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Visualizing Characteristics of Ocean Data Collected During the Shuttle Imaging Radar-B Experiment

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Abstract

Topographic measurements of sea surface elevation collected by the Surface Contour Radar (SCR) during NASA's Shuttle Imaging Radar (SIR-B) experiment are plotted as three dimensional surface plots to observe wave height variance along the track of a P-3 aircraft. Ocean wave spectra were computed from rotating altimeter measurements acquired by the Radar Ocean Wave Spectrometer (ROWS) aboard the same NASA aircraft as it was flown under the space shuttle Challenger. Fourier power spectra computed from SIR-B synthetic aperture radar (SAR) images of the ocean are compared to ROWS surface wave spectra. Fourier inversion of SAR spectra, after subtraction of spectral noise and modeling of wave height modulations, yields topography similar to direct measurements made by the SCR. Visual perspectives on the SCR and SAR ocean data are compared, although for surface tracks differing somewhat in space and time, for wind generated wave fields observed off the coast of Chile in October of 1984. Threshold distinctions between surface elevation and texture modulations of SAR data are considered within the context of a dynamic statistical model of rough surface scattering. The result of these endeavors is insight as to the physical mechanisms governing the imaging of ocean waves with synthetic aperture radar.

Keywords: Doppler radar, ocean waves, image processing, computer graphics

## Introduction

Remotely sensed earth science data offer the potential for monitoring global change in our environment. Large data sets now exist and much more information on the spectral properties of our oceans and atmospheres will be forthcoming in the next decade. Visualization is emerging as a scientific tool for investigating theoretical computer models of physical processes in relation to empirical data from a variety of sensors operating over a wide range of spatial and temporal scales. As an example, radar measurements of ocean wave height and slope along the ground track of airborne and spaceborne remote sensors are viewed as shaded surface perspectives to appreciate correlations in short-scale texture and long-scale sea state during the Shuttle Imaging Radar (SIR-B) experiment.

The NASA P-3 aircraft conducted underflights of the space shuttle Challenger as it approached the southwestern coast of Chile (55°S, 80°W) on each of 4 days, 9 October to 12 October 1984. As a result, directional surface wave spectra have been computed from data acquired by the Surface Contour Radar [SCR, Walsh et al., 1985] and Radar Ocean Wave Spectrometer [ROWS, Jackson et al., 1985] for comparison with Fourier wave power spectra computed from Synthetic Aperture Radar [SAR, Beal et al., 1986] image data. The four day period was characterized by a significant wave height that varied from 1.7 m to 4.6 m. The lowest sea state occurred on 10 October when an actively growing wind driven system with a wavelength of about 80 m appeared from the northeast propagating approximately -30° from the look direction of the SAR. This data set is typical of a fresh steeply sloped sea state in which non-homogeneous and transient hydrodynamic modulations of backscatter influence the SAR Doppler imaging technique. The highest sea state occurred the following day of 11 October when the three radar remote sensors reached a consensus in measuring a well developed swell with a wavelength of 270 m from the northwest. On 12 October this wave field was observed with a wavelength of 380 m having diminished to a significant wave height of about 3.5 m and turned so as to propagate along the shuttle track about 90° from the SAR look direction. The radars also detected an apparently new wave system with a wavelength of about 140 m developing again from the northeast on 12 October, the last day of the aircraft underflights. This data set is of particular interest in modeling the along track and across track imaging properties of SAR as it responds to waveheight modulations of surface velocity and texture.

Homogeneous ocean wave fields induced by distant storms and imaged with SAR may be fast Fourier transformed to estimate directional wave power spectra for oceanographic applications. However, individual wave groups are not necessarily well characterized by the normal statistics of the spectral approach and might be better examined in speckle reduced SAR images with restored wave height significance. Hence, Fourier domain restoration and enhancement filters have been developed [Tilley, 1987] to apply what has been learned about the SAR ocean-imaging modulation transfer function in the spectral domain and derive estimates of surface elevation in the image domain. Speckle reduction is based on empirical methods for determining a broadband spectral noise floor that can be subtracted as the random influence of transient surface facets tilted toward the radar as it looks down at a 23° incidence angle upon a homogeneous rough surface. Such a spatially stationary distribution of backscattering facets has been used to estimate the SAR wavenumber response for the SIR-B remote sensor [Tilley, 1986] using data collected over Baie Missisquoi near Montreal, Canada on October 7, 1984. This stationary response function can be used in an inverse Fourier filtering operation to improve the broadband spectral response of the SAR data obtained off the coast of Chile a few days later.

Non-homogeneous rough surface scattering may well be deterministically related to waveheight via a hydrodynamic modulation theory that is not well understood at present. However, it is apparent that the SAR along track wavenumber response is limited by ocean dynamics and can be partially restored [Tilley, 1987] with an empirical model of surface motion blurring based on a stochastic distribution of backscattering events in the time required for Doppler image synthesis. After the empirically estimated stationary and dynamic response functions are applied to SAR spectra, a broadband power threshold is applied to separate wave signal from random noise. A theoretical model of surface tilt and velocity modulation [Monaldo, 1987] is then applied to restore wave height significance to the Fourier image power. Advances in SAR spectral processing techniques are required to improve remote sensor estimates of ocean wave height variance, including distributions over wavelength and propagation direction, for the variety of sea states that are of interest to oceanographers, ship captains and coastal authorities. The object of ocean research with SAR is to develop theoretical descriptions of radar cross section modulations that can be parameterized by empirical analysis of Fourier statistical data. Fourier spectra can then be compared with ocean wave spectra, or inverse transformed and compared with ocean surface topography, to evaluate SAR methodology using non-Doppler radars (e.g., the ROWS and SCR) that make more direct measurements of geophysical surface statistics.

## Synergy of Aircraft and Spacecraft Ocean Observations

The SAR, SCR and ROW data collected during the SIR-B experiment at the Chilean site have all been processed to yield directional ocean wave height variance spectra in common units of $m^4$. Intercomparisons in this format have been reported [Beal, 1987] for the purpose of designing future SAR systems and assessing their potential value to computer wave models. In general, the three radar remote sensors were able to reach a consensus for all the sea states encountered, although the fresh wind-driven sea with low wave height on 10 October appeared to be somewhat misrepresented by the SAR. Therefore, this SAR scene is the subject of continuing investigation to develop assessments of the various algorithms applied for signal detection, clutter suppression and restoration of wave height significance. Comparisons with ROWS spectral estimates are considered in terms of action variance, in units of $m^2$. Once the ROWS data have served to guide the SAR to its best spectral estimates of the wave field, an inverse Fourier transform is applied to recreate SAR scenes of the surface elevation. Comparison with SCR measurements of surface topography are made by computing wave height statistics over similar ocean sites and by computing three dimensional surface visualizations of non-homogeneous wave grouping at these sites.

On 12 October at the Chilean site, the ROWS spectra depicted in Figure 1a indicates a 380 m wavelength system, propagating nearly along its eastern flight direction, that appears spread at low power to a more southerly heading. A weaker 140 m wavelength system, propagating across the ROWS flight direction, is apparently detected near the instrument's signal-to-noise limit and may be confused with or the cause of the broadening observed for the dominant swell. Both of these wave systems are also detected by the SAR, as shown in Figure 1b, when only the empirical instrument response functions are applied to estimate the wave action variance spectrum. The space shuttle was also travelling along an eastern flight direction, so it is not surprising that the SAR, as well as the ROWS, is able to detect the weak wind driven wave system via surface tilt modulations of backscatter occurring in the across track direction. The SAR also observed the dominant swell wave system travelling along its flight direction. An image of surface wave height variance can be computed by an inverse Fourier transform of the SAR spectrum after a theoretical ocean imaging transfer function is applied to account for both surface tilt and velocity modulations of the backscattered field. The interaction of the long 380 m wavelength swell and the 140 m wavelength wind driven sea are represented in Figure 2a as a computer generated visualization of the surface elevation. A similar visualization is depicted in Figure 2b where the direct ranging measurement of surface topography is depicted over 3 SCR aircraft tracks, each 400 m wide, to simulate the same coverage as the spacecraft SAR.

On 10 October at the Chilean site, the ROWS aircraft and the space shuttle carrying the SAR were even more closely aligned along eastern flight directions. Both remote sensors detected an 80 m wavelength wind driven system propagating at 60° and a 200 m wavelength swell propagating at 130° from their flight direction. The spectral amplitude of the wind driven sea dominated that of the longer swell for both the ROWS and SAR remote sensors after correction for their respective instrument response functions. The surface tilt and velocity modulations of radar cross section may not suffice to describe SAR ocean imaging when the non-homogeneous and transient seas violate the ergodic and stationary assumption of two-scale scattering models. Hence, the SAR image spectrum was inverse transformed both before and after the application of the ocean imaging transfer function traditionally used to restore wave height significance. The statistics of the two Fourier filtered SAR images are compared to SCR surface elevation statistics in Figure 3 over 6 $km^2$ ocean segments differing spatially by about 20 kilometers and temporally by about 2 hours. This data set also presents a unique opportunity to compare surface height and texture acting in hydrodynamic modulation of radar resonant wavelengths (i.e., 23 cm surface waves for the L-band SAR) by longer wind generated waves (i.e., the 80 m sea) with periods comparable to the scene integration time. The correlation properties of the surface elevation and texture are visualized as a shaded surface plot in Figure 4, assuming that the wave action spectrum is proportional to height variance without tilt and velocity bunching modulation.

## Computing and Display Technology

The radar data presented herein were collected in 1984 and have been processed and displayed using image processing and computer graphics workstations that have evolved in several different departmental facilities. Initial development of the SAR Fourier filtering algorithms was accomplished with a PDP-11/70 minicomputer system purchased from Digital Equipment Corporation at the beginning of the decade. Ocean images scaled to 32-bits in intensity over 512 x 512 arrays of picture elements (pixels) could be fast Fourier transformed in about 13 minutes using an optimized mass storage algorithm to coordinate data transfers between the 64K word memory partition of the 16-bit computer and large magnetic disk peripherals. Fortran program code was developed to apply filtering algorithms to the complex spectral database prior to inverse Fourier transformation. About 1 hour was typically required to restore wave height significance to a SAR ocean scene.

A Comtal Vision One/20 image processor was interfaced to the PDP-11/70 in 1981 allowing DMA transfers of the 512 x 512 x 8 bit pixel scenes over a UNIBUS in about 1 second. This system was equipped with 2 Mbytes image memory and an LSI-11 microprocessor controlling a pipeline delivering up to 30 ocean scenes a second to a 512 x 512 x 24 bit color monitor. A Matrix camera, Model 4007, was also acquired and interfaced to R,G,B outputs from the color monitor. This unit can be used to expose 35 mm roll film or format from 1 to 25 images on 8" x 10" sheet film. Figures found herein were photographed with this image processing and display system which now stands alone receiving its inputs from 9-track magnetic tape.

The SAR and SCR surface plots in the figures were computed using the PV-WAVE software package developed and supported by Precision Visuals, Inc. Version 2.2 of PV-WAVE running on a DECstation 3100 workstation offers the algorithms for using SAR texture information to shade a surface plot of ocean wave height visualized from a number of elevation and rotation angle perspectives. PV-WAVE, Version 1.0, is also installed on a VAXstation 3500 interfaced via a Q-bus to a QUEN-16 wavefront array processor. This desktop processor is being developed jointly by Interstate Electronic Corporation and The Johns Hopkins University Applied Physics Laboratory. Initial experimentation with the QUEN-16 have shown that a 512 x 512 x 32 bit two dimensional fast Fourier transform computes in about 20 seconds. Basic spectral filtering algorithms are now being programmed and tested on the QUEN/VAX system. Wave height perspectives will be computed from SAR image data in minutes, rather than hours, allowing experimentation with new Fourier filtering algorithms. Larger ocean scenes, from SAR processors producing up to 8192 x 8192 x 64 bits of complex pixel data, could be addressed with future improvements in this workstation. Such a capability will accelerate development of hydrodynamic imaging models that will improve our understanding of microwave radars like the SCR, SAR, and ROWS.

## Summary

Oceanographic remote sensors operated from aircraft and spacecraft as part of NASA's SIR-B experiment have yielded surface data at comparable resolution, but over ocean regions of different size. The spacecraft SAR images were Fourier filtered to obtain topographic information using a linear model of the SIR-B system response and modulation transfer function. The SAR instrument response functions were parameterized to yield Fourier spectra similar to those obtained by the ROWS instrument. A spectral power threshold was applied to segment the SAR image data to representation of surface elevation and texture.

The filtered SAR data were plotted as three dimensional surfaces to visually compare their estimate of wave height variance with that of the SCR. The SAR surface plots were also shaded with their texture information (generally referred to as speckle noise) to visually correlate short scale backscatter modulations with long wave height. For the wind driven sea observed on 10 October 1984 off the southwest coast of Chile, the synergistic study of SAR, SCR and ROWS data indicates that the speckled texture of SAR imagery may contain useful information and that a hydrodynamic theory of backscatter modulation is needed to supplement velocity bunching and tilt modulation theories.

The Johns Hopkins University Applied Physics Laboratory is developing the QUEN wavefront array processor [Dolecek, 1989] to serve as a rapid prototyping tool that can be applied to general purpose visualization in a desktop or personal computing environment. SAR processing algorithms are now being transferred to a QUEN-16 unit hosted by a VAXstation 3500 workstation to implement a menu driven user interface. Fourier filtering experiments applied quickly over larger ocean fields will accelerate research directed towards developing a hydrodynamic model [Tilley, 1990] of ocean imaging with spaceborne SAR remote sensors. High speed graphics visualization and flight simulations combined with simultaneous comparisons with scanning altimeter data will facilitate the communication of theoretical hypotheses and assist in their evaluation.

Applications of remote sensor technology for earth science include documentation of coastal erosion, surveillance of oil spills and prediction of hurricane tracks. Monitoring global change in our environment will require that remotely sensed data, collected at different scales in time and space, be reviewed, reduced and assimilated into physical models. High speed data distribution networks, desktop workstations, and advanced computing technology [Jenkins, 1989] are now being developed at The Johns Hopkins University Applied Physics Laboratory. Computer visualization is emerging as a combination of three-dimensional graphic concepts with two-dimensional image processing methods as a scientific tool for investigating relationships between theoretical models and empirical data. It is planned to apply these resources to models of microwave scattering from rough surfaces that can be investigated with radar data from oceanographic remote sensors. The result of this exemplary endeavor will be insight as to the physical processes governing the wind generation of ocean waves.

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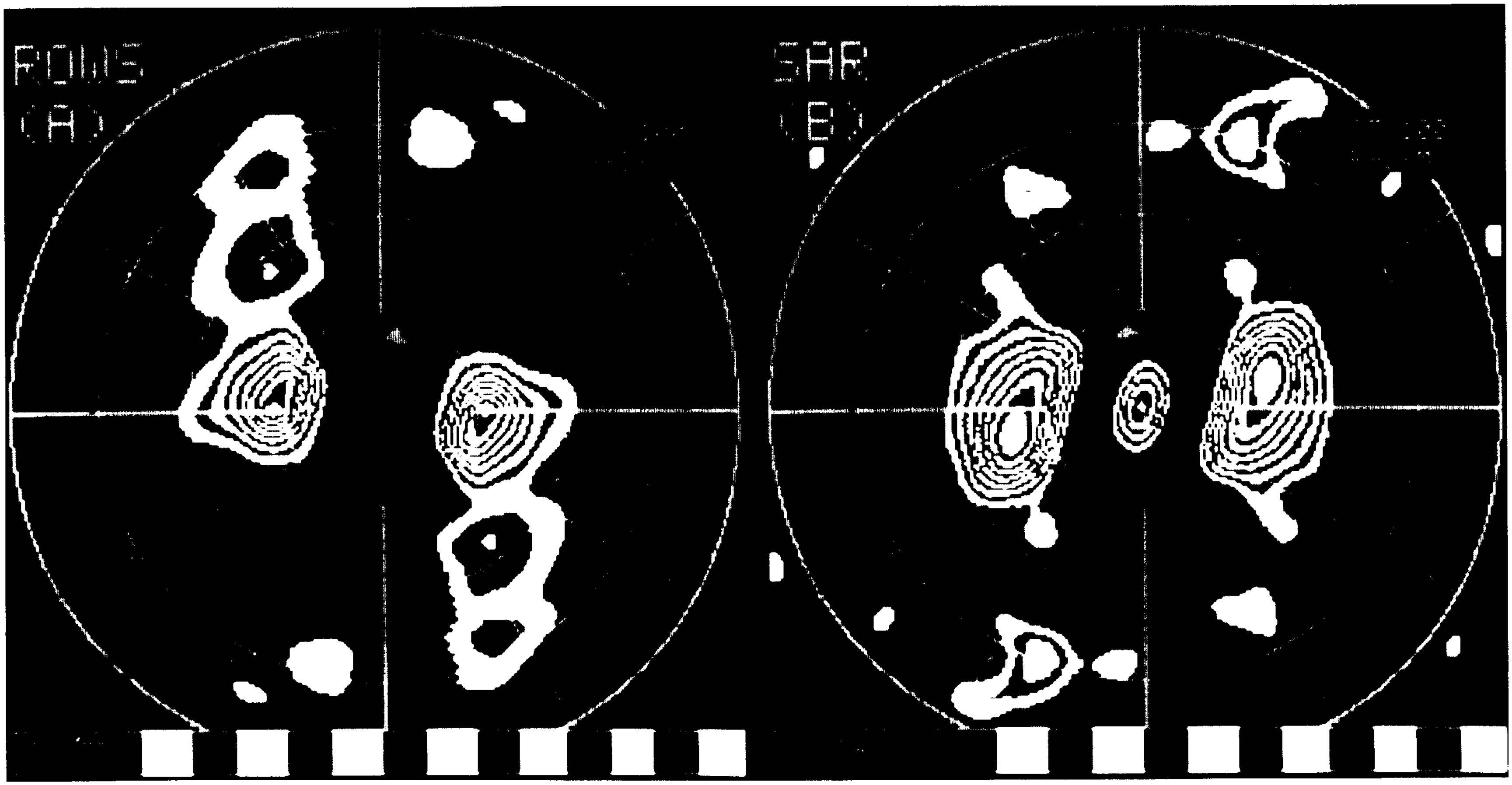


Figure 1  ROWS (a) and SAR (b) directional ocean wave spectra for wavelengths between 400 meters (inner circle) and 100 meters (outer circle).  Flight directions are from left to right, horizontally.

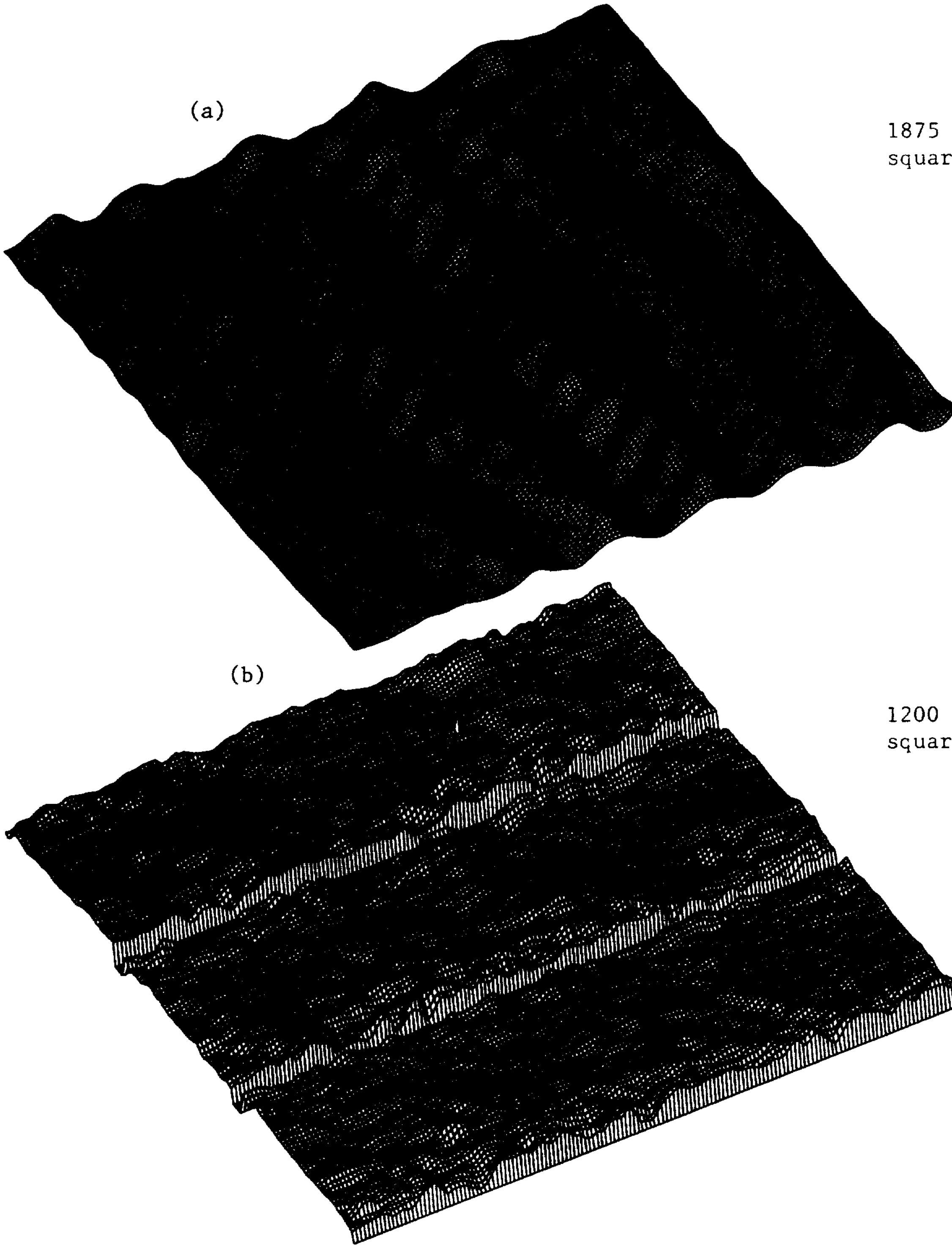


Figure 2 SAR (a) and SCR (b) surface elevation data are plotted as three dimensional graphs depicting wave height variance for a 380 meter swell and a 140 meter sea, respectively, propagating along and across the swaths of the remote sensors. The SCR swath was only 400 meters wide so that 3 data sets approximate the contiguous SAR segment, although at a different place and time.

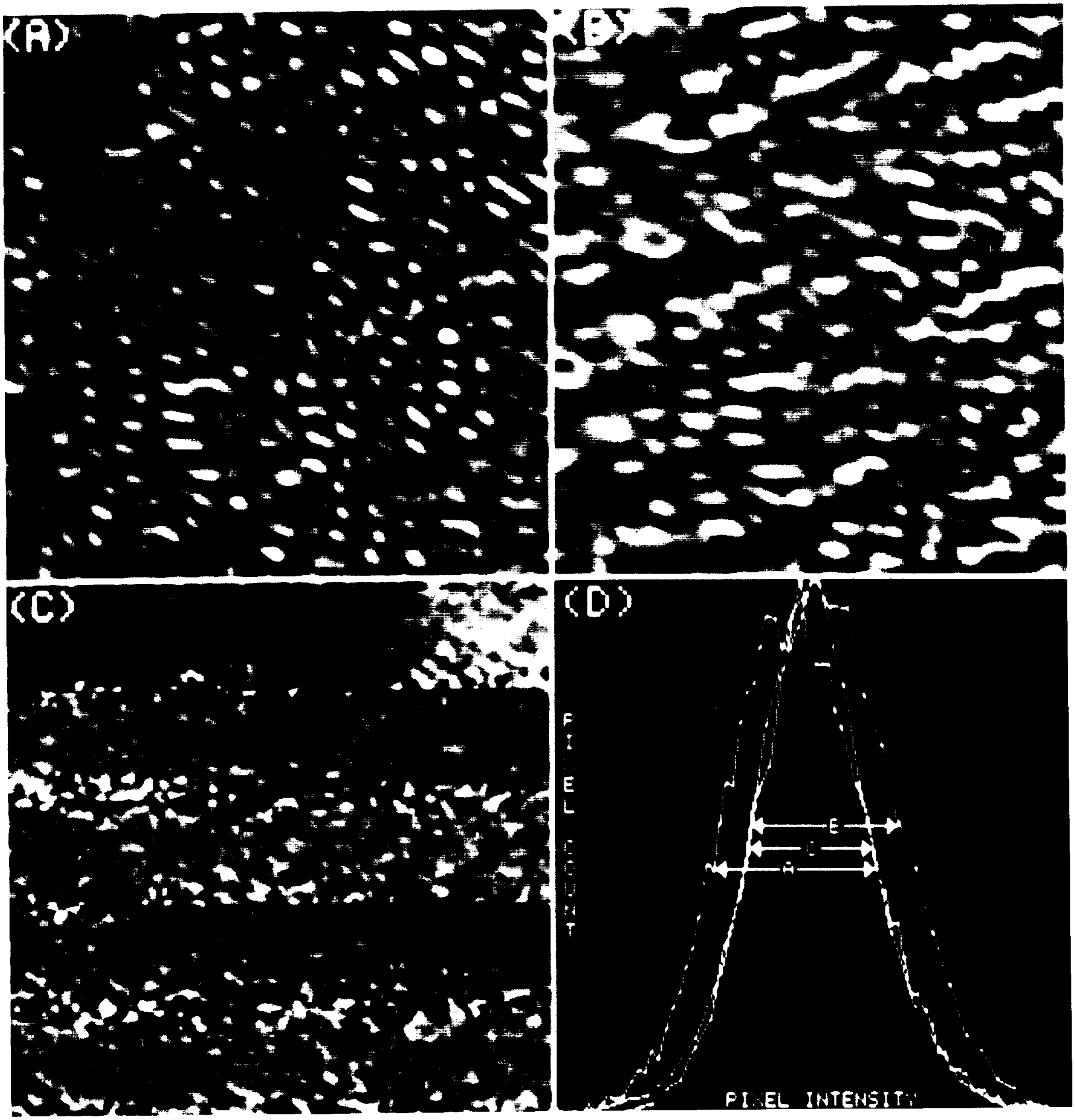


Figure 3  A 200x200 pixel segment of the Fourier filtered SAR image (a) is depicted as a two-dimensional distribution of the wave action intensity. Tilt and velocity bunching modulations of the SAR cross section can be included in the Fourier filter to simulate the wave height distribution (b), which can be compared with the SCR topography (c) along 5 separate aircraft tracks. Histograms (d) of pixel intensity counts are computed for the three data sets.

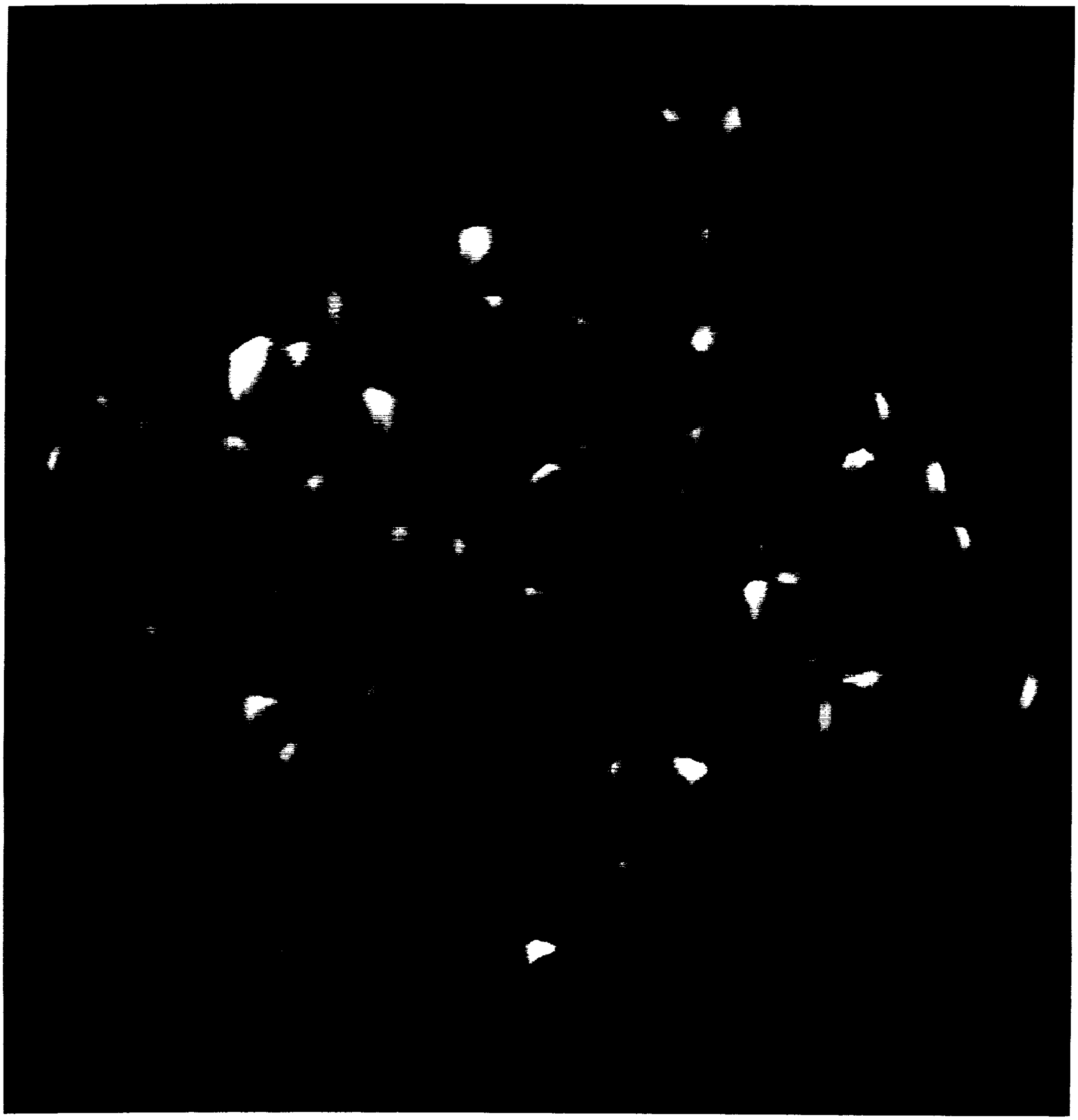

Figure 4 Long scale and short scale ocean wave correlations are evident in a three-dimensional surface plot of the SAR wave action intensity that has been shaded with speckled data values derived from the unfiltered SAR image.