Mapping Surface Currents with CODAR

This Emerging Technology—with Its Growing List of Applications—Uses HF Radar for Accurate, Real-Time, Remote Sensing.

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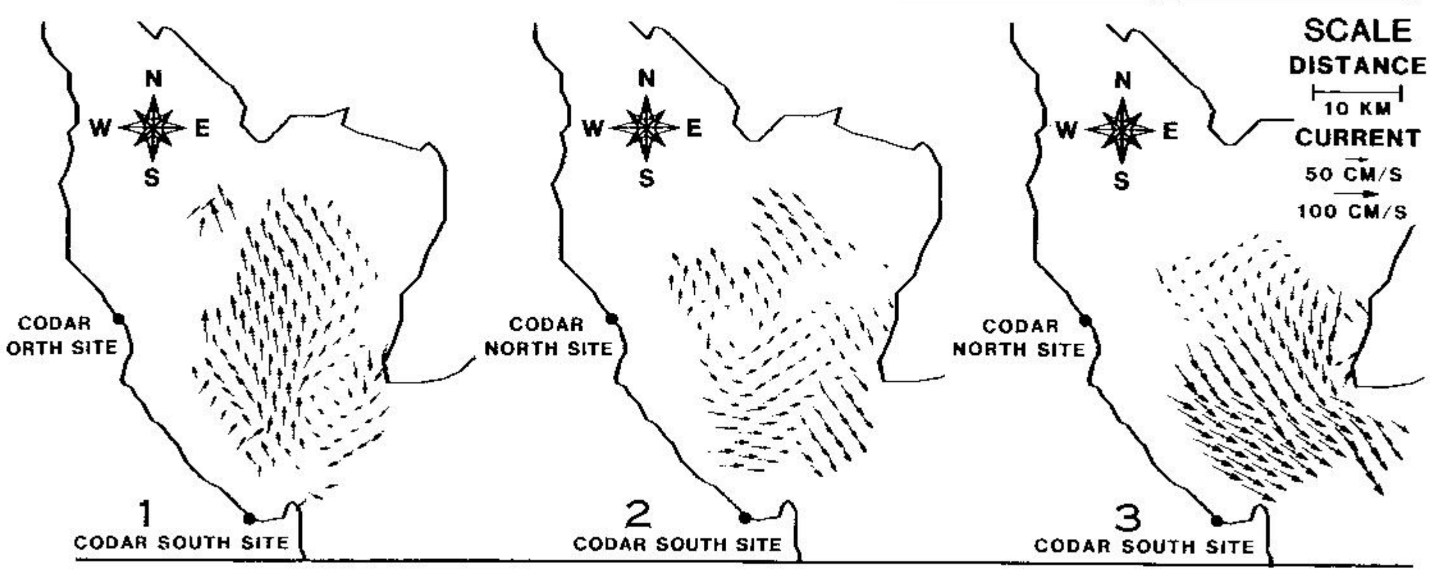
The vast majority of man's ocean-related activities take place on or near its surface. A listing of coastal and marine operations that are impacted by surface conditions would require pages. Yet timely, detailed and quantitative information about the variable surface currents and waves has always been in short supply because of the lack of reliable instrumentation to gather the data. Hence, there has been considerable incentive fueling the search for remote sensing methods—both satellite and land-based—that will one day provide enough informational detail to expand, improve and increase the safety of many types of ocean-related operations.

CODAR is now an operational real-time system that can fill many of these needs over areas of the order 100 x 100 square kilometers; in particular, it can map surface currents, provide waveheight directional spectral information, track expendable drifting transponders in position and instantaneous velocity and observe pack-ice and iceberg movements during arctic operations (see *Sea Technology,* December 1983, page 64, for discussion of arctic applications.). It has no instruments in the water and no moving parts, such as scanning antennas, to reduce reliability. The present article describes the current-mapping aspect of the system.

CODAR, which stands for Coastal Ocean Dynamics Applications Radar, has progressed through research, development and engineering phases to an operational status. The basic mechanism underlying its operation was discovered three decades ago when it was observed that high-frequency (HF) radar echoes scattered from the sea surface posesses a unique Doppler frequency "signature" due to motions of the waves. Theoretical solutions were then developed that related the echoes quantitively to the ocean surface properties. Because traditional HF radars have had to employ extremely large antenna systems (e.g. phased arrays exceed-



CODAR maps of Delaware Bay circulation at (1) 1226 hours EST, (2) 1352 hours, and (3) 1522 hours. Only vectors with uncertainties less than 10 centimeters/second were plotted.

ing 100 meters in length), an intensive efort began in 1974 at the National Oceanic and Atmospheric Administration laboratories in Boulder, Colorado to develop a compact, transportable version in order to expand potential applications.

Assisted by funding from NOAA/NOS CODAR Transitional Engineering Program, the final step to make systems and services commercially available was accomplished in 1982 when the principals at NOAA in Boulder formed companies (e.g. Codar Systems Incorporated) to market this technology.

Since then, several oil companies, mostly Gulf Oil Corporation, supported the adaptation of this technology to offer use for design studies and operations. CODAR has seen service in over twenty field operations over the past decade, all accompanied by some form of comparative instrumentation for "sea truthing." In the meantime, other countries have recently initiated programs and formed companies to exploit HF radar for surface measurements; advances in these areas were summarized at a recent international conference in Vancouver, British Columbia (*Sea Technology*, May 1985, page 42).

How CODAR Works

The unique echo signature of HF radar backscattered from ocean waves results from "Bragg" scatter, the same mechanism responsible for diffraction of X-rays passing through crystal lattices and for laser beams that reconstruct an image when they interact with a hologram.

At HF, the radar wave selectively backscatters from the two wavetrains half the radio wavelength, moving directly toward and away from the radar. At 25 MHz (the normal CODAR frequency), this corresponds to 6-meter long ocean waves with 2-second periods. The echo from these waves causes narrow spikes in the signal's Doppler spectrum at precisely 0.5 Hz from the carrier. If currents are transporting these waves, they will be shifted by an additional, measureable amount that is directly proportional to the current velocity component in the direction of the radar. Hence, these short ocean waves that are always present on the surface of the open ocean serve as "tracers" for the velocity of the underlying current. At 25 MHz the current sensed is an average over the upper one-meter layer. After Fourier transformation of the receiver time series, each Doppler frequency point corresponds to a unique radial velocity; the processing software then determines the corresponding range and bearing, and hence forms the current map.

Range from the observing station is determined by measuring the time delay of the echo from transmission; the pulse is 8 microseconds wide, giving a 1.2 kilometer range resolution. The bearing of the signal is derived from the voltage amplitudes received by the three elements of the system's compact antenna: two crossed loops and a monopole. Loops have been employed as signal direction finders for decades; here, separate signals from the three elements allow the bearings corresponding to each radial velocity to be found to better than 2°-3° accuracy. With CODAR, this is all done in software; the 2-meter-high antenna shown is not rotated mechanically.

Besides the distinctive antenna that serves as CODAR's electronic eye, the remainder of the radio and digital portions of the hardware occupy two 1-meter-high racks that weigh less than 60 kilograms. The DEC LSI 11/23 microcomputer controls the total functioning of the radar, allowing operations to be scheduled weeks ahead. All signal processing is done on this computer, with final data products available within minutes for display at the site, archival on tape, and/or transfer to a central station. Transmitting only 200 watts average power, the total system power consumption is less than 1 kw; therefore, that nearly any power source is adequate.

Yet with this tiny input power, CODAR's range for current mapping is 60 kilometers under typical oceanographic conditions.

Operating with Independent Pairs

Normal coastal operations employ two CODAR stations, operating independently and separated by about 30 kilometers. Since each measures only one component of the horizontal velocity vector (i.e. the component radial to each radar), together they give unambiguous estimates of total velocities, for example over of 2 x 2 kilometer grid of points. Such maps can be produced at programmable intervals, typically ranging between 1-3 hours, depending on the application.

Data has been transferred between separate sites by telemetry, modems or by physically transporting tapes when real time was not important.

Two factors determine the accuracy of CODAR (and almost every remote sensing device): noise and system resolution. Additive noise here is externally generated, normally 5-15 dB lower than the sea-echo signals;

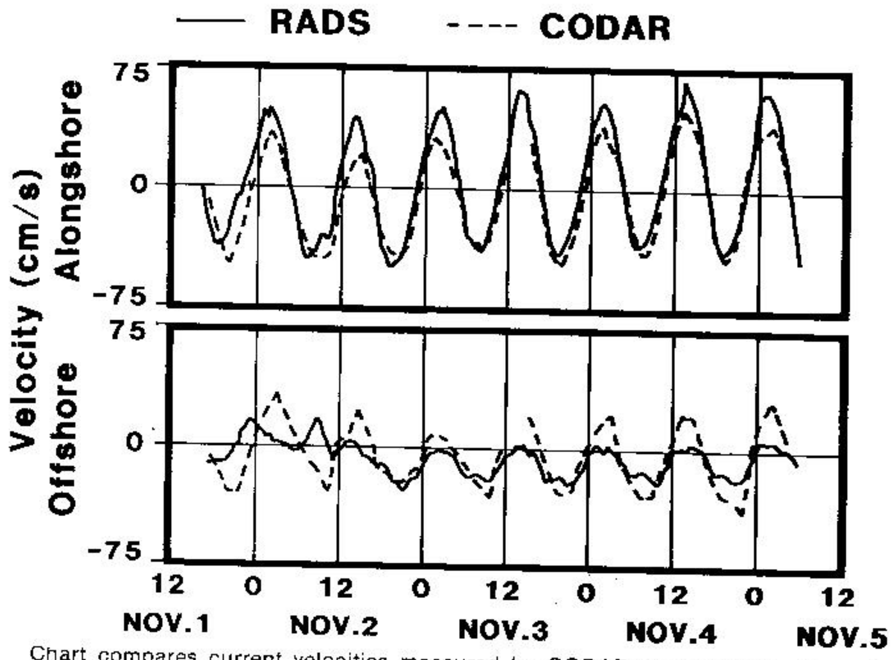


Chart compares current velocities measured by CODAR and a Remote Acoustic Doppler System (RADS) over a five-day period in Delaware Bay.

the latter themselves are random variables in amplitude because of the nature of the scattering ocean waves. Hence, averaging over time and space is used to reduce the resulting uncertainty in output products. A tradeoff exists between accuracy and resolution; too much averaging can destroy the finer-scale spatial or temporal features one may want to observe.

All data processing and information extraction with CODAR are done by applying maximum likelihood methods, which give optimum estimates of unknown parameters derived from noisy data. The basic output from each site is a radial velocity map in polar coordinates, with statistical uncertainties in each velocity component. Typical uncertainties for a 36-minute data run are 1-3 centimeters per second. In combining the radials to produce total vector maps, the user has a choice of options based on the application. The following parameters can be specified: (1) the grid spacing at which vectors are to be determined; (2) an uncertainty threshold, above which a total vector at a given point is not to be produced; and (3) the area resolution to be applied over the map.

Occasional gaps may appear on a map where the vector uncertainty exceeded the selected threshold, and in other cases where the currents are so weak that there is too little difference between adjacent, available points for quantization. In either case, the user can choose whether and how these gaps are filled in.

A single-site CODAR is often the only option when operating from an oil platform. The resulting radial velocity maps must then be interpreted differently. A total current vector can always be constructed at the platform, using the radial vectors for the nearest range cell. At greater ranges (up to 50 kilometers from the rig), a mathematical model of some type is fitted to the radials, using maximum likelihood. If care is exercised in the selection and use of a model, the total vectors obtained in this manner give a clear picture of surface circulation away from the rig. Only 20-30 total vectors are normally obtained in this manner, compared to about 500 vectors produced in two-site coastal operations.

A Sample Application

In Fall, 1984, a dual-site CODAR field operation was conducted in lower Delaware Bay, in conjunction with the NOAA/NOS Circulatory Survey, and supported jointly by the U.S. Army Corps of Engineers' Coastal Engineering Research Center (CERC). NOAA and CERC hope to understand the factors that govern circulation in such complex, enclosed areas so that accurate models can be constructed to produce nowcasts and forecasts of the three-dimensional circulation. The flow in this bay is strongly dominated by semi-diurnal tides and outflow from the north, but varies due to winds and waves generated by storms. The rapidly changing depth along with the enclosing, irregular coastline add to the complexity of circulation. CODAR provides a detailed look over space and time at the surface flow.

Measurements were made every 1.5 hours over nearly a month, with one site running automatically and unattended. In addition to CODAR, current meter moorings provided deeper currents at several points; a Remote Acoustic Doppler System (RADS) on the bottom at Brandywine Shoal gave a vertical profile of current at the center of the CODAR coverage area, to within 1 meter of the surface; conventional ship surveys were conducted; and meteorological data above the surface at Brandywine were collected.

The sequence of maps shows an example of changing circulatory patterns every 1.5 hours. Details of spatial features are more clearly observed here than they can be with alternative, point-sampling methods.

With an area resolution of about 5 kilometers selected for these maps, there is evidence of a weak gyre that forms at the mouth of the bay at slack current tide. This gyre then propagates some distance up the bay (seen in subsequent maps) at the phase velocity determined by the water depth in this area; these features tend to disintegrate due to varying depth over their spatial expanse. Although most such features repeat themselves with semi-diurnal regularity in calm conditions, CODAR shows that stiff winds cause significant departures from the norm, a factor that any successful model must include.

Comparisons of the along-channel components of surface current measured by CODAR at Brandywine and by the uppermost cell of RADS (at 1-2 meters below the surface) are also shown. Agreement is evident, despite the different spatial scale sizes and depths of the two techniques. The cross-channel component, being much weaker, shows interesting differences due to the highly variable flows that are well-known to mariners in this area.

Recent System Improvements

As a result of experience gained in operation deployments, a number of improvements have been developed and integrated into the system. The most significant advance involves a new crossed-loop antenna and associated switch gear. A complete redesign was forced by the constraints of offshore operations; the total antenna system must be very compact, lightweight (easy to erect at the top of the derrick on a rig), rugged (able to withstand 100-knot storm winds and icing), electrically efficient, but yet presenting no safety hazards due to arcing around petroleum and gas recovery operations or shock to personnel. Weight was reduced to less than 20 kilograms; electrical efficiency improved by several dB, with most of the structure fabricated from plastic and fiberglass; cost was reduced by a factor of three.

One of the major goals in the original development of CODAR at NOAA was unattended operation. This goal is being realized by several digital hardware and software improvements. Newer versions incorporate 60 megabyte compact cartridge tape units capable of storing several weeks of data. The system can also restart itself after a power failure; this is a "must" for operations on platforms and also for unmanned coastal applications, where such outages can be frequent.

Another important improvement makes the software far more "user friendly," by providing menu-driven system control. It is now possible for relatively inexperienced personnel to schedule the acquisition, processing and display of data. Examples of user-selectable options include sampling interval, current product accuracy and area resolution.

The sea echo itself is used to calibrate many of the gain and phase factors among the different channels (e.g., the three antenna elements) that, as in any system, can drift with time. Throughout the current and wave processing, there is no longer a requirement for knowledge of absolute signal levels or stability of system gains.

Experience has shown that when

operating from offshore rigs, significant distortion of the antenna patterns by nearby metal objects is unavoidable. Consequently the inversion methods and software have been modified to incorporate the actual distorted patterns measured by a boat pass around the rig, eliminating this source of error.

Immediate Applications Planned

Besides the use of CODAR by NOAA in circulatory surveys exemplified here by Delaware Bay, NOAA is presently installing two permanent stations looking eastward from the Miami-Fort Lauderdale region of Florida. Timely knowledge of the strong but variable currents of the Gulf Stream is important for shipping, for studies aimed at understanding heat transport into the North Atlantic, and for search and rescue in an area of heavy recreational boating. For the latter reason, the Coast Guard is a joint participant with NOAA's National Weather Service and National Ocean Service in these CODAR operations.

CODAR is now being operated from a semi-submersible drilling vessel in the North Sea for SAGA Petroleum, A.S., of Norway to give current velocity maps and wave information. One primary goal is to obtain advance warning of the strong eddy-current features ("whirls") that propagate northward along the Norweigian coast from the Skagerak. With strengths exceeding 150 centimeters/second at times, these whirls can cause severe constraints on offshore operations.

The U.S. Army's CERC operates its own CODAR system and requires coastal waveheight directional spectra, as well as currents, to predict and combat coastal erosion and silting of harbors and ports. After fall 1985 operations at their Duck, North Carolina, research pier, CERC plans to use the system for demonstrations off the coast of California, where other instrumentation is available for intercomparison.

The U.S. Navy, through its David Taylor Naval Ship R&D Center, is considering the use of CODAR at Kings Bay, Georgia, as part of a real-time environmental monitoring system. Data would be used to predict the probability of groundings of large ships as they traverse a narrow channel through shallow continental shelf waters, caused by both waves and currents.

Other field programs being planned and conducted by Codar Systems Incorporated are providing the experience to develop the concept of HF radar technology into a tool with many potential benefits to its users. As a result, modifications of the multi-function system are continually evolving to meet a wide variety of needs. The potential applications of just a few years ago are today already a reality. /st/

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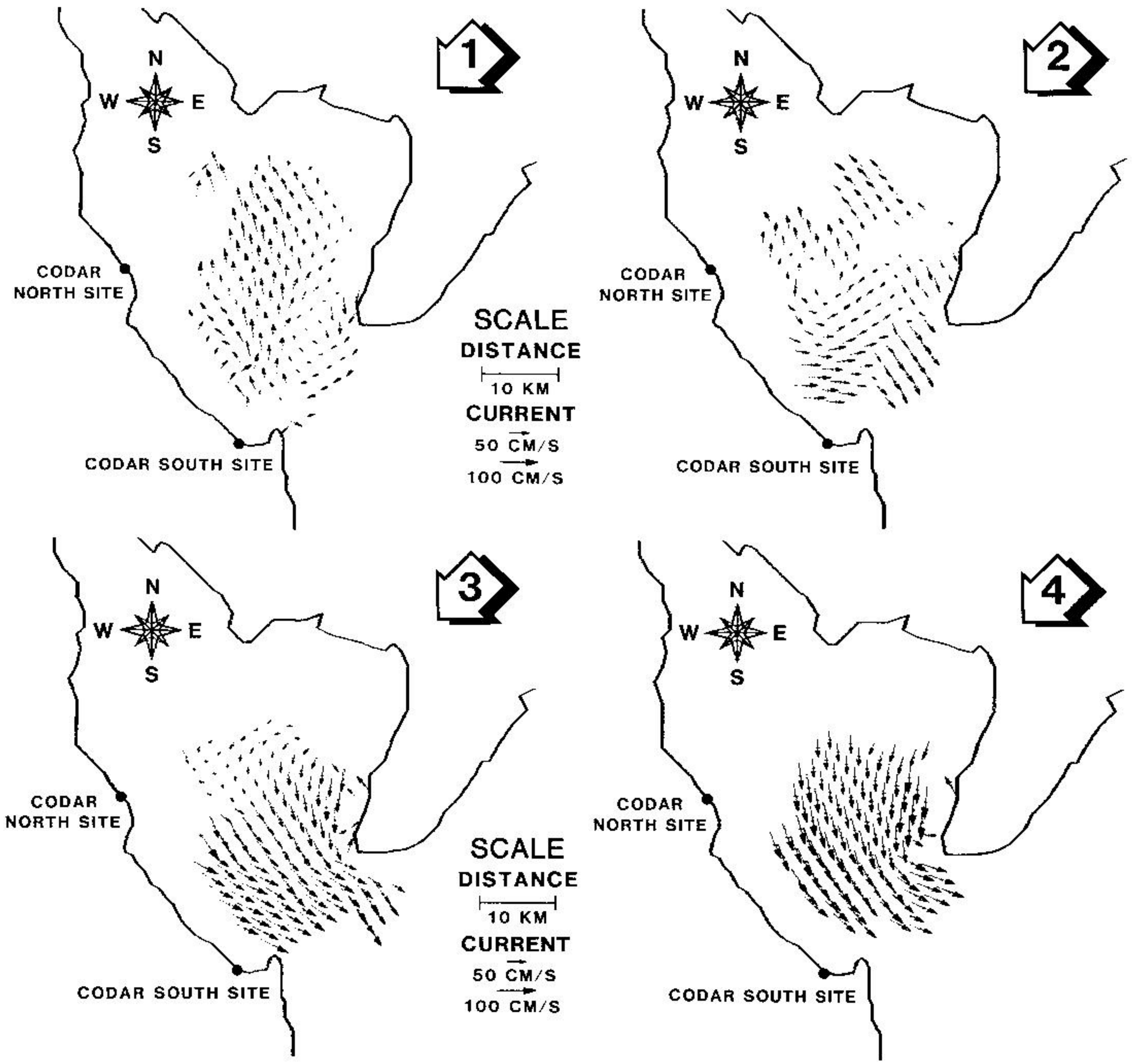
Dr. Belinda J. Lipa is president of Ocean Surface Research and directs the research and development of analysis methods and software that extract ocean current and wave information from CODAR signals. She pioneered the application of inversion theory to HF radar sea echo—from 1974 to 1980—while a research associate at Stanford University, SRI International and at Codar Research. Lipa received her bachelor of science and doctorate degrees in theoretical physics from the University of Western Australia.

Randy Crissman is vice president, Radar Systems Division, Codar Technology, Inc. Based in Houston, Texas, he provides marketing and project management support for CODAR operations. Crissman previously was with Gulf Oil Corp. where he directed the evaluation of CODAR for measuring sea ice motion. He holds a master's degree in civil engineering from State University of New York at Buffalo.

Delaware Bay Circulation



CODAR maps of Delaware Bay circulation, October 15, 1984. (1) 12:26 EST, (2) 13:52 EST, (3) 15:22 EST, (4) 16:52 EST. Radial velocities measured from the two CODAR sites were combined to form total velocity vectors on a 2 x 2 km grid by averaging over an area radius of 3 km. Only vectors with uncertainties less than 10 cm/sec were plotted.

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