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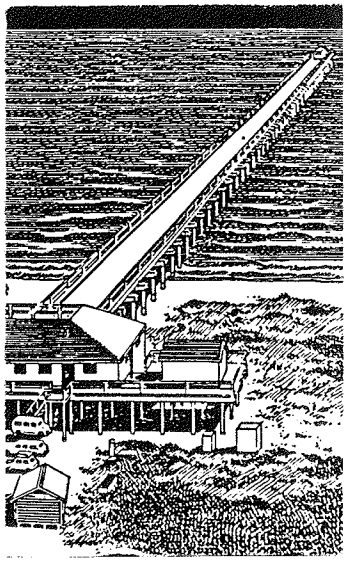

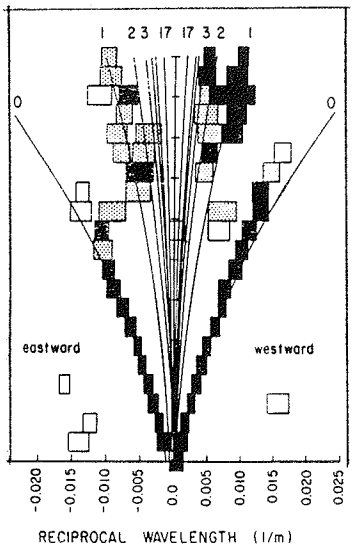

TECHNICAL REPORT CERC-89-8

INFRAGRAVITY ENERGY AND ITS IMPLICATIONS IN NEARSHORE SEDIMENT TRANSPORT AND SANDBAR DYNAMICS

by

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This report presents a tutorial on infragravity motions in the nearshore zone with particular attention given to the influence of infragravity motions on sediment transport and runup. This ubiquitous low-frequency wave motion, with periods from 30 sec to several minutes, often contributes a substantial portion to the surf zone energy especially during storms when erosion and sediment transport are most acute. The historical development of infragravity wave models and research is discussed as well as infragravity wave dynamics and theoretical generation mechanisms. Field studies identifying infragravity motions are discussed, including the various methods used to measure this complex phenomenon. Considerations for future research including studies to monitor the nearshore morphology, incident wind waves and swell, and infragravity waves are also discussed. These studies would help to understand the link between infragravity energy and nearshore processes (e.g., sediment transport, sandbar generation, beach cusps and other periodic morphologies, rip currents, and runup). An annotated bibliography is included as an appendix.

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PREFACE

The study herein was authorized by the Headquarters, US Army Corps of Engineers (HQUSACE), Coastal Engineering Area of Civil Works Research and Development. Work was performed under the Characteristics of Long-Period Waves in the Surf Zone, Work Unit 32430, Shore Protection and Restoration Program at the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES). Technical monitors were Messrs. John H. Lockhart, Jr., and John G. Housley, HQUSACE. CERC Program Manager was Dr. C. Linwood Vincent.

A growing body of knowledge documents the importance of wave energy in the infragravity frequency range (wave periods between 20 and 300 sec). Most important to the coastal engineer are field measurements which indicate that, particularly during storms, infragravity motions can dominate the surf zone energy spectrum and are responsible for the highest run-up and swash motions. Present numerical and physical models do not yet include infragravity wave motions. The purpose of this report is to serve as an introductory text on infragravity wave motions.

The report was prepared by Dr. Joan Oltman-Shay, Oregon State University, and Mr. Kent K. Hathaway, Field Research Facility Group of CERC. The report was prepared under the supervision of Mr. Thomas W. Richardson, Chief, Engineering Development Division, and under the general supervision of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Chief and Assistant Chief, CERC, respectively. This report was edited by Ms. Nancy J. Johnson, Information Products Division, Information Technology Laboratory, WES, under the Interpersonnel Agreement Act.

Acting Commander and Director of WES during preparation of this report was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

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INFRAGRAVITY ENERGY AND ITS IMPLICATIONS IN NEARSHORE SEDIMENT TRANSPORT AND SANDBAR DYNAMICS

PART I: INTRODUCTION

1. The study of extreme runup during storm conditions is a topic of vital interest, motivated in part by the costs incurred from coastal erosion and structure damage. Technically, runup refers to the maximum elevation of wave excursion up the shoreline above the still-water level. Contributing components to runup are set up due to breaking incident wind waves and swash motion about the setup. Setup is a well-understood phenomenon (Longuet-Higgins and Stewart 1964) and can be predicted and modeled. Swash, however, is more complex, composed of a full spectrum of motions. Energetic swash motion contains both wind wave (1 to 20 sec) and infragravity (30 sec to several minutes) period oscillations (Figure 1). Swash motion at wind wave frequencies is found to dominate on steep, reflective beaches where incident waves have not fully dissipated. On the other hand, infragravity frequency swash motions dominate on shallow-sloped, dissipative beaches (Holman 1981; Guza and Thornton 1982; Holman and Sallenger 1985; Holman 1986). On a fully

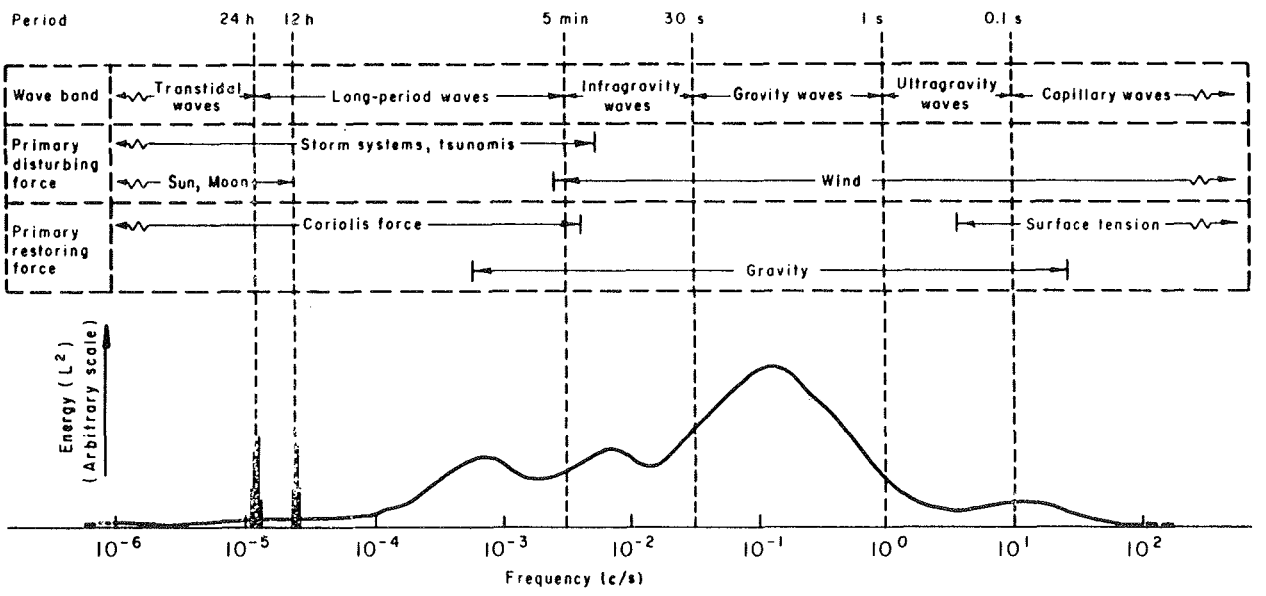

Figure 1. Approximate distribution of ocean surface wave energy illustrating the classification of surface waves by wave band, primary disturbing force, and primary restoring force

dissipative beach, the incident wind wave energy is observed to linearly decrease from a maximum at the breaker location to zero at the shoreline (Figure 2). Any increase in wind wave height serves only to broaden the surf zone and not to increase local surf or swash at wind wave frequencies. However, increased wind wave heights offshore will increase surf and swash at infragravity frequencies (Holman 1981; Guza and Thornton 1982; Holman and Sallenger 1985; Holman 1986).

2. Reflective beaches often become dissipative during storms and, as such, experience infragravity dominance. Infragravity band energy may therefore be of tremendous significance to some coasts and man-made structures, dominating many shorelines during storm conditions when erosion and sediment transport are most acute. Researchers are only now beginning to appreciate the ubiquitous nature of infragravity energy and are far from fully understanding its generation and behavior. However, it is known that in the quest for good working models that predict the dynamics of the nearshore, infragravity energy cannot be discounted.

3. The purpose of this report is to introduce the reader to the infragravity energy band of nearshore motions and to explore past and present infragravity research that has helped in understanding the nature of this energy. In particular, attention will be given to research that addresses the importance of the infragravity band, implicating it in surf and swash zone

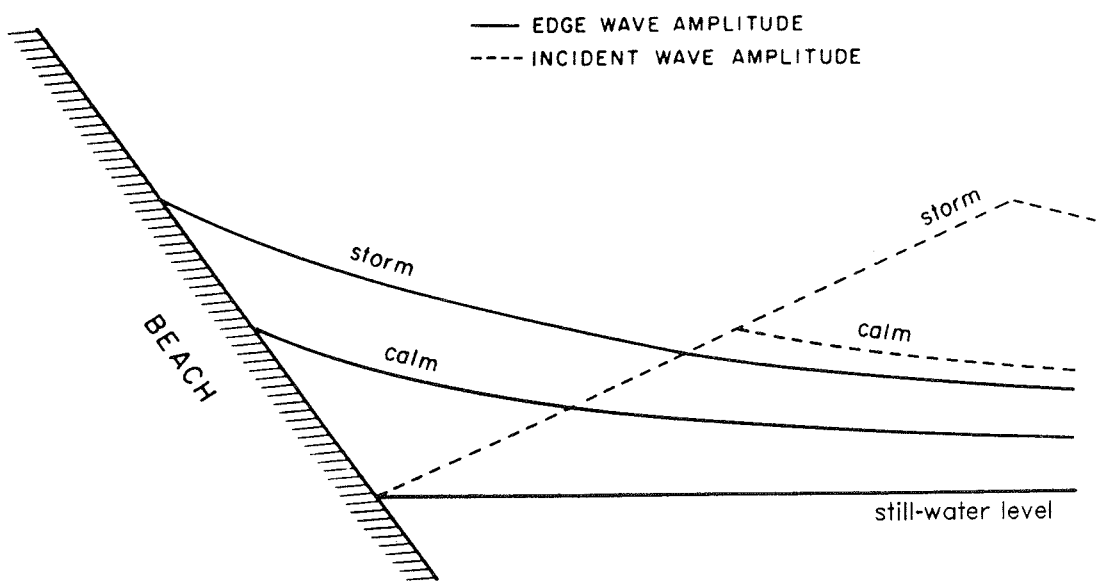

Figure 2. Offshore transect showing response of incident wave (dashed lines) and long wave (solid lines) energy to storm and calm conditions (after Holman 1983)

sediment transport. The frequency band, its wave content, and theorized generation mechanisms will be introduced. Field studies that address these issues and demonstrate the relative contribution of infragravity energy to the nearshore, and its role in sediment transport and sandbar generation will be examined. A discussion of future research needs will follow. In Appendix A an annotated bibliography is included to further serve the reader, and in Appendix B symbols and abbreviations are listed and identified.

PART II: INFRAGRAVITY WAVE DYNAMICS

Long Wave Categories

4. Originally, the term "infragravity" identified the band of frequency that contains fluid motions falling between those of the wind-generated surface gravity waves and astronomical tides. However, it has become more specifically identified with nearshore motions of periods from 30 sec to several minutes (Figure 1). Munk (1949) and Tucker (1950) were the first to observe infragravity motions. Using wave pressure recorders, they found small but measurable motions 300 m offshore with periods of 2 to 3 min. (Later studies have shown that these motions are larger closer to shore.)

5. Since these early observations, researchers have come to understand that infragravity energy is composed of organized motions in the form of long waves. These waves fall into three categories. They are (a) forced locally by the wind wave groups and bounded to them, traveling at the group velocity of the wind waves (bounded long waves); (b) forced nonlocally by the wind waves in shallow water, freely propagating and refractively trapped toward the shoreline (edge waves); and (c) forced nonlocally in deep or shallow water, freely propagating and escaping out to deep water upon reflection at the shoreline (leaky waves). Edge and leaky waves are free surface gravity waves, free to propagate away from the generation source. Bounded long waves, as their name implies, must remain with the forcing.

Free Surface Gravity Waves

Edge waves

6. The edge wave was first postulated as a component of infragravity energy by Isaacs, Williams, and Eckart (1951) immediately following the observations by Munk (1949) and Tucker (1950). Issacs, Williams, and Eckart conceived of the notion of the topographically trapped edge wave. This shallow-water surface gravity wave would travel alongshore in a natural wave guide, trapped on one side by reflection at the shoreline and on the other side by refraction over a sloping bathymetry.

Leaky waves

7. The complement to the edge wave is the leaky wave which escapes to deep water upon reflection at the shoreline. (It should be noted here that "deep water" and "shallow water" are relative terms. Surface gravity waves at these low frequencies have wavelengths longer than wind waves. Therefore, shallow water extends farther offshore for these waves.) The difference between leaky and edge waves is that the edge wave travels only in shallow water, concentrating its energy toward the shoreline, whereas the leaky wave will eventually travel far enough from shore to be effective in deep water, no longer refracting and lost forever from the nearshore.

8. These two wave types differ in the geometry of their approach to the shoreline. Leaky waves can approach from deep or shallow water, whereas edge waves must be shallow-water generated (if the nearshore has plane-parallel bathymetry). These differences can best be understood by following the propagation path of a single leaky wave. A wave that is generated in deep water will approach shallow water, refracting to a more normal angle of incidence, reflect, and travel offshore. As it travels offshore, the wave will follow the mirrored path of its approach path and therefore will not turn enough to again approach the shoreline, but instead will escape to deep water. So, by this argument, if the wave is generated in deep water, it will return to deep water. Thus, edge waves can be shallow-water generated only, whereas leaky waves can be shallow- or deep-water generated.

9. Freely propagating (unbounded) infragravity waves are not without mathematical foundation; they are the solutions to the homogeneous (unforced) equations of motion. Stokes (1846) actually noted the edge wave solution to the equations of motion but considered it one of those mathematical curiosities without any physical relevance (Lamb 1932). Eckart (1951), following up on the physical description of Isaacs, Williams, and Eckart (1951), found the edge wave solutions for the linear shallow-water equations on a plane-parallel beach. Soon afterwards, Ursell (1952) found edge wave solutions on a plane beach using the full linear equations of motion. A mathematical description for edge waves can be written as follows:

$$\eta(x,y,t) = a\phi(x) \cos (ky - \sigma t) \tag{1}$$

where*

η = elevation

x and y = cross-shore, longshore coordinates

x = 0, shoreline, increase offshore

t = time

a = edge wave shoreline amplitude

ϕ = cross-shore amplitude function

$k = 2\pi/L$

$\sigma = 2\pi/T$

k and σ = longshore wave numbers, radial frequency

L and T = longshore wavelength, period

There can be a number of edge wave modes at a given frequency that satisfy the boundary conditions of the nearshore waveguide. On a plane beach of slope, β , edge wave modes satisfy the relation,

$$\sigma^2 = gk \sin (2n + 1)\beta \; ; \; n = 0, 1, 2... \text{ and } (2n + 1)\beta < \pi/2 \qquad (2)$$

where

g = gravitational acceleration

n = mode number

Mode 0 edge waves have the largest longshore wave numbers (the smallest longshore wavelength) with higher modes having increasingly smaller wave numbers that converge on the deep-water wave number ($k = \sigma^2/g$). The highest mode number (cutoff mode) marks the lower limit on longshore wave number for which edge wave solutions exist ($k > \sigma^2/g$). This limit makes intuitive sense if one remembers that on plane-parallel bathymetry, the longshore wave number is constant as the wave propagates (Snell's law from optics). Therefore, if the longshore component of the wave number is larger than the wave number in deep water, this wave cannot exist in deep water; it has to remain trapped in shallow water. By the same argument, leaky wave solutions (Lamb 1932) occur for a continuum of longshore wave numbers that are less than their deep-water wave numbers ($k < \sigma^2/g$).

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* For convenience, symbols and abbreviations are listed and identified in Appendix B.

10. Since both leaky and edge waves have velocity components that reflect at the shoreline, they have a standing structure of nodes and anti-nodes in the crossshore (Figure 3). Note the similarity between modes,

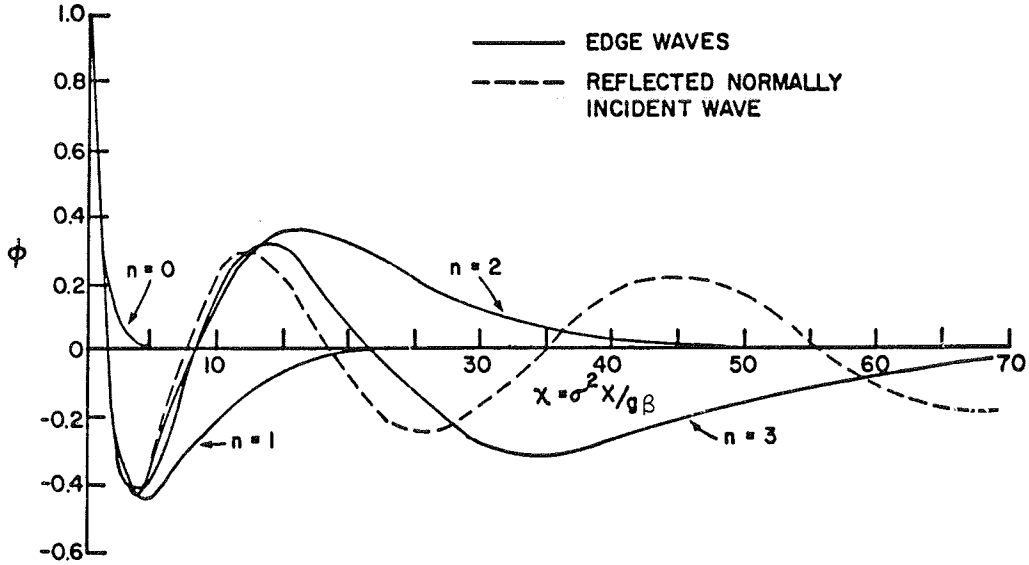


Figure 3. The offshore structure of edge wave modes 0 to 3 plotted in terms of nondimensional offshore distance χ

particularly near the shore. Note further that the standing incident wave, an example of the leaky waves, also looks similar. This structure for an edge wave is defined by the cross-shore amplitude function ϕ in Equation 1 and can be analytically determined for a few simple beach profiles. On a plane beach of slope β, it takes the form

$$\phi(x) = e^{-kx} L_n(2kx) \tag{3}$$

where

L_n = Laguerre polynomial of order n

n = the mode number of the edge wave (Eckart 1951)

The cross-shore functions for the first few modes are listed in Table 1. The mathematical solution for a normally incident leaky wave on a plane beach (Lamb 1932; Suhayda 1974) is

$$\eta(x,t) = a\, J_o(\sqrt{4\chi})\, \cos(\sigma t)$$
$$\chi = \frac{\sigma^2 x}{g\beta} \tag{4}$$

where

J_o = zeroth order Bessel function

χ = nondimensional offshore distance

11. The normally incident leaky wave theoretically has an infinity of nodes and antinodes extending out to deep water and beyond. On the other hand, the cross-shore structure of the trapped edge wave is exponentially decaying offshore with maximum amplitude at the shoreline, the number of nodes equaling the mode number of the wave. As shown in Table 1 and Figure 3, a mode 0 edge wave has only the exponential decay, whereas the mode 1 wave goes through one phase change (the node) as it exponentially decays. The higher modes have many nodes and antinodes and extend farther offshore. In fact, their cross-shore structure looks very much like that of the normally incident leaky wave close to shore. The physical dimensions of these waves also vary with frequency and beach slope. This is shown in the nondimensional cross-shore coordinate used in Figure 3; the cross-shore structure will be more tightly trapped to the shoreline in dimensional scales for high frequencies and shallow beach slopes.

Table 1

Offshore Description of the First Four Edge Wave Modes

n	$\phi(x)$
0	$1 \cdot e^{-kx}$
1	$(1 - 2kx) \cdot e^{-kx}$
2	$(1 - 4kx + 2k^2x^2) \cdot e^{-kx}$
3	$(1 - 6kx + 6k^2x^2 - \frac{4}{3} k^3x^3) \cdot e^{-kx}$

PART III: GENERATION MECHANISMS

12. Basic to the understanding of infragravity energy is its association with the incident wind waves. Munk (1949) and Tucker (1950) were not only the first to observe these low-frequency motions in the nearshore, but were also the first to propose such a link. They noticed significant correlations between the fluctuation of wind wave heights (groupiness) and the infragravity motions. (The term "surf beat" is often used in place of infragravity. Its origins are with Munk (1949), who coined the term to describe this association with wind wave groups or beats.) Field evidence has continued to support this relation. For instance, infragravity energy has repeatedly been shown to increase with the incident wind wave energy (Guza and Thornton 1982; Sallenger and Holman 1984; Holman and Sallenger 1985).

13. Field observation suggests the presence of both freely propagating and bounded surface gravity waves in the infragravity band. Bounded long waves are directly coupled to the local incident wind waves, whereas free (edge and leaky) waves are decoupled from its wind wave forcing. Both are probably generated through mechanisms that transfer energy from the groupy structure of the wind waves. However, the free waves most likely have enough nonlocal and/or broad-banded wind wave contribution to their total variance to decouple them from the local wind waves.

14. Longuet-Higgins and Stewart (1962) first suggested a generation mechanism for bounded long waves. They showed through radiation stress arguments that there is depression of the mean sea level under groups of high waves and a corresponding rise under low waves. This second-order bounded wave travels with the groups at the group velocity of the wind waves. They further speculated that it became a free wave, traveling back out to deep water upon reflection at the breakpoint. However, this was not theoretically justified.

15. A mechanism for generating free, long waves was proposed by Symonds, Huntley, and Bowen (1982). In a two-dimensional model of the surf zone, they demonstrated that the time-varying position of the breakpoint due to groupy structure could cause a concomitant variation in setup and generate freely propagating long waves. They predicted both seaward and shoreward propagation of the wave with the shoreward wave reflecting at the shoreline, thus setting up a standing wave in the surf zone.

16. Gallagher (1971) suggested the possibility of second-order nonlinear forcing of long waves through the difference frequency and longshore wave number interaction of wind waves. This mechanism permits forcing from the full spectrum of directionally distributed wind waves. Thus, it allows for the generation of directionally distributed long waves and as such is a mechanism that can generate edge waves. Since edge wave energy is contained in the nearshore with no leakage, even a weak coupling with wind waves could build up large edge waves.

Field Evidence

17. Field studies have clearly identified both bounded long waves and low-mode edge waves in the very nearshore. Leaky and/or high-mode edge waves have also been observed, but not resolved. During the 1970's, cross-shore arrays of sensors were used to compare the observed cross-shore structure of elevation or velocity with theory (Figure 3). Suhayda (1974) used a run-up meter, wave staff, and two pressure sensors in a cross-shore line to first demonstrate that the cross-shore structure of infragravity energy was in good agreement with the theoretical cross-shore standing structure of leaky waves. Guza (1974) pointed out that the cross-shore structure of leaky waves and high-mode edge waves are almost indistinguishable for the first few zero crossings. To separate edge waves from leaky waves using a cross-shore array, sensors would have to extend considerably beyond the last antinode of the theoretically highest edge wave mode that can be trapped (Figure 3). The added complications of partial reflection at the shoreline and the presence of several modes made cross-shore arrays generally unsatisfactory for distinguishing edge wave modes and leaky waves (Snodgrass, Munk, and Miller 1962). Nevertheless, Suhayda and others that followed (Huntley 1976; Sasaki, Horikawa, and Hotta 1976; Sasaki and Horikawa 1978; Huntley, Guza, and Thornton 1981; Holman 1981) clearly demonstrated that in the nearshore the infragravity band was dominated by waves that have standing structure in the cross shore.

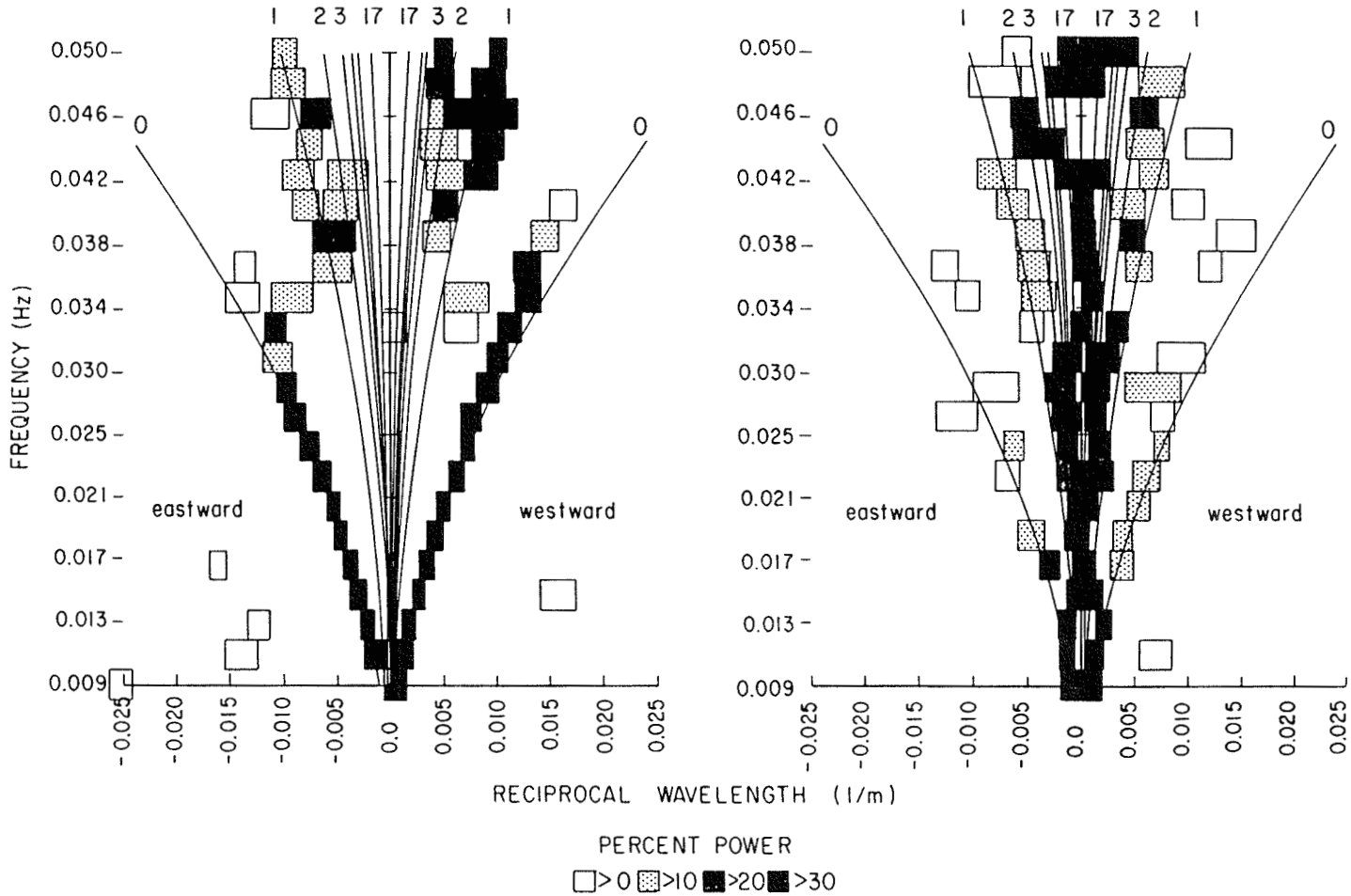
Longshore Array Data

18. Edge waves were most convincingly observed in the nearshore using a longshore array of bidirectional current meters in the surf zone (Huntley,

Guza, and Thornton 1981). The first in a series of such arrays was part of the Nearshore Sediment Transport Study (NSTS) at Torrey Pines beach, San Diego, in 1978. Two-dimensional f-k spectra for 2 consecutive days showed a lower limit of 30 ± 15 percent of the energy in the longshore current frequency band (0.006 to 0.023 Hz) to lie either on the mode 0 or 1 edge wave dispersion curves (Equation 2). The cross-shore current, while also containing low-mode edge waves, had spectra that had leaky and/or high-mode edge waves, often masking the low modes.

19. Oltman-Shay and Guza (1987) analyzed longshore array data from both the Torrey Pines 1978 and Santa Barbara 1980 NSTS field sites. Surf-zone infragravity energy on a total of 15 days studied at both beaches was always found to contain edge waves. Again, f-k spectra (Figure 4) were used to demonstrate the concentration of energy along the edge wave dispersion curves (Equation 2). Longshore current energy was observed to consist of 70- to 90-percent low-mode edge waves. Cross-shore currents also contained low-mode edge waves (i.e., 20 percent), but spectra were often dominated by low wave number energy that probably consisted of a combination of unresolvable high-mode edge waves and/or leaky waves. Another complication in resolving long waves in the cross-shore current may be partial phase locking (Huntley, Guza, and Thornton 1981). However the observation of high modes in the cross-shore current does not contradict the dominance of low modes in the longshore current because high-mode and leaky wave velocities have their largest component in the cross-shore current direction at the arrays. These data demonstrated that the nearshore infragravity field contains significant amounts of low-mode edge waves in the nearshore current and elevation field.

20. It is generally accepted that bounded long waves propagate from deep water with the incident wave groups. Huntley and Kim (1984) and List (1987) have demonstrated that significant amounts of the total variance (i.e., 25 percent) in the infragravity band outside the surf zone come from bounded long waves. Free long wave (edge and leaky) energy is generated in shallow water by Gallagher's (1971) or Symonds, Huntley, and Bowen's (1982) mechanism, the latter occurring only within the surf zone. The mechanisms of Gallagher and Symonds, Huntley, and Bowen can generate both leaky and edge waves (the Symonds generation model is presented in two dimensions and thus can generate only normally incident leaky waves; however, the extension to three dimensions is clear). Although it is possible that free leaky waves can propagate from



a. Longshore current

b. Cross-shore current

Figure 4. Typical f-k spectra in the surf zone at Leadbetter Beach, Santa Barbara, CA. The edge wave dispersion lines are drawn for a plane-beach assumption. The rectangular boxes mark the location of energy peaks. The wave number width of each box is the half-power bandwidth of the peak. The shading density indicates the percent power in the frequency bin that lies within the half-power bandwidth of the peak

deep water, there is not yet any evidence that significant amounts of infragravity energy are derived from this source.

21. A schematic breakdown of both the free and bounded infragravity long waves that contribute to infragravity motions in the nearshore of a sloping beach is shown in Figure 5. Both leaky and edge waves produce standing long waves in the surf zone. There is also the possibility that bounded long waves could be partially phase locked to seaward propagating leaky waves and generate a standing wave seaward of the surf zone. The diagrammed placement of these waves in and out of the surf zone is suggested by both observations and proposed generation mechanisms.

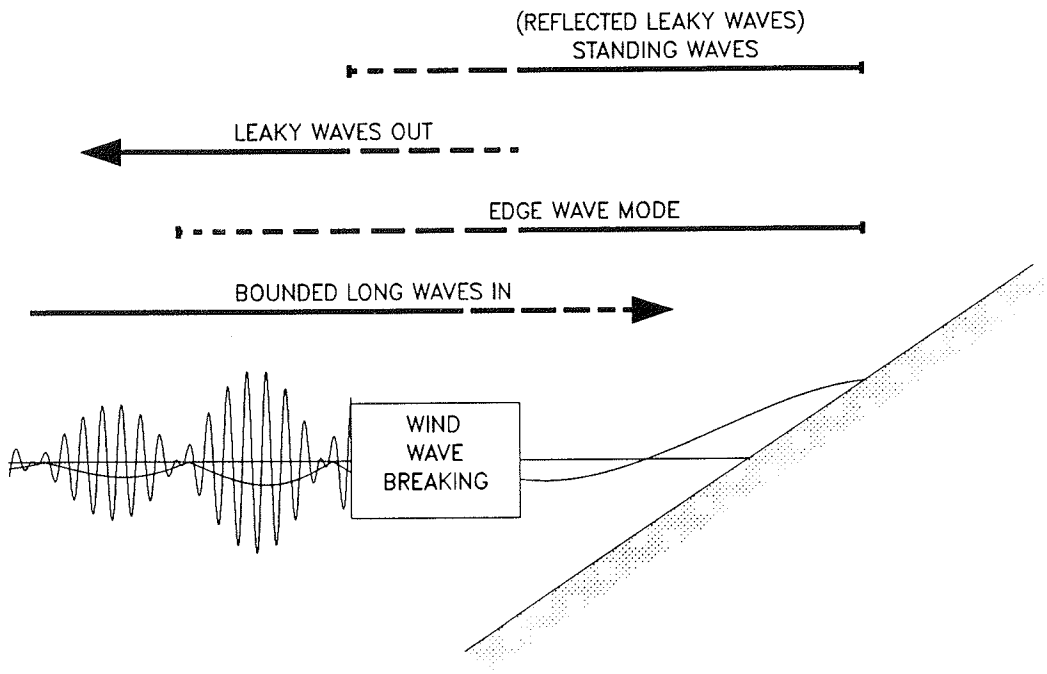


Figure 5. Schematic diagram of long waves on sloping beaches, with the top three lines representing free waves and the bottom line representing the phase-locked wave

Infragravity Energy and Sediment Transport

22. Infragravity energy contributes a substantial portion to the total shallow-water elevation and current variance in the nearshore (Emery and Gale 1951; Inman 1968a,b; Suhayda 1972, 1974; Sonu, Pettigrew, and Fredricks 1974; Goda 1975; Huntley and Bowen 1975; Sasaki and Horikawa 1975, 1978; Saski, Horikawa, and Hotta 1976; Huntley 1976; Wright, Thom, and Chappel 1978; Wright et al. 1979; Wright, Guza, and Short 1982; Bradshaw 1980; Holman 1981; Holman

and Sallenger 1985; Huntley, Guza and Thornton 1981; Guza and Thornton 1982, 1985; Oltman-Shay and Guza 1987; Beach and Sternberg 1987). It was pointed out in Part I that on a dissipative beach the infragravity contribution can dominate the surf zone. On such beaches, infragravity band variance has been shown to exceed that of wind waves by a factor of 4 (Wright, Guza, and Short 1982; Guza and Thornton 1982) with heights at the shoreline (vertical swash excursions) of approximately 70 percent of the incident significant wind wave heights (Guza and Thornton 1982). Goda (1975) showed infragravity heights, 1 m in depth, to be between 20 and 40 percent of the offshore wind wave heights. An extremely dissipative beach on the Oregon coast was observed to have vertical swash excursions of approximately 60 percent the incident significant wave height, with infragravity frequency completely dominating the run-up spectrum with 99.9 percent of the variance (Holman and Bowen 1984).

23. Differences in the relative amount of infragravity energy observed on any one beach have been demonstrated to be a function of the Irribaren number (Holman and Sallenger 1985; Holman 1986). The dimensionless surf-similarity parameter that measures the dissipative/reflective nature of a beach under varying incident wind wave conditions is

$$\xi_o = \frac{\beta}{\left(\frac{H_o}{L_o}\right)^{1/2}} \tag{5}$$

where

H_o = incident significant deep-water wave height

L_o = deep-water wavelength

Swash excursions are observed to be dominated by the incident wind wave frequency band for Irribaren numbers greater than 1.5. However, for lower values, swash becomes increasingly dominated by infragravity band energy (Holman 1986). Since storms are frequently associated with low Irribaren numbers, it is clear that infragravity long waves must be considered when shoreline erosion is examined.

24. Until recently, the link between infragravity motion and sediment transport had only been implied by the observed importance of infragravity energy in the surf and swash. A recent study attempting to directly address this link occurred on an extremely dissipative beach on the coast of Oregon

(Beach and Sternberg 1987). On this beach, infragravity motions accounted for 85 percent of the total variance in the inner surf zone with cross-shore currents as high as 240 cm/sec. Sediment suspension events associated with infragravity motions reached peak concentrations of 20 to 40 g/ℓ at 26 cm above the bed and persisted for periods of 30 to 45 sec. The mean suspended sediment load was three to four times larger than that associated with incident waves. Of course, this beach is unusual in the strength of infragravity motions. However, it does lend insight into the importance of infragravity motions in sediment suspension and transport during storm conditions on more typical beaches.

25. The offshore and longshore length scales of infragravity long waves suggest a dynamic relationship with common morphological features such as the linear and crescentic sandbars (Figure 6). Linear bars have been proposed to form under the cross-shore nodes or antinodes of long waves (Carter, Liu, and Mei 1973; Lau and Travis 1973; Short 1975; Bowen 1980; Sallenger, Holman, and Birkemeier 1985). Models for the generation of crescentic and welded bars (Bowen and Inman 1971, and Holman and Bowen 1982, respectively) have been based on the interaction of two phase-locked edge waves. The mechanism behind these generation models is the drift velocity of the long wave, where the local beach slope will alter so as to balance the "push" exerted by the drift velocity.

Figure 6. Oblique aerial view of crescentic sandbars at Cape Cod, MA. Infragravity edge waves offer an explanation for these complex morphologies

PART IV: FUTURE RESEARCH NEEDS

26. The actual role of infragravity long wave energy in surf and swash sediment transport is just now being addressed in observational studies. Their existence and importance have been proven. Theoretical scenarios of long wave generation and propagation through longshore currents and over different topographies remain to be tested in the field. Concrete answers to very serious problems are needed. For instance, do infragravity motions move sandbars? Do structures (i.e., breakwaters) that are built to damp and/or reflect incident wind wave energy, damp or amplify infragravity energy? Is infragravity energy important shoreward of breakwaters, within harbors? The answers are limited by the data.

27. Unfortunately (but understandably), researches are acutely interested in the dynamics of the nearshore during storm conditions when measurements are most difficult. Recently, a series of experiments held at the US Army Corps of Engineers Field Research Facility (FRF) at Duck, NC (Duck-82, October 1982; Duck-85, October 1985; and SUPERDUCK, October 1986), have striven in part to observe nearshore dynamics under such hostile conditions. The latest of the Duck experiments, SUPERDUCK, holds tremendous promise with its bathymetry, infragravity, and wind wave regimes well monitored. But all of these experiments are short in duration, typically only a few weeks in length. Researchers consider themselves lucky to catch one storm event during such efforts and unbelievably fortunate to have a well-defined morphological feature develop while instruments are in place.

28. A potentially invaluable next effort that would contribute greatly to the understanding of nearshore dynamics would be a long-term observational study of some of the pertinent variables. Such a study would lend insight into the behavior of the nearshore through storm events and help to answer questions such as, "how big is big" and "how typical is typical." A couple of years ago, a long-term observational study of the nearshore would have been a logistic impossibility. Such a study would need to monitor bathymetry (morphology), incident swell and wind wave climatology, infragravity wave content, and shoreline variance over months and hopefully years. However, times have changed and in place today at the FRF is a daily data acquisition facility that is presently monitoring most of these variables. So, the pieces are

almost in place to undertake a potentially important and rewarding observational study.

PART V: SUMMARY

29. Field studies have shown that the infragravity band of surf-zone energy is dominated by long waves that are standing in the cross shore. Some of these long waves are clearly low-mode edge waves. Significant amounts of the total variance in the infragravity band outside the surf zone come from bounded long waves traveling with incident wind wave groups. The presence of leaky and high-mode edge waves is less resolved. However, cross-shore currents appear to contain either or both in addition to low-mode edge waves.

30. The importance of infragravity band motions in the nearshore is unequivocally proven. On dissipative beaches these long waves dominate (80 to 100 percent) the surf and swash elevation and current field, with vertical swash excursions of 70 percent of the incident significant wave height. Data acquisition and analysis skills have overcome many difficulties in examining this energy band. Researchers are now at a level of understanding that allows them to begin addressing some of the more practical questions as to the actual role of infragravity long wave energy in surf and swash sediment transport and structure integrity.

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APPENDIX A: ANNOTATED BIBLIOGRAPHY

Bowen, A. J., and Guza, R. T. 1978. "Edge Waves and Surf Beat," Journal of Geophysical Research, Vol 83, No. C4, pp 1913-1920.

The nonlinear interaction of incident waves was considered as a mechanism for producing edge waves. Gallagher's (1971) model, edge wave forcing from interacting incident waves, was discussed and tested in laboratory wave tank. The experimental results found that surf-beat energy was greatest when resonance conditions for edge wave growth were satisfied, even when the incident waves were breaking. The laboratory experiment was centered around the case of two wave trains of slightly different frequencies approaching from the same deep-water direction. The mathematical descriptions and theoretical derivations in this article are moderately complex, more appropriate for the individual already familiar with edge waves.

Bowen, A. J., and Inman, D. L. 1971. "Edge Waves and Crescentic Bars," Journal of Geophysical Research, Vol 76, No. 36, pp 8662-8671.

This article was the first to tie edge waves with the formation of periodic beach morphologies, in particular crescentic bars and beach cusps. Theoretical arguments were developed for the production of crescentic bars by edge waves; a laboratory wave tank experiment was used to confirm the theory. It was shown that longshore standing edge waves are capable of producing crescentic bars that have a longshore wavelength of one-half that of the edge wave.

Gallagher, B. 1971. "Generation of Surf Beat by Non-Linear Wave Interactions," Journal of Fluid Mechanics, Vol 49, Part 1, pp 1-20.

The nonlinear interaction of two incident wave trains was suggested as a possible mechanism for transferring energy to low-frequency waves. It was shown that for certain combinations of incident wave frequencies and directions that satisfy the edge wave dispersion relationship, free edge waves trapped to the shore could be produced. However, this model was restricted to interactions in shallow water outside the surf zone; processes inside the surf zone have been neglected. A section was included on the derivation of the response spectrum which involves moderately complex mathematics.

Guza, R. T., and Thornton, E. B. 1982. "Swash Oscillations on a Natural Beach," Journal of Geophysical Research, Vol 87, No. C1, pp 483-491.

The authors demonstrated that wave breaking in the inner surf zone limits the energy at wind wave frequencies, but not at infragravity (surf-beat) frequencies. Swash oscillations were measured on a gently sloping beach with a wide range of incident wave conditions. The energy densities of the runup at incident wave frequencies were found to be independent of the offshore wave conditions, suggesting the energy was saturated because of wave breaking. However, run-up energy in the infragravity region increased nearly linearly with the offshore wave energy. Significant vertical excursion of these swash oscillations was approximately 70 percent of the offshore significant wave heights. The authors observed a roll-off slope of frequency^{-3} in the

saturated region of the run-up energy spectra. In contrast, Huntley, Guza, and Bowen (1977) observed roll-off slopes of frequency^{-4}. Guza and Thornton concluded that there does not appear to be a 'universal' run-up spectra as Huntley, Guza, and Bowen postulated. It should be noted that this experiment was performed with a wide range of incident wave heights, a single beach slope, and a narrow range of peak incident wave frequencies.

Guza, R. T., and Thornton, E. B. 1985. "Observations of Surf Beat," Journal of Geophysical Research, Vol 90, No. C2, pp 3161-3172.

Cross-shore velocities and elevation oscillations were analyzed from three different experiments. At surf-beat frequencies these motions were significantly correlated with the significant heights of the incident waves. The measured cross-shore velocity variance at surf-beat frequencies was between 10 and 100 times larger than the variance at 5-m depth. Numerical integration of the shallow-water wave equations for standing waves on a beach was used to model infragravity waves in the nearshore. Measured surf-beat run-up spectra was coupled with these numerically integrated equations to predict the energy spectrum at offshore locations and the coherence and phase between a run-up meter and the predicted offshore data. A qualitatively good agreement was found between the observations and the standing wave solutions.

Holman, R. A. 1981. "Infragravity Energy in the Surf Zone," Journal of Geophysical Research, Vol 86, No. C7, pp 6442-6450.

This article is an excellent introduction for describing the infragravity motions on real beaches, as well as for summarizing previous work of other investigators. A theoretical section was included describing edge wave kinematics and dynamics which presented pertinent equations for the infragravity motions but omitted the detailed derivations. An interesting result was found in the response of the infragravity motions to changes in the incident wave field. Theoretical arguments predicted that the infragravity amplitudes should vary linearly with the incident wave amplitudes. Field data collected during low- and high-energy periods supported this dependence. However, energy in the incident wave band was limited in the surf zone as a result of wave breaking. This indicated that infragravity energy will dominate the surf zone during storms. Spectral transformations were used for generating a spectrum at a particular offshore location given a white shoreline spectrum with unit energy density. Cross-shore (onshore) velocity spectra exhibited significant structure in the infragravity band. However, the transformation showed that most of the structure was a result of instrument position and did not represent frequency selection. This indicated the importance of instrument location for measuring infragravity motions. In addition, it was noted that an increase in the directional spread of the incident waves would tend to generate edge waves of many modes. Thus, it may be easier to measure edge waves on the Pacific coast, as opposed to the Atlantic coast, where there is often narrow band incident swell which should produce only a few low-mode edge waves.

Holman, R. A., and Bowen, A. J. 1979. "Edge Waves on Complex Beach Profiles," Journal of Geophysical Research, Vol 84, No. C10, pp 6339-6346.

The authors present a model for solving edge wave motions on complex beach profiles. Previous investigations generally used analytical solutions for describing edge waves. These solutions exist only for two types of beach topography, linear and exponential. This paper used a numerical method to solve the shallow-water wave equations for any form of cross-shore bottom profile. This model was used to determine the accuracy of the plane-beach assumption by testing the sensitivity of edge wave characteristics (e.g., wavelength and dispersion) to perturbations in beach profiles. The numerical model for the case of edge waves on a typical concave beach was compared to the linear slope analytical solution. The results showed that the plane-beach assumption could produce wavelength errors of a factor of 2.0. Considering computational expense, the plane-beach assumption is desirable over the numerical scheme. The errors in determining edge wave wavelengths for the plane beach can be greatly reduced with an appropriate choice of beach slope. A method for determining an effective beach slope was presented, which was a great improvement in estimating the edge wave dispersion relation for fairly complex topographies.

In addition to the effect of beach slope, changes in tidal elevations can dramatically alter the cross-shore edge wave profile on a concave beach compared to a plane beach. Edge waves forced at a particular frequency will vary in wavelength with the tidal elevation, which in turn may have an influence on the formation of rhythmic topography. Edge wave damping on a typical concave beach is also discussed with a conclusion that the edge wave energy spectra may be less energetic at low tide than at high tide. Thus, this paper covered many important considerations in interpreting field data for the measurement of edge waves.

Holman, R. A., Huntley, D. A., and Bowen, A. J. 1978. "Infragravity Waves in Storm Conditions," Proceedings, 16th Coastal Engineering Conference, American Society of Civil Engineers, pp 268-284.

A field study in Nova Scotia measured an increase in infragravity energy during a storm. The energy spectra were dominated by a strong 100-sec peak which remained constant in frequency despite significant changes in the incident waves. They felt that longshore topography was important in providing the length scale necessary for the frequency selection. Their observations indicated that for different incident wave conditions and different offshore profiles edge waves adjust to give the same wavelength, apparently a result of longshore topographic trapping.

Holman, R. A., and Sallenger, A. H. 1985. "Setup and Swash on a Natural Beach," Journal of Geophysical Research, Vol 90, No. C1, pp 945-953.

Set-up and swash measurements were made from a data set of 154 run-up time series with a wide variation in the relevant parameters. Incident wave heights ranged from 0.4 to 4.0 m, periods ranged from 6 to 16 sec, and foreshore slope β varied by a factor of 2. Runup was found to correlate with the

surf zone similarity parameter (or Irribaren number), $\xi_o = \beta(H_o/L_o)^{-(1/2)}$, where H_o and L_o are the respective deep-water wave height and wavelength. Energy spectra of swash oscillations were separated into two bands (incident waves with frequencies above 0.05 Hz, and an infragravity band for frequencies below 0.05 Hz). For low Irribaren numbers (e.g., large incident waves or low beach slope), the incident band swash was saturated. However, for low Irribaren numbers the infragravity band showed no saturation, and the infragravity energy increased with an increase in the incident wave heights. For large Irribaren numbers, neither band was saturated. Thus, the infragravity band was shown to dominate the swash energy for low values of ξ_o, below 1.75 for this study. The dimensionless parameter (vertical significant swash height divided by the offshore significant height) was found to be a good parameterization of the swash process when compared to the Irribaren number.

Huntley, D. A., Guza, R. T., and Thornton, E. B. 1981. "Field Observations of Surf Beat; 1. Progressive Edge Waves," Journal of Geophysical Research, Vol 86, No. C7, pp 6451-6466.

This paper was the first to offer conclusive evidence for the existence of edge waves using an alongshore array of bidirectional current meters. Progressive edge waves were measured by computing f-k spectra. The resolution of these spectra was increased by employing the Maximum Likelihood Estimator. From their observations it was evident that progressive edge waves were present with significant amplitude in the surf-zone velocity field. At least 30 percent of the longshore current energy was in the form of progressive edge waves.

This paper reads well, not overwhelming the reader with detailed derivations and numerous equations, and provides sufficient information describing the analysis techniques. In addition, a relatively concise but thorough introduction of previous infragravity studies is included. Most of the article presented and discussed the results of the field measurements, and described the relative importance of the different sources of surf-beat energy (i.e., progressive or standing edge waves, or leaky waves).

Huntley, D. A. 1976. "Long-Period Waves on a Natural Beach," Journal of Geophysical Research, Vol 81, No. 36, pp 6441-6449.

This article was one of the first to provide definitive evidence for edge waves at surf-beat frequencies on a natural beach. Data were obtained with 3 two-component current sensors aligned along a line normal to the shoreline out to 100 m offshore. Near the shoreline infragravity energy dominated over the incident wave energy. The amount of infragravity energy decreased as the distance from the shore increased. The observation of progressive low-mode edge waves was suggested by matching the measured velocity decay and phase relations to theoretical low-mode edge waves. The four lowest-frequency spectral peaks agreed well with the calculated frequencies of edge waves propagating at the cutoff frequencies for that beach. An explanation for the occurrence of cutoff edge waves is that they are strongly resonant. Another explanation presented is an energy exchange between cutoff modes through nonlinear interactions. A definite conclusion could not be made for the generation of these cutoff edge waves.

Huntley, D. A., and Bowen, A. J. 1975. "Field Observations of Edge Waves and Their Effect on Beach Material," Journal of the Geological Society, London, Vol 131, pp 69-81.

Direct measurements of the nearshore velocity field provided the first field evidence of short-period edge waves. These edge waves were observed at the first subharmonic ($\sigma/2$) of the incident wave frequency σ. These were verified to be subharmonic edge waves by matching the offshore decay of energy with the predicted decay for a mode zero edge wave and the zero phase shift between the onshore and longshore velocities. The dispersion relationship for an exponential beach was used for the determination of velocity decay offshore and the phase relationships. It was suggested that edge waves were formed by interactions of incident waves on the shore with the backwash. Observations of backwash and upwash interaction with incident breaking waves would result in a sequence of high breakers which had a repeat cycle at the first harmonic of the incident waves (cf. Mase 1988).

Isaacs, J. D., Williams, E. A., and Eckart, C. 1951. "Total Reflection of Surface Waves by Deep Water," Transactions, American Geophysical Union, Vol 32, No. 1, pp 37-40.

The authors were the first to describe a mechanism by which edge waves are produced and trapped to the shoreline. For surface gravity waves generated in shallow water and propagating offshore, it was shown that they can be refracted so that they are totally reflected from deep water. Standing waves are produced at resonant frequencies, alternately reflecting from the beach and from deep water. This article is easy to read, recognizes important features in the production of edge waves, and would be excellent for the reader unfamiliar with edge waves.

Mase, H. 1988. "Spectral Characteristics of Random Wave Runup," Coastal Engineering, Vol 12, No. 2, pp 175-189.

Run-up measurements were made on uniform beach slopes ranging between 1/5 and 1/30 using a wave flume. Run-up spectra exhibited the phenomena of energy saturation in the incident frequencies, implying that the run-up energy at the incident wave frequencies is independent of the incident wave energy. In this saturation region, the spectra have a f^{-4} dependence and a $\tan^4 \theta$ dependence (f is frequency, $\tan \theta$ is beach slope). At low frequencies the energy was not saturated and low-frequency run-up energy increased with incident wave energy. In addition to the experimental study, numerical simulation of run-up time series found low-frequency run-up components and high-frequency saturation that agreed with the experimental results. The simulated time history of run-up variations was made by superposition of parabolas. The author considered that up-rush and down-rush of bores on the beach have a leading edge with a parabolic shape. Thus, it was shown that the interaction of the up-rush and down-rush bores are one cause of low-frequency run-up components.

Meadows, G. A., Shuchman, R. A., and Lyden, J. D. 1982. "Analysis of Remotely Sensed Long-Period Wave Motions," Journal of Geophysical Research, Vol 87, No. C8, pp 5731-5740.

Infragravity waves with periods between 15 and 200 sec were measured with synthetic aperture radar (SAR). Data obtained in the nearshore region of Lake Michigan indicated that the infragravity motions were a forced response from interactions of wind generated incident waves. The results compared favorably with an in situ wave gage. This paper demonstrated that remote sensing with SAR was capable of measuring small-amplitude, low-frequency waves (surf beats). However, the data did not provide actual wave height information, and the exact transfer function for SAR returns from wave heights was not known.

Oltman-Shay, J., and Guza, R. T. 1987. "Infragravity Edge Wave Observations on Two California Beaches," Journal of Physical Oceanography, Vol 17, pp 644-663.

Surf-zone wave velocity data were obtained from longshore arrays of biaxial electromagnetic current meters for two different California beaches. Wave number-frequency spectra of the infragravity wave field were computed from 15 days of data. Resolution of the f-k spectra was increased by employing Maximum Likelihood Estimator (MLE). Low-mode ($n \leq 2$) edge waves were found, on the average, to constitute 69 percent of the longshore current variance, 17 percent of the cross-shore current and shoreline swash variance. The cross-shore velocity spectra were believed to also contain unresolvable high-mode edge and leaky waves.

The paper contains a concise and descriptive introduction on the historical development of infragravity wave motion theory and observations. A section was included which discussed the MLE method of obtaining high-resolution wave number spectra from relatively short arrays, as well as an appendix examining the estimator's capabilities and reliability with synthetic test spectra. In addition to examining the infragravity energy in the surf zone, a section describes edge wave energy at the shoreline measured as runup. Also, the assumption of a plane beach and the presence of mean longshore currents were shown to have a small but detectable effect on the measured edge wave dispersion curves.

APPENDIX B: NOTATION

a	Shoreline amplitude
g	Gravity
H_o	Incident significant deep-water wave height
J_o	Zeroth order Bessel function
k	Longshore wave numbers, $\delta\pi/L$
k and σ	Longshore wave numbers, radial frequency
L	Longshore wavelength
L and T	Longshore wavelength, period
L_o	Deep-water wavelength
L_n	Laguerre polynomial of order n
n	Mode number
t	Time
x	O, shoreline, increase offshore
x and y	Cross-shore, longshore coordinates
β	Plane beach of slope
η	Elevation
ξ	Surf-similarity parameter (Irribaren number)
σ	$\delta\pi/L$
ϕ	Cross-shore amplitude function
χ	Nondimensional offshore distoner