THE SURFACE CIRCULATION OF THE SANTA BARBARA CHANNEL AS OBSERVED WITH HIGH FREQUENCY RADAR

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ABSTRACT

We are using an array of high frequency (HF) radar systems to observe the surface circulation in the western Santa Barbara Channel. Observations of surface currents are important for understanding the basic physical processes controlling coastal circulation. In addition, the movements of river runoff plumes, buoyant pollutants such as oil, and larvae of many marine species are governed by surface currents. We have established a network of three HF radar sites along the northern boundary of the Santa Barbara Channel: at Coal Oil Point, near Refugio State Beach, and at Point Conception. Each radar system has a range of about 40 to 50 km, depending on conditions, and surface current maps are produced hourly. Preliminary analysis reveals that the surface circulation in the Channel is often dominated by eddies. Some of these eddies propagate westward at a few kilometers per day and have lifetimes of several days. Others are nearly stationary for several days. Eddies with both clockwise and counter-clockwise rotations are observed. At times, broad areas of the Channel rapidly respond to the local wind field. At other times, surface currents appear to result from remote forcing process. In addition to circulation studies, we are evaluating the performance of the HF radar systems by comparison with conventional, in situ current meters.

Keywords: Eddies, biogeographic boundaries, current measurement.

INTRODUCTION

The Santa Barbara Channel is a cross-roads for large-scale water masses moving along the California coast. Waters from the north are cooled by coastal upwelling as they move southward through sub-polar regions. Most of these waters pass outside the Channel Islands, but some are swept into the Channel through the western entrance. Warm water from the south, heated in the sub-tropics, flows northward along the coast and enters the Channel from the east. These contrasting waters swirl and mix in the Channel to form the complex patterns often visible in satellite images of sea surface temperature. These coastal currents bring together an abundance of diverse marine life from widely separated ocean regions. A series of oceanographic studies since the 1969 oil spill have greatly enhanced our knowledge of the circulation processes in the Channel. However, much remains to be learned. For example, the relationship between distributions of marine organisms and current patterns is not well understood, but is crucial for such practical issues as resource management and conservation.

The surface circulation of the Channel is of particular interest, because larvae of many marine organisms are transported by surface flows during the planktonic stages of their life cycles. Surface currents govern the dispersal of terrestrial runoff and pollutants into the coastal ocean. Accurate knowledge of surface circulation is important for navigation and the effective conduct of search and rescue operations. Surface flows in the Channel are exceedingly complex because they are produced by forces acting over a very wide range of time and space scales. The more persistent, large scale movements of water masses through the Channel result from dynamic process on scales much larger than the Channel itself. In contrast, local processes such as strong winds produce rapidly-evolving, energetic flows that vary over scales of several kilometers.

We are using a combination of remote sensing and in situ observations to study the surface circulation of the Channel. To observe directly the evolving structure of the flow field, we have deployed an array of high frequency (HF) radar systems along the mainland coast between the University of California Santa Barbara (UCSB) campus and Point Conception. This is the first time HF radar has been used to study oceanographic process in the Channel. The radar array provides higher spatial resolution than has previously been available. In this paper we provide an overview of our research employing the HF radar systems. We also discuss some of the interdisciplinary research being conducted to understand the consequences of the circulation for marine organisms.

MATERIALS AND METHODS

Measurement of ocean surface currents by HF radar is not new but has enjoyed renewed interest lately from the oceanographic community (for a recent review see Paduan and Graber 1997 and references therein). To make the measurement, a Doppler radar transmits electromagnetic energy (EMR) out over the ocean's surface and then detects the signal that is back-scattered from surface waves. The frequency of the back-scattered radar signal is Doppler-shifted because the velocities of the surface waves generally have components in the radial direction to the radar site. The received signal results from Bragg, scattering due to surface waves with wavelengths equal to one half the transmitted wavelength. For our radars, the transmitted frequency is 13 Mhz and, the wavelength is about 24 m. Thus the surface waves which back-scatter the EMR have a wavelength of 12 m. The frequency change of the received signal depends on the phase velocity of the surface waves and on the advection of the waves by surface currents. Because the waves producing the received signal have known wavelengths, their phase speed is known. The remaining part of the frequency change results from the surface current component. By measuring this change, the magnitude of surface current component along the radial path to the radar site can be determined. Use of multiple radars allows the total surface current vector to be determined over a broad area of the ocean's surface.

We have established an array of HF radar sites along the northern coast of the Channel (Figure 1) at the following locations: 1) Coal Oil Point on UCSB campus; 2) the Refugio operations center of the Channel Coast Ranger District; and 3) Point Conception. These installations were deployed in collaboration with the U.S. Coast Guard and the Channel Coast Ranger District of the California Department of Parks and Recreation. Apart from occasional power outages, the array has been collecting data hourly, around the clock since December 1997.

Each radar site has a Sea Sonde HF radar system (manufactured by CODAR Ocean Sensors, Ltd. of Los Altos, CA) consisting of a transmit antenna, a receive antenna, signal processing electronics, and a Macintosh Power PC computer. The transmitted power is about 50 watts at an adjustable frequency around 12.5 to 13 Mhz. The processing electronics and computer are mounted inside weatherproof housings at the sites. To maximize range, radar antennas are mounted as close to the water as is practical because the radar signals are attenuated rapidly over land.

The Sea Sonde systems operate autonomously to record data, which can be downloaded via modem from the three sites. The performance of the radar depends on factors such as sea state, atmospheric conditions, and wave direction. We find that the range is typically about 40 km, although longer ranges are often achieved. The coverage area from an individual site is occasionally much less than 40 km, however. This has been particularly true for the site at Point Conception. We do not know the reason for the diminished coverage, but are investigating a number of possibilities including interference from other signal sources and variable oceanic conditions.

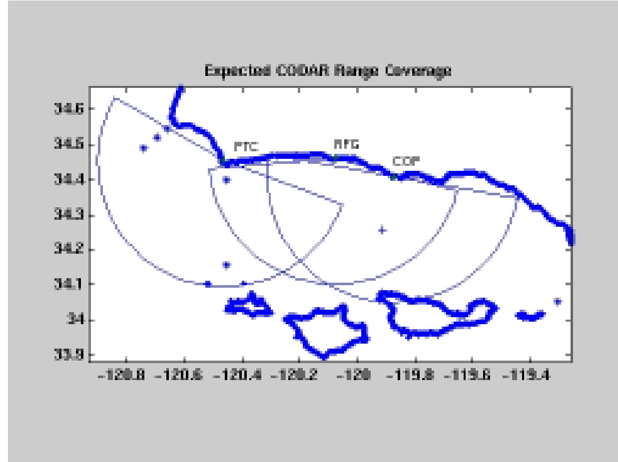

Figure 1. Approximate spatial coverage for each of the three Santa Barbara Channel HF radar sites. North and East ocean current velocity components are resolvable for regions covered by two or more HF radar sites.

Raw data is processed into hourly maps of surface currents over an area of about 700 km^2 of the western Santa Barbara Channel (Figure 1). Data from each site is first processed to give maps of the radial component of surface current over circular sectors centered on each radar site. Radial current data from all sites are then combined to produce a vector map of surface currents over a grid of points. We organize the surface current data into monthly time series with a current measurement for each hour at each grid point. A typically monthly file is about 50 megabytes of data.

RESULTS

The radar observations show that the surface current field in the western Santa Barbara Channel evolves rapidly, although persistent features such as eddies are commonly observed. Recent results presented by Harms and Winant (1998), and Hendershott and Winant (1996), show that the circulation in the Channel varies seasonally. In summer the dominant pattern is a counter-clockwise circulation producing westward flow along the mainland and eastward flow along the north coasts of the western Channel Islands. In winter the pattern is more complex. At times, either clockwise or counter-clockwise patterns prevail, while at other times general eastward and westward movements of water result from winter storms. Using the radar array, we observed the winter-to-summer transition in circulation from December 1997 through June 1998. We computed the mean rotation rate of waters in the western Channel over this period from all available radar data. The results show that from December through February, the rotation varied between clockwise and counter clockwise patterns on time scales of about two weeks. By mid-March, the mean rotation was counter-clockwise and remained so at least through June 1998 (the extent of our analysis at the time of this writing).

This reproduced the findings of Harms and Winant (1998). It also gives us some assurance that the radar system is useful for examining circulation processes on seasonal time scales.

To illustrate the complex surface circulation in the Channel, we present an example from winter. Figure 2a shows a clockwise eddy in the western Channel on 13 December 1997. Maximum current speeds are 0.4 m s^{-1} and the eddy diameter is about 30 km. Over the next two days the eddy propagates westward at a rate of a few kilometers per day (Figures 2b, 2c). On 16 December 1997 (Figure 2d), the eddy appears to be decaying and its flow field is less organized. The study of Harms and Winant (1998) indicates that the velocity field of eddies like that of Figure 2 extends to depths of at least 45 m. Recent observations indicate a much deeper extent. In June 1998, we collaborated with Mary Nishimoto of the Marine Science Institute (MSI) at UCSB in her survey of a counter-clockwise eddy of similar size and strength. Analysis of these data show that the eddy extended down to 200 m based on the deep temperature structure of the eddy. This indicates that these eddies are not merely surface features, but are important throughout the water column.

An important interdisciplinary goal of our research is to understand how the evolving circulation patterns affect the recruitment of marine larvae (such as those of rockfishes, urchins, and abalone) to coastal populations. It is well known that the recruitment is highly variable both spatially and temporally. However, the causes for the variability are not well understood. We are using our observations of surface currents to understand how advection and other coastal transport processes might affect recruitment. Studies from

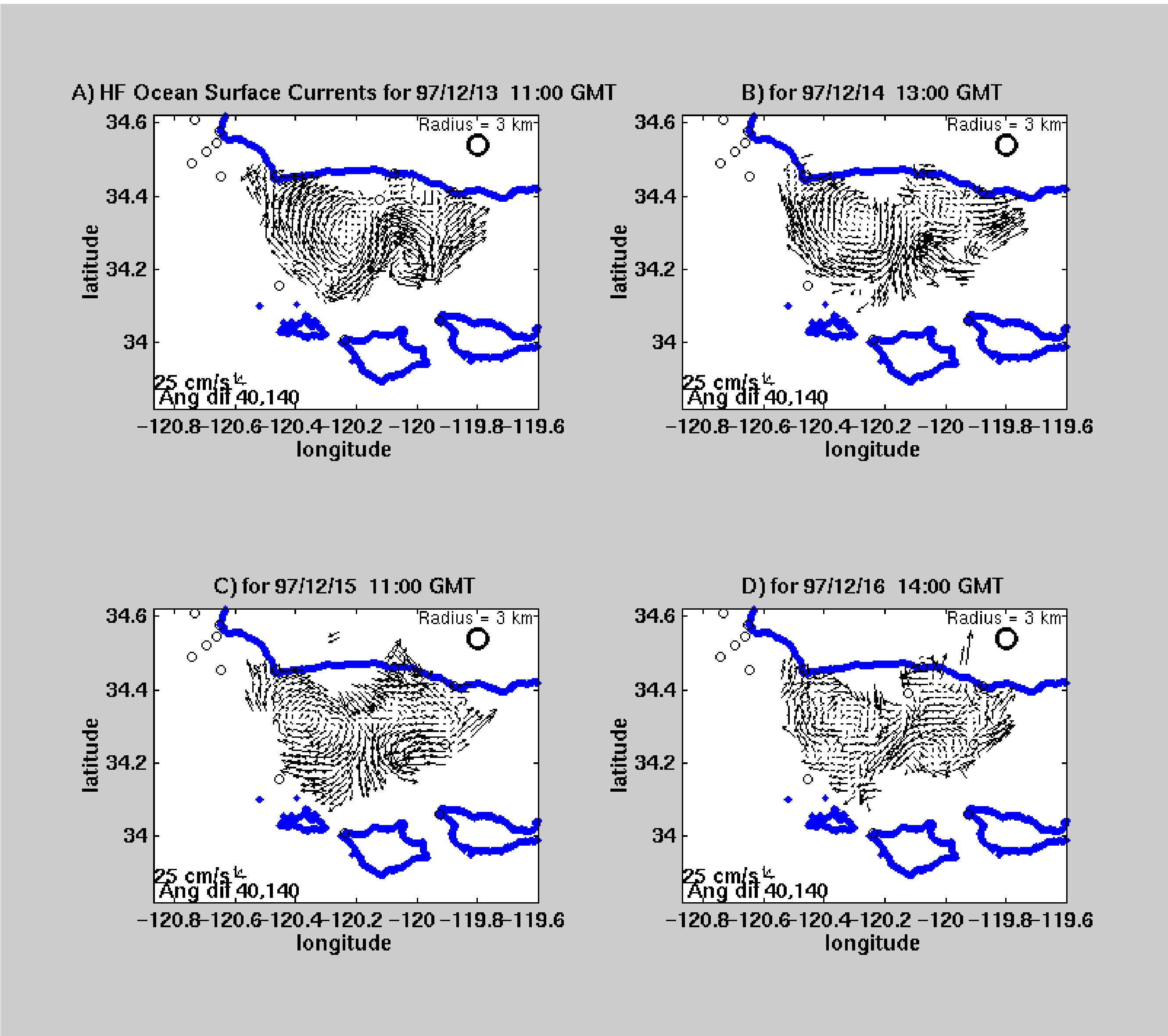

Figure 2. Surface current vectors in the western Santa Barbara Channel in December 1997 as measured by high frequency radar. A clockwise eddy is visible centered on 34.3ºN, 120.2ºW on 13 December (panel A). The eddy propagates westward at a few kilometers/day as seen on 14 December (panel B) and 15 December (panel C). By 16 December the eddy appeared to be dissipating (panel D). Radar stations are located at Coal Oil Point (COP), Refugio (RFG), and Point Conception (PTC). Scale at lower left indicates speed.

other areas indicate that coastal circulation processes are important in regulating recruitment (e.g., Farrell et al. 1991; Wing et al. 1995). An interesting characteristic of the Channel is that Point Conception is a significant biogeographic boundary: it is a northern range limit for many marine species. The reason why Point Conception is a biogeographic boundary is not understood at present. We are investigating the hypothesis that current patterns around the point inhibit northward transport of larvae. Other factors such as the large temperature gradients around the point may also be responsible.

To explain the spatial distributions of various invertebrate species along the California coast, a large array of intertidal sampling stations has been established from Ventura to San Simeon by Steven Gaines and colleagues from the MSI. At various piers and coastal sites, test substrates are placed below the low tide line such that larvae, if present, can settle out of the water column. The sampling indicates that occasional strong pulses of larvae arrive at the settlement sites. During these recruitment events, high numbers of larvae settle onto the substrates. Preliminary analysis suggests that some of these events may be associated with current reversals near shore. The reversals result from changes in the structure of eddies off shore as observed by our radar system. In an effort to understand the link between recruitment and flow patterns, we are extending our HF radar array to include two stations north of Point Conception: one at Point Arguello and another near Point Sal. This is being done in collaboration with Jack Harlan and colleagues of the Environmental Testing Laboratory of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado.

In other studies, we use our real-time observations of surface currents to direct field sampling in specific flow features such as eddies. In June 1998 for example, surface current data obtained by our radar array were used to direct sampling of juvenile fish populations in the Channel. The field work was part of a larger effort to understand the causes of spatial and temporal variations in fish populations in the area. Mary Nishimoto, Milton Love, and colleagues at MSI are conducting the study. Over a two week period several net trawls were made in a strong counter-clockwise eddy that occupied the western Channel. Based on patterns obtained by the radar observations, many of the trawls were made in the core of the eddy. A surprising finding was that within the eddy, the abundance of several groups of juvenile fishes was greatly enhanced (by factors of 10 to 100) compared with surrounding waters. Examination of flow patterns in weeks preceding the field sampling indicates that a general counter-clockwise flow pattern had been present for several weeks before the experiment. We speculate that the weakly swimming juvenile fishes may be retained in the eddy longer than they would in its absence. Such retention may increase their survival. We are presently investigating this and other hypotheses to understand these extraordinary concentrations of juvenile fishes.

Another important goal of our study is the validation of the HF radar-derived ocean currents. Several moorings located in the coverage area of the HF radar array contain conventional current meters such as vector measuring current meters (VMCM), electromagnetic current meters, and acoustic doppler current profilers (ADCPs). Most of the moorings are maintained by the Center for Coastal Studies at the Scripps Institution of Oceanography. These current meters have well known characteristics, and provide valuable ground truth information for testing the accuracy of the HF radar. Ground truth tests are made between the radar data from a single HF site, and the component of the current meter data in the direction to that radar site. This method tests the radar data in a basic form to determine the accuracy of the radar measurement. Preliminary results suggest a high correlation ($r^2 > 0.7$) between the HF radar and moored current meter data (Figure 3), despite the inherent differences in the measurements. For example, the HF radar data measures the upper 1 m of the water column, over a large spatial area of typically 3 km^2, while the moored current meters are considered a point measurement, at 5 m water depth. While the high correlation is encouraging, improvements in the moored current meter measurements, such as removing mooring motions and advanced processing of the ADCP data to measure nearer the surface, may improve the correlation. These results should provide valuable information for interpreting HF radar data.

DISCUSSION

Our observations using HF radar systems confirm the complex nature of the surface flow of the Santa Barbara, in agreement with previous studies. We build on this previous research by obtaining observations of the flow field with much higher spatial resolution.

Comparison of surface currents derived from conventional current meters and HF radar shows that the radar systems perform satisfactorily. They are capable of mapping surface currents to about 40 km from shore with a spatial resolution of 3 to 5 km.

The radar systems have proven useful in directing field experiments so that specific flow features can be sampled with precision. This has allowed us to examine how populations of juvenile fishes are distributed in a persistent eddy in the Channel. It illustrates the importance of sampling marine communities where flow structures are concurrently observed. We feel that the radar technique will prove increasingly valuable in interdisciplinary studies of the coastal ocean.

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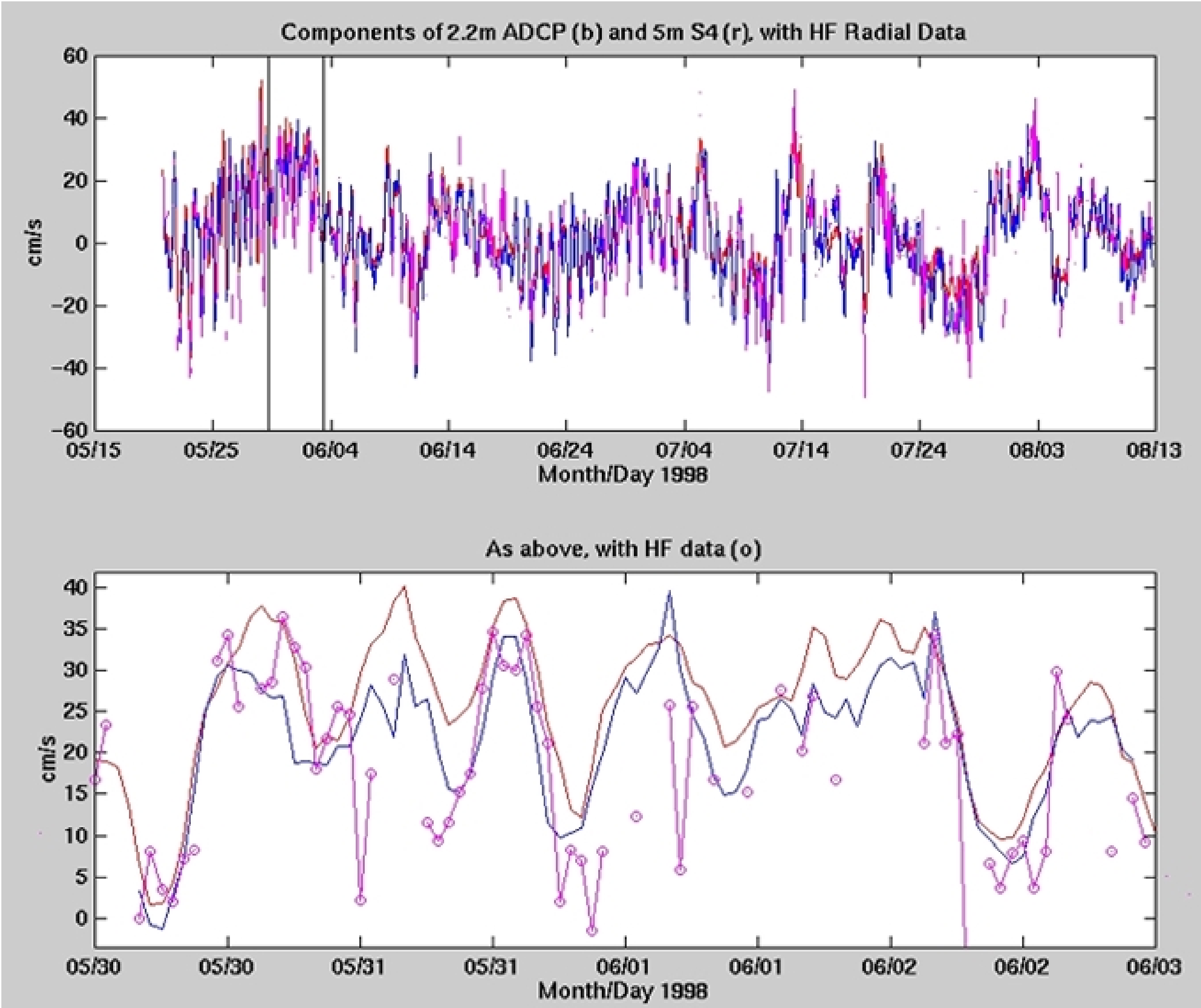

Figure 3. Time series of three independent ocean current measurements. Radial current speed measured from the COP HF radar site is plotted (magenta), along with the same component from an Acoustic Doppler Current Profiler (ADCP) at 2.2 m depth in blue, and an electromagnetic S4 current meter at 5 m depth in red. Velocity is positive in the direction toward the radar. The lower panel shows a three day section of the same time series. Comparing HF and ADCP measurements produces $r^2 = 0.67$, while comparing HF and S4 measurements produces $r^2 = 0.70$.

establishing the radar site at Refugio. We also thank the U.S. Coast Guard for allowing us to locate a radar site at the Point Conception lighthouse. Valuable assistance in setting up the radar systems and data processing has been provided by David Salazar, Ben Best, Chris Gotschalk, Krisada Lertchareonyong, and Michael Cook. We have benefited from valuable discussions with Brian Gaylord, Mary Nishimoto, Steve Gaines, Donna Schroeder, and Milton Love.

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