ROBERT C. BEAL, STEPHEN F. ODEN, JOHN L. MacARTHUR, and FRANCIS M. MONALDO

# REAL-TIME OCEAN WAVE MONITORING FROM SPACE: A THIRTY-YEAR QUEST ACHIEVED

Real-time ocean wave monitoring from space may substantially improve operational wave forecasting. Although waveheight has been measured globally with satellite altimeters for more than a decade, waves are more completely described by their directional energy spectra. The directional spectra tell us not only what the waves are doing now, but also where and how fast they are going and how their total energy is distributed in wavenumber and angle. Spaceborne synthetic aperture radar can estimate the directional spectrum if the platform and instrument are properly chosen. In April, an experimental APL real-time synthetic aperture radar processor produced 55,000 directional spectra in the Southern Ocean using the NASA Space Radar Laboratory. This article reviews the scientific motivation for the experiment, outlines the developmental history of the processor, and presents some early results showing the evolving directional ocean wave spectrum over very long spatial scales in the Southern Ocean.

## BACKGROUND

Thirty years ago this summer, at a Woods Hole conference on oceanography from space, Professor Willard Pierson of New York University gathered with other scientists to consider the potential role of satellites for oceanography. For monitoring wind waves and swell, Pierson[1] commented:

> From a synoptic wave forecasting point of view, it would be nice to get data from all the oceans once a day, say from a polar orbiting vehicle, that could measure something about the waves every 200 miles (or so) along its path. The ultimate would be enough data to provide an estimate of the directional spectrum at each point [using] the new side-scanning radars. [The spectra] could serve as an initial value input to the problem of forecasting the waves a day or so into the future.

A decade later, as part of a definition study for NASA's Seasat, APL proposed the addition of a real-time processor to a synthetic aperture radar (SAR) to produce the timely estimates of the spectrum, as Pierson had suggested. The Laboratory proposed[2] that wave directional spectra could be collected globally at a 25-KB/s data rate if the SAR information were appropriately sampled, buffered, processed, and stored. Using this processor, image information with a 25-m resolution would be collected in patches 10 to 20 km on a side at intervals of 250 km. Such a global mode would require about $1.5 \times 10^8$ bits of storage per orbit, which was well within the capability of standard NASA tape recorders at the time.

In 1978, the first civilian SAR flew on Seasat, revealing a wealth of oceanographic detail that provided the impetus for the European (ERS-1, 1991), Japanese (JERS-1, 1992), and Canadian (Radarsat, 1995) SAR monitoring satellites. Seasat did not produce any real-time spectra, however, for lack of time, money, and perhaps technology. In any event, as was soon realized, the spectra would have been seriously flawed. By 1980, it was clear from the curiously cigar-shaped Seasat spectra (Fig. 1a) that high-altitude SAR satellites, or more precisely SAR platforms with high range-to-velocity ratios R/V, could not detect the shorter ocean waves traveling along the satellite path. The rms velocity $v_{rms}$ of the radar scatterers, created by the (partly randomly moving) ocean waves, produces an along-track rms translation $x_{rms}$ of the scatterer positions (commonly referred to as "Doppler smear") given by

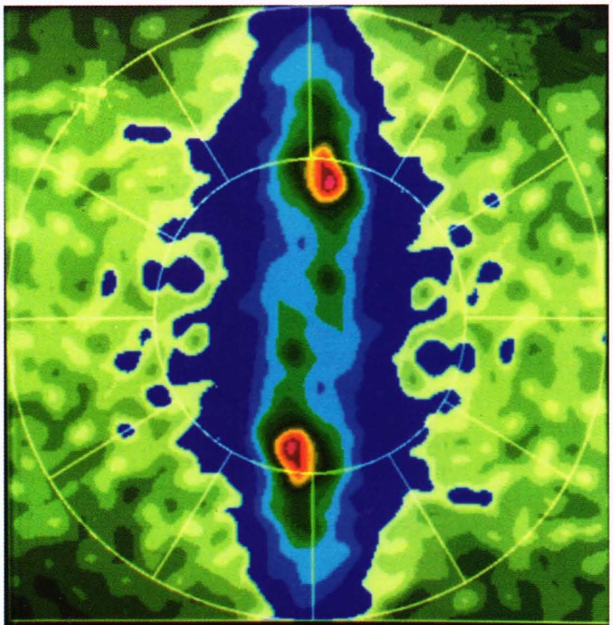
$$x_{rms} = (R/V)v_{rms} .$$

For Seasat, at an altitude of 800 km, R/V ≈ 130 s and a typical waveheight of 4 m ($v_{rms} = 2$ m/s), the resulting Doppler smear $x_{rms} \approx 260$ m. For higher seas, the Doppler smear is greater, increasing roughly as the square root of the waveheight.

Many energetic ocean waves are shorter than 260 m, and many storms of interest contain waveheights greater than 4 m. In fact, the average waveheight in the Southern Ocean (the vast ocean surrounding Antarctica) during winter is nearly 4 m. Major events exceed 10 m. The Doppler smear problem can be overcome only by lowering the altitude of the satellite to the point that atmospheric drag becomes excessive,[3] somewhere around 275 km. Such a low-altitude satellite would allow imaging of waves as short as 100 m, a much more useful limit for global wave monitoring and forecasting.[4]

In late 1984, the second NASA shuttle imaging radar, SIR-B, collected much improved spectra from its low-altitude (230-km) orbit. On 12 October, the last day of the mission, SIR-B sampled the active northeast quadrant of Hurricane Josephine, where waveheights exceeded 10 m. The SAR tracked three separately evolving wave systems through the center of the storm (Fig. 1b). In a separate SIR-B experiment at the southern end of Chile,

(a)



(b)

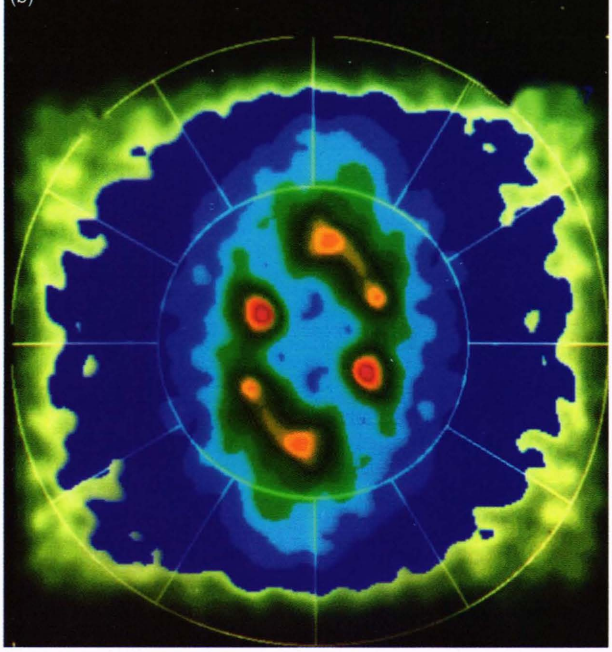


**Figure 1.** Typical directional ocean wave spectra plotted in linear wavenumber (inverse wavelength) out to $2\pi/50$ m, with the velocity vector of the spacecraft in the horizontal direction. Peaks in the spectrum correspond to the dominant wave systems present. No energy appears in the high-altitude spectrum for waves shorter than about 400 m. (a) 800-km altitude of Seasat in 1978. (b) 230-km altitude of SIR-B in 1984.

evidence accumulated that SAR spectral estimates from low-altitude spacecraft could be as accurate as those from other more conventional methods.[5]

Although SIR-B clearly demonstrated the potential of spaceborne SAR for ocean wave monitoring, it did nothing to alleviate operational concerns about processing time and data volume. Typically, several months elapsed between the collection of the data and the production of enough imagery for even a few dozen spectra. Data sets exceeding a few hundred spectra were rare from both Seasat and SIR-B. The perception of SAR as a complicated, operationally and scientifically inaccessible instrument was, even then, not so far from reality.

Not hundreds, but tens of thousands of spectra per day are necessary to adequately capture the morphology and dynamics of evolving storms around the globe. To be operationally useful for updating and initializing numerical wave forecast models, the spectra must be quickly accessible to both forecast centers and ships at sea. Rapid onboard processing, combined with rapid and wide dissemination, is needed to solve the practical operational problem.

## THE SPACE RADAR LABORATORY OPPORTUNITY

In 1985, soon after the successful SIR-B mission, NASA, in cooperation with Germany and Italy, began planning for the more ambitious Space Radar Laboratory (SRL). The SRL is an advanced three-frequency, dual-polarization SAR that has since become part of NASA's Mission to Planet Earth Program. L- and C-band SARs were to be provided by the Jet Propulsion Laboratory (JPL) and an X-band SAR by the Europeans. The SRL was to have flown in 1991, but various problems caused a 3-year slip to April 1994. (As it turned out, the delay was fortunate for APL because it allowed additional, valuable development time.) Even by early 1984, however, some of us at the Laboratory had begun to consider the feasibility of a smaller, special-purpose orbiting SAR for ocean wave spectra, based on processing ideas outlined in the 1974 Seasat definition study. The SRL seemed to present an ideal opportunity to test the concepts.

In 1986, NASA Headquarters approved APL's idea of adding a real-time SAR processor to the SRL, but with the caveat that we would not request new NASA funds, and that only readily available electrical outputs from the JPL instrument would be tapped. With this tentative agreement, but still with no financial support, the APL Independent Research and Development (IR&D) Committee was approached. Following a favorable review, work on the processor began in 1987 and continued through 1992, ultimately encompassing two consecutive IR&D initiatives. Finally, with credibility established, JPL began to modify its signal outputs to support the processor, and space was allocated on the shuttle pallet for the real-time SAR processor.

In July 1993, 7 years and about $1 million in IR&D funds later (followed by $200,000 in NASA science grants), APL delivered the completed processor[6] to Kennedy Space Center for integration with SRL. Keys to success were not only the unfaltering support of the APL IR&D Committee, but also innovative and thorough APL engineering design techniques, the ability to make compromises when necessary, a flexible quality assurance philosophy, outstanding cooperation from our JPL counterparts, and, last but not least, a tolerance for risk-taking. For this last ingredient especially, the lack of an external sponsor was definitely an asset.

## SOME EARLY RESULTS

The first flight of SRL occurred in April 1994. The APL processor, working from the JPL C-band receiver, collected spectra exclusively over the Southern Ocean between 30 and 58°S. This region is the spawning ground of many of the largest storms on the planet. Fortunately, it was also geographically well separated from other potentially conflicting locations of SRL experiments. Because the processor's operating mode needed very little SRL transmitter power and had no high data rate transmission or storage requirements, extremely long data-takes were possible with little effect on the overall SRL experiment. Figure 2 shows the SAR platform geometry for collecting ocean wave spectra.

By the end of 8 days of data collection during the April mission, the APL processor had delivered 55,000 spectra in over 40 h of operation; 44,000 spectra were received and archived in real time by APL personnel at the Mission Control Center in Houston. (Incomplete global coverage from the NASA data relay satellites caused a loss of about 20% of the real-time spectra, but the entire data set was obtained using an onboard recorder with a low data rate.) Because the "APL processor mode" was so benign, nearly half of SRL's total operating time was dedicated to the Southern Ocean experiment. A typical Southern Ocean data-take during the last half of the experiment was 30 min long, beginning, for example, in the South Indian Ocean, passing under Australia and New Zealand, and ending in the Western Pacific. A single 30-min data-take produced more than 600 spectral estimates at 20-km intervals. Often a single storm was cut through five or six times in a day; hundreds of spectral samples per cut were delivered to the ground in real time.

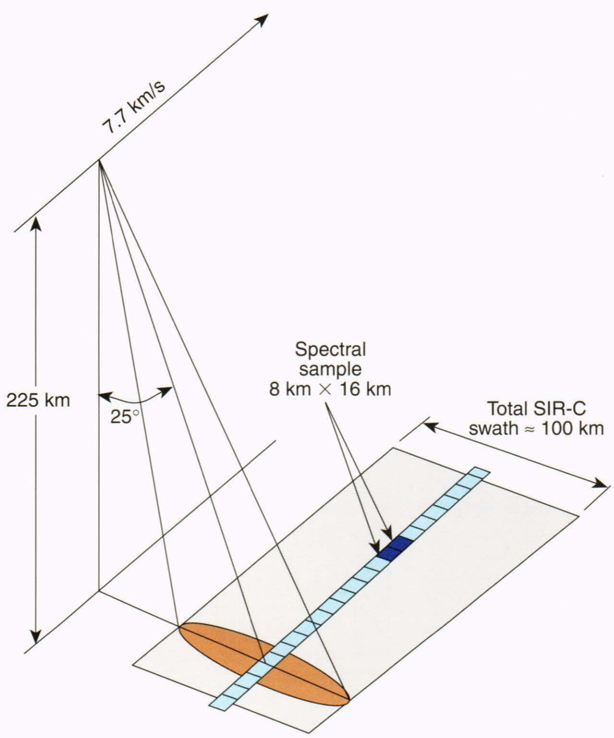



**Figure 2.** Platform geometry for the APL real-time processor aboard the Space Radar Laboratory in 1994. The radar looks 25° off nadir. The APL processor works on 8-km patches of 1-bit imagery to create a nearly contiguous series of "imagettes" of 256 × 256 pixels. The imagettes are Fourier transformed and then spectrally smoothed and spatially averaged to create the final low-bit-rate serial data stream.

Figure 3 suggests some of the ultimate potential of the Southern Ocean data. A set of 20 sequential spectra from a single 30-min data-take, centered around 10:00 GMT on 18 April 1994, is shown along a shuttle track centered south of Australia. Dominant spectral peaks are represented on the (altitude) map by vectors whose lengths correspond to 12-h travel times. For clarity, these dominant wave propagation vectors are shown only every 400 km, even though the original data are 20 times more dense. The SAR spectrum is radially symmetric, and so contains a 180° ambiguity in the wave propagation direction. However, with only a little knowledge from a wave model, the ambiguity can be removed. According to a Navy wave nowcast, a large storm having maximum 8-m waves was then centered directly south of Australia, halfway to the Antarctic coast, and moving to the east. Evidence of this event can be seen in the rapidly rotating wave vector plots in that region. Typically, these large events spawn waves traveling to the east and northeast (in this case, toward the southern Australian coast).

## SUMMARY

We have presented only an early glimpse of a small portion of the unique data set collected in April 1994 by the APL spectral processor during the first SRL mission. Because the complete data set is so dense, it appears that the Southern Ocean was sufficiently sampled to allow a reasonably complete time/space history of the dominant wave systems to be re-created. However, before we can make progress in extracting the large-scale wave dynamics, or even in comparing measured spectra with model spectra, we must first work carefully to understand and remove the effects of both the SAR system[7] and the APL processor.

The second mission, originally scheduled for August but now expected in early October, should increase the total number of spectra to well over 100,000. The combined April and October data sets will yield new insight into the morphology, dynamics, and seasonal variability of extreme storms in the Southern Ocean. Ultimately, the data are expected to provide strong evidence showing how model forecasts could be improved by the routine and systematic measurement of ocean wave spectra from future low-altitude satellites.

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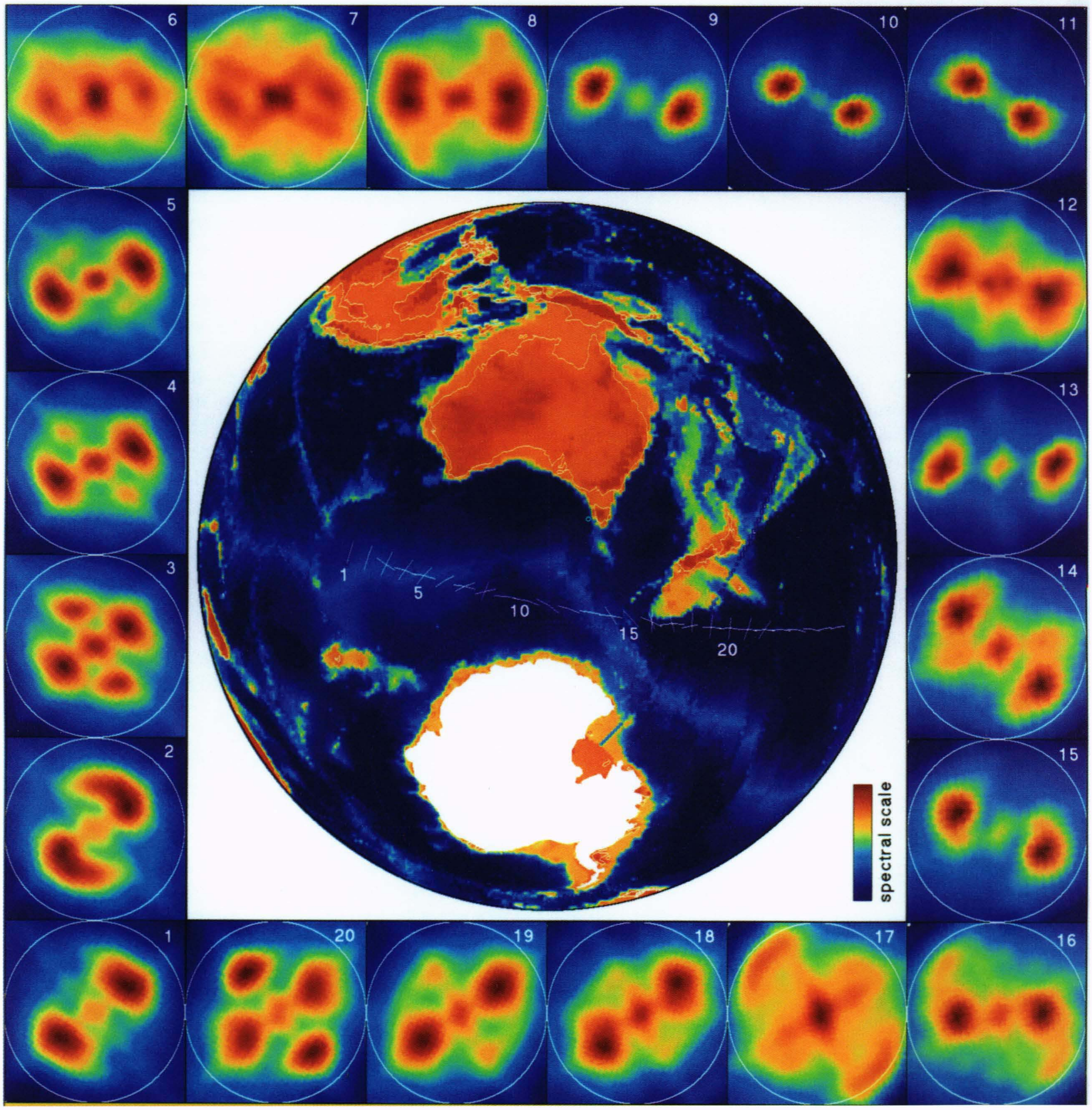


**Figure 3.** A typical sequence of directional ocean wave spectra from the APL processor along a 30-min data-take south of Australia collected on 18 April 1994. The 20 spectra are spaced every 400 km along the pass and show a dynamic evolution of multiple wave systems. North is vertical, and the circle represents a wavelength of 120 m. Dominant wave vectors taken from the spectral sequence are plotted on the globe to show the smoothly evolving spatial pattern typical of large-scale storms in the Southern Ocean. Navy wave forecasts showed a large storm just to the south of spectrum 10.

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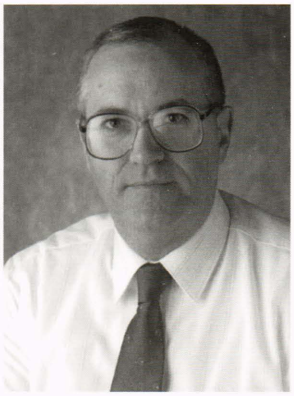

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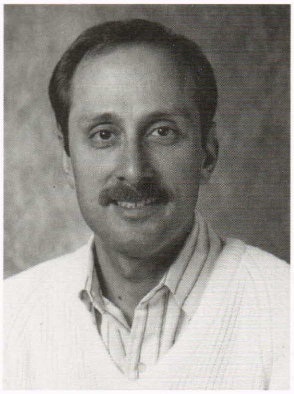

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