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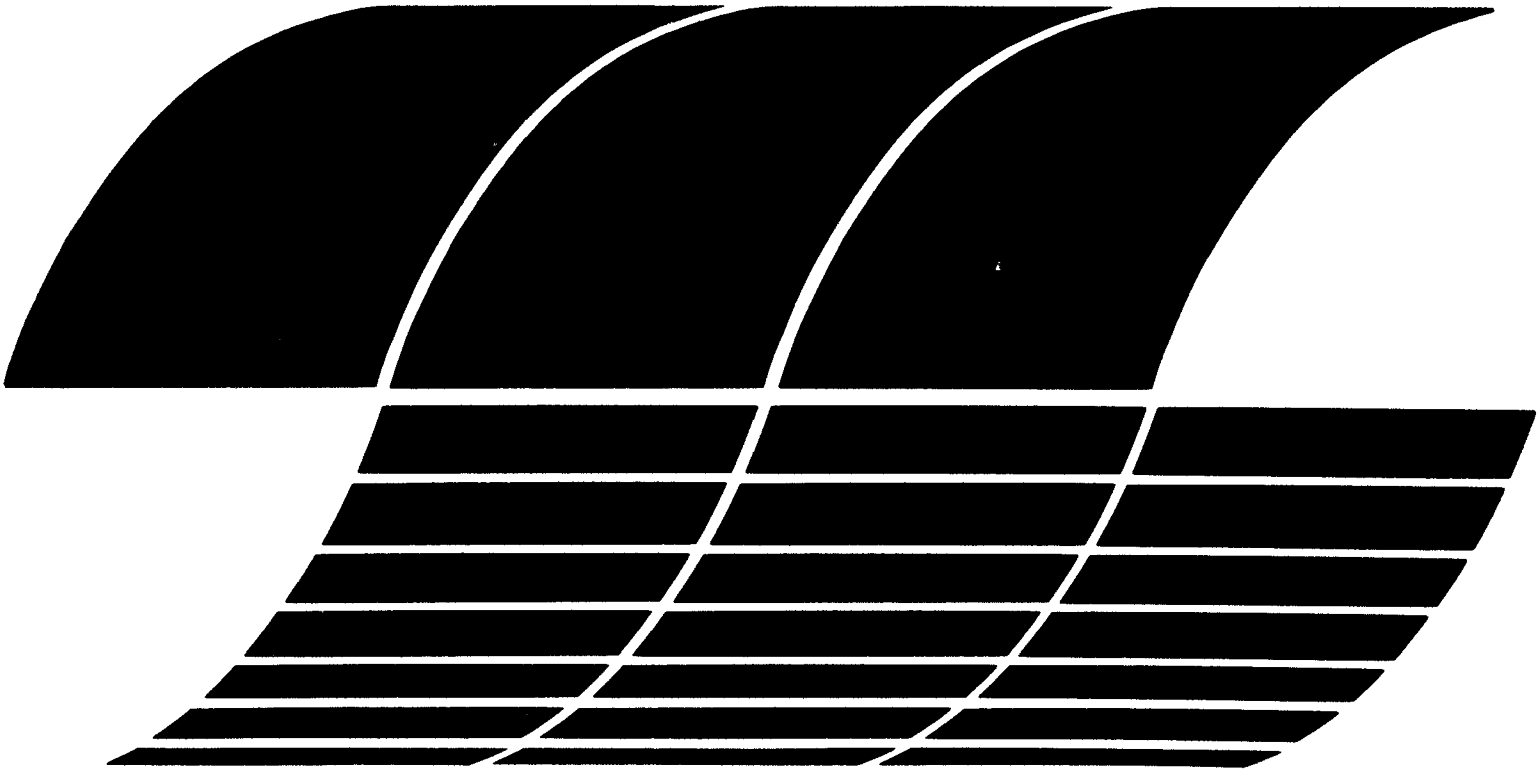
Circulation and Trajectory Calculations in the Eastern Strait of Juan de Fuca Using a CODAR System



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CIRCULATION AND TRAJECTORY CALCULATIONS IN THE EASTERN STRAIT OF JUAN DE FUCA USING A CODAR SYSTEM

by

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DISCLAIMER

This work is the result of research sponsored by the Environmental Protection Agency and administered by the National Oceanic and Atmospheric Administration.

FOREWORD

In this report we present CODAR (Coastal Applications Dynamics Radar) measurements in the Eastern Strait of Juan de Fuca. These measurements were taken over a 4-day interval in 1978 and another 5-day interval in 1979. We have estimated the mean surface flow and the semi-diurnal and diurnal components of tidal flow. The semi-diurnal components from the two years were combined to give a representation of the semi-diurnal flow over the areas covered in both years. The current velocity components were included across the radar baseline using a special interpolation technique. Finally, we have tried to estimate areas of shoreline that would be impacted by an oil leak from a proposed pipeline.

These measurements and calculations demonstrate the ability of CODAR to measure the extreme complexity of the surface circulations and help in understanding the physical oceanography of this complicated, ecologically sensitive region.

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ABSTRACT

During the summers of 1978 and 1979, the surface currents of the Eastern Strait of Juan de Fuca were mapped with a high frequency (HF) radar system (CODAR). This system measures surface currents over several hundred square kilometers. During 1978, we measured currents in the vicinity of New Dungeness Spit and Point Wilson for three days, and then moved one of the sites to measure currents near New Dungeness Spit and Ediz Hook. In 1979, we measured surface currents in the vicinity of New Dungeness Spit and Partridge Point, concentrating on an area around Protection Island, a site near a proposed oil pipeline.

In this study, we have used data from both years to make a composite picture of the tidal flow over an area covered by the radar in all the experiments. Because the area across the radar baseline in our 1979 study is important, we have used an interpolation technique to fill in this data. In addition, because of the potential impact from an oil leak along the path of a proposed oil pipeline, we have simulated a continuous release of a material and computed a trajectory for a no-wind condition.

ACKNOWLEDGMENTS

The authors acknowledge the indispensable support ot the following people without whom this study would not have been possible. We thank Don Barrick for his leadership and direction before and during the experiment. The operation and maintenance of the radar were largely due to Mike Evans, Dan Law, Alan Carr, Karl Sutterfield, and John Forberg. These same people designed, built, and operated the radar system that will permit oceanographers to view the sea through new "eyes."

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INTRODUCTION

During the summers of 1978 and 1979, the Sea State Studies Area provided surface current measurements, in order to understand the circulation in the Eastern Strait of Juan de Fuca and its impact on a possible oil spill. The need for this information has increased in the last few years because of expanded oil tanker traffic and a proposed oil pipeline in the region. In a report on the tidal hydrodynamics of this region, Parker (1977) points out that the damage due to oil spills on the marine environment could be detrimental to the large salmon and shellfish industries, as well as to the larger commercial fishing and recreation industries.

To predict where spilled oil will go, one needs to know the spatial and temporal distribution of currents. The acquisition of such a data base with conventional techniques, such as use of moored current meters or tracking floating objects, is a formidable task that would still fall short of providing an adequate understanding in certain situations.

The CODAR system has the capability of measuring the surface current in great detail. In addition, when these currents are separated into their tidal, wind, and mean circulations, we gain some knowledge of the subsurface circulation, since the tidal components are fairly constant with water depth under many conditions. The tidal and mean flows give the background condition, upon which we can add wind effects for a more general approach to any trajectory predictions.

During 1978, the NOAA/WPL CODAR Group was joined by other investigators from NOAA's Pacific Marine Environmental Laboratory, Evans-Hamilton, Inc., and the Canadian Institute of Ocean Sciences (IOS). During this particular experiment, both oceanographic and meteorological data were gathered for various lengths of time. Current meter and meteorological data were collected over several months; the surface current data from CODAR were collected over a 4-day period. During the summer of 1979, the CODAR Group operated independently, with no coordinated observations made by other institutes in the radar coverage area. Most of the information obtained during these two summers has been published (Frisch and Holbrook, 1980; Frisch, 1980) and will not be repeated here. This report gives details of some further analysis of the data which:

1. Gives a composite picture of the semi-diurnal tidal flow over the areas covered in both years, referenced to 7 July 1979.

2. Fills in some of the spatial gaps previously appearing in the tidal flow across the radar baseline.

3. Shows trajectory estimates and shoreline impact areas that one might expect from an oil line leak in the vicinity of Protection Island.

In our previous reports (Frisch and Holbrook, 1980; Frisch, 1980), we harmonically decomposed the observed flow into mean, 12-hour, and 24-hour tidal components. The data were taken at the Port Angeles site over only a 24-hour period, so the 24-hour component was not accurate, and we did not include it. The 1979 data set is limited in that we had no two-dimensional currents in part of the area of interest near the proposed pipeline, because of the radar locations. This happens whenever the velocity measurements are along a line between the two radars; only the component along that line from each radar can be resolved. Since we do not have the component normal to the line, we cannot compute the two-dimensional Cartesian velocity components in this region directly.

Because there is a proposal to place an oil pipeline in the vicinity of Protection Island, we computed surface trajectories with the radar data that start at various locations along the proposed pipeline. These calculations assume that floating material would move with the surface current, and have no corrections for direct wind force on the object; they should be helpful in showing how and where an oil leak might drift in the absence of wind. These calculations illustrate that the trajectory is not only very sensitive to the initial location of the leak, but also to the time when the trajectory starts relative to the tidal components.

Since the radar has a fixed range, it cannot always cover the whole area that might be affected by an oil leak; and, therefore, some trajectories must be terminated when they reach the coverage boundary. As a result, we may be losing some of our "hits" on the shore, since the floating material that drifted out may have been returned into the radar coverage area by the tides or mean flow.

CONCLUSIONS

We used the results of two summers' observations (1978, 1979) to put together a composite picture of the M2 tidal flow in the Eastern Strait of Juan de Fuca and interpolated this flow across the radar baseline. In addition, we have simulated trajectories from sources along a proposed oil pipeline using CODAR-derived tidal and mean flow coefficients. These results show that for the three-sample source locations (1) the floating material would hit the shore in several locations, and (2) the trajectory is very sensitive not only to the location of the source, but also to the time it was started relative to the tidal cycle.

RECOMMENDATIONS

We believe that this technique is the best way to measure the spatial distribution of surface currents. We must develop a more reliable way to interpolate across the radar baseline where we have only one component of velocity. In addition, higher operating frequencies and shorter range gates should be developed to permit higher spatial resolution for the study of small water bodies.

RADAR OPERATION

During 1978 two CODAR units were deployed at the Eastern Strait of Juan de Fuca. One unit operated continuously from New Dungeness Spit for 115 hours. The other unit operated first from Point Wilson for 73 hours and then Ediz Hook for 28 hours. The locations of these radar sites and the principal regions mapped during this year are shown in Figure 1, and the dates and times when the data were collected are shown in Figure 2 (Frisch and Holbrook, 1980).

During 1979 the CODAR group deployed two units at the end of New Dungeness Spit and at Fort Ebey on Whidbey Island (Figure 3). This set of data were obtained 3 hours for most of the 5-day interval starting at 0130 Pacific Daylight Time on 5 July until 1200 on 10 July. Occasionally, one hour sampling was undertaken for immediate needs.

RADAR ANALYSIS

The radar measures the phase velocity of a six-meter ocean wave, which is shifted by currents (Barrick et al., 1977). This phase velocity is also affected by dynamic wave action relative to the surface current, limiting the accuracy of the radar-measured currents to a few centimeters per second (Barrick and Weber, 1977; Weber and Barrick, 1977).

One of the measurement problems is the inability of the CODAR system to measure total current velocity in the area along and adjacent to a line between the two radars. There is no velocity data perpendicular to this line. There are two possible ways to fill in the data between the baseline. One is an interpolation technique developed by Leise (personal communication) and the other is to integrate the continuity equation in polar coordinates ignoring the vertical velocity at the ocean surface (Frisch and Leise, 1981).

One can see that if $\nabla . U = 0$

expressed as

$$\frac{1}{r}\frac{\partial}{\partial r}(rU_r) + \frac{1}{r}\frac{\partial}{\partial \Theta}(U_\Theta) + \frac{\partial}{\partial z}U_z = 0 \ . \ . \ . \qquad (1)$$

where r is the radial coordinate, Θ the azimuthal coordinate, z the vertical coordinate and the subscripted U's are the velocity components in the direction of the subscript. If we ignore the vertical velocity, then the equation reduces to

$$\frac{1}{r}\frac{\partial}{\partial r}(rU_r) + y_r \frac{\partial}{\partial \Theta}U_\Theta = 0 \ . \ . \ . \qquad (2)$$

By placing the origin of this coordinate system at one of the radar locations, then the U_r corresponds to the radial velocity component measured by that radar, and U_Θ is the velocity perpendicular to that radial velocity. Thus we can integrate the equation of continuity (2) with respect to Θ and obtain

$$U_\Theta(\Theta,r) = U_\Theta(\Theta_o,r) - \int_{\Theta_o}^{\Theta} \frac{\partial}{\partial r}(r\, U_r(\Theta,r)d\partial \ . \ . \ . \qquad (3)$$

In the area outside of the baseline, we can compute $U_\Theta(\Theta_0,r)$ from measurements by both radars. We can use (3) to solve for $U_\Theta(\Theta,r)$ in the area between the baseline.

One significant potential error in this estimate results from ignoring the $\frac{\partial U_z}{\partial z}$ term (Eq. 1). Since the bathymetry effect of strong tidal flow on $\frac{\partial U_z}{\partial z}$ could not easily be evaluated, we felt that Leise's interpolation technique could be applied with as much accuracy and was available.

Since the 1978 experiment had some data taken west of New Dungeness Spit and we had a longer data set in 1979 for the area east of New Dungeness Spit (and, therefore, statistically more accurate), we made a composite picture of the M2 tidal flow by adjusting the size of the 1978 tidal ellipses based on comparisons of the ellipses for both years in the common overlap area which was just north of New Dungeness Spit. (The 1978 ellipses were about a factor of two smaller than the ones for 1979 at the same location.) We then adjusted the ellipses from 1978 to correspond to the 1979 ellipses by multiplying them all by a constant factor of about 2.0. (It should be noted that this picture is very qualitative because of the short sample length in 1978.)

The trajectory calculations were made using the semi-diurnal, diurnal, and mean flow computed from our 1979 data set. We used this set because it was the longest, had the best spatial resolution, and was taken around an area where a proposed oil pipeline may be placed.

The position of a particle can be computed if one knows the velocity field over the area of interest and for the time of interest. The location is given by

$$x(t) = x_0 + \int_{t_0}^{t} U_x(x,y,t)dt$$

$$y(t) = y_0 + \int_{t_0}^{t} U_y(x,y,t)dt$$

where t is the time after the particle has been released (t_0 is the release time), and $U_x(x,y,t)$ and $U_y(x,y,t)$ are the two surface velocity components. If one is interested in computing the trajectory of a particle for the mean tidal components, these $U_x(x,y,t)$ and $U_y(x,y,t)$ would be those tidal components.

In our case, we used the semi-diurnal and diurnal components along with the mean flow derived from the 1979 data for the trajectory calculations.

Data were collected from 0130 Pacific Daylight Time (PDT) on 5 July until 1200 on 10 July. Further details of the experiment can be found in Frisch (1980).

RESULTS

Tidal Flow

The results presented here illustrate surface circulation patterns in the Eastern Strait of Juan de Fuca derived from HF radar observations. Of particular use is the calculation of the surface trajectory, based only on tidal components and the mean flow. This type of trajectory calculation gives the surface drift with no wind, on which we can later superimpose the wind-driven circulation. This technique will become increasingly useful for planning and cleanup as tanker traffic increases in the Strait of Juan de Fuca area. The data sets were tidally analyzed by least squares fitting the data to two dominant tidal components, namely the K1 and M2 (Holbrook and Frisch, 1980). We display these tidal components as ellipses, since most people are familiar with this kind of display. The ellipses have the advantage that a large quantity of data can be displayed in a very compact form.

We put together a tidal model for the 12-hour component based upon results from 1978 and 1979 (Figure 4). This model is very crude, since we had data from only one day for the calculations of the M2 components (semidiurnal) west of New Dungeness Spit, and the data contained a surge event (Frisch, Holbrook, and Ages, 1981). We did not compute a composite for the 24-hour component (Lyons and Frisch, 1980) because of the short sample and this surge event.

Trajectory Calculations

We computed the trajectory of a surface particle at three locations in the southern region between New Dungeness Spit and Admiralty Inlet. We used the tidal coefficients alone, along with the mean current, to compute these trajectories over a three-day interval to illustrate no-wind conditions. The trajectories that we calculated depended not only on the initial position, but also on when we started it.

We show an example of three trajectory calculations in Figures 5a, 5b, and 5c having the same starting location but slightly different starting times. The trajectory at 1100 (Figure 5a) goes west of the island. Starting just one-half hour later (5b), the trajectory loops to the east of Protection Island, and makes two loops about 2 km to the east of the previous trajectory. In the third example (Figure 5c) at 1200 we see that initially the trajectory is similar to the trajectory at 1100, but instead of making several complicated loops, it travels south and is displaced enough west that it intersects the shore. This trajectory information can be used to show where a floating contaminant will be carried on

If we compute these trajectories over a longer time interval, we can see the possible extent of shore contamination from a continuous source of floating pollutants. As an example, we have taken three different locations along a proposed pipeline route, computed trajectories in 10-minute increments from each location, and marked the area of the shore where the contaminants will hit. In Figure 6 we indicate three sources along the proposed pipeline path; the shoreline areas that will be affected by a continuous leak from each location are depicted by different degrees of shading. 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, and the tentative baseline interpolation technique used here needs more verification. Because calculation for this area stopped, we cannot say whether the trajectory would continue away from the southern coast or be carried back onto the southern shore.

Accuracy

The type of tidal analysis done herein has been done by Frisch and Weber (1980), and the radar-derived tidal components have been compared with current metered data by Holbrook and Frisch (1980). In this comparison, they found that current-meter-derived tidal coefficients and the HF radar coefficients were within 10 cm/sec of each other at the K1 and M2 tidal frequencies. Part of the errors in the computation of these components will be due to the sampling (both the interval and the length), as well as to the errors in the radar measurement.

Simulations of tidal coefficient recovery with noise present indicates that when we take measurements for five days, the K1 and M2 components will have only a few percent error in the amplitude and phase. Therefore, the average magnitude of the current fluctuation errors in the coverage area is ±10 cm/sec (Lyons and Frisch, 1980).

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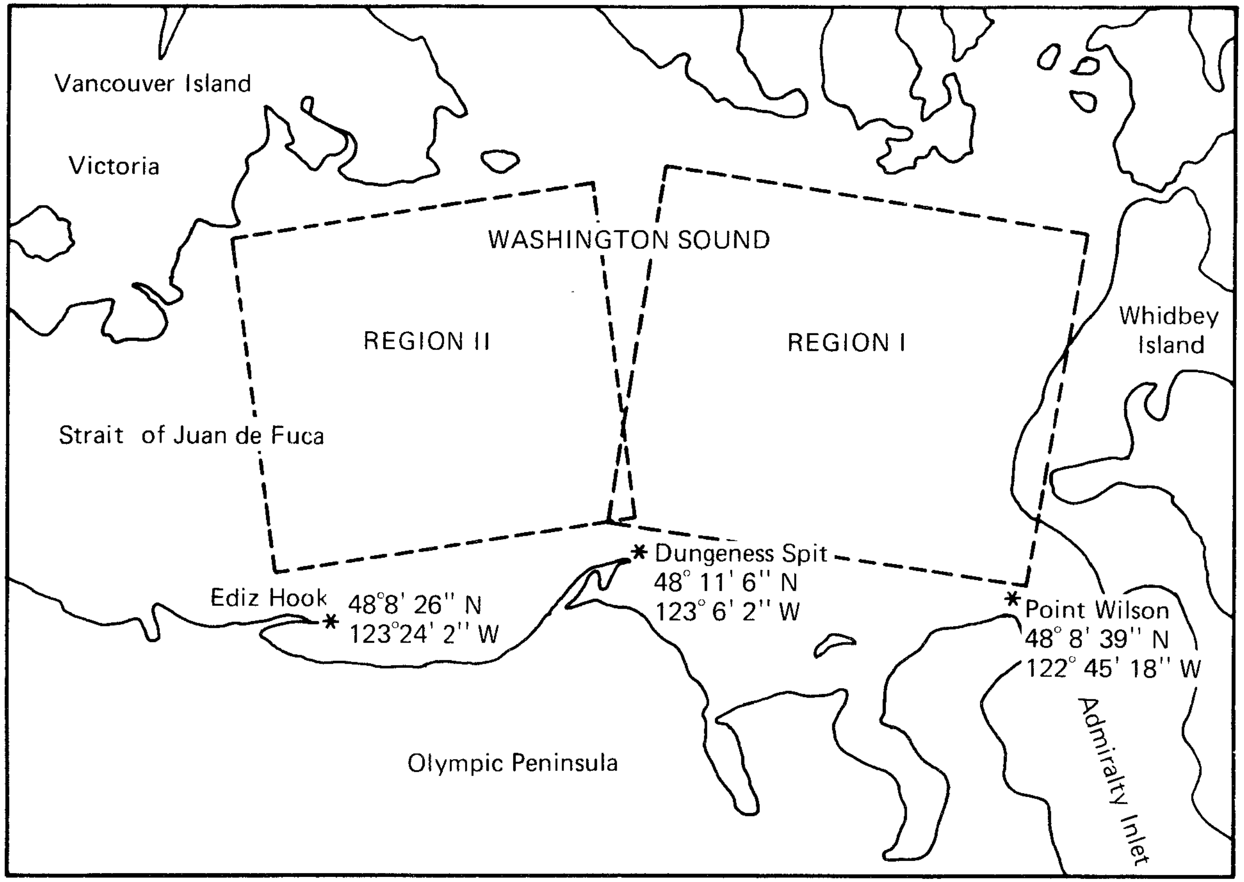

Figure 1. Locations of radars for 1978. The two radar units were operated from the three indicated sites at Dungeness Spit, Point Wilson, and Ediz Hook. Region I is the main area mapped with the Dungeness Spit/Point Wilson site combination, and Region II is the principal area mapped with the Dungeness Spit/Ediz Hook site combination. The latitude and longitude of each of the sites is given next to each of the site symbols.

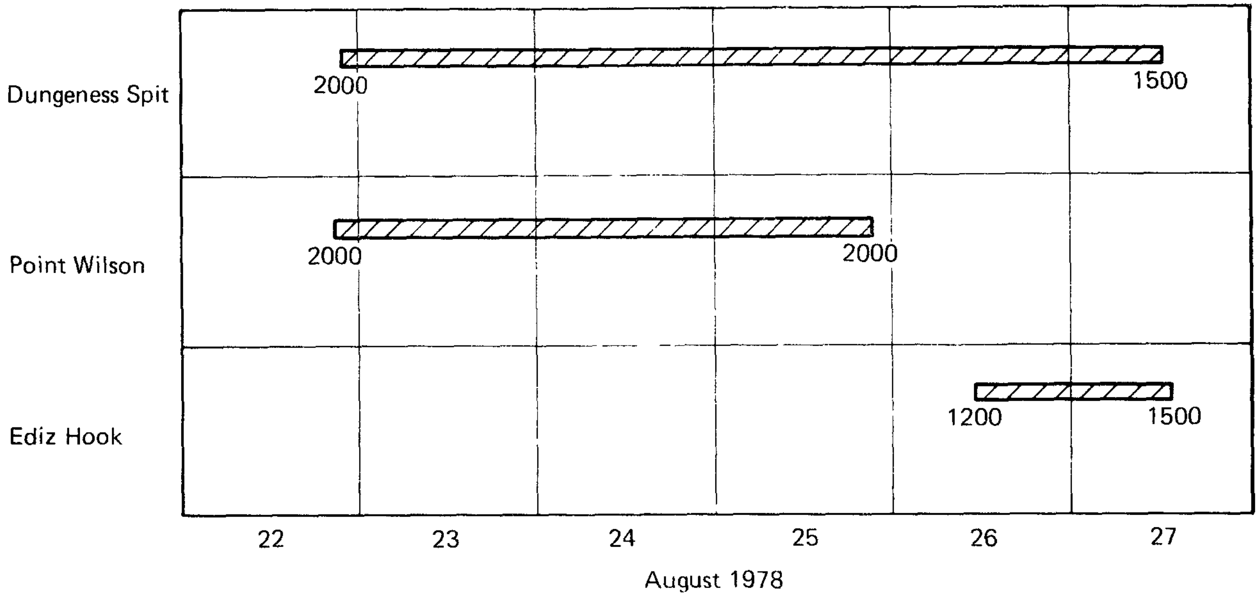

Figure 2. CODAR operating times for 1978. Two HF Doppler radar units were operated between 22 and 27 August 1978. One unit operated at the Dungeness Spit site uninterrupted throughout the period. The other unit operated successively from the Point Wilson and Ediz Hook sites. All data collection commenced on the hour (PDT), every hour and continued for 36 minutes.

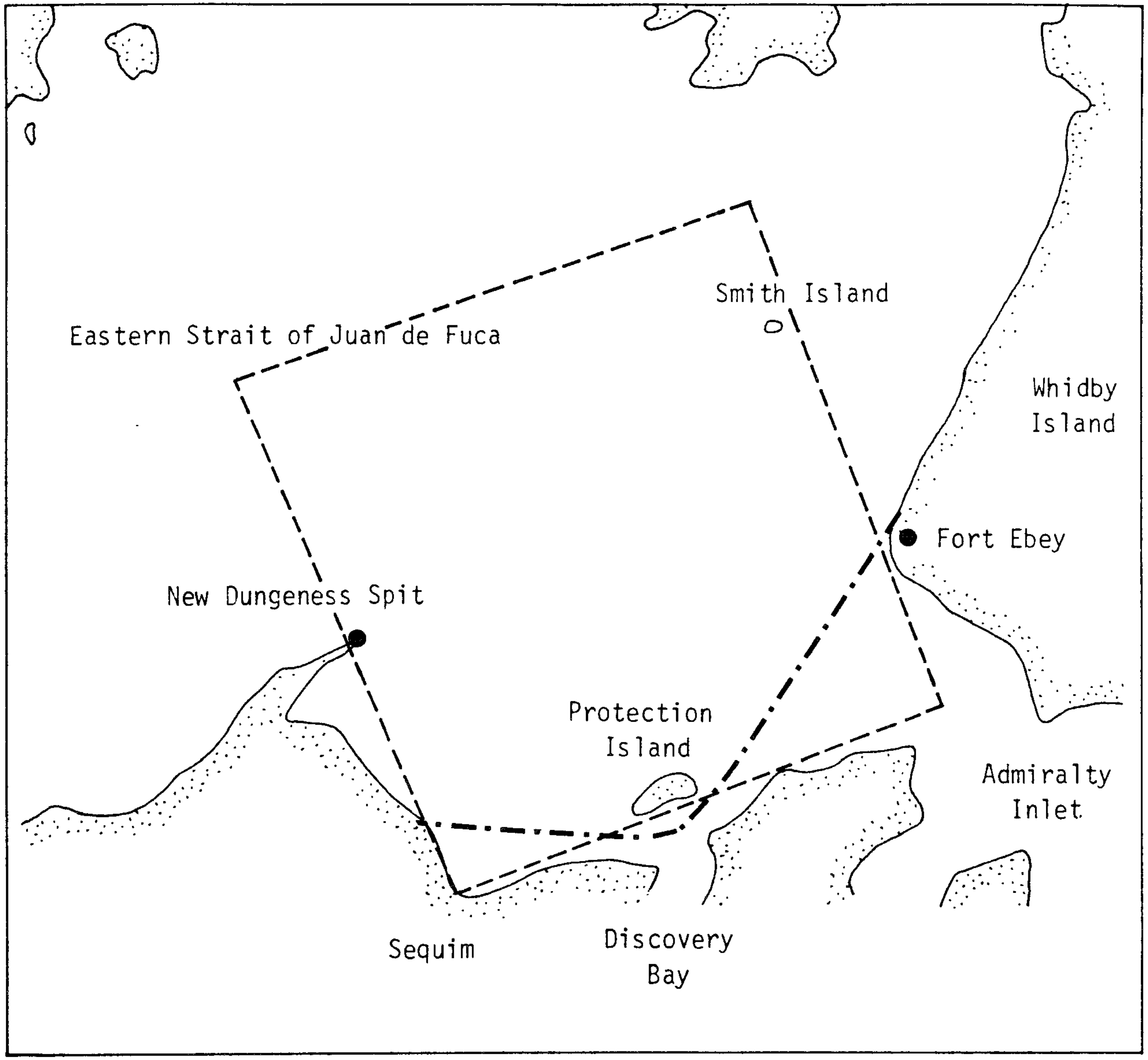

Figure 3. Radar locations for 1979. The location of radars for the 1979 experiment were at New Dungeness Spit and Fort Ebey. The rectangular area indicates the approximate coverage area for surface current measurements. The dashed-dot line depicts the proposed oil route.

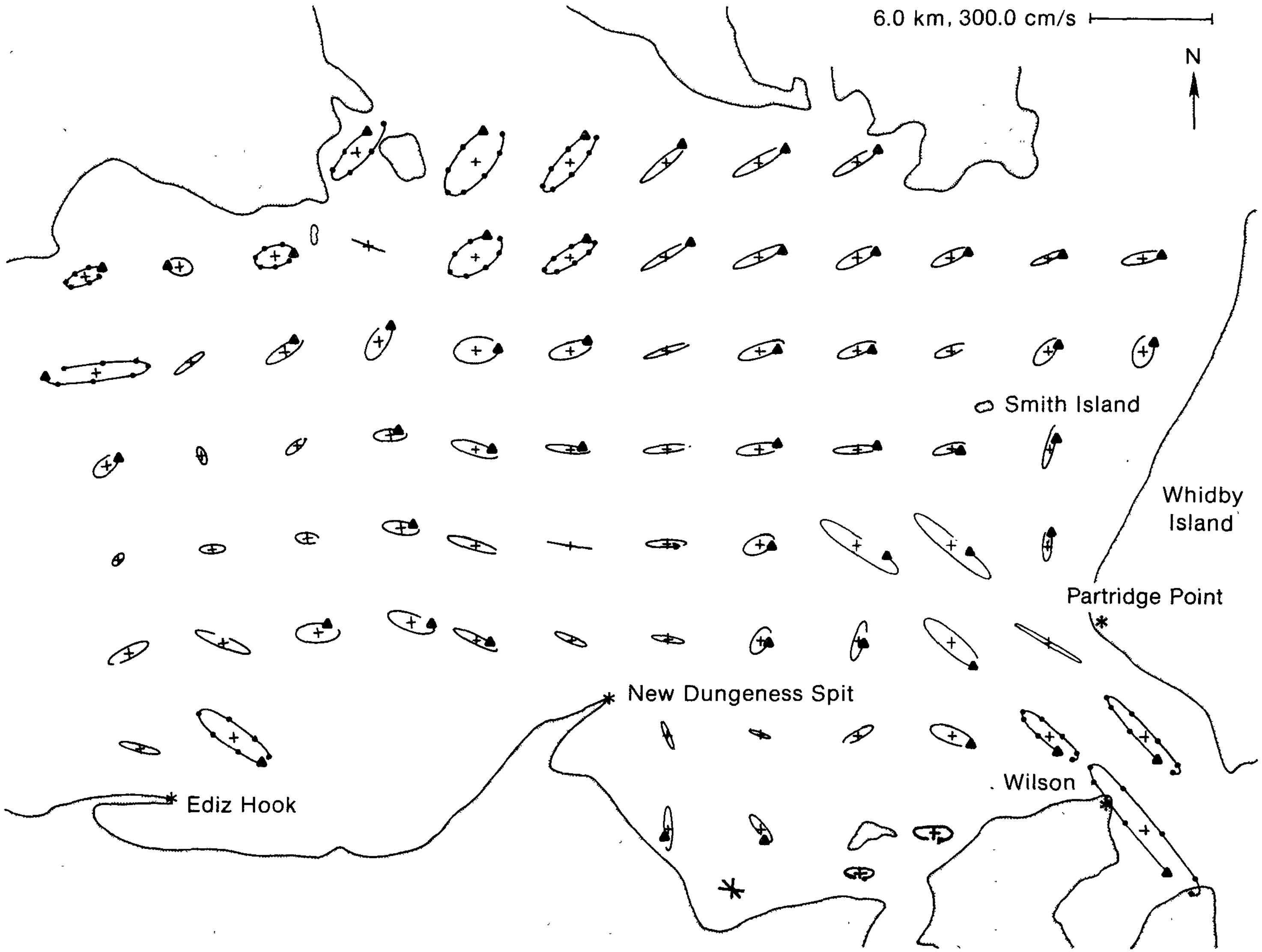

Figure 4. Composite tidal ellipses for 1978 and 1979. This model was made by adjusting the amplitudes of the ellipses at the common boundary, i.e., New Dungeness Spit. This is only schematic; to do a more accurate model, data should be taken for several days in each area of interest.

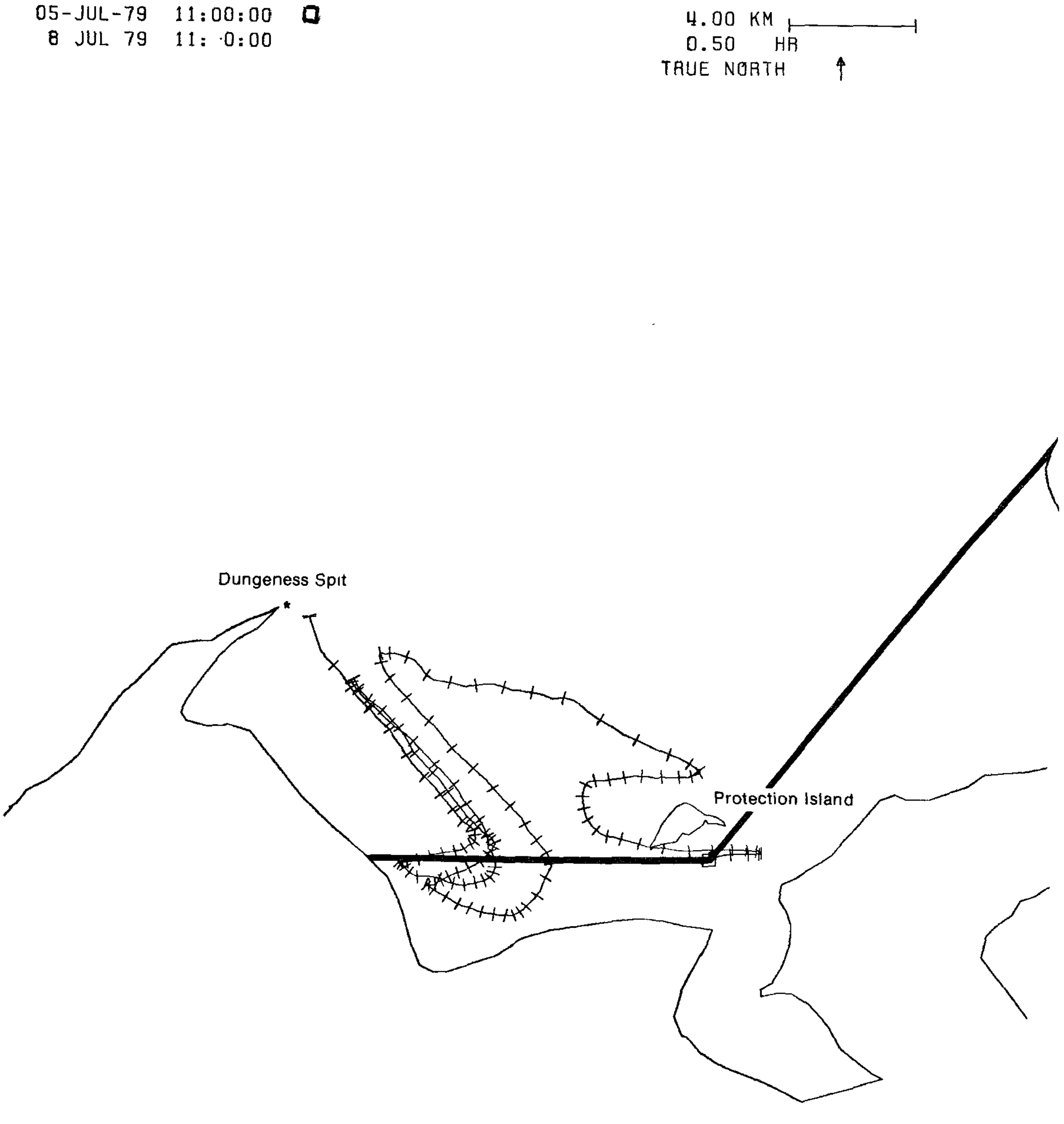

Figure 5a. Drifter trajectory computed from CODAR-derived tidal and ocean surface currents. The trajectory calculation starts at 1100 using radar-derived tidal and mean flows. The upper left corner indicates the times used for the calculation. Each tick mark along the trajectory is one half hour. The small square box at the end of the trajectory indicates the starting point. The solid line depicts the proposed oil pipelines.

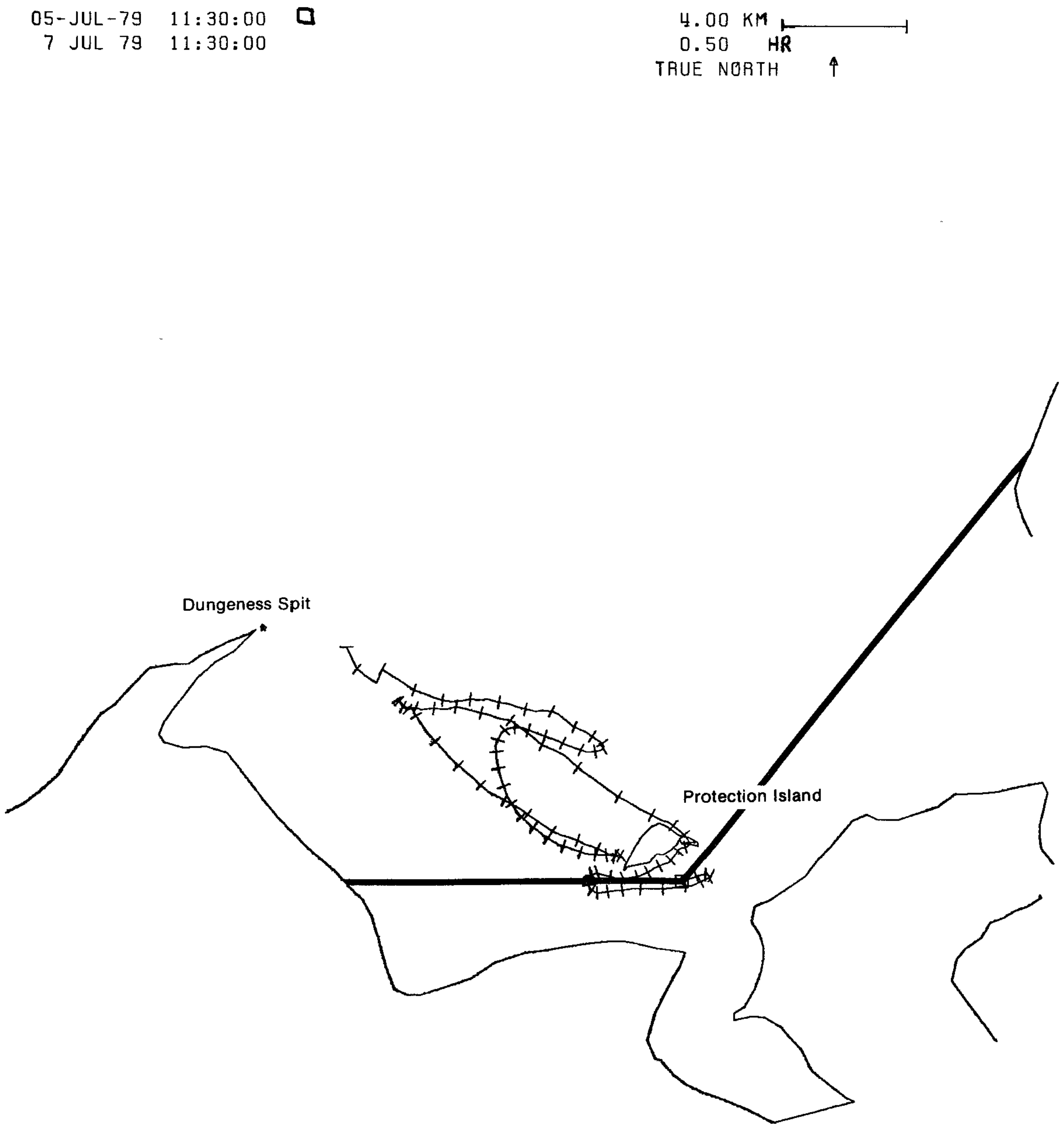

Figure 5b. Drifter trajectory computed from CODAR-derived tidal and ocean surface currents. The trajectory calculation starts at 1130 using radar-derived tidal and mean flows. The upper left corner indicates the times used for the calculation. Each tick mark along the trajectory is one half hour. The small square box at the end of the trajectory indicates the starting point. The solid line depicts the proposed oil pipelines.

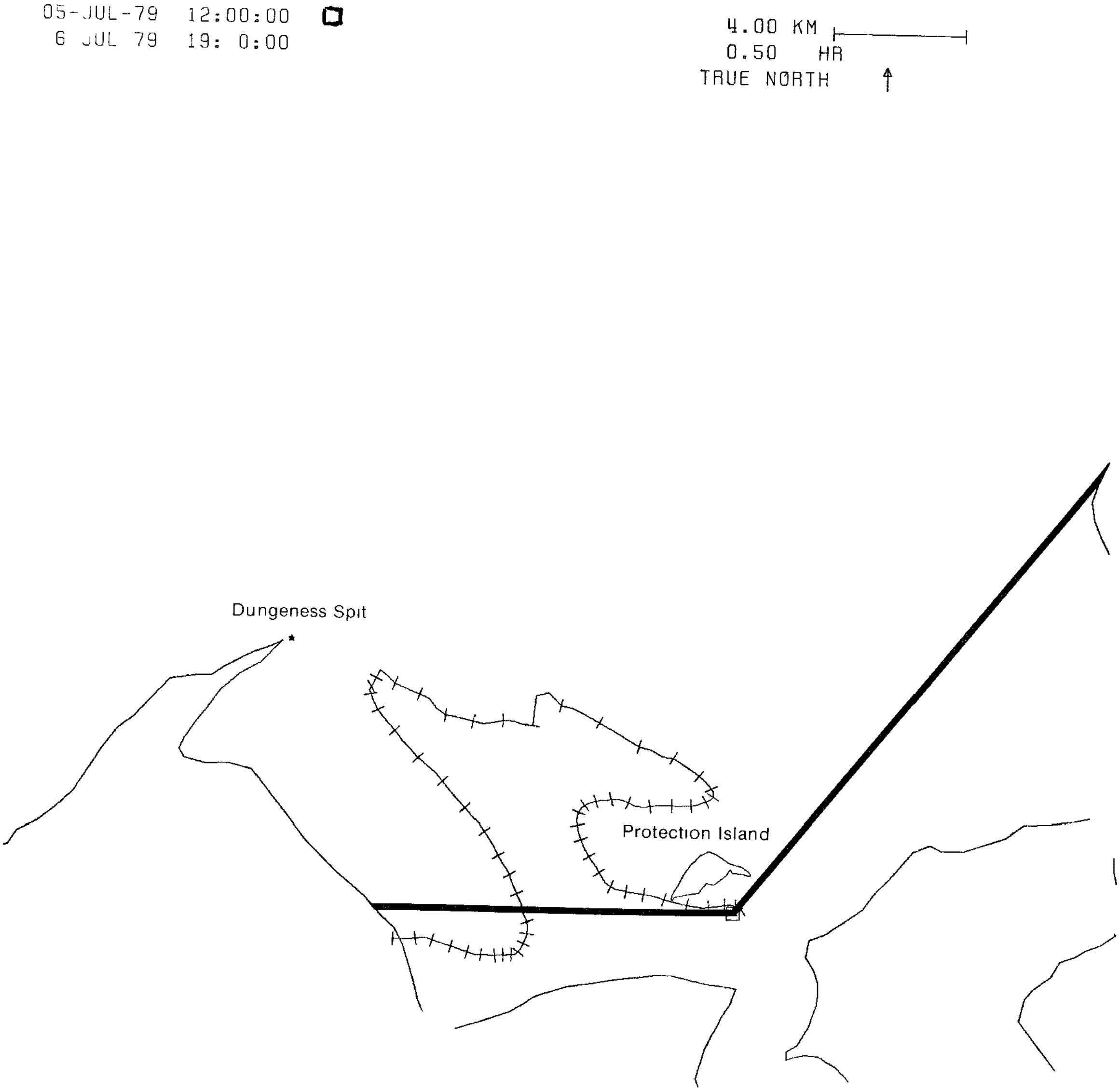

Figure 5c. Drifter trajectory computed from CODAR-derived tidal and ocean surface currents. The trajectory calculation starts at 1200 using radar-derived tidal and mean flows. The upper left corner indicates the times used for the calculation. Each tick mark along the trajectory is one half hour. The small square box at the end of the trajectory indicates the starting point. The solid line depicts the proposed oil pipelines.

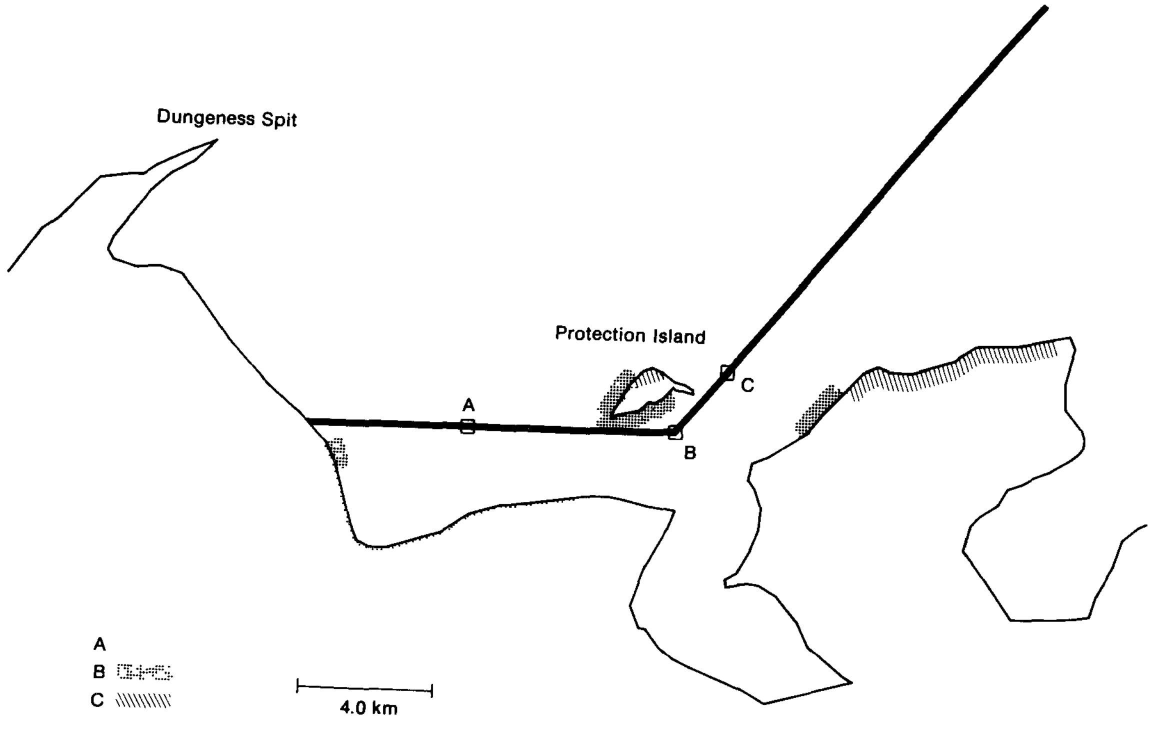

Figure 6. Impacted shore areas. Shore areas affected by trajectories starting at A, B, and C. Solid line depicts the proposed oil pipeline location and the various shadings the shore area affected by each leak.

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