Applications of Dual-Doppler HF Radar Measurements of Ocean Surface Currents

A. S. FRISCH and B. L. WEBER

NOAA/ERL/Wave Propagation Laboratory, Boulder, Colorado 80303

HF Doppler radar measurements of near-shore sea-surface currents is a relatively new technique. It has the advantage of covering a wide area of the sea surface simultaneously while being shore-based. In this paper, we compute the M_2, K_1, and mean currents over an area of the eastern Strait of Juan de Fuca from HF radar measurements made during the summer of 1979. From these components, we computed trajectories of simulated continuous leaks from a proposed oil pipeline in this area. By computing the trajectory over one day, we estimated the shoreline locations that would be impacted by the oil.

Introduction

The need for current measurements in the eastern Straits of Juan de Fuca has increased in the last few years because of potential spills from increased oil tanker traffic and a proposed oil pipeline. To predict where spilled oil will go, knowledge of the spatial and temporal distribution of currents is needed. The acquisition of such a data base with conventional techniques such as current meters or drifters would be a formidable task and might not be adequate for some situations. The dual HF Doppler surface-current measuring system (CODAR), however, has the capability of measuring surface currents in great detail.

The use of high-frequency (HF) Doppler radar techniques for measuring these surface currents (Barrick and Evans, 1976; Barrick et al., 1977) was made possible by the initial discovery of surface-current effects on backscattered waves by Crombie (1972). Since this discovery, theoretical and experimental studies of surface current effects have been made by Barrick et al. (1974), Stewart and Joy (1973), and Barrick et al. (1977). Use of HF-radar in oceanographic studies have been made by Frisch and Weber (1980), Maresca et al. (1980), Frisch et al. (1981), and Holbrook and Frisch (1981).

The particular HF current measuring system used in this study has two radars positioned along a coast at the edge of the water. Each radar measures the phase velocity of a particular wavelength ocean wave which is propagating radially toward or away from each radar. The ocean waves that scatter the HF waves directly back to the radar must be exactly one-half the HF wavelength because of the scattering mechanism known as Bragg scattering. This scattering is analogous to the diffraction of light by optical gratings. Thus, the backscattered HF energy comes only from the wave components having wavelengths of half the transmitted wavelength. If we measure the Doppler shift, then we can selectively measure the phase velocity of these particular ocean waves. Because the velocity of the waves at this wavelength is known to a high degree of

0034-4257/82/040273-10$02.75

accuracy when there is no current, any deviation of this velocity is due to the surface currents. Since the scattering process is over several square kilometers, the measurement is an area-averaged current. By measuring the radial velocities of the surface currents from two locations, we can compute the horizontal current vector for a particular patch of the sea surface. We illuminate a large area of the sea surface and using a pulse of transmission and gated receiver with a direction finding receiving antenna array, we can "map" the currents over a large area of the sea surface.

Once we have many of these "maps" of the surface currents, we can separate these currents into their tidal, and long-time-averaged mean circulations. The tidal and mean flows will give us the background condition, from which one can add wind effects using models for a more detailed approach to any trajectory calculations.

The accuracy of these trajectory calculations are dependent upon the accuracy of the tidal and mean flow calculations, which in turn depend upon the accuracy of the surface-current measurements. Because the HF surface-current measurement is an area average of the Eulerian velocity, it is difficult to compare with drifters or current meters. Some effort in this direction has been made, however. For example, HF radar-derived surface-current tidal analysis has been done by Frisch and Weber (1980) and comparisons of the radar and current meter data have been made by Holbrook and Frisch (1981). In their comparison, Holbrook and Frisch found that current-meter-derived tidal coefficient amplitudes and the HF radar-derived coefficients were within 6 cm/sec of each other for the K_1 and M_2 components. Differences in the computation of these components may be due to the interval and the length of the sampling of the meter data, as well as to spatial averaging in the radar measurements. Simulations of tidal-coefficient calculations that include noise indicate that when we take measurements for 5 days, the K_1 and M_2 components will have a small percentage of error (less than 2%) in amplitude and phase when the radar measurement error is less than ± 10 cm/sec (Lyons and Frisch, 1982) and the tidal amplitudes are on the order of 50 cm/sec. The maximum error in trajectory after 24 hr would be about 1 km under these circumstances.

Experiment

During July 1979, the NOAA/WPL CODAR group deployed an HF surface-current radar system (Barrick et al., 1977) at Dungeness Spit and Fort Ebey, Washington (Fig. 1). Because of this positioning, we were able to measure the surface currents in the area south of these two sites, where the proposed pipeline would lie, as well as the area north of the two sites. Also, we were able to see the influence of both tidal and nontidal flow at the mouth of Admiralty Inlet on the flow in the eastern strait. In addition, of practical importance was the calculation of potential trajectories of any floating material in the vicinity of Protection Island.

We began recording surface currents on 5 July 1979, at 2:00 PDT with a sample length of 36 min. These observations continued for 5 days and nights. During the day, we recorded radar observations every hour because of other simultaneous experiments, whereas at

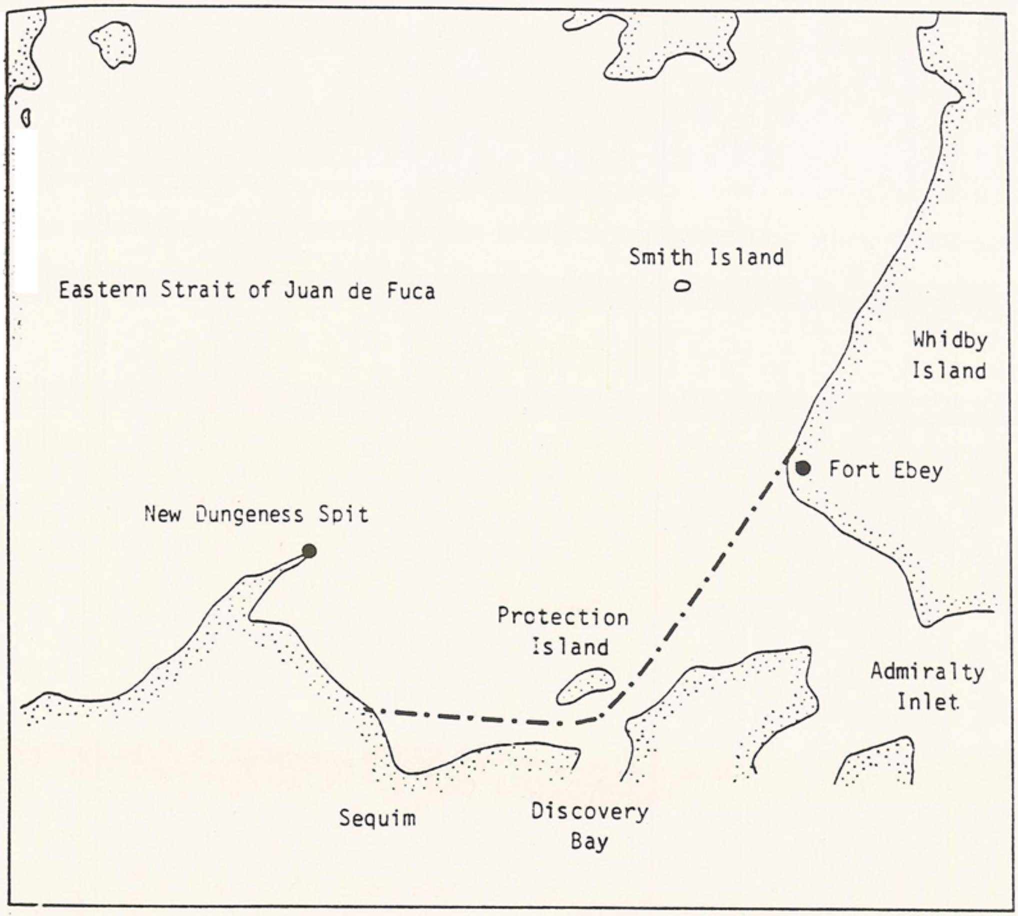


FIGURE 1. Map of HF-Doppler radar measurement area. Radars were at Dungeness Spit and Fort Ebey. The coverage area was to the north and south of a line drawn between the two radars. A proposed pipeline route is shown as a dashed line.

night we recorded observations every 3 hr. The resulting data set was tidally analyzed by a least-squares fit of the data to two dominant tidal components, K_1 and M_2 (Holbrook et al., 1980) and trajectories calculated by integrating the velocities starting at some initial location.

Results

Figure 2 shows the M_2 tidal component ellipses. We use ellipses since this is a familiar kind of display, which permits a large quantity of data to be presented in a very compact form. The triangle on some of the ellipses represents the time given in the upper left-hand corner.

We see large spatial variations in the tidal circulation which are correlated with the flow into and out of Admiralty Inlet, as well as the other adjoining straits. The Admiralty Inlet flow is the strongest, in excess of 150 cm/sec, and appears to have a significant influence on the main flow in the eastern strait. We see this apparent influence by the tilt of the tidal

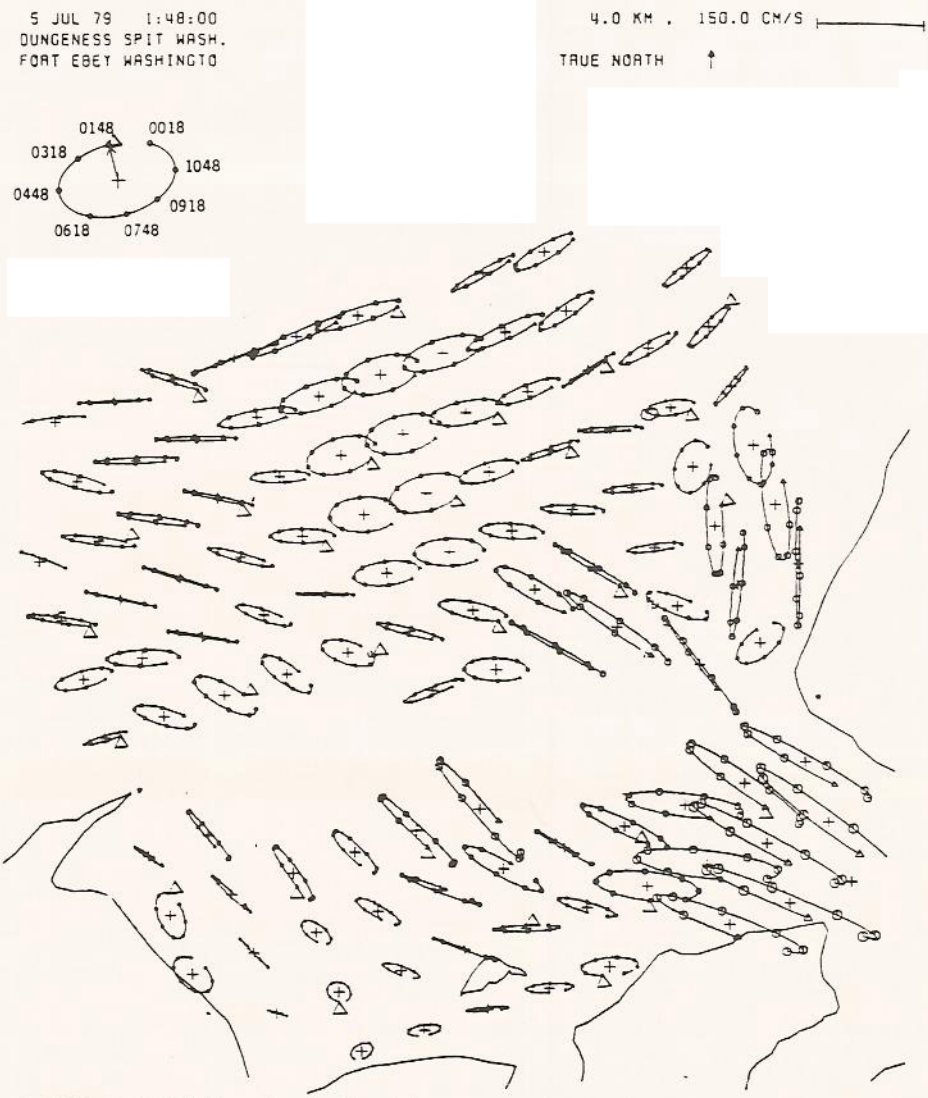


FIGURE 2. Tidal ellipses for the M2 tidal component, the triangle represents the start time (0148) for that ellipse.

ellipses on the left side of Fig. 2. There is also a great contrast in the tidal flow just west of Admiralty Inlet compared to the Inlet, where the tidal flow is less than 50 cm/sec about 10 km west of Protection Island. Because we cannot compute the current vector in the region near the line between the two radars in the region near this line, we cannot compute tidal ellipses or the convective currents in this region.

The K_1 tidal component is much weaker than the M_2 (Fig. 3). However, the flow pattern is similar to that of the M_2 component, with the effect of Admiralty Inlet to the southeast very apparent (lower left-hand corner of the figure). Like the M_2 component, the K_1 component is quite weak to the west of Protection Island. The mean circulation, which is the average surface flow over a 5 1/2 day period,

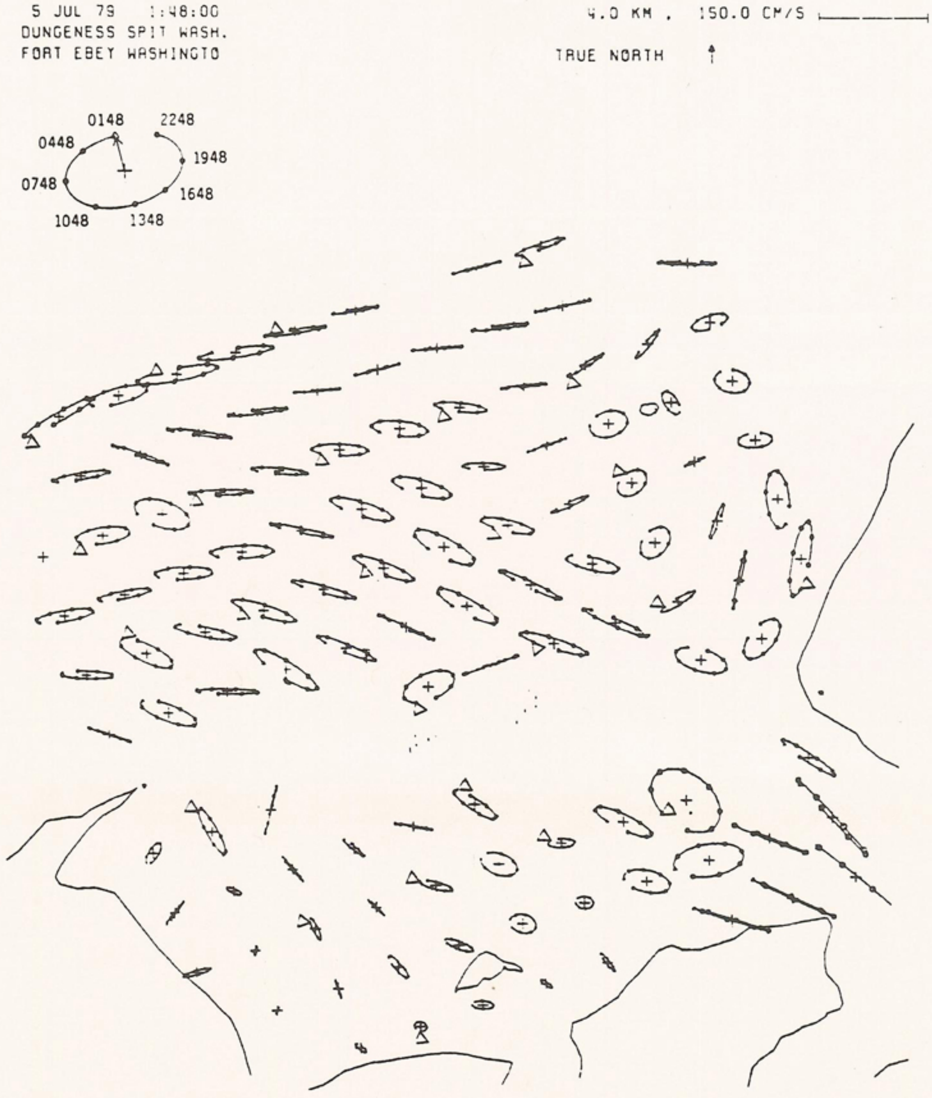


FIGURE 3. Tidal ellipses for the K1 tidal components. The triangle represents the start time (0148) for that ellipse.

is shown in Fig. 4. There is strong flow out of Admiralty Inlet, dominating part of the pattern in the eastern strait across the radar baseline. This pattern exhibits the expected estuarine outflux from the strait to the western part of the radar coverage area. The flow is similar to that reported by Frisch et al. (1980).

We use the radar-observed tidal information to compute trajectories in the vicinity of the proposed pipeline. As an example, we computed the trajectories of a particle at a location between Dungeness Spit and Admiralty Inlet. We used the tidal coefficients along with the mean current to compute these trajectories and simulate a nonwind period (there was almost no wind during this observation period). The trajectory that we calculate will also depend not only on the initial

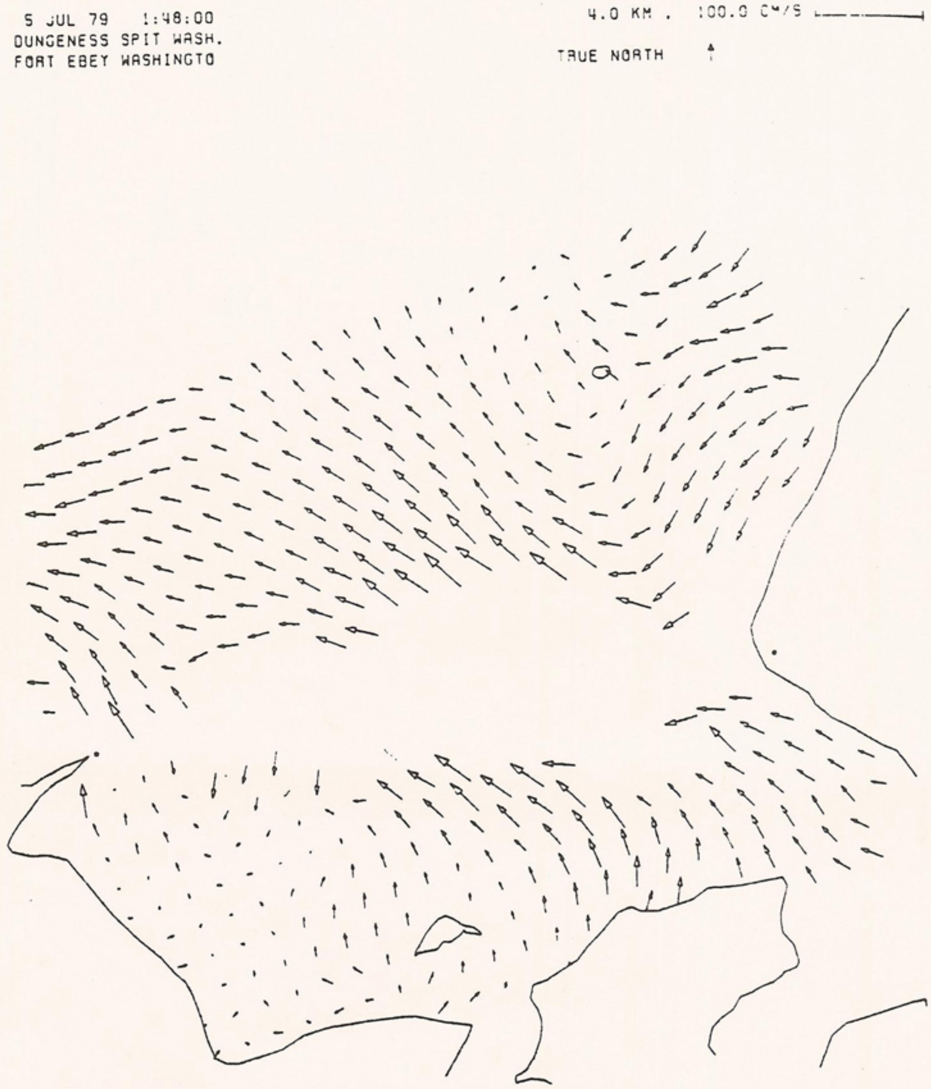


FIGURE 4. Mean or convective current computed from data for 5 1/2 days.

position, but also on when we start it. We show an example of three trajectory calculations in Figs. 5a, 5b, and 5c which have the same starting position but different starting times. For example, the trajectory at 11:00 [Fig. 5(a)] goes west of Protection Island and makes several complicated loops north and west of the Island. Starting at the same location just one-half hour later [Fig. 5(b)], the trajectory loops to the east of Protection Island, and makes a couple of loops about 2 km to the east of the previous trajectory. In the third example [Figure 5(c)], at 12:00, we see that the trajectory is initially similar to the trajectory at 11:00, but instead of making several complicated loops, it travels south and is displaced enough west that it intersects the shore. This trajectory information might be used to see where a

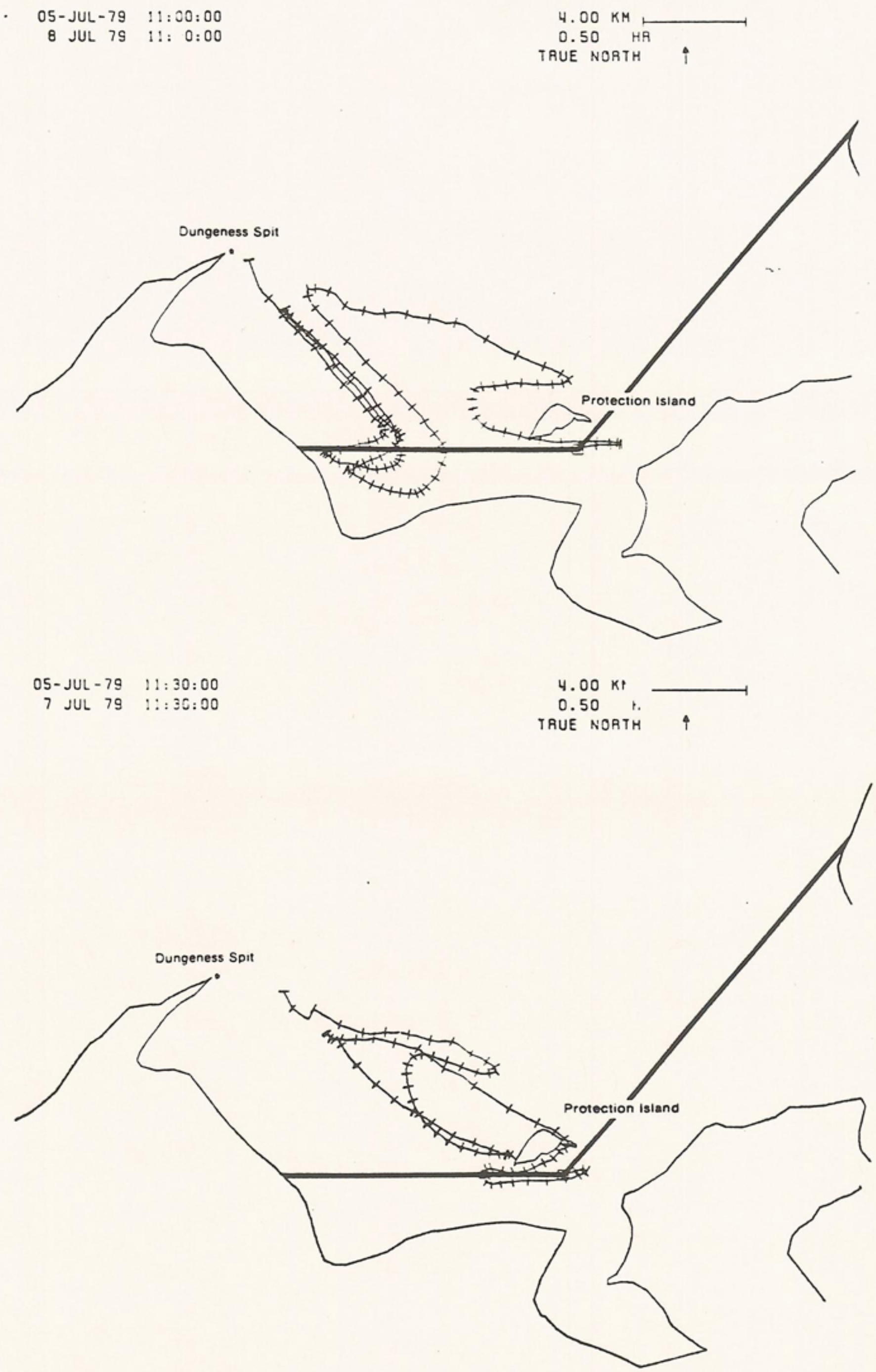
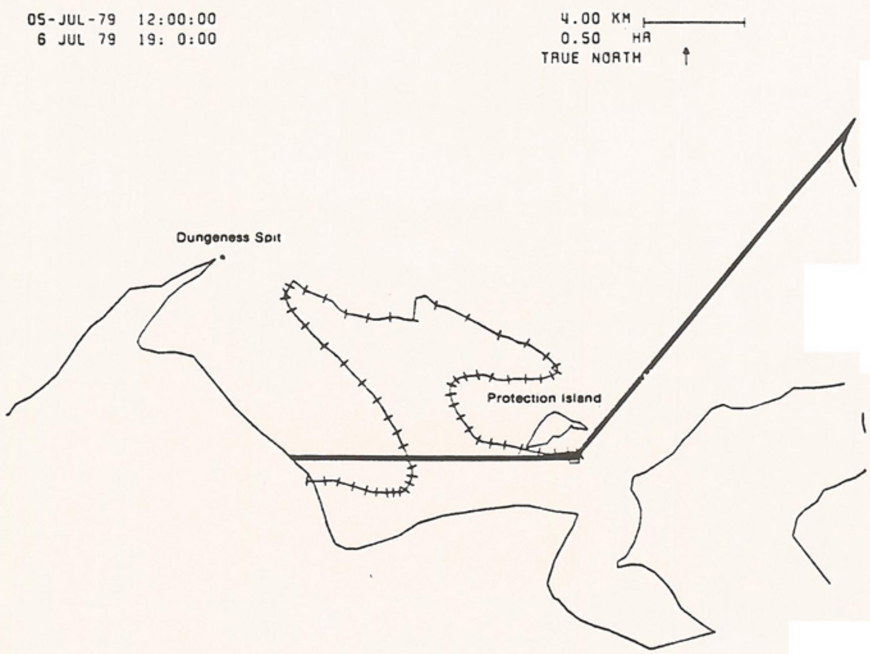


FIGURE 5. Trajectories computed from the mean (a), M2 (b), and K1 (c) tidal components starting at 11:00, 11:30, and 12:00 respectively. Each tick mark represents 1/2 hr and the dot–dash line shows location of proposed pipeline.



floating contaminant could be carried toward shore. If we compute these trajectories over several days, we can see the extent of shore coverage from a continuous source of contaminants in the absence of wind. As an example, we have taken three different locations along a proposed pipeline route, computed trajectories in 1-hr increments from each location, and marked the area of the shore where the contaminants would hit. Figure 6 represents a simulation of continuous leaks at three locations and the shoreline that would be affected. One represents a source south and west of Protection Island with the shoreline that would be affected by a continuous leak depicted by one kind of shaded lines. Similarly, we show a potential source and effects in a location south of Protection Island and a source east of Protection Island. The time of arrival between the release of a particle and its arrival on shore varied between two hours and two days. If the trajectory intersected a region near the baseline between the two radars, we stopped the calculation because we had no two-dimensional surface current velocity in this area. By stopping the calculation in this area, we do not know whether the trajectory would continue away from the southern coast, or be carried back onto the southern shore.

Conclusions

The dual-HF Doppler radar measurements of surface currents can be extremely useful in understanding the spatial distribution of tidal and mean surface currents and in determining the trajectory and potential impact area of an oil spill. In this example, we can see that if there were a leak in the proposed oil pipeline across part of the eastern Strait of Juan De Fuca in the simulated locations, several kilometers of the shoreline might be impacted.

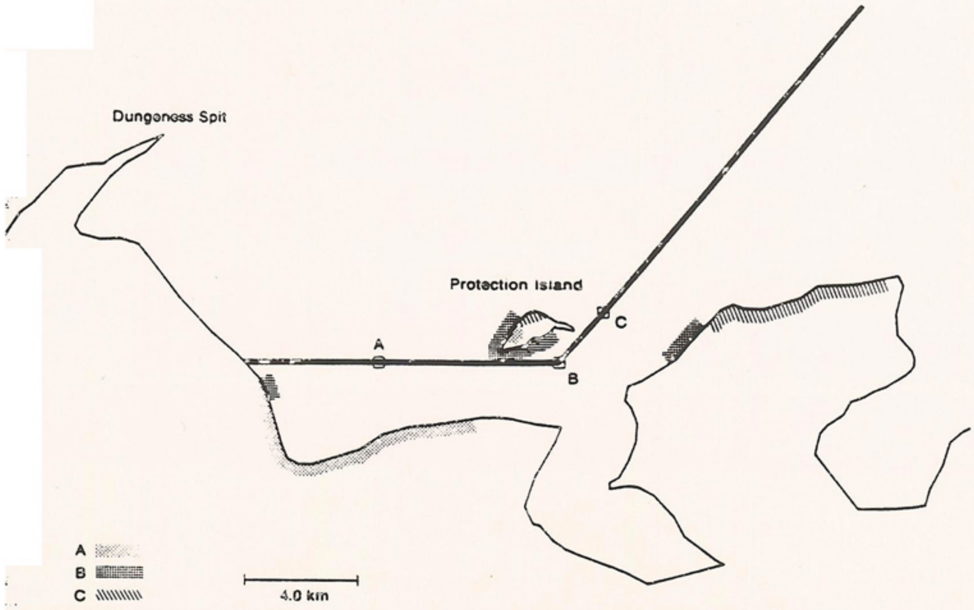


FIGURE 6. Shows the locations of the shoreline intersected by drifting material whose source is represented by the small square. The shoreline intersection for each source is represented by different kinds of shadings. The dashed line represents the location of a proposed oil pipeline.

This research was primarily sponsored by the Environmental Protection Agency and administered by the NOAA/MESA Puget Sound Project, Seattle, Washington, and by Ocean Technology and Engineering Services (NOAA/OTES), Rockville, Maryland. We thank D. E. Barrick and the members of his Sea State Studies Group, particularly M. W. Evans, D. Law, and C. Sutterfield, who collected the HF radar data.

References

Barrick, D. E. and Evans, M. W. (1976), Implementation of coastal current mapping HF radar system, Progress Report 1, NOAA., Tech. Rep. ERL 373-WPL-47.

Barrick, D. E., Evans, M. W., and Weber, B. L. (1977), Ocean surface currents mapped by radar, *Science* 198:138–144.

Barrick, D. E., Headrick, J. M., Bogle, R. W., and Crombie D. D. (1974), Sea backscatter at HF: interpretation and utilization of the echo, *Proc. IEEE* 62: 673–680.

Crombie, D. C. (1972), Resonant backscatter and its application to physical oceanography, in *Proceedings of IEEE Ocean '72 Conference on Engineering in the Ocean Environments*, Institute of Electrical and Electronic Engineers, New York, pp. 174–179.

Frisch, A. S., Holbrook, J., and Ages, A. B. (1981), Observations of a summertime reversal in circulation in the Strait of Juan de Fuca. *J. Geophys. Res.* 86:2044–2048.

Frisch, A. S. and Weber, B. L. (1980), A new technique for measuring tidal currents by using a two-site HF Doppler radar system, *J. Geophys. Res.* 85:485–493.

Holbrook, J. R. and Frisch, A. S. (1981), A comparison of near-surface CODAR and VACM measurements in the Strait of Juan de Fuca. J. Geophys. Res. 86:10908–10912.

Holbrook, J. R., Muench, R. D., Kachel, D. C., and Wright, C. (1980), Circulation in the Strait of Juan de Fuca: Recent oceanographic observations in the eastern basin, NOAA/ERL Tech. Report. in press.

Lyons, R. S. and Frisch, A. S. (1982), Error analysis for tidal coefficients with application to HF radar surface current measurements, *Remote Sens. Environ*. 12:283–294.

Maresca, J. W. Jr., Padder, R. A., Cheng, R. T., and Seibel, X. X. (1980), HF radar measurements of tidal currents flowing through the San Pablo Strait, San Francisco Bay, *Limnol. Oceanogr*. 25:929–935.

Stewart, R. H., and Joy, J. W. (1973), HF measurements of surface currents, *Deep Sea Res*. 21:1039–1049.

Received 31 March 1981; revised 13 January 1982