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Key Points:

- Infragravity waves are larger over the shallow reef platforms than in the adjacent lagoon and channels
- Despite the irregular bathymetry, cross-shore standing waves persist along the entire reef system
- The upcoast and downcoast propagating wave components of oblique infragravity waves generate an alongshore standing wave pattern

Supporting Information:

- Supporting Information S1

Correspondence to:

G. Winter,
gundula.winter@research.uwa.edu.au

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Standing infragravity waves over an alongshore irregular rocky bathymetry

G. Winter^{1,2,3} , R. J. Lowe^{1,2,3}, G. Symonds^{1,2}, J. E. Hansen^{1,2} , and A. R. van Dongeren⁴
¹UWA Oceans Institute, University of Western Australia, Crawley, Western Australia, Australia, ²School of Earth Sciences, University of Western Australia, Crawley, Western Australia, Australia, ³ARC Centre of Excellence for Coral Reef Studies, University of Western Australia, Crawley, Western Australia, Australia, ⁴Department of ZKS and HYE, Deltares, Delft, Netherlands

Abstract Rocky reef coastlines typically feature highly variable and often abrupt cross-shore and along-shore changes in bathymetry. The effects of this irregular rocky bathymetry on the dynamics of infragravity waves are largely unknown. Most models of infragravity wave dynamics have been developed and validated on smooth alongshore-uniform bathymetries, which may break down over these highly variable bathymetries. A 2 week field experiment was conducted on a rocky reef-fringed beach to investigate how the variable bathymetry affects the spatial and temporal variability of infragravity waves. The height of short (sea-swell) waves decreased over the shallow reef due to breaking, whereas the height of infragravity waves increased toward the shoreline. Both during a storm event ($H_{m0} = 2.3$ m) and under moderate wave conditions ($H_{m0} = 1.0$ – 1.8 m), the infragravity waves formed a persistent cross-shore standing wave pattern along the entire shoreline, despite the irregular bathymetry. In addition, the alongshore components of infragravity waves refracted by the presence of the nearshore reef were observed to propagate in opposite directions up and down the coast resulting in a local alongshore standing wave pattern. Thus, the presence of highly variable nearshore bathymetry, which commonly occurs along rocky reef coastlines, may produce both cross-shore and alongshore standing wave patterns.

1. Introduction

Coasts with rocky geologic features are commonly found in all parts of the world [Davis and Fitzgerald, 2004; Vousdoukas et al., 2007]. These features can be composed of a range of materials such as limestone, sedimentary and igneous rock, as well as artificially placed concrete and rubble [Larson and Kraus, 2000]. Rocky reefs are a subcategory of these features and are often characterized by having highly variable cross-shore and alongshore bathymetry. They can be either submerged or partially emerged and may range from shore-attached reef platforms to isolated reefs offshore, often with abrupt steps at the reef platform edges [for a review see Gallop et al., 2011].

It has been demonstrated at a number of field sites globally that rocky reefs close to shore affect the morphology of sandy beaches in their lee [Larson and Kraus, 2000; Sanderson, 2000; Vousdoukas et al., 2007; Gallop et al., 2011]. In addition, studies of submerged breakwaters, with geometries analogous to shore-detached reef platforms, have reported variable beach responses ranging from accretion to erosion [Rana-singhe et al., 2010]. Recent studies have demonstrated that the shoreline response (e.g., beach width) is also dynamic adjacent to rocky reefs [Gallop et al., 2015] and that it differs strongly along the shore [Gallop et al., 2013; Velegarakis et al., 2016]. Thus, reefs cannot be considered to universally offer natural protection from coastal erosion. In order to understand this shoreline variability, it is essential to first understand how the hydrodynamic processes are affected by the presence of a rocky reef. As studies on sandy beaches have revealed how low-frequency infragravity waves (waves with periods between 30 and 250 s) play an important role in coastal erosion processes [e.g., van Thiel de Vries et al., 2008], in this manuscript we assess how infragravity waves may be modified along a rocky reef coastline.

Infragravity waves have been most rigorously studied on sandy beaches with mostly alongshore uniform bathymetries. They were first attributed to forced motions induced by short (sea-swell waves with periods between 3 and 30 s) wave groups, which were believed to be released in shallow water [Tucker, 1950;

Longuet-Higgins, 1962]. Hasselmann [1961] showed that infragravity waves are generated at a wave group scale through nonlinear interactions among shortwave components. Over mild beach slopes this process is positively reinforced in the shortwave shoaling zone due to an increasing phase lag between these so-called “bound” infragravity waves and the incident wave groups, which allows more energy to be transferred from the short to the infragravity waves [Battjes *et al.*, 2004]. In contrast, on steeper slopes infragravity waves have been found to be predominantly generated in the outer surf zone by a time-varying breakpoint mechanism [Symonds *et al.*, 1982; Baldock, 2012]. In both cases, the infragravity waves become free waves inside the surf zone, where they may dissipate due to bottom friction [Pomeroy *et al.*, 2012], nonlinear energy transfer back to the short waves [Henderson *et al.*, 2006; Thomson *et al.*, 2006; Péquignot *et al.*, 2014], infragravity wave breaking [Battjes *et al.*, 2004; van Dongeren *et al.*, 2007; de Bakker *et al.*, 2014] or a combination of nonlinear energy transfer and breaking [Ruju *et al.*, 2012].

When dissipation is weak, incident infragravity waves may be reflected at the shoreline and may appear as cross-shore standing waves that have a cross-shore variable wave height related to the nodes and antinodes of the standing wave pattern [Suhayda, 1974]. However, the cross-shore nodal structure of these standing “leaky” waves is almost indistinguishable from the nodal structure of edge waves with modes larger than zero [Guza, 1974]. Edge waves are defined as refractively trapped infragravity waves that are similarly generated by nonlinear sea-swell wave interactions [Gallagher, 1971] or an alongshore time-varying breakpoint [Lippmann *et al.*, 1997]. On beaches, edge wave energy tends to be largest near the shoreline, because the amplitude of an edge wave decays exponentially seaward [Huntley *et al.*, 1981]. Huntley and Bowen [1973] were the first to suggest the existence of edge waves within the infragravity frequency band in the field with a single cross-shore array of instruments. However, it was not until alongshore instrument arrays were used, that unambiguous measurements of edge waves could be confirmed by assessing alongshore wavenumber-frequency spectra [Huntley *et al.*, 1981; Oltman-Shay and Guza, 1987]. In fact, laboratory [Bowen and Guza, 1978] and field [Holman, 1981] measurements suggest that infragravity wave motions in the surf zone at alongshore uniform sandy beaches may predominantly be composed of edge waves, unless waves are narrowly spread and normally incident, which is infrequent in nature. How these infragravity wave patterns differ in a highly variable rocky reef bathymetry remains unclear.

Rocky reefs share some similar morphological characteristics with coastal rock platforms and fringing coral reefs that also have highly variable bathymetry and steep bathymetry gradients; however, studies of rock platforms have tended to focus on alongshore uniform sites and coral reefs are often orders of magnitude larger (in both distance from shore and alongshore extent). While recent studies have highlighted the importance of infragravity waves on rock platforms [Beetham and Kench, 2011; Marshall and Stephenson, 2011; Ogawa *et al.*, 2015], infragravity waves have been studied more extensively in coral reef environments. In both environments, the shallow submerged structures have been shown to act as an effective filter of shortwave energy, so that infragravity waves often dominate near the shore or inside the lagoon of coral reefs [Kench, 1998; Lugo-Fernández *et al.*, 1998; Farrell *et al.*, 2009; Ogawa *et al.*, 2011; Pomeroy *et al.*, 2012]. Infragravity waves may also resonate in coral reef environments, when the width of the reef is an odd multiple of a quarter of the infragravity wavelength, which can lead to the amplification of cross-shore standing infragravity waves [Becker *et al.*, 2016; Gawehn *et al.*, 2016], and in turn can drive coastal inundation [Péquignot *et al.*, 2009; Cheriton *et al.*, 2016]. Importantly, in both rocky platform and coral reef environments, much of what is known about infragravity waves has been derived from quasi-alongshore uniform environments [Pomeroy *et al.*, 2012; Péquignot *et al.*, 2014; Ogawa *et al.*, 2015] that do not consider the effect of large bed level gradients over short (order ~ 100 m) alongshore and cross-shore distances that typically characterize rocky reef environments. Consequently studies on rock platforms and coral reefs have focused solely on infragravity wave height transformation in the cross-shore direction assuming alongshore uniformity.

In this paper, we investigate how infragravity wave transformation is affected by a rocky reef with alongshore variable bathymetry. The objectives of this study were to: (1) assess the relative importance of short waves and infragravity waves over a rocky reef bathymetry, (2) to identify the spatial infragravity wave height variability, and (3) to investigate the propagation pattern of infragravity waves (i.e., whether they are standing or progressive). In section 2, the field experiment is described, including an overview of the field site, the instrumentation deployed, and the data analysis methods. The results of the experiment are then

presented in section 3. The observed infragravity wave height distribution and its relation to infragravity standing wave patterns are discussed in section 4.

2. Field Experiment and Methods

2.1. Field Experiment and Site Description

An approximately 2 week field experiment was conducted during the austral winter (22 May to 7 June 2014) along a ~ 500 m stretch of coastline at Garden Island in southwestern Australia (Figure 1a). At this location, shallow limestone reef platforms predominantly covered by macroalgae front a sandy shoreline, which is exposed to seasonally variable wave energy. The study area includes a shore-attached reef platform that is flanked to the south by both a lagoon and a seaward oriented channel, and to the north by a shore-detached reef and a second seaward channel (Figure 1c). The central reef platform rises from 5 m

Figure 1. (a) Location of the field site in southwestern Australia. (b) Location of wave gauges (Nortek AWACs) A1 and A2 offshore of the reef in 10.5 and 8 m water depth, respectively. (c) Instrumentation within the reef and bathymetry (colors indicate bed level below AHD). The reef platforms are outlined in orange and isobaths (at 1 m depth interval) are plotted in black. The reef platforms are typically ~ 1 m deep, the lagoon ~ 2 –3 m, and the channels ~ 5 m. The colored symbols indicate the locations of the instruments (see Table 1 for the instrument depth and sampling regime at each site). The gray lines mark the alongshore bathymetry transects presented in Figure 1d.

Table 1. Instrument Sampling Regime^a

Site	Instrument	Depth	Sampling Regime
Offshore			
A1	Nortek AWAC	10.5 m	Pressure and surface velocities in hourly bursts of 2048 s at 2 Hz, velocity profile hourly in 0.5 m bins
A2	Nortek AWAC	7.9 m	
Northern Channel			
CN2	Nortek Aquadopp (ADP)	5.5 m	Pressure and velocity profile at 0.033 Hz continuous in 0.25 m bins
Southern Channel			
CS2	Nortek ADP High Resolution (HR)	3.1 m	Pressure and velocity profile at 1 Hz continuous in 0.05 m bins
CS4	RDI ADCP	5.4 m	Pressure and velocity profile at 1 Hz continuous in 0.1 m bins
Central Reef Platform			
R1	RBR Virtuoso	1.1 m	1 Hz continuous
R2	Nortek ADV	1.2 m	2 Hz continuous
R3	RBR Virtuoso	0.8 m	1 Hz continuous
R4	Nortek ADV	1.0 m	2 Hz continuous
R5	Nortek ADV	1.2 m	
R6	RBR Virtuoso	1.6 m	1 Hz continuous
R7	RBR Virtuoso	5.2 m	
Northern Reef Patch			
N1	RBR Virtuoso	1.4 m	1 Hz continuous
N2	RBR Virtuoso	1.5 m	
N3	RBR Virtuoso	2.0 m	
N4	RBR Virtuoso	2.2 m	
N5	RBR Virtuoso	2.8 m	
N6	RBR Virtuoso	3.7 m	
N7	Nortek ADP HR	2.2 m	See description for CS2
Southern Lagoon			
S1	RBR Virtuoso	1.5 m	1 Hz continuous
S2	RBR Virtuoso	2.0 m	
S3	RBR Virtuoso	0.9 m	
S4	RBR Virtuoso	2.3 m	
S5	RBR Virtuoso	1.8 m	
S6	RBR Virtuoso	0.8 m	
S7	Nortek ADV	2.3 m	2 Hz continuous

^a"A" denotes offshore instruments, CN and CS instruments in the northern and southern channel respectively, "R" instruments on the reef platform, "N" north of it and "S" south of it.

depth offshore at an average slope of 1:40 to a flat platform with a mean still water depth of 0.75 m below Australian Height Datum (AHD, approximately equal to mean sea level; Figure c). The sandy shoreline features a seasonally variable salient in the lee of the reef platform that extends seaward during summer when wave energy is lowest. Approximately 100 m north of the central reef platform is another reef patch of ~1 m depth that stretches 160 m in the cross-shore and 60 m in the alongshore. The lagoon to the south of the central platform is 2–3 m deep (Figure 1c) and is fringed by a reef of ~1 m depth. The major channels to the north and south that bound this group of reefs are each ~100 m wide. The arrangement of reef platforms and channels results in a highly variable alongshore bathymetry with bed level differences of ~3 m over a distance of 150 m alongshore (Figure 1d).

2.2. Instrument Layout

An array of pressure sensors, current meters, and current profilers were deployed within and offshore of the reef system (Figure 1c). This included 18 pressure sensors (RBR Virtuoso) organized into a two-dimensional array that spanned the reefs, channels, and lagoon (R1, R3, R6, R7, N1–6, and S1–6 in Figure 1c). Three acoustic Doppler velocimeters (ADV, Nortek Vector) were deployed at R2, R4, and R5 in a cross-shore array on the central reef platform, and one ADV was deployed in the southern lagoon at S7 to the south of the central reef platform. During low tide, the ADV at R5 occasionally emerged as wave troughs passed over this location and thus the velocity data were excluded during these times.

A current profiler (Nortek Aquadopp HR) was placed at N7 in a small depression between the central reef platform and the northern reef patch. In the northern channel, a Nortek Aquadopp Profiler (ADP) was deployed at CN2. Due to a storm event during the early part of the experiment, this instrument was partially buried and data were unusable after 25 May 2014. Two current profilers were also placed in the southern main channel: an ADP at CS2 at the shoreward end, and an RD Instruments Acoustic Doppler Current Profiler (ADCP) at CS4 at the seaward end of the channel. Incident waves were measured with two Acoustic

Wave and Current profilers (Nortek AWAC) at A1 and A2 in 10.5 and 8.0 m water depth at a distance of 1100 and 450 m from the shoreline, respectively (Figure 1b).

The bathymetry was surveyed in 2009 using an aerial LiDAR system with 5 m horizontal resolution and ± 0.45 m vertical accuracy [Department of Transport, 2009]. A detailed survey using a single beam echosounder and RTK-GPS system fitted to a small boat was also conducted during the experiment. The shoreline position was surveyed every second day throughout the experiment with a backpack mounted RTK-GPS system with a complete subaerial beach survey conducted immediately following the experiment. The uncertainty of the bathymetric surveys and subaerial beach surveys is estimated at 0.1 m [MacMahan, 2001] and 0.05 m, respectively [Barnard et al., 2012].

2.3. Data Analysis

2.3.1. Infragravity Wave Heights

To assess the relative importance of short and infragravity waves, the significant wave heights were computed from pressure data that were corrected for atmospheric pressure and converted to surface elevation using linear wave theory [Tucker and Pitt, 2001]. Spectra were estimated over 4 h data segments using a Hamming window of 1024 s length with 50% overlap. This resulted in 71 degrees of freedom and a frequency bandwidth of 0.001 Hz. Significant wave heights H_{m0} were calculated from the variance density spectra S for both the short and infragravity frequency (f) bands as [Holthuijsen, 2007]:

$$H_{m0} = 4 \sqrt{\int_{f_{lower}}^{f_{upper}} S(f) df} \quad (1)$$

with $f_{lower} = 0.035$ Hz and $f_{upper} = 0.3$ Hz for the short waves and $f_{lower} = 0.004$ Hz and $f_{upper} = 0.035$ Hz for the infragravity waves. The frequency cutoff between the short and infragravity waves (0.035 Hz) was set at half of the peak frequency in the total energy spectrum averaged over the experiment period [Wilson, 1966]. Mean wave direction and directional spreading were estimated from the Fourier coefficients of the frequency-directional spectra [Kuik et al., 1988].

2.3.2. Phase Lag Analysis

To assess the infragravity wave propagation patterns at the field site, the phase lags between two instruments in a cross-shore transect were analyzed to identify the presence of cross-shore standing wave nodes. The phase lag (ϕ) was calculated from the cospectrum and quadrature spectrum (C_{ij} and Q_{ij} , respectively) that contribute to the cross spectrum between two given instruments i and j [Emery and Thomson, 2014]:

$$\phi_{ij}(f) = \tan^{-1} \left[\frac{-Q_{ij}(f)}{C_{ij}(f)} \right] \quad (2)$$

Cross spectra were estimated from 4 h data segments using a Hamming window of 2048 s length with 50% overlap resulting in 35 degrees of freedom and a bandwidth of 0.0005 Hz. Results were significant at a 95% confidence level when the cross coherence exceeded 0.17. Signals between the instruments that are in phase or antiphase indicate the existence of standing waves in the cross shore [Péquignat et al., 2009] (see also Table 2). Instruments that are in phase (antiphase) have an even (odd) number of cross-shore nodes between them. Cross-shore nodes can be a feature of standing leaky or edge waves.

Table 2. Phase Relationships Between Infragravity Surface Elevation and Horizontal Velocities, Which Aid in the Distinction Between Leaky Infragravity Waves and Edge Waves (for Background on the Theoretical Basis for These Phase Relationships See Supporting Information, Ursell [1952], Huntley and Bowen [1973], Suhayda [1974], Huntley [1976], Holman [1981], and Péquignat et al. [2009])

Phase Relationships	Leaky Infragravity Waves			Edge Waves	
	Cross-Shore and Alongshore Progressive	Cross-Shore Standing, Alongshore Progressive	Cross-Shore and Alongshore Standing	Progressive (Cross-Shore Standing, Alongshore Progressive)	Standing (Cross-Shore and Alongshore Standing)
Instruments in a cross-shore array	Nonconstant	0° or $\pm 180^\circ$	0° or $\pm 180^\circ$	0° or $\pm 180^\circ$	0° or $\pm 180^\circ$
Instruments in an alongshore array	Nonconstant	Nonconstant	0° or $\pm 180^\circ$	Nonconstant	0° or $\pm 180^\circ$
u and v	0° or $\pm 180^\circ$	$\pm 90^\circ$	0° or $\pm 180^\circ$	$\pm 90^\circ$	0° or $\pm 180^\circ$
η and u	0°	$\pm 90^\circ$	$\pm 90^\circ$	$\pm 90^\circ$	$\pm 90^\circ$
η and v	0°	0°	$\pm 90^\circ$	0°	$\pm 90^\circ$

To assess the contribution of edge and leaky waves to the total infragravity wave energy, usually frequency-alongshore wave number ($f-k_y$) spectra would be employed, as in the case of relatively alongshore uniform beaches [Huntley *et al.*, 1981]. This method requires stationary conditions both in time and space (along the coast). However, the conditions at our study site are not stationary in space, because the alongshore wave-number would change over the highly variable bathymetry and thus $f-k_y$ spectra are not applicable. Instead, we assessed the types of infragravity waves within the reef system based on the phase relationships between water levels and horizontal velocities at individual instrument sites (refer to the summary in Table 2 and the more detailed discussion of the methodology in the supporting information, Ursell [1952], Huntley and Bowen [1973], Suhayda [1974], Huntley [1976], Holman [1981], and Péquignot *et al.* [2009]). The horizontal velocities were rotated using a principal component analysis so that the shore-normal velocity (u) aligned with the major infragravity wave direction, deviating between -23° and $+9^\circ$ from the east-west axis for the sites considered, and the alongshore velocity (v) was rotated 90° counterclockwise from the shore-normal. For cross-shore standing and alongshore progressive waves (including progressive edge waves), the phase lag between cross-shore and alongshore velocities (as well as cross-shore velocity and surface elevation) is 90° . Conversely, for cross-shore progressive leaky waves and cross-shore and alongshore standing waves (including standing edge waves) the phase lag is either 0° or $\pm 180^\circ$ between cross-shore and alongshore velocities (or cross-shore velocity and surface elevation, respectively) [Huntley and Bowen, 1974]. The phase lag between alongshore velocity and surface elevation is 0° for alongshore progressive waves and $\pm 90^\circ$ for alongshore standing waves. In the presence of alongshore standing waves, surface elevations and alongshore velocities are either 0° or $\pm 180^\circ$ out of phase between alongshore separated instruments.

2.3.3. Infragravity Wave Reflection

For infragravity waves to be standing in the shore-normal direction, the dissipation of these waves needs to be weak and reflection at the shoreline needs to be strong. This reflection coefficient may be estimated as the ratio of incoming and outgoing shore-normal fluxes [Sheremet *et al.*, 2002]

$$R^2 = \frac{F_{x,IG}^-}{F_{x,IG}^+} \quad (3)$$

where the incoming and outgoing infragravity energy fluxes are calculated as follows by integrating over the entire infragravity energy band:

$$F_{x,IG}^\pm = \sqrt{gh} \int_{f=0.004}^{0.035} \frac{1}{4} \left[S_{\eta\eta}(f) + \frac{h}{g} S_{uu}(f) \pm \sqrt{\frac{h}{g}} S_{\eta u}(f) \right] df \quad (4)$$

Here g is the acceleration due to gravity, h is the mean water depth, $S_{ij}(f)$ is the cross-spectral or autospectral estimate of the variables x_i and x_j , which can either be the water surface elevation η or the shore-normal or alongshore velocity (u or v). Cross spectra were estimated using the same spectral parameters as outlined above. Using only the linear energy fluxes was justified, because the nonlinear energy fluxes calculated following Henderson *et al.* [2006] were small ($<7\%$ of the net linear fluxes). As the reflection coefficient only contains the shore-normal component of the incoming and outgoing infragravity energy fluxes, it accounts only partially for infragravity waves that are incident or reflected under an angle with the shore-normal. This will have an effect on the reflection coefficient, when the incident wave angle differs strongly from the outgoing wave angle.

2.3.4. Spatial Pattern Analysis

To assess the two-dimensional variability of the observed water level variance across the reef system at N1–7, R1–6, and S1–7 (Figure 1c), we conducted an empirical orthogonal function (EOF) analysis, which has been previously applied in the analysis of cross-shore infragravity wave patterns [Péquignot *et al.*, 2009; Becker *et al.*, 2016]. The mean and linear trends of 4 h data segments were removed and subsequently the data were bandpass-filtered to include only the lower infragravity frequencies from 0.004 to 0.025 Hz. Infragravity frequencies above 0.025 Hz have been omitted because these contained only a minimal amount of the infragravity potential energy and the subsequent spatial interpolation is more accurate for longer wavelengths. The filtered signals were interpolated onto a 30×30 m grid using the objective mapping method [Emery and Thomson, 2014] with a maximum separation distance of 60 m between grid point and instrument location. The EOF analysis decomposes the surface elevation time series $\eta_m(t)$ at each grid point m

into a spatially variable i th orthogonal mode ψ_{im} and its temporally varying amplitude $a_i(t)$, where the total number of modes M equals the number of grid points [Emery and Thomson, 2014]:

$$\eta_m(t) = \sum_{i=1}^M [a_i(t) \psi_{im}] \quad (5)$$

Standing wave nodes would appear as a change from positive to negative values in the spatial EOF modes.

To further explore the presence of standing waves, we qualitatively assessed how the transfer function, describing the ratio of the cross-spectral amplitude between the offshore site A1 and inshore sites to the autospectrum at the offshore site, varied spatially. Standing wave nodes would cause locally low amplification of the infragravity wave signal relative to offshore. The transfer function is defined as [Emery and Thomson, 2014]:

$$|H_{01}(f)| = \frac{|C_{01}^2(f) + Q_{01}^2(f)|^{1/2}}{S_{00}(f)} \quad (6)$$

where $C_{01}(f)$ and $Q_{01}(f)$ are the cospectrum and quadrature spectrum between the records at sensor 0 (offshore) and 1 (inshore) and $S_{00}(f)$ is the autospectrum at the offshore sensor. Because the offshore sensor was chosen to be the AWAC at A1, which sampled in hourly 34 min bursts at 2 Hz, the cross spectra were calculated using four consecutive 34 min bursts consisting of three 1024 s long windows each. The spectral estimates of these consecutive bursts were averaged so that the resultant estimate had 40 degrees of freedom and a frequency bandwidth of 0.001 Hz. This averaging decreased the absolute value of the transfer function slightly, but it greatly improved the confidence interval, so that results were significant at a 95% confidence level when the coherence exceeded 0.15.

3. Results

3.1. Environmental Conditions and Wave Height Transformation

The study area is microtidal with tidal water levels ranging from -0.1 m below to 0.6 m above Australian Height Datum (AHD) during the experiment (Figure 2a). Incident significant wave heights at A1 (at 10.5 m depth) ranged between 0.7 and 2.3 m, with a mean value over the experiment of 1.1 m (Figure 2b). The largest waves were recorded during a storm on 24 May where wind speeds exceeded 15 m s^{-1} and a wave buoy located offshore from the continental shelf 30 km to the northwest (32.10°S , 115.40°E) recorded significant wave heights of 6 m. Refraction and dissipation over the continental shelf reduced the wave height to 2.3 m on the inner shelf at A1. During the remainder of the experiment, the peak wave period ranged between 7 and 20 s (Figure 2c) and waves approached the coast predominantly from 265°N (Figure 2d) with a directional spreading between 20° and 35° (Figure 2e). The analysis

Figure 2. Offshore wave and water level conditions measured at A1 (at 10.5 m depth). (a) Water level relative to AHD, (b) significant sea-swell wave height, (c) peak period, (d) peak direction, and (e) peak directional spreading.

Figure 3. (a) Significant shortwave height and (b) significant infragravity wave height at R1 (near the shoreline) and R7 (seaward edge of the reef platform). (c) Significant sea-swell wave height and (d) significant infragravity wave height during the storm condition (black line in Figures 3a and 3b).

that follows will largely focus on the storm condition on 24 May at 8:00 A.M., but the manuscript will also assess the persistence of observed infragravity wave patterns during moderate conditions.

The largest infragravity waves were observed on the reef platform during the storm condition (Figure 3b), when also the largest short waves were recorded on the forereef at R7 (Figure 3a). The shortwave heights decreased from the outer reef (site R7 at ~5 m depth) to the shoreline, with the largest wave height reduction across the central reef platform (Figure 3c). In contrast, the infragravity wave heights first decreased and then increased toward the shoreline over the central reef (Figure 3d). Across the lagoon, infragravity wave heights were smaller than on the reef platform and the reef patch to the north.

The cross-shore wave height transformations were examined in more detail across the central reef platform. During storm conditions, the sea-swell wave height increased from A2 to R7 and then decayed toward the

Figure 4. (a) Bed elevation and instrument locations across the central reef platform and (b) significant sea-swell (blue) and infragravity (green) wave heights during the storm condition.

shoreline due to wave breaking (Figure 4b, blue markers). The infragravity wave height also increased from A2 to R7, decreased slightly to R3 and finally increased again to a maximum at R1 near the shoreline (Figure 4b, green markers).

The spectral wave transformation across the central reef platform was evaluated by means of the potential wave energy at the pressure sensors (R1, R3, R6, and R7) and by means of the potential and kinetic energy at the sites with collocated velocity meters and pressure sensors (R2, R4, and R5). Potential wave energy in the shortwave band (0.035–0.3 Hz) decreased from R7 (offshore) to R1 (near the shoreline), while potential energy in the infragravity wave band (0.004–0.035 Hz) first increased at R6, then decreased at R3 and finally increased again to dominate the energy density spectrum at R1 near the shoreline during the storm condition (Figure 5a). The potential energy density spectrum was dominated by short waves with a peak frequency of $f_p = 0.07$ Hz at R7 on the forereef. Shoreward from that site, the spectrum was dominated by potential infragravity wave energy, which peaked at 0.008, 0.014, and 0.018 Hz at R1 (Figure 5a). Not all of these peaks were observed at the remaining instruments, e.g., at R3 the potential energy was much lower around 0.014 and 0.018 Hz; this isolated decrease at R3 is investigated further in section 3.2. At R4 and R5, the potential energy was low and dipped at around $f \sim 0.018$ Hz at R4 (Figure 5c, blue line) and at around $f \sim 0.01$ Hz at R5 (Figure 5d, blue line), while the cross-shore kinetic energy density was high around $f \sim 0.018$ Hz at R4 and at around $f \sim 0.014$ Hz at R5 (Figures 5c and 5d, green line). This suggests the existence of a surface elevation node and cross-shore velocity antinode near R4 and R5 near the respective frequencies. At R2, the alongshore and cross-shore kinetic energy were of similar magnitude at 0.015 Hz and above. Energy in the alongshore velocity spectra at R4 and R5 was smaller than in the cross-shore velocity spectra and was equally distributed over all frequencies without any significant peaks (Figures 5b–5d, red line).

3.2. Cross-Shore Infragravity Wave Propagation Patterns

Spectral phase lags for the surface elevations and velocities between R2 and R5 were computed to further assess if infragravity waves in the cross-shore direction were standing or progressive. From Table 2, a constant phase lag in time of either 0° or $\pm 180^\circ$ indicates a standing wave pattern, with a phase lag of $\pm 180^\circ$ indicating the presence of an odd number of cross-shore nodes between instruments and a phase lag of 0° indicating an even number of cross-shore nodes between instruments. During the storm, water levels were 180° out of phase around 0.02 Hz (Figure 6d), while cross-shore velocities were in phase on the reef platform (0° , Figure 6e); thus suggesting that a surface elevation node and a cross-shore velocity antinode occurred between R2 and R5. From 0.01 to 0.017 Hz the phase between surface elevations was linearly

Figure 5. (a) Potential energy spectra for a 4 h window during the storm condition at R1, R3, R6, and R7. R7 is located at the reef edge and R1 near the shoreline. All instruments are in the cross-shore transect across the central reef platform. The vertical black line indicates the infragravity cutoff frequency 0.035 Hz. (b–d) Potential (η) and shore-normal (u) and alongshore (v) kinetic energy spectra for a 4 h window during the storm condition at (b, near the shoreline) R2, (c) R4, and (d) R5. Please note the different frequency range in Figure 5a.

changing, which may indicate a partially standing and partially progressive wave. However, the surface elevation (potential energy) spectrum was low around 0.01 Hz at R5 due to a possible standing wave node, which may have decreased the accuracy of the phase lag calculation for this frequency range. The phase lag between surface elevations at sites R1 and R6, which were located further away from potential standing wave nodes, was closer to 180° from 0.01 to 0.02 Hz (blue markers in Figure 7). When comparing these results over the entire experimental record, we find that the phase lags were remarkably consistent, with only the frequency of phase jumps being slightly modulated on a tidal time scale (Figures 6a and 6b for the central reef platform, others not shown). The phase lag was also 0° or $\pm 180^\circ$ in the remaining cross-shore transects both north and south of the central reef platform (Figure 7), which indicates that the cross-shore nodal pattern was not only persistent in time, but also along the shore.

To form a cross-shore standing wave pattern, the incoming and outgoing infragravity wave energy need to be of equal magnitude, i.e., the reflection coefficient R^2 needs to be close to 1, which was the case ($0.75 \leq R^2 \leq 1.25$) at R2 (near the shoreline) and A2 (on the inner shelf) for the entire experiment period (Figure 6c). During larger wave conditions and particularly during the storm, the reflection coefficient R^2 occasionally dropped to 0.5, which indicates that waves may have been partially standing and partially progressive at A1 and R5. However, we also emphasize that the infragravity energy fluxes are separated along the shore-normal direction, and energy fluxes of obliquely incident and reflected infragravity waves are partially contained within the cross-shore and alongshore fluxes. Thus, unless the incident and reflected wave angle are equal, changes in the reflection coefficient may not solely be caused by energy gain or dissipation in the infragravity wave band, but also by wave refraction.

Figure 6. Frequency versus time of phase lags (colors) between sites R2 and R5 on the reef platform of (a) surface elevations and (b) cross-shore velocities. Phase lags are only shown where coherence is above the 95% confidence level. Phase lags for the storm condition (black line in Figures 6a and 6b) for (d) surface elevations and (e) cross-shore velocities. (c) Time series of the reflection coefficient R^2 (equation (3)) across the reef platform at A1 (offshore), A2, R5, R4, and R2 (near the shoreline). The error of the reflection coefficient R^2 was estimated to be smaller than 4% [Sheremet *et al.*, 2002].

3.3. Two-Dimensional Infragravity Wave Variability

To investigate the potential existence of standing wave motions, we calculated the first two EOF modes (equation (5)), which together accounted for 76% of the total variance of the surface elevation during the storm condition. The first mode (accounting for 57% of the total variance) displayed the characteristics of a cross-shore standing wave with a sign change along a transect from N2 over R5 to S7 (Figure 8a) and a peak frequency in the first EOF mode energy at 0.014 Hz (Figure 8c, blue line), consistent with the peak frequency of the potential infragravity energy. The second mode (19% of the total variance) displayed the characteristics of an alongshore standing wave with a node along the axis of the central reef platform (Figure 8b). The amplitude variance of the second mode was high between 0.013 and 0.022 Hz (Figure 8c, green line) consistent with elevated alongshore kinetic energy at these frequencies at R2 on the reef platform. During the moderate wave condition on 30 May at 10:00 am the spatial EOF modes and amplitudes were similar (Figures 8d–8f).

To further investigate the spatial variability of infragravity waves, we computed the transfer function between the offshore and inshore instruments using equation (6). To isolate the distinct nodal wave pattern displayed by the first EOF mode, the transfer function was integrated over the frequency band between 0.013 and 0.016 Hz, which contained the peak of the potential infragravity energy and the peak amplitude variance of the first EOF mode. In this frequency band, the infragravity wave amplification decreased along an alongshore transect from N2 through R5 to S7 (dashed line in Figure 9); however, the energy was amplified onshore and offshore of this transect. The cross-shore pattern of strong and weak amplification is consistent with the first EOF mode (Figure 8a) and corresponds to a wavelength of approximately 300 m at 0.014 Hz. This wavelength is consistent with shallow water wave theory of a wave traveling in 2 m depth, which is close to the mean water depth between R7 and R1 corrected for the tidal elevation and wave setup estimated following Lowe *et al.* [2009]. At frequencies above 0.017 Hz the amplitude variance of the first and second EOF mode was not significantly different at a 95% confidence interval (Figure 8c) and thus the transfer function was not consistent with either of the first two EOF modes.

Figure 7. Phase lags between surface elevations in selected cross-shore transects on (R1, R6), north of (N1, N3) and south of (S4, S6) the central reef platform as well as in the southern channel (CS2, CS4) for the storm condition. The vertical lines mark the phase jumps that were derived from linear wave theory in a one-dimensional model of standing waves over the respective cross-shore bathymetry transects. The black dashed line marks the frequency $f = 0.014$ Hz that was used for the linear wave theory model presented in Figure 12.

shore velocity node south of the reef platform (Figure 11c). The existence of an alongshore velocity node in the lagoon was further supported by the low alongshore kinetic energy at S7 (not shown). The alongshore velocity node and the surface elevation node of an alongshore standing wave are separated by a quarter of the alongshore wavelength and thus the location of this node is consistent with the pattern of the second EOF mode (Figure 8b). Between the reef platform (R2) and the reef patch to the north of it (N7), the phase between alongshore velocities was around 0° for frequencies between 0.01 and 0.02 Hz, which does not allow for identification of the wave pattern, but it was close to $+180^\circ$ at 0.025 Hz and above (Figure 11d). Again, these phase relationships were persistent throughout the experiment including the storm event and moderate wave conditions (Figures 11a and 11b).

4. Discussion

Infragravity waves have previously been studied in relatively alongshore-uniform environments such as sandy beaches [e.g., Guza and Thornton, 1985] and fringing coral reefs [e.g., Péquignot et al., 2014]. This study presents new quantitative insight into the impact that an alongshore-irregular bathymetry has on the relative importance of infragravity waves compared to short waves, the spatial distribution of infragravity wave heights and the infragravity wave propagation patterns.

The study site consisted of a shore-attached reef platform with an adjacent lagoon and patch reefs. Short and infragravity waves were transformed differently within these two regions. Over the shore-attached reef, short waves gradually dissipated due to depth-induced breaking, as observed in other shore-attached reef and rock platform studies [e.g., Farrell et al., 2009; Vetter et al., 2010; Ogawa et al., 2011]. However, across the lagoon transects, the short waves initially decreased over the reef platform and then remained constant

To assess whether the cross-shore nodal structure and the EOF modes were related to alongshore progressive or alongshore standing waves, the phase relationships between surface elevation and horizontal velocity components were calculated via cross-spectral analysis. During the storm, the cross-shore and alongshore velocities were in antiphase ($\pm 180^\circ$, Figure 10d), while surface elevation and cross-shore velocity, as well as surface elevation and alongshore velocity, were in quadrature ($\pm 90^\circ$) within the frequency band from 0.01 to 0.02 Hz (Figures 10e and 10f). This phase signature, which persisted throughout the experiment (Figures 10a–10c), is consistent with the phase lags of a cross-shore and locally alongshore standing wave pattern or a standing edge wave (see Table 2).

The phase relationships between alongshore velocities at sites along the shore were calculated to further investigate the potential for standing wave variability in the alongshore. From the lagoon south of the reef platform (S7) to the reef platform (R2), the phase was around $+180^\circ$ for frequencies between 0.01 and 0.02 Hz suggesting the existence of an alongshore standing wave pattern with an along-

Figure 8. The (a) first and (b) second EOF modes (equation (5)) of the spatially interpolated surface elevation that together explain 76% of the total variance of the water surface between 0.004 and 0.025 Hz during the storm condition. (c) Amplitude spectra of the first two EOF modes during the storm condition. (d–f) The same as in a–c) during a moderate wave condition on 30 May. The black circles in Figure 8a, 8b, 8d, and 8e mark instrument locations.

inside the deeper lagoon area, which is similar to fringing coral reefs with lagoons [Gourlay, 1994; Pomeroy *et al.*, 2012].

In contrast, the infragravity wave height increased over the shore-attached reef platform and was similar to the shortwave height near the shoreline, consistent with observations at sandy beaches [e.g., Guza and Thornton, 1985; Ruessink, 1998; de Bakker *et al.*, 2014] and over rock platforms [Beetham and Kench, 2011; Ogawa *et al.*, 2011, 2012, 2015]. In the lagoon, the infragravity waves were smaller than on the reef and remained smaller than the short waves. In contrast to larger-scale coral reef morphologies, where infragravity waves can be significantly reduced in height due to frictional losses when they propagate across an extensive reef flat and lagoon [Pomeroy *et al.*, 2012], the infragravity wave reflection coefficients were high over the rocky reef bathymetry.

Infragravity waves were generally larger over the shallow reef platforms than inside the lagoon, which may be due to infragravity wave shoaling [van Dongeren *et al.*, 2007]. In addition, infragravity waves may refract around the shallow reef structures to focus on the central reef platform. An analogous behavior of infragravity waves has been observed over a complex bathymetry on the southern California inner shelf, which was attributed to refraction and reflection off submarine canyons [Thomson *et al.*, 2007].

Infragravity wave heights also varied in the cross shore across the reef platform; they were largest near the salient and at the seaward edge of the reef platform, while slightly smaller at the center of the platform. This wave height reduction and subsequent amplification near the shoreline is not attributed to wave refraction and shoaling, but rather to a cross-shore standing wave pattern with a surface elevation node on the reef platform.

Figure 9. Transfer function between surface elevation at A1 and the nearshore instrument sites (equation (6)) between 0.013 and 0.016 Hz for the storm condition. The dashed line connects instruments with the lowest transfer function in the respective cross-shore transects.

4.1. Standing Wave Patterns

The strong reflection of infragravity wave energy ($R^2 > 0.75$ at R2, R4, and A1) allows for the formation of cross-shore standing waves. Surface elevation nodes of these waves persisted along the reef in the infragravity wave band between 0.01 and 0.02 Hz where the infragravity wave energy was largest. The presence of these nodes can explain the reduction in the transfer function magnitude along the instrument transect from site N2 (north of the central reef platform) over R5 (on the reef platform) to S5, which were approximately equidistant from the shoreline. The amplification of the infragravity wave energy onshore, and particularly offshore of this transect, is related to the standing wave pattern. Shoaling and refraction alone would only cause the infragravity waves to be amplified on the reef platform and near the shoreline.

At A2 and R5 reflection was weaker, particularly during the storm ($R^2 = 0.5$ at R5 and A2), which suggests that waves may have been only partially standing in the cross shore. This is consistent with the nonconstant phase lag between surface elevation at R2 and R5, but inconsistent

Figure 10. Phase lags at R2 on the reef platform between (a) cross-shore and alongshore velocities, (b) surface elevation and cross-shore velocity as well as (c) surface elevation and alongshore velocity. The phase is calculated for 4 h blocks and shown in white where the coherence drops below the 95% level. (d–f) The corresponding phase lags during the storm condition (black line in Figures 10a–10c).

Figure 11. Frequency versus time of phase lags (colors) between alongshore velocity at alongshore separated sites (a) S7 in the lagoon and R2 on the reef platform and (b) R2 on the reef platform and N7 to the north of it. Phase lags are only shown where coherence is above the 95% confidence level. (c and d) Phase lags during the storm condition (black line in Figures 11a and 11b) for both instrument pairs.

Figure 12. Analytically derived cross-shore standing wave patterns for the average infragravity peak frequency at R1 ($f = 0.014$ Hz) in the transect across the (a) central reef, (b–c) north of it, (d–e) across the southern lagoon, and (f) in the southern channel.

with the in phase cross-shore velocities at those sites (Figure 9) and the out of phase surface elevations at R1 and R6 in the same transect (Figure 7). It is unclear, whether the decrease in R^2 at R5 and A2 was due to wave dissipation or wave refraction. Numerical modeling of the two-dimensional infragravity energy flux gradients over the complex bathymetry of the study site, such as recently conducted on a barred beach [e.g., *Rijnsdorp et al., 2015*], could provide useful insight into the mechanics of infragravity wave dissipation and generation at the site in a future study.

The observed cross-shore standing wave patterns persisted over the entire experiment and are similar to previous studies on beaches [Suhayda, 1974; Guza and Thornton, 1985] and fringing reefs with alongshore uniform bathymetries [Péquignot et al., 2009]. In this study, standing waves were observed and consistent along the shore (Figure 7), despite the irregular alongshore

Figure 13. Conceptual model of a cross-shore and alongshore standing infragravity wave pattern. (a) Plain view of the surface elevation over an even topography, (b) alongshore standing wave pattern, (c) cross-shore standing wave pattern. The red dots indicate standing wave nodes.

cross-shore bathymetry causes the nodes to move; for example, in the southern channel the nodes move further apart (50–100 m shoreward and seaward, Figure 12f), but the spatial resolution of the observations is not high enough to detect these changes.

On a plane beach, the cross-shore nodal structure in the infragravity band may be characteristic of a cross-shore standing leaky wave or an edge wave [Guza, 1974; Guza and Thornton, 1985]. At the study site, the phase relationships between cross-shore and alongshore velocities and the surface elevation on the central reef platform (at R2, Figure 10) and the phase relationships between alongshore velocities on the reef platform (R2) and in the lagoon (S7, Figure 11) were consistent with standing edge waves. However, edge wave theory was developed for alongshore uniform bathymetries [Ursell, 1952], so that the underlying assumptions are technically violated in this environment. Therefore, we propose a conceptual model of a cross-shore and alongshore standing leaky wave that can explain the observed phase relationships and that is consistent with the observed EOF modes (Figure 8), which suggest an energetic cross-shore standing wave pattern and a less energetic alongshore standing wave pattern. According to this model, the cross-shore components of the incident and reflected waves form a cross-shore standing wave (Figure 13) similar to an alongshore uniform beach. The alongshore components of infragravity waves that refract toward each other propagate in opposite directions and create a standing wave pattern in the alongshore as well. This alongshore standing wave pattern only exists locally over the reef platform where refracted infragravity waves cross. For this cross-shore and alongshore standing wave pattern cross-shore and alongshore velocities are in phase (0° or $\pm 180^\circ$) and the cross-shore velocity and surface elevation as well as the alongshore velocity and surface elevation are in quadrature ($\pm 90^\circ$, see Table 2). The cross-shore amplitude resulting from the combined cross-shore and alongshore standing wave pattern would be sinusoidal, in contrast to the one of a standing edge wave, which would follow a Laguerre polynomial. While this conceptualized wave pattern is expected to be rare on alongshore-uniform coasts, where it may only occur when waves originate from two offshore sources, for example, two distant storm systems or wave refraction around offshore islands, it may occur more frequently in alongshore

bathymetry with depths changing from ~ 3 m in the lagoon to ~ 0.5 m on the reefs over a distance of only a few meters. To assess why the irregular alongshore bathymetry does not appear to affect the standing wave pattern, we analytically estimate the location of standing wave nodes in elevation for the average infragravity peak frequency $f = 0.014$ Hz at R1 (Figure 12). At the shoreline, we assume a standing wave antinode in elevation and then calculate the elevation of the incident and reflected infragravity wave under the assumption that waves propagate in the same direction in all transects at shallow water wave speed without frictional dissipation, which is justified by the strong observed reflection at most instruments. The phase lags between the instrument pairs in the respective cross-shore bathymetry transects derived from this model agree well with the observed phase lags (vertical lines in Figure 7), although this simple 1-D model neglects the two-dimensional bathymetry and infragravity wave dissipation. The variable

nonuniform environments that cause significant refractive wave focusing, as is the case along alongshore variable rocky reef coasts.

5. Conclusions

A field experiment was conducted on a rocky reef-fringed coast in southwestern Australia to investigate how the highly alongshore-variable bathymetry of the reef-lagoon system affects infragravity wave heights and propagation patterns along the coast. Over the highly irregular bathymetry, infragravity wave heights displayed not only strong variability in the cross-shore direction but also in the alongshore direction. Infragravity waves were generally smaller in the lagoon, where they were constant in height, than on the reef platform, where they increased toward the shore. Wave focusing and shoaling amplified the waves over the shallow reef platform near the shoreline salient, where they were largest throughout the entire experiment. Incident and reflected infragravity waves resulted in a persistent cross-shore standing wave pattern at frequencies near 0.014 Hz along the entire reef-lagoon system. Refracted waves additionally caused a local, alongshore standing wave pattern, which was evident in the phase relationships between surface elevation and horizontal velocities. This alongshore standing wave pattern was equally energetic as the cross-shore wave pattern at infragravity frequencies above 0.015 Hz and was only present on the reef platform. Finally, results from the study clearly demonstrate that in highly alongshore-variable bathymetries, a purely one-dimensional view of the dynamics is not sufficient to understand the transformation and propagation of infragravity waves. This is because alongshore standing wave patterns, wave refraction and alongshore irregular shoaling induce considerable infragravity wave height variability in the nearshore.

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