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

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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 assess 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.

Keywords: Structure-from-Motion (SfM); Agisoft Photoscan; rugosity; fractal dimension; coral reef; Heron Reef
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. Meter and sub-meter 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 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 (meter scale) and very-high resolution (sub-meter 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 880x880 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 x 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 m²). For this study, we elaborate a very-high spatial resolution DTM (mm pixel size) covering 100s 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 km²) 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 km²) 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 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 cameras were used (~30 cm apart) and the transect was swam slowly (15 minutes along 250 m) in order to ensure at least 70% side and forward overlaps. A handheld Garmin eTrex 10 GPS (horizontal accuracy < 5 m) was used to georeference two pairs of 20 cm plastic discs indicating the start and end of the transect. In addition, nine lead weights with known dimensions were spread evenly along the transect for scaling and ground control.

The off-the-shelf photogrammetric software Agisoft® Photoscan Professional edition v1.0 was used to generate the DTM and orthophoto mosaic based on SfM. The procedure followed four steps: i) Aerial triangulation, ii) Optimization, iii) Dense...
surface reconstruction, iv) Orthopoto generation. Parameters were chosen based on recommended settings by the software developers and test-and-trial (Table 1). A workstation with six cores (12 HT cores) and 64 GB RAM was used to perform the analysis.

The first step consisted of selecting and triangulating the images, also known as the “Photo alignment” step in Photoscan. The software’s “Image Quality” function was used to filter photos. Only photos with a quality > 0.5 were selected. Photo alignment was done by detecting points in the images which are stable under several perspective and lighting variations (at least from 3 photos) and matching them based on their local neighbourhood. Photoscan uses a proprietary algorithm similar to the scale invariant feature transform (SIFT) object recognition algorithm derived by Lowe (1999) but slightly modified for higher alignment quality. Positions for each photo were estimated using the GPS coordinates corresponding to the beginning and end of the transect and by sequentially adding an offset distance derived from the total number of photos, transect length and survey time (assuming constant swimming speed and direction). Including coordinates for each photo (ground control pair selection mode, Table 1) considerably improved the photo alignment performance in terms of speed and quality.

The image triangulation process generated a sparse point cloud based on the estimated camera positions. The internal and external camera orientation parameters, including non-linear radial distortions, were derived using only the camera type and focal length information included in the image’s EXIF metadata. Photoscan uses a greedy algorithm to find approximate camera locations and refines
them later using a bundle-adjustment algorithm. However, these parameters are prone to significant errors and depend on many factors such as the amount of overlap between the neighbouring photos or the complexity of the surveyed terrain. These errors can lead to non-linear deformations of the final model (e.g. “bowl effect”) (Agisoft LLC., 2013). PhotoScan software allows optimizing the estimated sparse point cloud and camera parameters in order to remove possible non-linear deformations of the model. The second step of optimization involved two stages. First, the sparse point cloud was edited manually by removing obvious outliers and mislocated points. Second, ground control objects (four discs, five lead weights) were used to scale and adjust camera parameters by minimizing the sum of reprojection error and reference coordinate misalignment error. The remaining four ground control points were used for accuracy assessment of the model.

The third step, dense surface reconstruction, was based on the optimized camera positions. Pair-wise depth maps were computed for each image and combined into a final dense point cloud. The dense point cloud was further used to build a mesh for the final model. The fourth step, orthophoto generation, is undertaken by calculating a texture atlas for the model which is used to create the orthophoto mosaic. Finally, both the meshed DTM and orthophoto mosaic were exported using a pixel resolution of 1 mm.

### 2.3 Surface roughness calculation

The DTM was pre-processed using a series of geomorphometric techniques in order to derive surface roughness parameters. A low-pass mean filter (3x3 pixels window) was first applied to remove outliers. The smoothed DTM was then de-trended by
applying a regional median filter (500x500 pixels window) and subtracting it from the
DTM. The resultant residual relief surface avoids systematic biases when estimating
terrain heights (Hiller and Smith, 2008; 2014) and was used as an input to calculate
surface roughness (Fig. 2).

In order to analyse surface roughness spatially, the 250 m transect was sub-sampled
using 100 randomly located tiles (1 m$^2$) (Fig. 1). The three roughness parameters
were calculated for each individual tile. The parameters chosen as proxies of surface
roughness were: Root mean square height ($RMS$), Tortuosity or rugosity index ($\xi$),
and Fractal dimension (D). The $RMS$ (or standard deviation of elevation) is an easy
to calculate and commonly used parameter to characterise surface roughness
(Shepard et al., 2001). The higher the value, the more pronounced the vertical
variations and hence a rougher surface. The Tortuosity index is the ratio between the
3D surface area and the projected planar area. It is easy to calculate and accounts
for both horizontal and vertical scales of roughness (Bertuzzi et al., 1990). It is also
commonly referred to as “rugosity” within the coral reef literature (e.g. Brock et al.,
2004; Knudby and LeDrew, 2007; Friedman et al., 2012; Harborne et al., 2012;
Dustan et al., 2013) and has values equal to or greater than one (flat, smooth area),
with a typical value of four corresponding to rougher surfaces.

The last parameter calculated to characterise surface roughness was the scale-
invariant fractal dimension (D). Following previous studies relating D to coral reef
roughness (e.g. Zawada and Brock, 2009; Zawada et al., 2010), the fractal
dimension was calculated using the variation method (Dubuc et al., 1989). In short,
for each tile, the average range (absolute difference between minimum and
maximum values) of elevation values \( \bar{\nu}(\epsilon) \) was determined using a square
neighbourhood with side length \( L \) at different observation scales \( \epsilon \), such that:
\[
L = 2 \epsilon + 1
\]
As recommended by Zawada and Brock (2009), \( \epsilon \) was chosen to span more than two
orders of magnitude for meaningful estimates of the fractal dimension. Neighbourhood windows for each tile varied in length from 3 to 993 pixels, with
associated \( \epsilon \) values ranging from 1 to 496. \( D \) was calculated as \( 3 - m \), where \( m \) is
the slope of the regression \( \log_{10}[\bar{\nu}(\epsilon)] \) against \( \log_{10}[\epsilon] \). \( D \) values increase from 2 to 3
as the surface becomes more complex (rough) and fills its bounding volumes
(Zawada and Brock, 2009).

3 Results

A total of 1,370 overlapping photos were used to produce the DTM and orthophoto
mosaic. The footprint for each camera covered a width and length of approximately
0.7 m, resulting in a transect ~1.5 m wide and 250 m long. Overall, approximately 5
days of processing were required, including computational processing time and
interactive adjustments.

The root mean square error for the 3D model, as calculated from the subset of four
ground control points, was 0.605 mm. This sub-millimeter accuracy value is
consistent with reported accuracies for DTMs derived using consumer cameras and
close-range digital photogrammetry (Chandler et al., 2005).

The very-high spatial resolution and highly accurate DTM and orthophoto mosaic
succesfully resolved features to the benthic community and biotope/patch scales
(sub-meter to sub-cm). Typical benthic zones across the outer and inner reef flats of Heron Reef are shown in Figure 3.

The typical measured amount of DTM variation or relief across the shallow reef flat was 0.1 m with a maximum value of 0.42 m over areas covered with live coral. The mean area of individual structures detected along the transect was 0.02 m² with a maximum area of 0.46 m².

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, where there were more consistent cover types present. The average values for $RMS$ was 0.04 m, ranging from 0 to 0.09 m. Following a very similar trend along the transect, the average $\xi$ value was 1.87, ranging from 1.07 to 2.98. Finally, the average $D$ value for each tile (mean associated coefficients of determination ($R^2$) for the linear regressions = 0.96) was 2.45, ranging from 2.2 to 2.59 (Fig. 4).

Local values of $RMS$ and $\xi$ appeared to be very high on areas where roughness values are intuitively expected to be low, such as along the lagoonward sandy inner reef flat (vicinity of tile 100, Fig. 1). Conversely, some local values of $RMS$ and $\xi$ appeared very low on areas where roughness values are intuitively expected to be high, such as along the live coral covered outer reef flat (vicinity of tile 1, Fig. 1). This pattern was not observed with $D$ values (for example see dashed lines in Fig. 4). On the contrary, high $D$ values (2.45-2.6) were found on areas where roughness is intuitively expected to be large such as the coral and coral algae benthic substrates...
(Figs. 5a and 5b). Lower values of D (2.2-2.4) were observed on less rough benthic substrates such as the inner reef flat covered with algae, rubble and sediment (Fig. 5c and 5d).

4 Discussion

4.1 Production of coral reef digital terrain model (DTM) from close-range photogrammetry

The application of close-range photogrammetry based on Structure-from-Motion (SfM) algorithms resulted in a precise and very-high resolution DTM and orthophoto mosaic of the coral reef flat. The energetic conditions of the reef crest and flat areas during the field survey presented three challenges. First, data collection from energetic and shallow reef environments is extremely challenging due to passage of waves, from wave-breaking conditions on the crest to propagating short period waves on the reef flat (Leon et al., 2013), even for unmanned vessels (Matthew Dunbabin, pers. Comm). However, an experienced snorkeler may be able to efficiently compensate for water oscillations and movement, making this technique appropriate in these environments.

Second, changes in light levels at the benthos, due to passing waves and wave focussing, along with movement of objects due to currents (e.g. soft coral, algae) and moving objects (e.g. fishes) hindered the photo alignment process and precision of final products. A potential solution could be using a frame with strobes in order to standardise the lighting conditions.
Third, the relatively shallow water depth (~2 m) resulted in images with very small footprints (< 1 m in width) even when using a wide angle lens. Hence, a large number of photos were required to cover the extent of the transect. This increased computational time but can be resolved by working with different subsets (chunks) of the model (Agisoft LLC., 2013).

Even though only a 250 m long by 1.5 m wide transect was surveyed for the purposes of this study, it is evident the technique developed could be applied to larger reef areas (> km²) with ease due to its simplicity to implement and cost-effectiveness. The construction of a rig with various cameras or deploying multiple snorkeler teams simultaneously could increase coverage without increasing costs considerably.

Based on this study, ~0.002 km² of shallow reef flat can be mapped per hour. In comparison, a ship-based multi-beam (MBES) Sound Navigation and Ranging (SoNAR) system covers ~0.5 km²/hr in intermediate water depths (10-50 m), two orders of magnitude faster, but adding high costs associated with equipment and data processing (Costa et al., 2009). In addition, shallow waters (< 5 m) and breaking waves on reef flats represent a hazard for navigation (Leon et al., 2013). Bathymetric LiDAR systems such as LADS MKII are much faster (~10.1 km²/hr) and in some cases 6.6 % less expensive than MBES for large areas (10s km²) (Costa et al., 2009). However, even very high scan-rate, state-of-the-art systems, such as the Experimental Advanced Airborne Research LIDAR (EAARL), cannot resolve shallow depths < 2 m or map areas where white-caps are present (Klemas, 2011).
The technique presented in this study is an appropriate approach to generate very-high spatial resolution terrain datasets for shallow and energetic coral reefs. The resultant geospatial products provide a means to assess a previously un-measureable link between marine ecology and geomorphology based on remote sensing (Knudby and LeDrew, 2007). These products can also be integrated and used to semi-automatically classify additional benthic properties (e.g. coral coverage or size-distribution) using techniques such as object-based image analysis (Leon et al., 2012). Furthermore, the technique can be used for rapid response surveys (e.g. after cyclone or bleaching events) and monitoring approaches, providing much needed multispacial, multitemporal scale measurements required to understand processes that affect reef function and structure (Phinn et al., 2012).

4.2 Coral reef roughness

Three different parameters were calculated as proxies for coral reef roughness. Root mean square height (RMS) and tortuosity/rugosity (\( \xi \)) parameters are commonly used and relatively simple to compute. Both parameters were highly correlated and followed a very similar trend across the surveyed transect. However, values did not correlate with known distribution of coral reef benthic substrates. This can be explained due to the RMS parameter not taking into account the horizontal structure of a surface. The \( \xi \) parameter, on the other hand, does not appropriately characterise anisotropy (directional roughness), which is pronounced in the case of reef flats due to wave processes acting mostly in one predominant direction (Bradbury and Young, 1981).
The fractal dimension (D) parameter better characterised reef roughness compared to the other parameters measured, as evidenced by a better agreement with the distribution of coral benthic substrates (Fig. 5). Values of D for different benthic zones were consistent with previously reported values on other coral reef systems (Zawada and Brock, 2009; Zawada et al., 2010).

The fractal analysis presented in this study is the first one to analyse scale-invariant coral reef roughness at the benthic community and biotope/patch scales within shallow reef flats. Results could be used to improve the modelling of hydrodynamic or ecological process. However, further research is required in order to compare the relationships between fractal characteristics of local biotope, benthic and synoptic geomorphic zones within reef systems and across different coral reef regions.

5 Conclusions

The cost-effective methods presented here are readily available, require minimum training and are an appropriate approach for data collection, processing and analysis to generate very-high resolution DTMs and orthophoto mosaics of shallow and energetic coral reefs. The fractal dimension (D) parameter better characterises reef roughness than the root mean square error or rugosity parameters, as evidenced by a better 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 scales (cm-m).
Acknowledgments

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assessment of the relationship between reef flat community calcium carbonate


Table 1: Parameters used in Photoscan software
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). Transect along study site is shown, with photo from tile 1 being closest to reef crest through to photo tile 100, moving towards the lagoon.

Figure 2: Workflow of methods used to derive the very-high spatial resolution digital terrain model (DTM) and orthophoto mosaic using SfM algorithms and subsequent derivation of roughness parameters.

Figure 3: 3D perspective views of digital terrain models (DTMs) draped with orthophoto mosaics (1 mm spatial resolution) of 4 typical benthic zones with different roughness characteristics: A) Outer reef flat covered with algae, live and dead coral; B) Outer reef flat covered with live coral; C) Outer reef flat covered with algae, coral rubble, live and dead coral; D) Inner reef flat covered with algae, coral rubble and sediment (See Fig. 4 for locations). Horizontal scale varies with perspective but average width of transect is 1.5 m. Vertical scale represents 0.2 m.

Fig. 4: Roughness characterization of transect as a function of length along a 250 m transect. Tile 1 is located to reef crest and tile 100 is closest to inner reef flat (See Fig. 1 for location). Three roughness parameters are shown: Fractal dimension (upper panel), Tortuosity index (middle panel) and Root mean square heights (lower panel).
Fig. 5: Fractal dimension for tiles 1 through 100 along a 250 m coral reef transect shown on benthic community map derived by Phinn et al. (2012). Insets A-D show orthophotos of four typical benthic zones and associated fractal dimension values. Red scale bar on insets represent 1 m.
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Abstract

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At smaller spatial extents (m²), 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 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 (meter scale) and very-high resolution (sub-meter 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—can be a more appropriate 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 880x880 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 x 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 (> $10^2$ m$^2$). For this study, we elaborate a very-high spatial resolution DTM (mm pixel size) covering 100s meters of an intertidal 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 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 cameras were used (~30 cm apart) and the transect was swam slowly (15 minutes along 250 m) in order to ensure at least 70% side and forward overlaps. A handheld Garmin eTrex 10 GPS (horizontal accuracy < 5 m) was used to georeference two pairs of 20 cm plastic discs indicating the start and end of the transect. In addition, nine lead weights with known dimensions were spread evenly along the transect for scaling and ground control.

The off-the-shelf photogrammetric software Agisoft® Photoscan Professional edition v1.0 was used to generate the DTM and orthophoto mosaic based on SfM. The procedure followed four steps: i) Aerial triangulation, ii) Optimization, iii) Dense
surface reconstruction, iv) Orthopoto generation. Parameters were chosen based on recommended settings by the software developers and test-and-trial (Table 1). A workstation with six cores (12 HT cores) and 64 GB RAM was used to perform the analysis.

The first step consisted of selecting and triangulating the images, also known as the “Photo alignment” step in Photoscan. The software’s “Image Quality” function was used to filter photos. Only photos with a quality > 0.5 were selected. Photo alignment was done by detecting points in the images which are stable under several perspective and lighting variations (at least from 3 photos) and matching them based on their local neighbourhood. Photoscan uses a proprietary algorithm similar to the scale invariant feature transform (SIFT) object recognition algorithm derived by Lowe (1999) but slightly modified for higher alignment quality. Positions for each photo were estimated using the GPS coordinates corresponding to the beginning and end of the transect and by sequentially adding an offset distance derived from the total number of photos, transect length and survey time (assuming constant swimming speed and direction). Including coordinates for each photo (ground control pair selection mode, Table 1) considerably improved the photo alignment performance in terms of speed and quality.

The image triangulation process generated a sparse point cloud based on the estimated camera positions. The internal and external camera orientation parameters, including non-linear radial distortions, were derived using only the camera type and focal length information included in the image’s EXIF metadata. Photoscan uses a greedy algorithm to find approximate camera locations and refines
them later using a bundle-adjustment algorithm. However, these parameters are prone to significant errors and depend on many factors such as the amount of overlap between the neighbouring photos or the complexity of the surveyed terrain. These errors can lead to non-linear deformations of the final model (e.g. “bowl effect”) (Agisoft LLC., 2013). PhotoScan software allows optimizing the estimated sparse point cloud and camera parameters in order to remove possible non-linear deformations of the model. The second step of optimization involved two stages. First, the sparse point cloud was edited manually by removing obvious outliers and mislocated points. Second, ground control objects (four discs, five lead weights) were used to scale and adjust camera parameters by minimizing the sum of reprojection error and reference coordinate misalignment error. The remaining four ground control points were used for accuracy assessment of the model.

The third step, dense surface reconstruction, was based on the optimized camera positions. Pair-wise depth maps were computed for each image and combined into a final dense point cloud. The dense point cloud was further used to build a mesh for the final model. The fourth step, orthophoto generation, is undertaken by calculating a texture atlas for the model which is used to create the orthophoto mosaic. Finally, both the meshed DTM and orthophoto mosaic were exported using a pixel resolution of 1 mm.

### 2.3 Surface roughness calculation

The DTM was pre-processed using a series of geomorphometric techniques in order to derive surface roughness parameters. A low-pass mean filter (3x3 pixels window) was first applied to remove outliers. The smoothed DTM was then de-trended by
applying a regional median filter (500x500 pixels window) and subtracting it from the DTM. The resultant residual relief surface avoids systematic biases when estimating terrain heights (Hiller and Smith, 2008; 2014) and was used as an input to calculate surface roughness (Fig. 2).

In order to analyse surface roughness spatially, the 250 m transect was sub-sampled using 100 randomly located tiles (1 m²) (Fig. 1). The three roughness parameters were calculated for each individual tile. The parameters chosen as proxies of surface roughness were: Root mean square height (RMS), Tortuosity or rugosity index (ξ), and Fractal dimension (D). The RMS (or standard deviation of elevation) is an easy to calculate and commonly used parameter to characterise surface roughness (Shepard et al., 2001). The higher the value, the more pronounced the vertical variations and hence a rougher surface. The Tortuosity index is the ratio between the 3D surface area and the projected planar area. It is easy to calculate and accounts for both horizontal and vertical scales of roughness (Bertuzzi et al., 1990). It is also commonly referred to as “rugosity” within the coral reef literature (e.g. Brock et al., 2004; Knudby and LeDrew, 2007; Friedman et al., 2012; Harborne et al., 2012; Dustan et al., 2013) and has values equal to or greater than one (flat, smooth area), with a typical value of four corresponding to rougher surfaces.

The last parameter calculated to characterise surface roughness was the scale-invariant fractal dimension (D). Following previous studies relating D to coral reef roughness (e.g. Zawada and Brock, 2009; Zawada et al., 2010), the fractal dimension was calculated using the variation method (Dubuc et al., 1989). In short, for each tile, the average range (absolute difference between minimum and
maximum values) of elevation values \[ \tilde{h}(\varepsilon) \] was determined using a square
neighbourhood with side length (L) at different observation scales (\varepsilon), such that:

\[
L = 2^\varepsilon + 1
\]

As recommended by Zawada and Brock (2009), \( \varepsilon \) was chosen to span more than two
orders of magnitude for meaningful estimates of the fractal dimension.

Neighbourhood windows for each tile varied in length from 3 to 993 pixels, with
associated \( \varepsilon \) values ranging from 1 to 496. D was calculated as 3 – \( m \), where \( m \) is
the slope of the regression \( \log_{10} [\tilde{h}(\varepsilon)] \) against \( \log_{10} [\varepsilon] \). D values increase from 2 to 3
as the surface becomes more complex (rough) and fills its bounding volumes
(Zawada and Brock, 2009).

3 Results

A total of 1,370 overlapping photos were used to produce the DTM and orthophoto
mosaic. The footprint for each camera covered a width and length of approximately
0.7 m, resulting in a transect ~1.5 m wide and 250 m long. Overall, approximately 5
days of processing were required, including computational processing time
and interactive adjustments.

The root mean square error for the 3D model, as calculated from the subset of four
ground control points, was 0.605 mm. This sub-millimeter accuracy value is
consistent with reported accuracies for DTMs derived using consumer cameras and
close-range digital photogrammetry (Chandler et al., 2005).

The very-high spatial resolution and highly accurate DTM and orthophoto mosaic
succesfully resolved features to the benthic community and biotope/patch scales
Typical benthic zones across the outer and inner reef flats of Heron Reef are shown in Figure 3 and Fig. 5.

The typical measured amount of DTM variation or relief across the shallow reef flat was 0.1 m with a maximum value of 0.42 m over areas covered with live coral. The mean area of individual structures detected along the transect was 0.02 m² with a maximum area of 0.46 m².

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, where there were more consistent cover types present. The average values for RMS was 0.04 m, ranging from 0 to 0.09 m. Following a very similar trend along the transect, the average $\xi$ value was 1.87, ranging from 1.07 to 2.98. Finally, the average D value for each tile (mean associated coefficients of determination ($R^2$) for the linear regressions = 0.96) was 2.45, ranging from 2.2 to 2.59 (Fig. 4).

Local values of RMS and $\xi$ appeared to be very high on areas where roughness values are intuitively expected to be low, such as along the lagoonward sandy inner reef flat (vicinity of tile 100, Fig. 1). Conversely, some local values of RMS and $\xi$ appeared very low on areas where roughness values are intuitively expected to be high, such as along the live coral covered outer reef flat (vicinity of tile 1, Fig. 1). This pattern was not observed with D values (for example see dashed lines in Fig. 4). On the contrary, high D values (2.45-2.6) were found on areas where roughness is intuitively expected to be large such as the coral and coral algae benthic substrates.
Lower values of D (2.2-2.4) were observed on less rough benthic substrates such as the inner reef flat covered with algae, rubble and sediment (Fig. 5c and 5d).

4 Discussion

4.1 Production of coral reef digital terrain model (DTM) from close-range photogrammetry

The application of close-range photogrammetry based on Structure-from-Motion (SfM) algorithms resulted in a precise and very-high resolution DTM and orthophoto mosaic of the coral reef flat. The energetic conditions of the reef crest and flat areas during the field survey presented three challenges. First, data collection from energetic and shallow reef environments is extremely challenging due to passage of waves, from wave-breaking conditions on the crest to propagating short period waves on the reef flat (Leon et al., 2013), even for unmanned vessels (Matthew Dunbabin, pers. Comm). However, an experienced snorkeler may be able to efficiently compensate for water oscillations and movement, making this technique appropriate in these environments.

Second, changes in light levels at the benthos, due to passing waves and wave focussing, along with movement of objects due to currents (e.g. soft coral, algae) and moving objects (e.g. fishes) hindered the photo alignment process and precision of final products. A potential solution could be using a frame with strobes in order to standardise the lighting conditions.
Third, the relatively shallow water depth (~2 m) resulted in images with very small footprints (< 1m in width) even when using a wide angle lens. Hence, a large number of photos were required to cover the extent of the transect. This increased computational time but can be resolved by working with different subsets (chunks) of the model (Agisoft LLC., 2013).

Even though only a 250 m long by 1.5 m wide transect was surveyed for the purposes of this study, it is evident the technique developed could be applied to larger reef areas (> km²) with ease due to its simplicity to implement and cost-effectiveness. The construction of a rig with various cameras or deploying multiple snorkeler teams simultaneously could increase coverage without increasing costs considerably.

Based on this study, ~0.002 km² of shallow reef flat can be mapped per hour. In comparison, a ship-based multi-beam (MBES) Sound Navigation and Ranging (SoNAR) system covers ~0.5 km²/hr in intermediate water depths (10-50 m), two orders of magnitude faster, but adding high costs associated with equipment and data processing (Costa et al., 2009). In addition, shallow waters (< 5 m) and breaking waves on reef flats represent a hazard for navigation (Leon et al., 2013). Bathymetric LiDAR systems such as LADS MKII are much faster (~10.1 km²/hr ) and in some cases 6.6 % less expensive than MBES for large areas (10s km²) (Costa et al., 2009). However, even very high scan-rate, state-of-the-art systems, such as the Experimental Advanced Airborne Research LIDAR (EAARL), cannot resolve shallow depths < 2 m or map areas where white-caps are present (Klemas, 2011).
The technique presented in this study is an appropriate approach to generate very-high spatial resolution terrain datasets for shallow and energetic coral reefs. The resultant geospatial products provide a means to assess a previously un-measureable link between marine ecology and geomorphology based on remote sensing (Knudby and LeDrew, 2007). These products can also be integrated and used to semi-automatically classify additional benthic properties (e.g. coral coverage or size-distribution) using techniques such as object-based image analysis (Leon et al., 2012). Furthermore, the technique can be used for rapid response surveys (e.g. after cyclone or bleaching events) and monitoring approaches, providing much needed multispatial, multitemporal scale measurements required to understand processes that affect reef function and structure (Phinn et al., 2012).

4.2 Coral reef roughness

Three different parameters were calculated as proxies for coral reef roughness. Root mean square height (RMS) and tortuosity/rugosity ($\xi$) parameters are commonly used and relatively simple to compute. Both parameters were highly correlated and followed a very similar trend across the surveyed transect. However, values did not correlate with known distribution of coral reef benthic substrates. This can be explained due to the $RMS$ parameter not taking into account the horizontal structure of a surface. The $\xi$ parameter, on the other hand, does not appropriately characterise anisotropy (directional roughness), which is pronounced in the case of reef flats due to wave processes acting mostly in one predominant direction (Bradbury and Young, 1981).
The fractal dimension (D) parameter better characterised reef roughness compared to the other parameters measured, as evidenced by a better agreement with the distribution of coral benthic substrates (Fig. 5). Values of D for different benthic zones were consistent with previously reported values on other coral reef systems (Zawada and Brock, 2009; Zawada et al., 2010).

The fractal analysis presented in this study is the first one to analyse scale-invariant coral reef roughness at the benthic community and biotope/patch scales within shallow reef flats. Results could be used to improve the modelling of hydrodynamic or ecological process. However, further research is required in order to compare the relationships between fractal characteristics of local biotope, benthic and synoptic geomorphic zones within reef systems and across different coral reef regions.

5 Conclusions

The cost-effective methods presented here are readily available, require minimum training and are an appropriate approach for data collection, processing and analysis to generate very-high resolution DTMs and orthophoto mosaics of shallow and energetic coral reefs. The fractal dimension (D) parameter better characterises reef roughness than the root mean square error or rugosity parameters, as evidenced by a better 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 scales (cm-m).
Acknowledgments

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Figure 2: Workflow of methods used to derive the very-high spatial resolution digital terrain model (DTM) and orthophoto mosaic using SfM algorithms and subsequent derivation of roughness parameters.

Figure 3: 3D perspective views of digital terrain models (DTMs) draped with orthophoto mosaics (1 mm spatial resolution) of 4 typical benthic zones with different roughness characteristics: A) Outer reef flat covered with algae, live and dead coral; B) Outer reef flat covered with live coral; C) Outer reef flat covered with algae, coral rubble, live and dead coral; D) Inner reef flat covered with algae, coral rubble and sediment (See Fig. 4 for locations). Horizontal scale varies with perspective but average width of transect is 1.5 m. Vertical scale represents 0.2 m.

Fig. 4: Roughness characterization of transect as a function of length along a 250 m transect. Tile 1 is located to reef crest and tile 100 is closest to inner reef flat (See Fig. 1 for location). Three roughness parameters are shown: Fractal dimension (upper panel), Tortuosity index (middle panel) and Root mean square heights (lower panel).
Fig. 5: Fractal dimension for tiles 1 through 100 along a 250 m coral reef transect shown on benthic community map derived by Phinn et al. (2012). Insets A-D show orthophotos of four typical benthic zones and associated fractal dimension values. Red scale bar on insets represent 1 m.
## Photo alignment parameters

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## Building model texture

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*Table 1*
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Click here to download high resolution image
Figure (BW) 4

Click here to download high resolution image