogrammetry based on structure from motion (SfM) algorithms was used to derive a very high spatial resolution DTM and orthophoto mosaic (1 mm) (Fig. 2). The transect was chosen so various geomorphic and benthic zones on the reef flat, as defined by Phinn et al. (2012), were crossed. A pair of consumer digital non-metric cameras (Lumix DMC-FT3, 12 megapixels, ~US$200), set at their widest angle (28 mm), were used to take photos relatively perpendicular to the ground at high tide (~1.5 m of water depth) under calm conditions by a snorkeler. Two

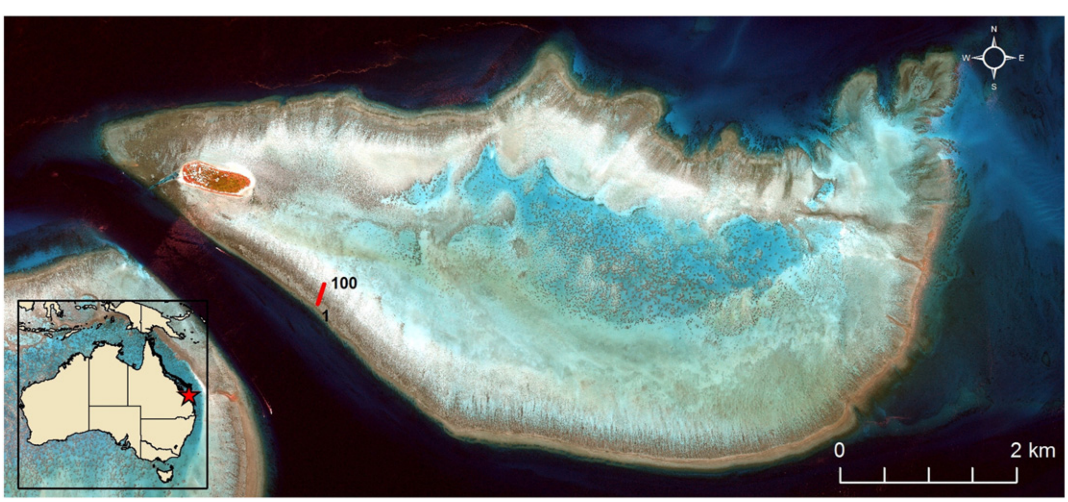

Fig. 1. Location of Heron Reef on the southern Great Barrier Reef, Australia as shown by a Worldview 2 image acquired on 30/11/2011 (true colour composite using bands 5, 3, and 2 as red, green, and blue). The transect along the study site is shown, with the photo from tile 1 being closest to the reef crest through photo tile 100, moving towards the lagoon.