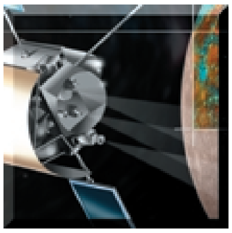


Ocean Remote Sensing Research and Applications at APL

Richard F. Gasparovic, R. Keith Raney, and Robert C. Beal

Scientists and engineers in the APL Space Department have made notable contributions to ocean remote sensing science and technology for more than a quarter of a century. Radar altimeters designed and built at APL have set the standard for measurement precision and reliability, and concepts for new instruments promise to maintain this leadership. A variety of techniques have also been developed to extract quantitative information about ocean winds, waves, and currents from radar images. These accomplishments provide some of the technology base needed for the development of integrated ocean information systems that can address environmental issues ranging from climate change to management of marine resources. (Keywords: Internal waves, Ocean remote sensing, Radar altimeters, Synthetic aperture radar, Winds and waves.)

INTRODUCTION

If someone were to ask, "What impact has the ocean had on your life?" many of us would recall fond memories of summer holidays spent at ocean resorts, cruises to Caribbean islands, or perhaps an encounter with the coastal devastation of a major hurricane. Others might remember long months at sea away from families and loved ones while serving their country. Yet even the millions of people who have never seen the ocean have been profoundly influenced by the large water masses that cover approximately 70% of the Earth's surface. Our weather systems and long-term climate, the global economy, and many important historical events are linked in one way or another to the ocean environment. Understanding the role of the oceans in shaping our world is important not only for placing the past in perspective but also for forming a vision of the future as we approach the start of a new millennium.

Historically, the earliest explorers and fishermen concentrated on observing the dominant forces affecting their ability to move about and survive at the air–sea interface: the winds, waves, and currents. Later, as measurement techniques were developed, seafarers began to probe the ocean interior to record water temperatures, the chemical composition of seawater, and the depth of the sea bed. The demands of naval operations during World War II provided the impetus for modern day ocean science and gave rise to an explosive growth in our ability to observe and understand the myriad processes taking place in the ocean and their influence on our terrestrial environment. The early days of the space age in the late 1960s brought a significant improvement in this observational capability with the launch of the first satellites to monitor global weather systems. For the first time, we could begin to assemble a truly synoptic view of some of the important consequences of energy exchange between the world's oceans and its atmosphere. At the same time, the remote sensing community began to develop optical, infrared, and microwave sensors for aircraft observations of ocean parameters. Many of these became prototypes for spaceborne instruments, and some dared to ask what we could learn about the ocean itself from space. Scientists and engineers in the APL Space Department have participated in the search for an answer to this question for the past quarter century.

APL RESEARCH THEMES

Our remote sensing research has been focused on a few broad areas despite having been sponsored by several agencies with diverse interests. The largest efforts have been concerned with the science and technology of radar altimetry and the extraction of oceanographic information from synthetic aperture radar (SAR) imagery. Underlying both of these efforts has been a substantial research program addressing the physics of microwave scattering from the sea surface. Numerous projects associated with applications of optical and infrared remote sensing techniques have also been part of our repertoire. Sponsoring agencies have included NASA, the National Oceanic and Atmospheric Administration (NOAA), the Office of Naval Research (ONR), the Defense Advanced Research Projects Agency (DARPA), and various other Navy offices.

RADAR ALTIMETRY

GEOS 3 and Seasat—The Beginning

APL's contributions to the science and technology of satellite radar altimetry began in 1971 with the Geodynamics Experimental Ocean Satellite (GEOS 3) Project managed by the NASA Wallops Flight Center. APL was selected as the spacecraft and experiment hardware contractor; the General Electric Company provided the radar altimeter. The GEOS 3 satellite, launched on 9 April 1975, was designed to improve our knowledge of the Earth's gravitational field, the size and shape of the terrestrial geoid, deep ocean tides, sea state, current structure, and solid earth dynamics.[1] GEOS 3 provided over 3.5 years of data and demonstrated the feasibility of directly measuring geodetic, oceanographic, and geophysical parameters through the reduction and analysis of the altimeter height measurements and the shape and structure of the return waveform. In addition, the altimeter was shown to be capable of providing valid measurements over land and sea ice.

In 1972, even before the launch of GEOS 3, NASA began planning for the Seasat satellite, the first multisensor spacecraft dedicated specifically to ocean observations. APL designed and built the radar altimeter for Seasat, which was launched in June 1978. The APL design introduced a novel signal processing methodology known as the full deramp technique that allowed height to be measured to a precision of a few centimeters, an order of magnitude improvement over the GEOS 3 altimeter.[2] Despite the premature demise of the Seasat spacecraft after only 100 days in orbit, the altimeter performance clearly demonstrated the significance of the APL processing innovation, and it was adopted as the standard approach for future satellite radar altimeters.[3]

Geosat—The Way to the Future

After the loss of Seasat, the Navy funded the Geosat altimeter mission to obtain a densely sampled, precise mapping of the Earth's geoid over the ocean during an 18-month period. APL was selected to be the prime contractor responsible for constructing the spacecraft bus and building the radar altimeter as well as for performing the spacecraft command and control operations, collecting mission data, and processing the data into sensor data records for distribution to the user community. During mission planning, it was recognized that valuable environmental data also could be obtained from the Geosat altimeter. The Oceanographer of the Navy responded with the Global Ocean Applications Program to exploit the altimeter observations for operational physical oceanography during an extended mission following completion of the classified geodetic mission.

The Geosat primary mission began with its launch on 12 March 1985 into an 800-km-altitude orbit that generated 3-day near-repeat ground tracks. The average spacing of the ground-track grid was 4 km. On 1 October 1986, at the completion of the 18-month primary geodetic mission, APL maneuvered the spacecraft into a 17.05-day exact repeat orbit to make the spacecraft subtrack coincide with the Seasat orbit and allow unclassified distribution of the data to users. The Exact Repeat Mission (ERM) began on 8 November 1986 and continued until January 1990, when the mission was terminated owing to degradation of the altimeter's output power.

The Geosat geoid data were declassified in 1995 and released to the scientific community. One of the first uses of those data was to generate a global seafloor topography map offering more than twice the resolution of the best previous global map.[4] The oceanographic data from the ERM became a critical component of the Navy's operational mesoscale analyses. They were used also by the scientific community to determine sea-level variability and absolute dynamic height to scales of thousands of kilometers for studies of long-term sea-level variability in diverse regions of the globe, including the first-ever basin-wide synoptic view of sea-level change during El Niño.[5] APL scientists made important contributions to the validation of the wind and wave measurements from Geosat,[6,7] as well as to operational applications associated with forecasting the Gulf Stream.[8,9]

Topex/Poseidon—The State of the Art

Topex/Poseidon, launched on 10 August 1992, is the first space mission specifically designed for observing the circulation of the world's oceans. The primary instrument for this joint U.S./France mission is Topex, the first spaceborne dual-frequency (5.3 and 13.6 GHz) altimeter, developed and built by APL. The design is based on the previous Seasat and Geosat altimeters with significant improvements, including the 5.3-GHz channel for ionospheric delay measurements, more precise height measurements, and longer lifetime.[10]

The Topex altimeter data are being used by an international team of more than 200 investigators to address many of the aspects of the ocean's role in climate change, such as the transport of heat and carbon dioxide; improving our understanding of winds, waves, and ocean tides; and development of techniques for the assimilation of altimeter data with *in situ* observations into ocean circulation models to produce an optimal description of the state of the ocean circulation.

Although the Topex altimeter was designed for a mission to last for at least 3 years with a possible extension to 6 years, it continues to operate satisfactorily after nearly 7 years on orbit. This extended lifetime is the result of an APL design that incorporates a fully redundant set of radio-frequency and signal processing electronics for the altimeter. The second side was activated in April 1999, which should extend the mission for an additional 2 to 3 years.

ADVANCED RADAR ALTIMETER TECHNIQUES—VISIONS OF THE FUTURE

Delay/Doppler Processing

Despite the excellent performance of contemporary satellite radar altimeters, there are definite limitations for observations near coastlines and over other surfaces such as continental ice sheets. In response to these deficiencies, in 1994 APL began developing a new type of radar altimeter that incorporates features derived from SAR technology. The result is the delay/Doppler radar altimeter.[11] The central innovation in this state-of-the-art altimeter is that the returns from a group of transmissions along track are coherently processed together, rather than incoherently as is customary. The coherent along-track processing allows much more of the instrument's radiated power to be converted into height measurement data, among other advantages. The delay/Doppler technique leads to a smaller instrument that requires less power, yet simulations indicate that its measurement precision is finer than that of a conventional radar altimeter, and its waveform is much better suited to ice sheet, coastal, and terrestrial applications.

The along-track processing transforms the data into the Doppler frequency domain where delay corrections are applied, analogous to range curvature correction in a SAR.[12] Doppler processing determines the size and location of the along-track footprint (Fig. 1), which is (1) smaller than the pulse-limited diameter, (2) a constant of the system, and (3) relatively immune to surface topographic variations and coastal proximity. When the waveforms from parallel Doppler bins are coregistered and summed, the resulting height measurements benefit from more incoherent averaging. The delay/Doppler flat-surface response is an impulse rather than the more familiar step function produced by conventional satellite radar altimeters.

The velocity of a conventional satellite altimeter causes the effective footprint for a multipulse waveform to be elongated along track. Detected returns from many pulses are averaged together to build each multilook waveform. Such signal summations typically extend over 1.0 s, during which time the antenna illumination pattern progresses in the along-track direction by an appreciable distance, approximately 6 km. As a result, the effective postaveraging footprint for a conventional altimeter is a set of elliptical annuli, elongated along track, rather than the circular single-pulse footprints normally cited in the literature. In contrast, the relative location of each delay/Doppler-derived height estimate is synchronized to coincide with the forward motion of the instrument, thus eliminating along-track elongation of the footprint. Typical delay/Doppler footprints measure only 250 m along track. The cross-track footprint is determined by the pulse-limited condition, as is the case for conventional satellite radar altimeters.[3]

Phase-Monopulse Technique

The phase between two otherwise identical coherent signals is a direct measure of the time shift between them. If the geometry of the observation space is known, then the observed phase shift can be inverted to an angular offset. The phase-monopulse technique

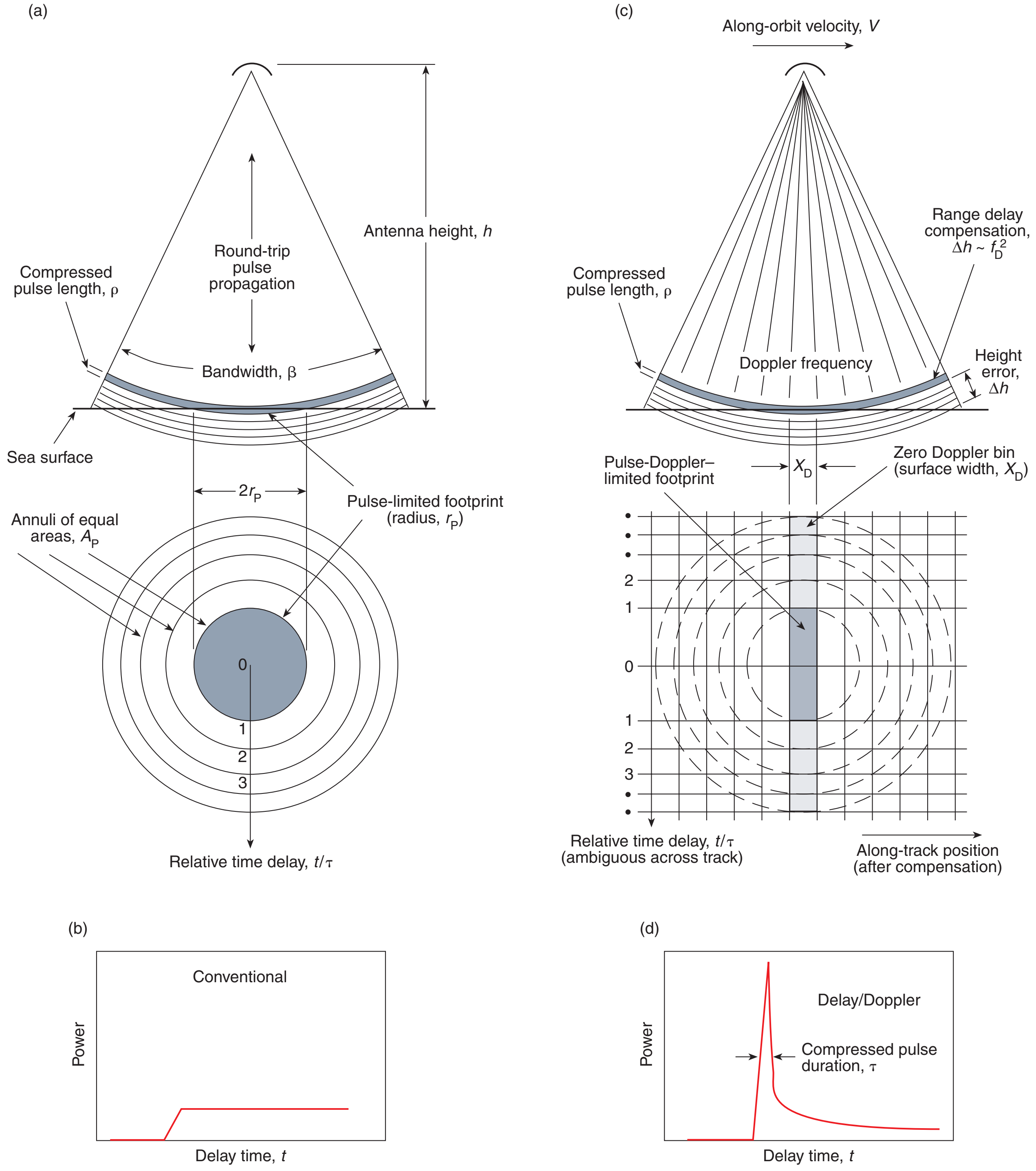


Figure 1. Comparison of a conventional pulse-limited radar altimeter's (a) illumination geometry (side view) and footprint (plan view) and (b) impulse response, with a delay/Doppler altimeter's (c) illumination geometry and footprint and (d) impulse response.

uses this principle to estimate the angle of arrival between two signals collected through separated antennas. Two such antennas may be arranged orthogonally to the flight direction of a radar altimeter (Fig. 2). In a radar altimeter that uses the phase-monopulse technique,[13] a scatterer at cross-track distance Δy away from nadir produces a path-length difference ΔR, observable through the cross-channel differential phase. The cross-track phase-monopulse technique can measure the presence of small (mean) cross-track surface slopes, or satellite-roll errors, when over a nominally level surface such as the sea. Once measured, either

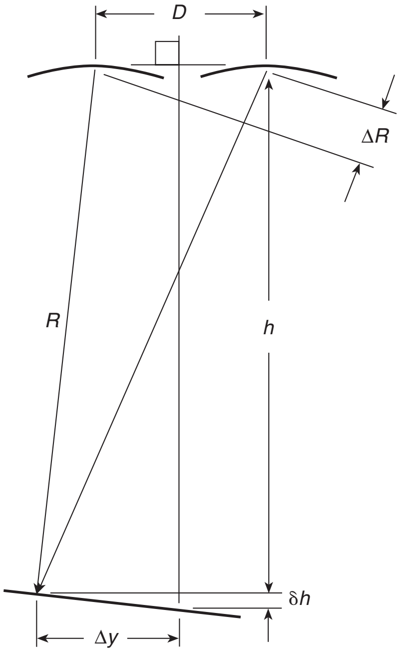


Figure 2. The across-track (mean) surface slope can be estimated by a measurement of the phase difference between the same return observed through two separated antennas. The range difference ΔR is proportional to this phase difference, from which the slope-induced height correction δh can be calculated.

slope- or attitude-induced waveform errors can be corrected to compensate for the differential height δh, thus leading to more accurate estimates of the height h. The cross-track phase-monopulse technique complements the delay/Doppler technique, which is an along-track enhancement.

NASA's Instrument Incubator Project

APL's proposal, "The New Generation of Radar Altimeters: Proof of Concept," was selected by NASA in the fall of 1998 as one of the first group of Instrument Incubator Projects. Its objective is to demonstrate through airborne flight tests the fundamental viability and desirability of an innovative altimeter concept that combines the delay/Doppler and the phase-monopulse techniques into one instrument, the first of its kind. This advanced instrument is known as the D2P altimeter. In future satellite versions, a flight-proven D2P radar altimeter will offer unprecedented measurement accuracy over continental ice sheets and better precision from a smaller instrument over the open ocean. For the first time, near-shore (1-km) satellite-based radar altimetry will be possible. Variations on the D2P approach should support remote depth sounding of ice or terrestrial elevation altimetry. The D2P concept is the first of a new generation of radar altimeters that simultaneously satisfies high signal-to-noise ratio, high signal-to-speckle ratio, and high signal-to-clutter ratio. These characteristics represent a substantial and innovative breakthrough.

The APL Instrument Incubator Project will (1) complete the detailed design of the altimeter, (2) build and test the altimeter in the laboratory, (3) perform demonstration aircraft flight tests of the altimeter over the ocean and the ice sheets of southern Greenland, (4) evaluate the results, and (5) design, build, and demonstrate in the laboratory a real-rate signal processing unit sufficient to support the demands of an orbital D2P altimeter. The size, cost, and performance of a future satellite version of this altimeter will also be estimated.

WINDS AND WAVES

Seasat—Another Beginning

In 1975, NASA decided to include a high-resolution SAR as an experimental instrument on Seasat on the premise that it might allow the directional spectrum of ocean waves to be measured on global scales, quasi-continuously, and under extreme and variable sea conditions. Although aircraft SAR systems had acquired images of the sea surface in the early 1970s that showed evidence of wave-like features, it was not at all certain that quantitative wave information could be extracted from satellite SAR observations. The fundamental problem here is that the ocean waves move during the interval (1 s or so) that the radar acquires sufficient data to form an image. The decision to fly a SAR on Seasat with little more than a hope that it would yield useful ocean information (an unlikely decision in today's funding climate) became the impetus for a nearly 20-year effort by APL scientists and other researchers to understand the nuances of radar imaging of ocean waves. A sampling of the rich variety of oceanographic imagery recorded by the Seasat SAR can be found in Ref. 14, which documents the principal results of a symposium held at APL in March 1980.

The effort to interpret SAR images of large storms encountered during the Seasat mission[15] and subsequent data from the second Shuttle Imaging Radar experiment (SIR-B) in 1984 (1) paved the way for the development of wave imaging theories and new techniques to extract wave information, and (2) demonstrated the effects of spacecraft altitude and velocity on the ability of a SAR to measure the directional wave spectrum (see the boxed insert). A symposium entitled "Measuring Ocean Waves from Space" was held at APL in April 1986 to reexamine the scientific and operational motivation for observing ocean waves from space, to review the SIR-B results and their implications, and to explore and debate the benefits of a global wave-monitoring capability.[16] An opportunity to blend SAR images with *in situ* wave observations and wave model predictions came in March 1987 with the Labrador Sea Extreme Waves Experiment (LEWEX), the subject of yet another APL-hosted symposium in April 1989.[17,18]

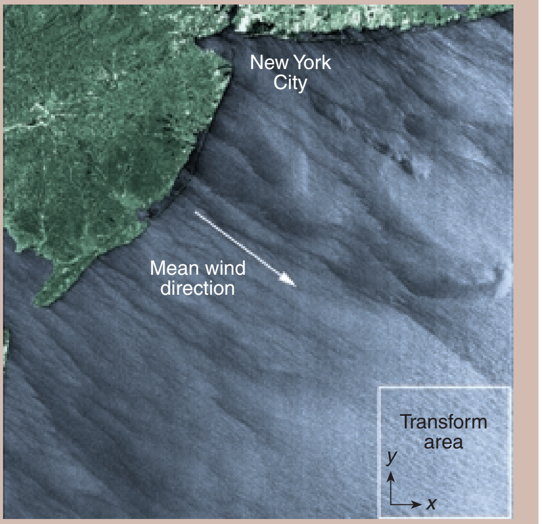
One of the more remarkable, and unexpected, results from the Seasat SAR images was the observation that the images often showed an identifiable

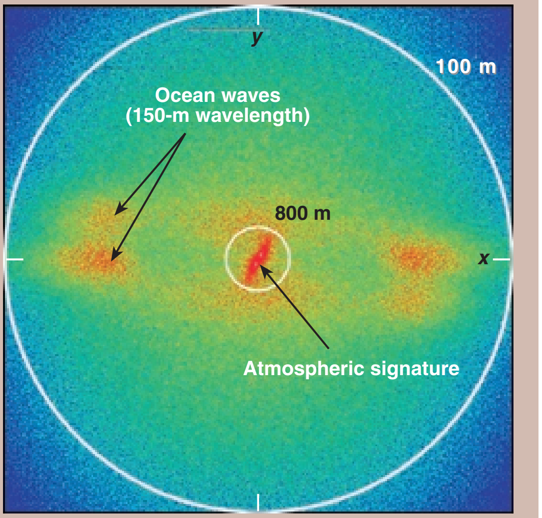
ATMOSPHERIC SIGNATURES IN SAR IMAGERY

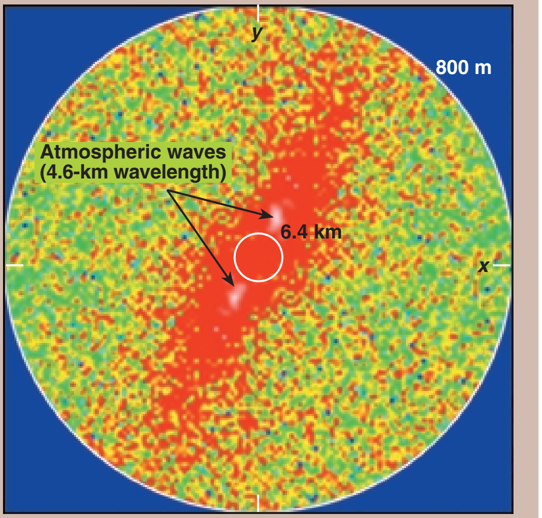
Periodic spatial structures caused by wind and waves are often evident in SAR ocean imagery. The top figure shows a 300-km-wide Radarsat image (50-m pixels) acquired on 6 March 1997 over the New Jersey coast. A steady wind of 12–15 m/s from the northwest was blowing nearly normal to the coast at overpass time. Gusts to 25 m/s were reported; widespread power outages occurred in eastern Pennsylvania. It takes little imagination to infer the mean wind direction from the SAR image. A downwind segment of the SAR image (box at lower right) contains a number of interesting oceanic and atmospheric signatures, even more manifest in the two-dimensional (or directional) spatial spectrum. These signatures give insight into the physical processes operating on and above the air–sea boundary and also illustrate some of the intrinsic limitations imposed by the SAR image formation process.

The center figure is the wavenumber spectrum of the transform area of the top figure. It shows all scales in the directional spectrum longer than 100 m. Here the spectrum indicates a dominant wavelength of about 150 m (10-s period), travelling nearly normal to the SAR velocity vector (which is toward the top). But the wave spectral energy distribution exhibits two suspicious characteristics: (1) it is apparently split into two modes, with a propagation angle difference of about 20°, and (2) it is confined to a narrow wavenumber band normal to the SAR velocity vector (not in the downwind direction). Neither of these “instrument contaminations” is new with Radarsat; each was first observed 20 years ago in Seasat data and more recently in ERS-1 and ERS-2 images. They are intrinsic limitations of a high-altitude SAR and can be overcome only by lowering the altitude to about 300 km or so. Such a low-altitude SAR is not likely to be realized soon, since higher atmospheric drag would require substantial onboard propellant.

The bottom figure is an expanded spectrum of the middle portion of the center figure. It shows the very longest wavelength scales in the SAR wavenumber spectrum, from 800 m to approximately 50 km, that are often associated with atmospheric signatures such as boundary-layer rolls. This particular spectral signature is typical of an unstable boundary layer, often seen in the aftermath of a cold air outbreak along the U.S. East Coast. The long axis of the energy bundle is nearly normal to the local wind direction, and the spectral peak (seen in the figure at about 4.6 km) reveals the periodic structure of the surface signature of the boundary-layer rolls. This horizontal dimension is directly related to the vertical depth of the boundary layer. Thus, SAR ocean images often contain information on the three-dimensional structure of the marine boundary layer. This is one of the most promising emerging applications of SAR, and one that is sure to be increasingly exploited in the coming decade.







signature of the local wind direction.[19] These signatures arise from local modulations of the surface wind by various atmospheric processes, which in turn alter the local surface roughness and hence the radar backscatter used to form the SAR image. While noted almost in passing during the time when interest was focused on extracting wave information from SAR images, these observations of wind signatures were to become the genesis of substantial research now under way to extract high-resolution wind information from SAR images. More on this topic later (also see the boxed insert).

ERS-1, SIR-C, and Radarsat—The Way to the Future

Progress during the 1980s was hampered by the dearth of spaceborne SAR imagery. Despite the acknowledged success of the Seasat SAR, no national commitment for a follow-on satellite capability was forthcoming in the United States. Space agencies in other nations were not so timid, and SAR satellites were launched by Russia (1987, 1991), Europe (1991, 1995), Japan (1992), and Canada (1995). After a long delay because of the shuttle Challenger disaster, NASA launched the third SIR experiment (SIR-C) in April 1994, with a follow-up flight in October 1994. SIR-C provided APL investigators with an opportunity to demonstrate real-time, onboard processing of SAR data to produce ocean wave spectra using a specialized processor built at the Laboratory.[20] These processed spectra were downlinked to APL scientists at the ground station in Houston and compared with real-time wave forecasts from the Navy's Fleet Numerical Oceanographic Center in Monterey to demonstrate the operational utility of such data.[21] The European Space Agency implemented a similar approach using ground processing of SAR imagery after the launch of their European Remote Sensing satellite (ERS-1) in 1991 and plans to continue the use of SAR imagery for operational wave forecasting with the launch of the Envisat satellite in 2000.

When SAR imagery from ERS-1, ERS-2 (1995), and the Canadian Radarsat satellites became available, APL investigators turned their attention to larger-scale features associated with atmospheric phenomena.[22] There is now compelling evidence that wide-swath (300- to 500-km) SAR images, when properly calibrated and interpreted in the context of supplementary sensor fields and model estimates, can yield unique information on the marine atmospheric boundary layer. The first-order scientific product is a very high resolution (order of 300 m) surface wind field[23]; second-order products include both the height of the atmospheric boundary layer and the horizontal and vertical structure of the atmospheric momentum fluxes. The importance of these uniquely SAR-associated geophysical quantities is difficult to overestimate. Conventional 10- to 25-km-resolution scatterometer or radiometer estimates will always be seriously limited in coastal regions and will always underestimate the local variability.

Figure 3 shows an example of this application of wide-swath SAR, generated from a Radarsat acquisition over the Gulf of Maine on 22 November 1997. Here the radar backscatter values have been converted to wind speed using well-known scatterometer relationships, with wind direction taken from both a numerical model (white-bordered arrows) and a coastal buoy network (black-bordered arrows). The resulting wind field shows variability resulting both from coastal sheltering and from the atmospheric instability present at the overpass time.

A collaborative effort with NOAA scientists is now under way to develop techniques for extracting high-resolution surface wind vector information from SAR images off the East Coast of the United States. Next year a larger effort will begin in the Gulf of Alaska as a prototype operational demonstration of the utility of SAR imagery for coastal wind forecasts.

INTERNAL WAVES AND CURRENTS

Ocean currents manifest themselves in SAR images because of wave–current interactions, which modify the small-scale wave structure responsible for radar backscatter. The signatures are most prominent where there are large current gradients. One of the major

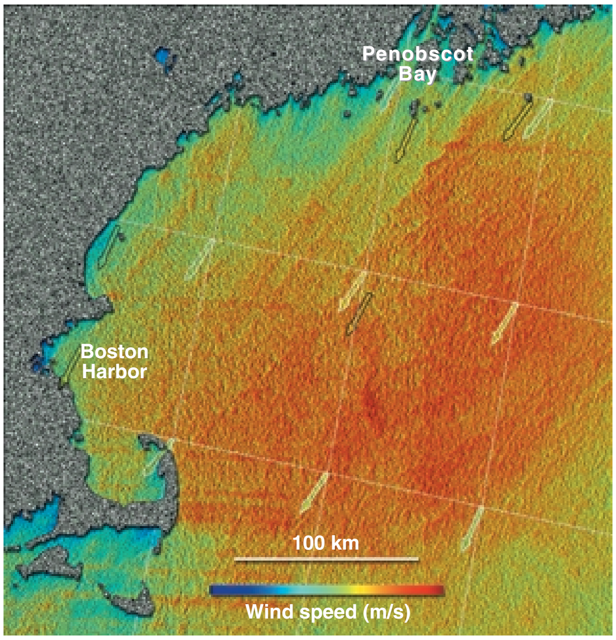


Figure 3. Radarsat wide-swath SAR image processed to show the surface wind variations over the Gulf of Maine on 22 November 1997.

themes of ocean remote sensing research at APL has been to understand the details of how surface expressions of oceanic currents arise in radar images. This requires investigation of a lengthy chain of processes, beginning with the hydrodynamics of wave–current interactions, to the physics of radar backscattering from the sea surface, the impact of ambient winds and waves on the visibility of current features, and ending with the signature dependence on radar parameters and imaging geometry.

Packets of coastal internal waves are convenient sources of surface currents for these types of studies. Solar heating warms the upper ocean during the late spring, producing a 10- to 15-m-deep layer of warm water above colder water extending to the seafloor over continental shelf regions. Semidiurnal tidal flows over the shelf break excite groups of large-amplitude, nonlinear internal waves (known as solitons) at the interface of the warm and cold waters, analogous to the generation of ocean waves by wind forcing at the air–sea interface. These groups of internal wave solitons propagate toward the shore at speeds of about 0.5 m/s, generating regions of converging and diverging flows at the surface that appear as bright and dark features in radar images. Figure 4 shows a SAR image of coastal internal waves in the New York Bight recorded by the ERS-1 satellite during a joint U.S./Russia experiment in 1992.[24]

Tidal forcing is not the only way to generate internal waves. In many coastal inlets where there is substantial runoff from rivers or melting snow, a freshwater layer of a few meters in depth forms over more saline, denser water. The disturbance from a moving ship can generate a V-shaped pattern of internal waves at the interface of the two fluids, similar to the way in which ship hulls generate the well-known Kelvin wave pattern on the surface. An example of a ship-generated pattern of internal waves observed with an airborne SAR in Loch Linnhe, Scotland, can be seen in Fig. 5.[25]

Laboratory scientists have studied both types of internal waves in an extensive series of radar imaging experiments conducted since 1983 with oceanographers and remote sensing experts from several countries. Table 1 lists these experiments. Theories and models for radar imaging of internal waves have been developed to interpret the results from these experiments,[26,27] and some recent work has shown that information can be extracted from radar images of coastal internal waves to estimate the depth of the pycnocline and the density of the surface layer.[28]

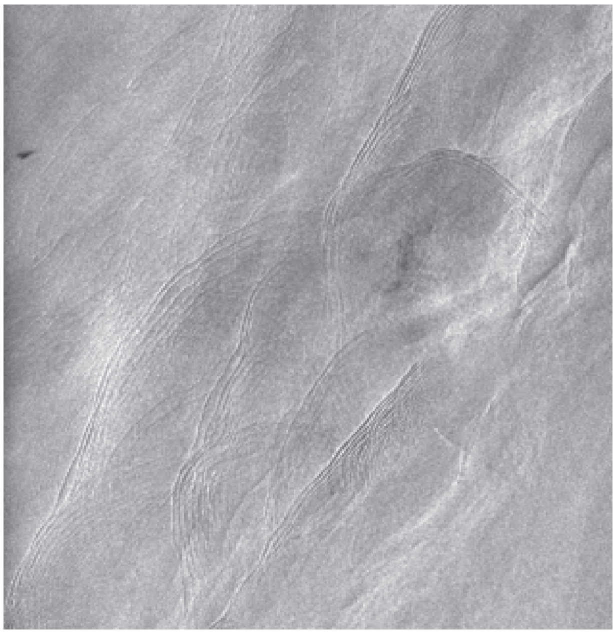


Figure 4. ERS-1 SAR image showing internal wave signatures in a 100 × 100 km region of the New York Bight. (© European Space Agency, 1992.)

Larger-scale ocean currents can also be measured by imaging radars using a technique known as along-track interferometry. Here the SAR system uses two closely spaced antennas to receive the radiation backscattered from the sea surface, and the phase difference of the two signals is used to derive the component of the surface current along the radar line of sight. A theory for this technique was first developed by APL investigators to explain internal wave observations during one of the Loch Linnhe experiments[29] and was subsequently validated against *in situ* current measurements (Fig. 6) during the ONR High Res Experiment in 1993 off the coast of Cape Hatteras.[30] Thus, high-resolution surface current information, along with high-resolution surface wind data mentioned previously, can now be obtained remotely using novel SAR image analysis techniques pioneered by APL remote sensing scientists.

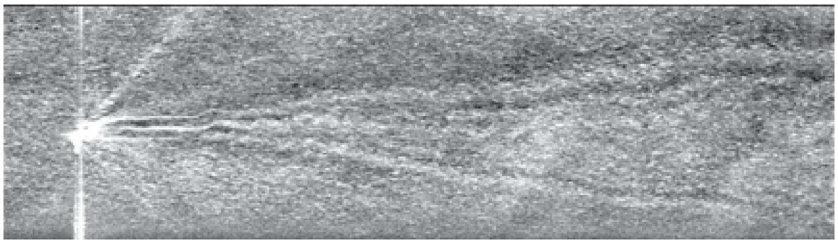


Figure 5. Radar image of a ship-generated internal wave pattern recorded in Loch Linnhe, Scotland, in 1989. Note that the vertical scale has been expanded to twice that of the horizontal to exhibit the details in the wave pattern. The bright return at the left of the image is caused by the reflection from the ship.

Table 1. Internal wave imaging experiments.

Date	Location	Participants	Internal wave source
1983	Georgia Strait, Canada	U.S./Canada	Tidal flows
1984	New York Bight	U.S./Canada	Coastal solitons
1987, 1989	Loch Linnhe, Scotland	U.S./U.K.	Ship-generated waves
1988, 1995	Sognefjord, Norway	U.S./Norway	Ship-generated waves
1992	New York Bight	U.S./Russia	Coastal solitons

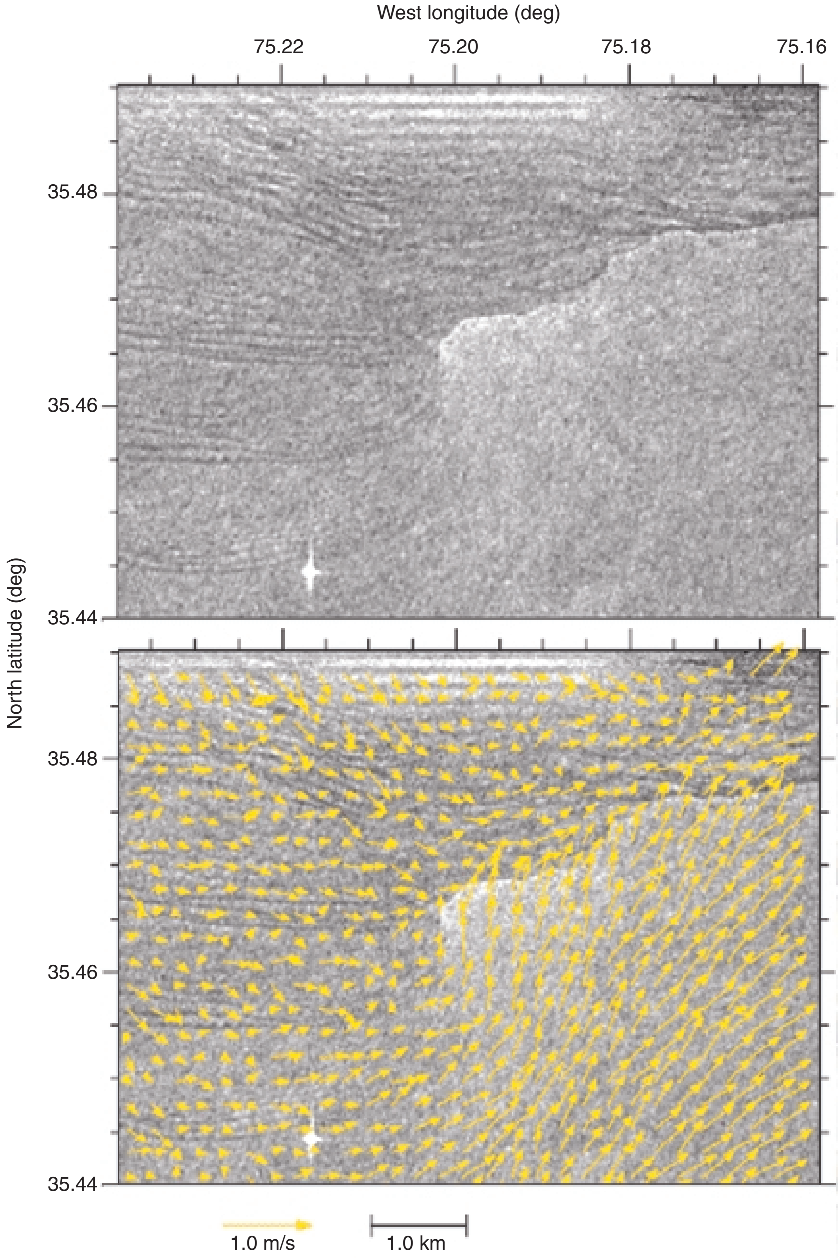


Figure 6. Interferometric SAR image (top) from which surface current vectors (yellow arrows, bottom) were derived.

FUTURE DIRECTIONS

The science and technology of ocean remote sensing have now matured to the stage where serious efforts are being undertaken to assemble integrated ocean information systems to address a range of environmental issues from climate change to management of marine resources. These systems will combine *in situ* and remote observations with sophisticated numerical models to monitor and forecast ocean conditions, providing products to a diverse user community of scientists, resource managers, disaster management teams, and other decision makers in the same fashion that meteorologists now use data and computer models for weather and climate predictions.

Information systems focused on coastal regions are of particular interest to the Laboratory's program in remote sensing. These fragile ocean boundary areas are very susceptible to long-term degradation from human activities and shipping accidents, and they sustain periodic damage from winds and flooding during major storms and hurricanes. They also encompass the biologically productive waters that are home to much of the world's fishing industry, mandating a critical need for information to promote sound management of marine resources to maintain stocks and avoid irreversible depletion of fisheries.

Providing creative solutions to these types of important system-level problems is a difficult challenge, one that merits our best efforts in APL's long tradition of such endeavors. A key ingredient in this process will be the scientific approach taken by APL remote sensing specialists, one that blends theory and modeling with *in situ* ocean observations to understand the physical basis for phenomena observed in remote sensor data, followed by real-world testing and validation, leading in some cases to the development of new observational methods to advance the state of the art.

REFERENCES

[1] Stanley, H. R., "The Geos 3 Project," *J. Geophys. Res.* **84**, 3779–3783 (1979).

[2] Chelton, D. B., Walsh, E. J., and MacArthur, J. L., "Pulse Compression and Sea Level Tracking in Satellite Altimetry," *J. Atmos. Oceanic Technol.* **6**, 407–438 (1989).

[3] Raney, R. K., "Radar Altimetry," in *Wiley Encyclopedia of Electrical and Electronics Engineering*, J. G. Webster (ed.), Vol. 17, John Wiley and Sons, New York, pp. 547–560 (1999).

[4] Smith, W. H. F., and Sandwell, D. T., "Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings," *Science* **277**, 1956–1961 (1997).

[5] Miller, L., Cheney, R. E., and Douglas, B. C., "Geosat Altimeter Observations of Kelvin Waves and the 1986-87 El Niño," *Science* **239**, 52–54 (1988).

[6] Dobson, E., Monaldo, F. M., Goldhirsh, J., and Wilkerson, J., "Validation of Geosat Altimeter-Derived Wind Speeds and Significant Wave Heights Using Buoy Data," *J. Geophys. Res.* **92**, 10,719–10,731 (1987).

[7] Monaldo, F. M., "Expected Differences Between Buoy and Radar Estimates of Wind Speed and Significant Wave Height and Their Implications on Buoy-Altimeter Comparisons," *J. Geophys. Res.* **93**, 2285–2301 (1988).

[8] Glenn, S. M., Porter, D. L., and Robinson, A. R., "A Synthetic Geoid Validation of Geosat Mesoscale Dynamic Topography in the Gulf Stream Region," *J. Geophys. Res.* **96**, 7145–7166 (1991).

[9] Porter, D. L., Glenn, S. M., Dobson, E. B., and Crowley, M. F., "Extension and Validation of a Gulf Stream Geosat Synthetic Geoid," *J. Atmos. Oceanic Technol.* **13**, 514–531 (1996).

[10] Fu, L.-L., Christensen, E. J., and Yamarone, C. A., Jr., "TOPEX/Poseidon Mission Overview," *J. Geophys. Res.* **99**, 24,369–24,381 (1994).

[11] Raney, R. K., "The Delay/Doppler Radar Altimeter," *Trans. IEEE Geosci. Remote Sens.* **36**, 1578–1588 (1998).

[12] Raney, R. K., "Radar Fundamentals: Technical Perspective," Chap. 2, in *Principles and Applications of Imaging Radar, Manual of Remote Sensing*, 3rd Ed., F. Henderson and A. Lewis (eds.), John Wiley and Sons, New York, pp. 9–130 (1998).

[13] Jensen, J. R., "Angle Measurement with a Phase Monopulse Radar Altimeter," *IEEE Trans. Antennas Propag.* **47**, 715–724 (1999).

[14] Beal, R. C., DeLeonibus, P. S., and Katz, I. (eds.), *Spaceborne Synthetic Aperture Radar for Oceanography*, The Johns Hopkins University Press, Baltimore, MD (1981).

[15] Beal, R. C., Gerling, T. W., Irvine, D. E., Monaldo, F. M., and Tilley, D. G., "Spatial Variations of Ocean Wave Directional Spectra from the Seasat Synthetic Aperture Radar," *J. Geophys. Res.* **91**, 2433–2449 (1986).

[16] Beal, R. C. (guest editor), "Proceedings of the Symposium Measuring Ocean Waves from Space," *Johns Hopkins APL Tech. Dig.* **8**(1) (1987).

[17] Beal, R. C., "Guest Editor's Introduction," *Johns Hopkins APL Tech. Dig.* **11**, 363–364 (1990).

[18] Beal, R. C. (ed.), *Directional Ocean Wave Spectra*, The Johns Hopkins University Press, Baltimore, MD (1991).

[19] Gerling, T. W., "Structure of the Surface Wind Field from the Seasat SAR," *J. Geophys. Res.* **91**, 2308–2320 (1986).

[20] Beal, R. C., Oden, S. F., and MacArthur, J. L., "A Real-Time On-Board SAR Processor for Global Ocean Wave Spectra from Low Altitude Platforms," in *Proc. Int. Geoscience and Remote Sensing Symp.*, pp. 443–446 (1991).

[21] Monaldo, F. M., and Beal, R. C., "Comparison of SIR-C SAR Wavenumber Spectra with WAM Model Predictions," *J. Geophys. Res.* **103**, 18,815–18,825 (1998).

[22] Sikora, T. D., Young, G. S., Beal, R. C., and Edson, J. B., "Use of Spaceborne Synthetic Aperture Radar Imagery of the Sea Surface in Detecting the Presence and Structure of the Convective Marine Atmospheric Boundary Layer," *Mon. Wea. Rev.* **123**, 3623–3632 (1995).

[23] Thompson, D. R., and Beal, R. C., "Mapping Mesoscale and Submesoscale Wind Fields Using Synthetic Aperture Radar," in *Proc. Int. Geoscience and Remote Sensing Symp.*, pp. 1382–1384 (1998).

[24] Gasparovic, R. F., and Etkin, V. S., "An Overview of the Joint US/Russia Internal Wave Remote Sensing Experiment," in *Proc. Int. Geoscience and Remote Sensing Symp.*, pp. 741–743 (1994).

[25] Hogan, G. G., Chapman, R. D., Watson, G., and Thompson, D. R., "Observations of Ship-Generated Internal Waves in SAR Images from Loch Linnhe, Scotland, and Comparisons with Theory and In Situ Internal Wave Measurements," *IEEE Trans. Geosci. Remote Sens.* **34**, 532–542 (1996).

[26] Thompson, D. R., Gotwols, B. L., and Sterner, R. E. II, "A Comparison of Measured Surface-Wave Spectral Modulations with Predictions from a Wave-Current Interaction Model," *J. Geophys. Res.* **93**, 12,339–12,343 (1988).

[27] Thompson, D. R., "Calculation of Radar Backscatter Modulations from Internal Waves," *J. Geophys. Res.* **93**, 12,371–12,380 (1988).

[28] Porter, D. L., and Thompson, D. R., "Continental Shelf Parameters Inferred from SAR Internal Wave Observations," *J. Atmos. Oceanic Technol.* **16**, 475–487 (1999).

[29] Thompson, D. R., and Jensen, J. R., "Synthetic Aperture Radar Interferometry Applied to Ship-Generated Internal Waves in the 1989 Loch Linnhe Experiment," *J. Geophys. Res.* **98**, 10,259–10,269 (1993).

[30] Graber, H. C., Thompson, D. R., and Carande, R. E., "Ocean Surface Features and Currents Measured with Synthetic Aperture Radar Interferometry and HF Radar," *J. Geophys. Res.* **101**, 25,813–25,832 (1996).

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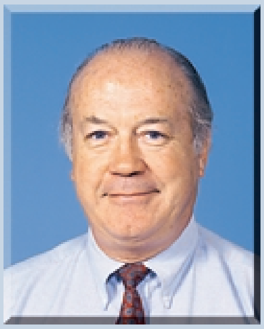

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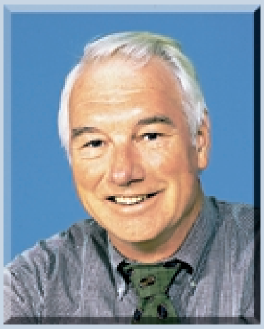

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