Ocean Current Measurements from Submarine Set and Drift

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Abstract - A procedure for calculating ocean currents from submarine set and drift is described. Relationships for the response length of the submarine to velocity perturbations are given. These lengths are found to be 3-10 boat lengths, and they represent a limit to the spatial resolution of the current measurements. A procedure for the in-situ calibration of the submarine speed sensor is described. An example shows that the current vectors are consistent from one leg of the submarine track to another and with satellite observations. Ocean current measurement capability is presently being integrated into an oceanographic monitoring system for tactical applications.

I. INTRODUCTION

For a vessel underway, the vector difference between the velocity determined by navigation (the absolute velocity) and the velocity derived from dead reckoning (the relative velocity) is known as the set and drift of the vessel. Historically, set and drift calculation was the principal technique for estimating ocean currents until other types of current meters came into common use in the last 30 years. Some of the factors that have limited the accuracy and applicability of drift-based current measurements are accuracy and resolution of navigation systems and the spurious effect of windage on the vessel. On a modern nuclear submarine, however, accurate navigation information is continuously available, and there is no windage when submerged, making this a very attractive platform for calculating ocean currents from set and drift data.

This paper describes the method used for calculating ocean currents from submarine set and drift. Factors considered include averaging intervals, criteria for valid data, and sensor calibrations. An example illustrates the results of the calculations. A Gulf Stream ring is clearly evident in the data, but more subtle features can also be distinguished. Comparisons with satellite imagery show good agreement with the drift-based currents. A real-time application in the Tactical Oceanographic Monitoring System (TOMS) is discussed. In TOMS, ocean currents are used in conjunction with CTD (conductivity, temperature, depth) information for evaluating the local oceanographic conditions.

II. CALCULATION PROCEDURE

While conceptually very simple, the calculation of drift currents involves some assumptions, thus, incorrect results may be obtained if the assumed conditions are not observed. The basic assumption in calculating set and drift is that the vector sum of the relative velocity through the water and the ocean current is equal to the absolute velocity or inertial velocity relative to the earth. In a submarine the electromagnetic (EM) log gives the speed through the water, and the vector velocity is computed from this speed and the ship's heading. One of the problems arises when the ship is executing a turn or change of course. When this happens the ship's velocity vector is no longer parallel to the heading as it "side slips" through the turn. For this reason, current estimates during course changes are inaccurate and must be edited from the data set.

The quantities that are used for the calculations are EM log speed, heading from the inertial navigation system (INS) or another gyroscope, north and east inertial velocities and position from the INS, and time. Depth is also used to aid in the interpretation of the data. In practice, ship's systems produce estimates of these quantities at various sampling rates from once per second to once per minute. Intuitively, the current estimates from closely spaced samples will not be independent, which suggests that averaging is appropriate. In fact, the response of the submarine to a change in current may be computed from a simple dynamic analysis.

Consider a submarine traveling at constant speed and course in equilibrium with the local current. If there is a perturbation in the current, either along or transverse to the track, how long does it take to achieve a new equilibrium? Extending the analysis of [1] from the case of a freely sinking body to a self-propelled vehicle, yields expressions for the response length for the longitudinal and transverse perturbations, L_L and L_T respectively. The form of the
solution is a low pass filter, where the response length is the half-power point in the filter. This length may also be thought of as the distance required for the submarine to acquire 1/e of a step change in current. The response lengths are given by

\[ L_L = \frac{1 + C_M}{C_D} \]
\[ L_T = 2 \frac{1 + C_M}{C_D} \]

for the longitudinal and transverse perturbations, respectively, where the added mass coefficient \( C_M << 1 \), and the drag coefficient \( C_D = 0.2 - 0.3 \) for a typical submarine [2]. Using these values, the response length is 3 to 10 times the length of the submarine. Note that if the drag coefficient is independent of velocity, the response lengths are also independent of velocity and that independent samples depend on the distance between samples, not the time. This suggests that the averaging should be specified in terms of distance rather than time. In practice, the averaging length of 1 kilometer, corresponding to about 10 ship lengths, is often used.

III. SPEED LOG CALIBRATION

On U.S. submarines, the principal speed sensor is the EM log. This sensor is an electromagnetic current meter whose sensing element is a cylindrical element or "sword" approximately 1 meter long extending out from the underside of the submarine. In this position, the flow at the sensor is significantly affected by the submarine and not representative of the speed of the submarine. As a result, the sensor must be calibrated in position to account for the flow distortion by the submarine. This sensor is important for many aspects of submarine operations and is routinely calibrated in situ by executing a pattern with two opposite legs run at constant speed and depth. Assuming the current does not change during the time between the two legs, the error in the EM log is computed by comparing the average speed from dead reckoning to the speed derived from the INS velocity. Although this procedure is performed regularly, there are often residual errors in the EM log calibrations that must be compensated to obtain accurate current measurements. These errors may be due to drift since the last calibration or small errors in the calibrations themselves. Since the drift current calculation is essentially the small difference between two relatively large numbers, small errors in calibration of one of the sensors can have a large impact on the accuracy of the result. To compute and minimize these errors, a procedure has been developed to refine the calibration using consistency checks on the computed ocean current each time the submarine makes a course change.

The procedure is actually a generalization of the standard calibration procedure and is essentially the same as a method often used on surface ships [3] to calibrate acoustic Doppler speed logs. First, the average relative and inertial velocities before and after a course change are computed. These averages are taken as close to the turn as possible while, ensuring that the boat is on a steady course. Assuming that the ocean current does not change during the time it takes to execute the course change, two algebraic equations can be written for the two components of the horizontal velocity. These components are resolved into the velocity along the track (fore and aft in the submarine coordinate system) and perpendicular to the track in the horizontal plane (athwartships), and the unknowns are the speed error and the angle error. This formulation tacitly assumes that all errors can be attributed to speed and angle errors relative to the submarine, which would be characteristic of an error in the EM log.

While this calibration procedure is subject to error for each individual realization, it is repeated many times over a range of speeds to obtain a statistical description of the calibration. Typically, there are several or more course changes per day that are suitable for calibrations, so that a statistical calibration data base is rapidly accumulated in the course of normal operations.

IV. EXAMPLE

Fig. 1 shows an example of the ocean currents computed from submarine set and drift in the Sargasso Sea. These data were collected by a submarine during a 16-hour period in an area south of the Gulf Stream. Each dot represents the position of a 1-kilometer average, and the arrows indicate the amplitude and direction of the current. At the points where there is a dot and no arrow, the speed or heading were changing enough that the root-mean-square velocity for the 1 kilometer averaging interval was greater than a threshold, which was set to 0.2 knot for this plot. The threshold is used to eliminate data where maneuvering results in errors in the current estimates. The scale for the current vectors is indicated at the origin where an arrow with a length of 1 knot is shown.

\[ 1 \text{ knot} = 0.5144 \text{ m/s}. \]
The strong eastward flow in the upper half of the figure is associated with the southern edge of a cyclonic cold-core Gulf Stream Ring. The National Weather Service (NWS) [4], using images of infrared radiation measured from satellites, has charted the southern boundary the ring just north of the northernmost current measurements in the figure. Other submarine measurements farther north, within the ring structure, found currents in excess of 3 knots that were nearly concurrent with the NWS charts. In the lower part of the figure, the submarine track consists of a 50-kilometer leg to the south-southeast, followed by a 25-kilometer leg due west, and another 50-kilometer leg to the north-northwest in a direction directly opposite to the first.

This part of the track illustrates several important characteristics of the current measurements. First, note that the current vectors are consistent when the submarine changes course. If there was an error in the EM log calibration, it would show up as a discrepancy between the current measurements on the two courses. An analysis of 33 course changes over a period of a week using the procedures described in Section III, including the data in Fig. 1, showed that there was no significant calibration error in the speed or the angle for EM log at the 90 percent confidence level. Second, there is an anti-cyclonic circulation that is evident on both of the north-south legs. There is a strong shear in the zonal velocity with an average value greater than $10^{-2} \text{ s}^{-1}$ with a node near 33.4\degree N on both legs. This feature was not identified in the infrared imagery, even though the currents are greater than 1 knot. Finally, there is smaller scale structure in the velocity field that is most evident in the modulation of the north component along the track.

Fig. 2 is a plot of the north and east velocity components as a function of distance along the three legs of the pattern, designated Leg A, Leg B, and Leg C in the plots. The smaller scale structure appears most clearly in the north component on legs A and C. These regular fluctuations have wavelengths of 5-10 kilometers and peak-to-peak amplitudes of 0.3-0.5 knots, where leg A has larger amplitudes and longer wavelength. These fluctuations are similar to those measured at the North Atlantic subtropical convergence zone [5] approximately 3\degree south of the present measurements. In this case the amplitudes were similar, but the wavelengths were 30-50 kilometers versus 5-10 kilometers here. In [5], the fluctuations were attributed to inertial waves radiating from the front. In this case, the Gulf Stream Ring lying immediately to the north is a potential source of inertial waves.
Fig. 2b. Current components for Leg B on West bearing

Fig. 2c. Current components for Leg C on NNE bearing

V. TOMS

The Tactical Oceanographic Monitoring System (TOMS) has been developed by the U. S. Navy to monitor local oceanographic conditions on submarines. This system includes a conductivity, temperature, depth (CTD) instrument mounted on the submarine sail with several other external sensors, a pair of Apple Macintosh computers, and an interface to the ship's computer systems. This interface allows access to the ship's functions, such as speed, depth, and heading, and the INS data that are required for the current calculations. The Macintosh computers allow the crew to display, manipulate, and store the data collected by TOMS. The system is presently being upgraded to provide current calculations, including geographic displays similar to Fig. 1. These improvements will be completed in the fall of 1993.

REFERENCES