SPATIAL VARIATIONS OF OCEAN WAVE SPECTRA IN COASTAL REGIONS FROM RADARSAT AND ERS SYNTHETIC APERTURE RADAR IMAGES*

Francisco J. Ocampo-Torres♦ and Paris W. Vachon
Canada Centre for Remote Sensing
588 Booth St., Ottawa, Ontario, Canada K1A 0Y7

ABSTRACT

Complex ocean wave patterns are visible in ERS-2 and RADARSAT synthetic aperture radar (SAR) images. Within the coastal zone, bathymetry, coastal currents, and changing wind conditions can enhance the wave field's non-linear nature. It is, therefore, appropriate to use a wavelet decomposition to avoid homogeneity assumptions. Through this analysis, the spatial variability of the wave field is revealed and its spectral evolution can be measured as the waves approach the coast. We address the spatial evolution of the wave field in an ERS-2 SAR image of a coastal zone and in a RADARSAT SAR image of Hurricane Mitch.

1. INTRODUCTION

A spatial description of the wave field is important for many applications in the near-shore region. For example, an accurate prediction of the wave spectrum is required for safe navigation, planing coastal and maritime activities, and for prompt identification of mixing that waves might induce when oil spills threaten coastal environments. Wave modelling often lacks appropriate resolution, input information, as well as boundary and initial conditions. Furthermore, updating model results would benefit from wave data with adequate spatial and temporal sampling and resolution. While obtaining this wave information is not an easy task, synthetic aperture radar (SAR) images could provide some help since appropriate coverage and spatial resolution is achieved with this class of sensor.

Some characteristics of wave evolution have been determined from ERS-2 and RDARSAT SAR images in the coastal region along the Northwest coast of Baja California (Ocampo-Torres, 1999). Differences between these two radar systems were not important when studying the varying energy within the most energetic wave components as they propagate towards shore.

Coastal environments can enhance non-homogeneous wave properties. Another significant influence is the variable wind field associated with extreme storms such as hurricanes. In this paper, wave information from SAR images is analyzed for both coastal waters and Hurricane Mitch. The main objective is to determine some characteristics of the spatial variability and evolution of the wave field.

Since microwaves can penetrate clouds, we can measure the sea surface beneath a hurricane with SAR. Measuring large waves with SAR, however, is not straightforward. In fact, there have been very few reports of SAR image of ocean waves under hurricane conditions. The first analysis was reported about 20 years ago. Hurricane Iva (13 August 1978) generated waves with wavelengths from 166 to 211m that were observed by SEASAT (Gonzalez, 1982). Swell of 350m length was detected near the US east coast during Hurricane Bonnie (25 August 1998) with a RADARSAT ScanSAR image (Friedman and Li, 2000).

---

* Presented at the Sixth International Conference on Remote Sensing for Marine and Coastal Environments, Charleston, South Carolina, 1-3 May 2000.

♦ On sabbatical leave from Departamento de Oceanografía Física, CICESE, Ensenada, México.

2. DATA AND ANALYSIS PROCEDURES

ERS-2 and RADARSAT acquired SAR images over the Northwest coast of Baja California, México, providing an opportunity to observe coastal processes and to study the evolution of waves in shallow waters. An example is shown in Fig. 1. This image was acquired by ERS-2 on 6 August 1997. The image covers about 100km by 100km with a pixel size of 12.5m by 12.5m. The Baja California coast is clearly visible, running diagonally between the Northwest and Southeast corners. Some dark features near the coast are thought to be due to wind sheltering effects. The transect denoted A-B was extracted for subsequent wavelet processing and analysis.

Wavelet decomposition can provide a proper interpretation of the local distribution of wave energy at various scales. Among other applications, the wavelet technique has been used to study similarities between atmospheric (wind speed) and surface signatures (in terms of normalized radar cross section), at scales of 0.5 to 4.0 km (Mourad *et al.*, 2000); to study the linking mechanisms between wind, waves and C-band backscatter (Zecchetto *et al.*, 1999), and to analyze the transfer of energy to low frequency wave components in blocking and trapping zones of waves in inhomogeneous flows (Long *et al.*, 1993).

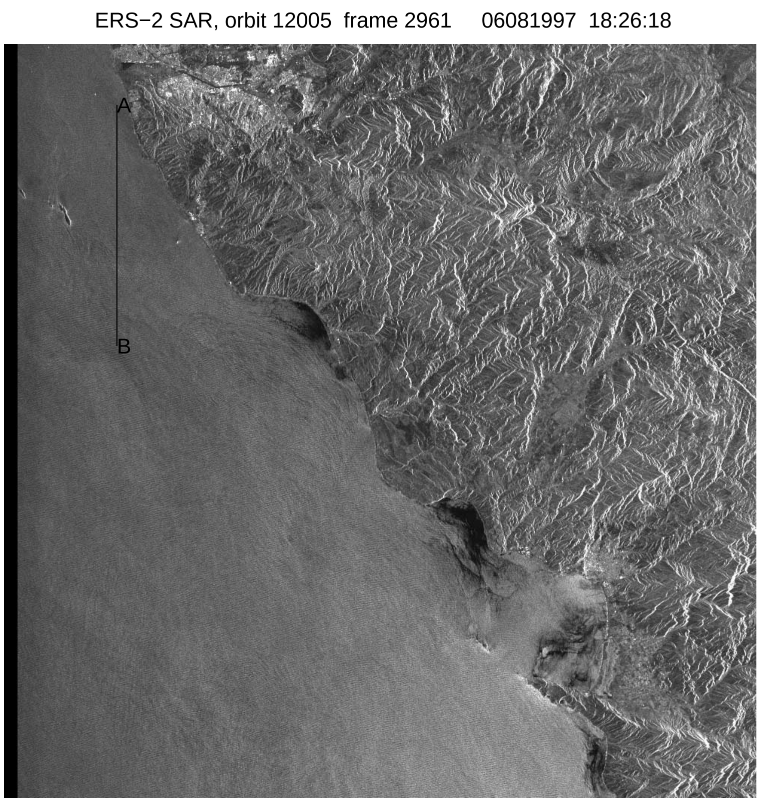

Figure 1: ERS-2 SAR image (orbit 12005, frame 2961) for the Northwest coast of Baja California acquired by the Norman Station on 6 August 1997 at 18:26 UTC. Coordinates for the image centre are roughly 32N, 117W. (©ESA, 1995)

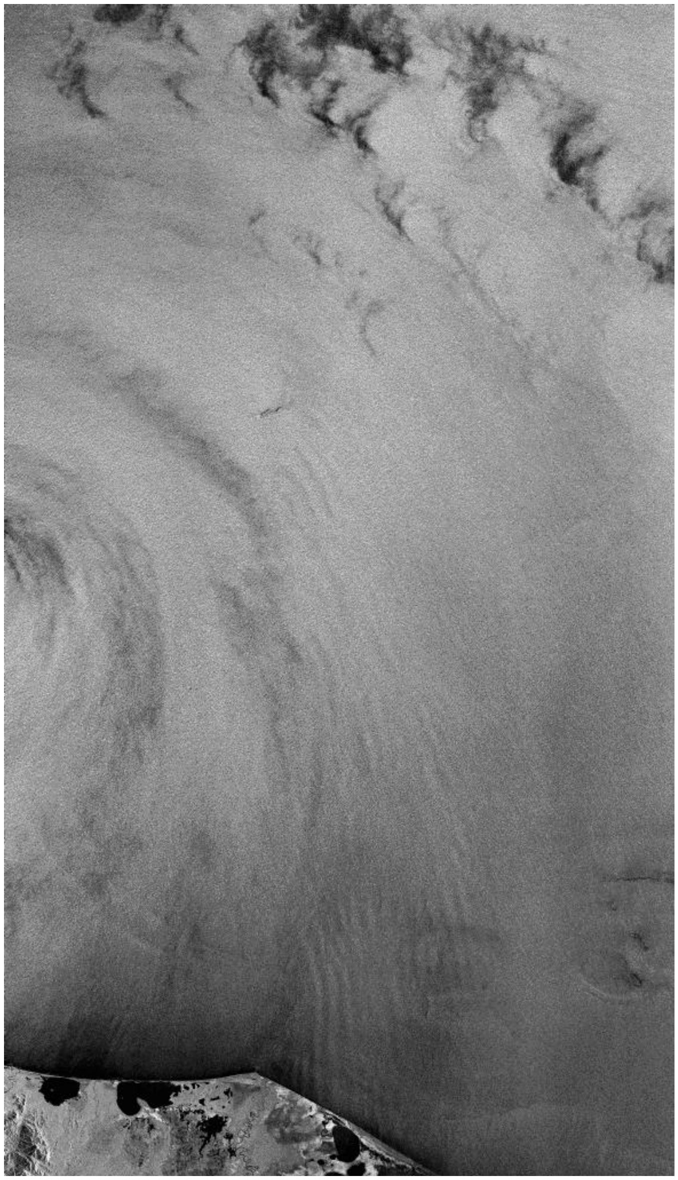

Figure 2: RADARSAT SAR image acquired over the Caribbean Sea during Hurricane Mitch, on 27 October 1998 at 11:34 UTC. (©CSA, 1998).

A Wide beam mode RADARSAT SAR image acquired to the east of the eye of Hurricane Mitch on 27 October 1998 is shown in Fig. 2. The image covers roughly 184km by 320km with a pixel spacing of 12.5m by 12.5m. The wind direction can be deduced from the orientation of the long scale surface features. The wind field characteristics and other atmospheric features of interest detectable by SAR during hurricanes have been discussed by Katsaros *et al.* (2000). To analyze the wave variability in this image, a set of image spectra were estimated using FFT procedures on 44 regularly spaced sub-scenes. Presently, the inter-look cross spectrum technique (Engen and Johnsen, 1995) is being used to reduce speckle noise in the estimated spectra and to resolve the wave propagation direction ambiguity.

3. COASTAL WATERS

It is known that the wave field varies considerably when propagating from intermediate to shallow water regions. A description of this evolution for the case of range travelling waves, as measured from an ERS-2 SAR image using a series of image spectra, has been given elsewhere (Ocampo-Torres, 1999). This analysis revealed the non-homogeneous character of the wave field.

The results of a wavelet decomposition applied to the transect A-B of Figure 1, are shown in Fig. 3. The decomposition illustrates the variations of energy density over the various wave scale components that are present, as a function of the distance along the transect, in this case, essentially along a wave ray as the wave field was propagating nearly northward (i.e., in the azimuth direction). The spectral energy density that is estimated through traditional FFT methods is equivalent to the average of the energy density that is obtained by wavelet decomposition. The most energetic wave component would be that associated with the spectral peak. Under wavelet decomposition, however, this wave component, with a scale of L ~ 166m (i.e., $1/L \sim 0.006 m^{-1}$) is seen to be variable through the propagation space.

The waves in this image are essentially azimuth travelling and our intention is to illustrate relative wave variations. Therefore, even if dealing only with image spectral information, the azimuthal cut off induced by the orbital motion of surface scatterers could, in principle, reduce the ability of SAR to observe this type of wave. From the wavelet transform, it is apparent that the least resolved wave components show the most variability along the transect.

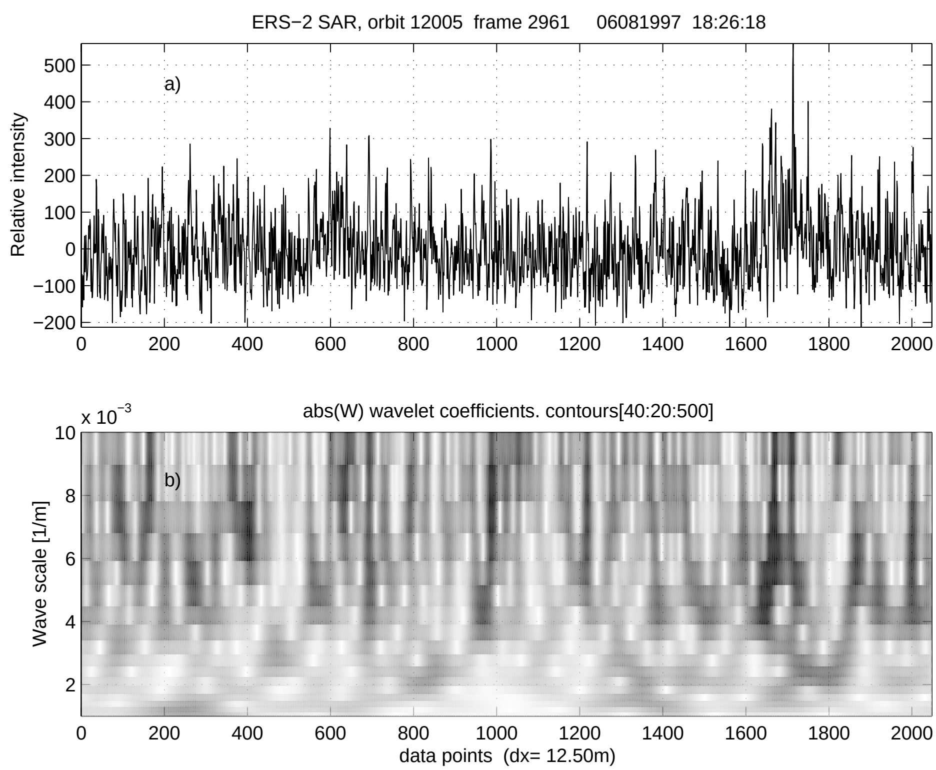

Figure 3: The image transect A-B in Fig. 1 (top); and the wavelet decomposition as the absolute value of the wavelet coefficient (bottom). Grey tones represent relative spectral density.

4. HURRICANE MITCH

An example image spectrum for one sub-scene is shown in Fig. 4. The grey tone representation shows the symmetric pattern of the spectral energy. The wave propagation direction cannot be resolved from this analysis alone. It does show, however, the behaviour of the spectral shape, in particular, if a series of sequential spectra are extracted from the image.

Image spectra from the 44 sub-scenes across the Hurricane Mitch image are shown in Fig. 5. The axes and dimensions, as well as the grey-scale palette, are the same as those used in Fig. 4. Therefore, the relative wave variability across the whole scene may be observed.

This is a unique representation of the wave field under the influence of an intense storm. It is evident that near the hurricane's eye, the wave signal is reduced and more confused, while both north and south away of the eye (see the first column of spectra in Fig. 5) the wave signal is better defined, although the propagation direction is not resolved. Another important feature is the presence of range travelling waves over most of the lower half of the spectral set. This signal remains stronger towards the central region, where a clear deviation from the range direction is noted.

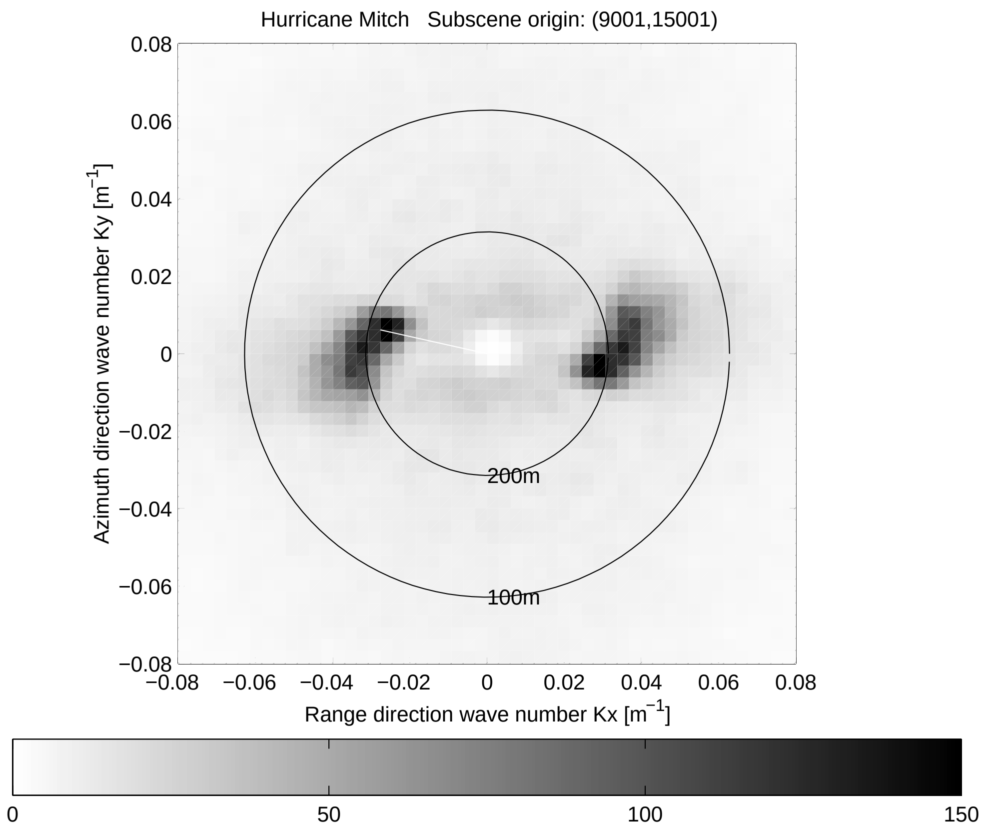

Figure 4: An example image spectrum estimated from a sub-scene of the Hurricane Mitch RADARSAT SAR image. The spectral energy density is given as grey tones as a function of wavenumber components in the range and azimuth directions. Wavenumber is measured from the origin outward and the loci for 200m and 100m wavelength components are as indicated by the two circles.

It may seem surprising that range travelling waves can be detected in the central region of the image where the winds are mainly in the azimuth direction. Apparently, actively generated waves still have a considerable range component. At this location, SAR might be blind to any azimuth travelling waves. These spectra, however, indicate that the wave spectrum is very broad. The wave vectors estimated from the spectral peak components are shown in Fig. 6. There has not been any attempt to resolve the 180º ambiguity in wave propagation direction.

Figure 5: Image spectra for 44 sub-scenes from the Hurricane Mitch image (see Fig. 4 for details).

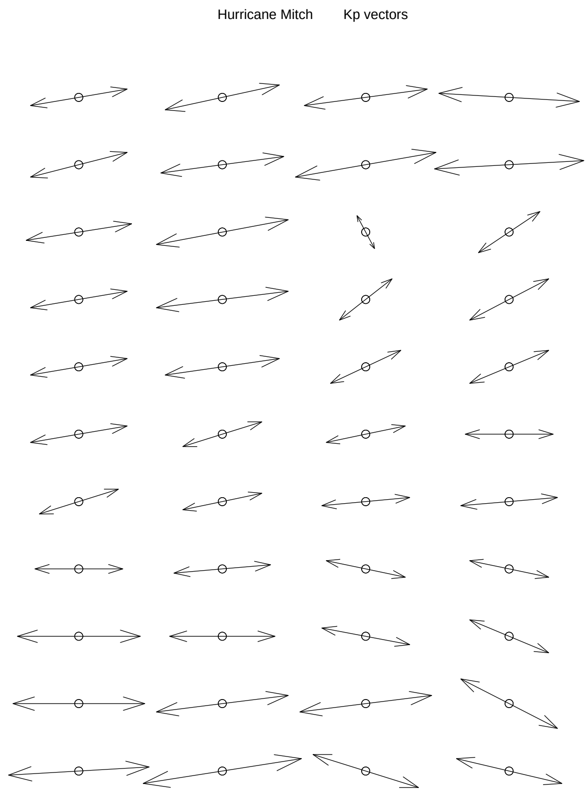

Figure 6: Peak spectral wavenumber components derived from Hurricane Mitch image spectra.

The results from an inter-look cross-spectral analysis (not presented here) show that the propagation direction in the upper (lower) part of the image is essentially Westward (Eastward). This suggests that the imaged waves, although restricted to those with strong range components, are locally generated. It is interesting to note that in the central part of the image, where the wind is mostly azimuth in direction, range-travelling waves can still be observed. This is not to say that range travelling waves are the only waves present. It is clear that azimuth-travelling waves have been filtered out by the SAR transfer function, which reinforces the idea that the wave field has a very broad spectrum under the intense forcing of hurricane winds.

5. FINAL REMARKS

Analysis of the waves in SAR images of coastal regions shows that the variability of the wave field is considerable. In general, we must proceed with caution when trying to obtain further details of the wave field. When examining an average area through traditional spectral analysis methods, we must bear in mind that the details of the local wave evolution may be lost.

Nevertheless, application of FFT-based spectral analysis techniques can provide useful information on the spatial evolution of the wave field under certain conditions. For the case of a wave field under extreme hurricane conditions, image spectra show that the spatial variations are considerable. In general, SAR images provide a novel view of the wave field during a hurricane.

REFERENCES

G. Engen, and H. Johnsen, "SAR-ocean wave inversion using image cross spectra", *IEEE Trans. Geosci. Remote Sensing*, Vol. 33, No. 4, pp. 1047-1056, 1995.

K. S. Friedman and X. Li, "Monitoring hurricanes over the ocean with wide swath SAR", *Johns Hopkins APL Tech. Digest*, Vol. 21, No. 1, pp. 80-85, 2000.

F. I. Gonzalez, "SEASAT wind and wave observations of Northeast Pacific Hurricane Iva, August 13, 1978", *J. Geophys. Res*., Vol. 87, No. C5, pp. 3431-3438, 1980.

K. B. Katsaros, P. W. Vachon, P. G. Black, P. P. Dodge, and E. W. Uhlhorn, "Wind fields from SAR: Could they improve our understanding of storm dynamics?", *Johns Hopkins APL Tech. Digest*, Vol. 21, No. 1, pp. 86-93, 2000.

S. R. Long, R. J. Lai, N. E. Huang, and G. R. Spedding, "Blocking and trapping of waves in an inhomogeneous flow", *Dynamics of Atmospheres and Oceans*, Vol. 20, pp. 79-106, 1993.

P. D. Mourad, D. R. Thompson, and D. C. Vandemark, "Extracting fine-scale wind fields from synthetic aperture radar images of the ocean surface", *Johns Hopkins APL Tech. Digest*, Vol. 21, No. 1, pp. 108-115, 2000.

F. J. Ocampo-Torres, "On the homogeneity of the wave field in coastal regions as determined from RADARSAT synthetic aperture radar images of the ocean surface", Submitted to *Scientia Marina*, 1999.

S. Zecchetto, F. Debiasio, and P. Trivero, "Local properties of radar backscatter at C-band and off nadir angles", In *The Wind-Driven Air-Sea Interface. Electromagnetic and Acoustic Sensing, Wave Dynamics and Turbulent Fluxes*, ed. M. L. Banner, The University of New South Wales, Sydney, Australia, pp. 441-448, 1999.