Altimetric Sensing of Currents: Spatial Averaging and Sampling Impacts on Ocean Routing

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Strategic ship routing impacts of various spatial resolutions associated with satellite-based altimetric sensing of ocean currents are evaluated. Underlying true current patterns are averaged to more aggregate grids, routes are chosen designed to exploit the currents from these aggregate estimates, and the underlying true current patterns are used to simulate relative fuel consumption on these routes. The underlying current patterns are produced from an advanced model of a spatially variable area of the North Atlantic Gulf Stream, and the route origins and destinations are confined to this region. The results indicate that the 5 × 5 degree spatial resolution of available data is too coarse to be of use in strategic routing in this area. However, the improved resolution that would be compatible with satellite altimeter systems would lead to positive fuel savings, and savings that are fairly close to those available if the underlying data were known in their finest detail. Sampling along geographically separated ground tracks can still lead to positive fuel savings, even in this spatially variable region. Impacts for practical applications are discussed.

Weather and waves are the principal environmental inputs to the choice of a commercial ocean vessel's general path (*1,2*). If ocean currents are considered in the attempt to reduce fuel costs or time of passage, it is usually through grossly averaged (in time and space) pilot chart data. Even these gross averages are strong enough and oriented in such a way that they can influence strategic ship routes (*3*). However, currents are dynamic (*4*), and to be of use in strategic routing, estimates would have to be obtained with better frequency than that offered by the pilot charts. But, other than in a few special cases (*5,6*), dynamic estimates of current patterns have not been available.

For these reasons, a collaborative project has been designed to provide timely estimates of current patterns to the shipping industry. The ability to do so is predicated on the technical advances in satellite altimetry and the schedule of proposed altimeter missions (*7*). An altimeter measures sea surface heights, which can then be analyzed to deduce ocean currents. Altimeters offer distinct advantages, compared with infrared sensors, for example. They can obtain measurements in cloudy areas and determine current velocitites, as well as locations. They can also sense current activity below the water surface, which is important for ships of any draft. Simulation studies (*8*) indicate that the 5-cm accuracy of the GEOSAT altimeter and, therefore, the improved 2-cm accuracy of the planned TOPEX/Poseidon altimeter (*6*) are more than sufficient for estimating current velocities, giving variances of less than 0.03 nautical mph. Orbit errors (*6*) would have even less of an effect (*8*), because they occur over much greater arc lengths than those used to determine ocean currents. Moreover, the need to determine only sea surface slopes in the geostrophic analysis (*9*), rather than absolute heights, eliminates much of the spatially correlated error signal (*8*).

However, there remain potential difficulties associated with using altimeters for sensing of ocean currents (*7*). The systems being developed would take advantage of altimeters flown for primarily scientific and military reasons (*5–7*). This strategy would greatly reduce the costs to the shipping community, but the dependence on other owners, operators, and preprocessors increases the institutional risk (*7*) associated with data supply. On the technological and scientific side, errors from estimating the geoid, the equipotential gravitational surface from which sea surface slopes must be referenced for analysis (*6*); missing data, arising primarily from the time it takes the altimeter to lock back into proper measurement angle after flying over land (*10*); the temporal resolution of an orbiting altimeter (*4*); and the spatial coverage offered are presently being investigated. The independent effects of the separate error sources are being investigated to see which ones seem most critical. As an example, measurement accuracy or orbit error are no longer of concern, although this was not the case before conducting of studies (*8*). Moreover, this type of independent error analysis can lead to lower-bound estimates of the combined effects.

Two aspects associated with the spatial resolution of a current estimating system are investigated. The first deals with the inherent spatial variability of current patterns. Any sensing and estimating system will produce current estimates at relatively coarse spatial scales compared to the tens of meters which would affect a ship. Does spatially averaging mask the inherent structure which is important to route selection? The second aspect relates to the sampling schemes of orbiting altimeters. Satellites on which altimeters are flown circle the earth, sampling the ocean along spatially separated ground tracks, For example, the North Atlantic ground tracks of the GEOSAT altimeter (*10*) are shown in Figure 1. The spatial separation of the tracks is 1.53 degrees (approximately 166 km) at the Equator and 1.46 degrees (approximately 123 km) at the midlatitudes, where the variable Gulf Stream becomes important to ship routes. The upcoming TOPEX mission will have even greater separation between ground tracks (*11*). Can such sparse sampling lead to estimates that represent the spatial structure well enough to assist in strategic routing?

In order to answer these questions, the best available data

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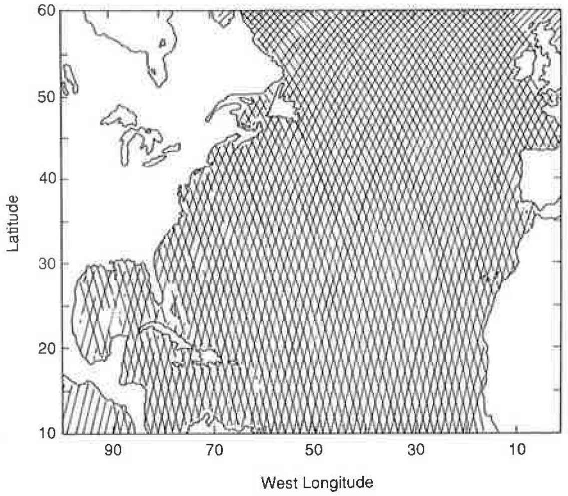

FIGURE 1 GEOSAT ground tracks in North Atlantic.

set on current patterns is used. In response to the first question, these data are aggregated to various levels of spatial resolution, routes are chosen on the basis of the current data, and ship performance is simulated on the basis of the original disaggregate data. To address the second question, sampling is conducted only along satellite ground tracks before aggregating the data.

The methodology is discussed in more detail in the next section. In the third section, the results are presented that show that choosing routes based on data aggregated to levels consistent with planned altimeter missions can still lead to interesting fuel savings. Moreover, the effect of spatially sampling only along ground tracks before aggregating has a slight, but not overwhelming effect. The results also indicate that the spatial resolution of traditional data is too coarse to be of much use for strategic routing, at least in regions as spatially variable as the one used here. One should be careful in interpreting the results, however. Although the results show that the spatial resolution in itself is no problem, the same may not be true when the time necessary to obtain this resolution is considered.

METHODOLOGY AND DATA

The basic design used to investigate the effect of spatially averaging current vectors can be summarized by the following steps: (a) Select a data set of ocean currents in a given region with a given spatial resolution and consider this as the true data; (b) Partition the region into grid cells consistent with a given coarser spatial resolution; (c) For each cell, determine a single representative current vector based on all the vectors in the cell; (d) For each of a set of origin-destination pairs on the boundaries of the region, choose a strategic route through the gridded current data and a route that would be followed if the current data were ignored; (e) Determine a performance measure of the current-based route relative to the route that ignores the current information by simulating the effect of the original current data set on the routes selected; (f) Repeat Steps (b) through (e) with partitions consistent with different spatial resolutions; (g) Repeat Steps (b) through (f) with different origin-destination pairs; (h) Repeat Steps (a) through (g) for different data sets. The design used to investigate the effect of sampling only along ground tracks is the same except that only current vectors in the original data set that intersect the satellite ground tracks (see, e.g., Figure 1) are used when forming the representative currents in Step (c).

The process uses three general inputs—a set of ocean currents, a strategic ship routing model, and a performance measure. Each of these is described in more detail.

Ocean Current Data

Harvard University has been working with the U.S. Navy to develop a forecasting model *(12,13)* for an area of the Gulf Stream (see Figure 2) bordered by (north) latitude and (west) longitude coordinates (39°, 74°), (32°, 72°), (38°, 50°), and (46°, 55°). The model is driven by altimetry, infrared observations, and in situ measurements. Harvard researchers submitted surface current output on a 15- by 15-km grid for two 5-week periods. The fine resolution of this data, coupled with the advanced modeling techniques and the data acquisition systems used, makes this the best and most comprehensive data set compiled over a defined geographical region.

The 15- × 15-km Harvard data were aggregated into grid cells of 0.1° latitude by 0.5° longitude, with a current vector (actually, two orthogonal current velocity components) in each cell. This partition, which is referred to as 0.1 × 0.5 resolution for simplicity, served as the underlying true data. The model Gulf Stream region was also partitioned into cells 0.3° latitude by 1.5° longitude, 0.5 ° latitude by 2.5° longitude, 0.6° latitude by 3.0° longitude, 1.0° latitude by 5.0° longitude, and 5.0° latitude by 5.0° longitude (see Table 1). The 0.3 × 1.5, 0.5 × 2.5, and 1.0 × 5.0 resolutions correspond to resolutions that would allow only a few, several, and many, observations from the GEOSAT ground tracks, respectively. The 0.6 × 3.0 resolution would allow several observations from TOPEX ground tracks. The 5.0 × 5.0 resolution corresponds to that offered by the traditional pilot charts.

In order to determine the current vectors representing a cell at a given resolution, the arithmetic average of each of the two orthogonal velocity components for each Harvard observation falling into the cell was taken. Figures 3 and 4

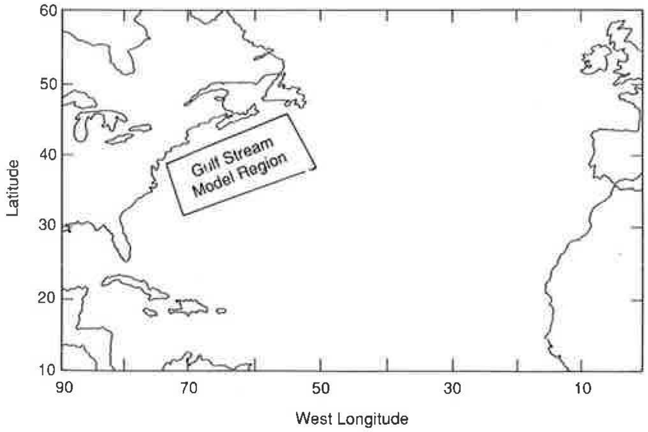

FIGURE 2 Location of Harvard Gulf Stream Model region.

TABLE 1 SPATIAL RESOLUTION OF GRID CELLS USED IN CURRENT AVERAGING

Resolution (degrees latitude × degrees longitude)	Mnemonic
0.1 × 0.5	Underlying "True" Data
0.3 × 1.5	Fine GEOSAT Resolution
0.5 × 2.5	Moderate GEOSAT, Fine
0.6 × 3.0	Moderate Topex Resolution
1.0 × 5.0	Coarse GEOSAT Resolution
5.0 × 5.0	Pilot Chart Resolution

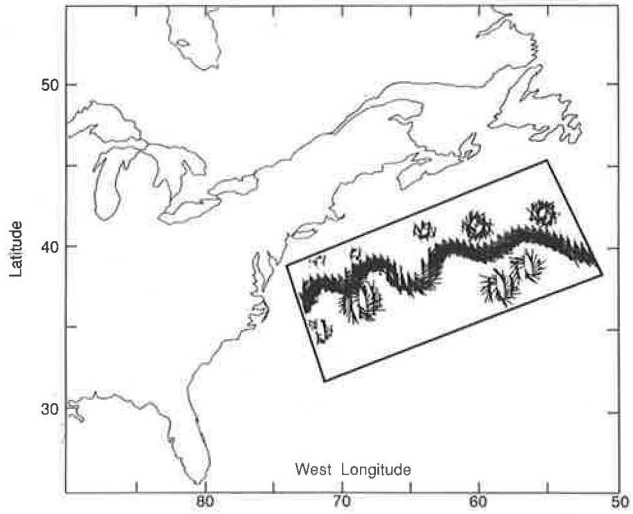

FIGURE 3 Study region current pattern at 0.1 × 0.5 resolution.

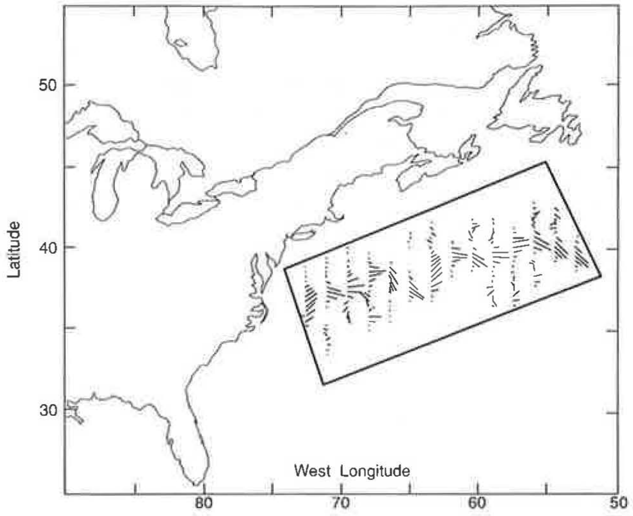

FIGURE 4 Study region current pattern at 0.3 × 1.5 resolution.

show one set of data at 0.1 × 0.5 and 0.3 × 1.5 resolutions. When analyzing the impact of sampling along GEOSAT or TOPEX ground tracks, only cell components of Harvard data that intersected these ground tracks were averaged. In both cases, for any resolution level, there was a single current vector (i.e., two orthogonal current speed components) for each cell at the end of this step.

Routing Model

For each resolution level, two routes were found—one that would be followed to minimize fuel consumption in the absence of current information, and one that would exploit the information in trying to minimize fuel consumption. In both cases, a ship traveling at constant velocity relative to the water and arriving at its destination (the exit point of the region) T hours after departing its origin (the entrance to the region) was considered. The constant relative velocity policy is optimal in the absence of information and is often recommended in practice (*3*). Moreover, Lo et al. (*3*) found relative fuel savings to be insensitive to this policy. Because the study area was in the open ocean (see Figure 2), fixing the time T to be the same along the two routes was equivalent to specifying boundary conditions and putting the two cases on the same footing. It also made determining the performance measure more straightforward and less dependent on arbitrary assumptions between time and fuel consumption tradeoffs.

The route followed in the absence of current information was the shortest-distance route. For a given origin-destination pair, this shortest-distance route would be the same for any level of current resolution and only had to be determined once. For expository purposes, however, it is easier to think of it as a separate route in each case. The time T was found by simulating a passage through the underlying currents over this route at constant velocity Vr relative to the water. A velocity Vr = 16 knots representative of tankers, the class of ships offering the largest potential fuel savings from current routing (*14*), was used. The route selected in the presence of currents was the minimum time route, through the estimated currents, from the origin to the destination. The velocity was that which would ensure arriving at the destination in time T along this route. The marginal impact of currents can, as a first approximation, be added to the effects of weather and waves (*3*), unless there is some reason to believe that these factors are highly correlated with the current activity. Moreover, as found by Lo et al. (*3*), currents shift routes only slightly, finely tuning the routes at much smaller spatial scales than would be consistent with storm-generated wind and wave patterns.

In order to find the minimum time route between the origin and destination, the ocean surface was discretized into a network, where node $N_n = (X_n, Y_n)$ represented a geographic location with longitude X_n and latitude Y_n, and the impedance on each arc was the time to go from its tail node to its head node. Approximating the earth as a sphere, the distance d_{ij} between two nodes $N_i = (X_i, Y_i)$ and $N_j = (X_j, Y_j)$ was calculated by Robinson et al. (*15*) as

$$d_{ij} = \cos^{-1}[(\sin Y_i \sin Y_j) + (\cos Y_i \cos Y_j \cos P)] * R \qquad (1)$$

where P was the number of degrees longitude between the two nodes (i.e., $P = |X_j - X_i|$), and R was the radius of the earth (taken as 3,440.4 nautical miles).

An arc could traverse several grid cells, each with different current vectors. The average current velocity, Vc_{ij}, along an arc connecting nodes as N_i and N_j was calculated as the distance-weighted projection of the current vectors in cells through which the arc passed in the direction of the arc. The velocity with which the ship would cover the distance d_{ij}—the over-the-ground velocity Vg_{ij}—was found by vector addition of the current velocity Vc_{ij} to the constant velocity of the ship through the water Vr = 16 knots (i.e., $\mathrm{Vg}_{ij} = \mathrm{Vc}_{ij} + 16$). Knowing d_{ij} from Equation 1, the time to traverse the link was then

$$t_{ij} = d_{ij}/(\mathrm{Vc}_{ij} + 16) \tag{2}$$

So, given a network configuration and the grid cells of current vectors for a specific resolution, t_{ij} could be uniquely determined for each arc of the network. The minimum time route through the estimated current vectors could then be found using any traditional shortest-path algorithm [see, e.g., Larson and Odoni (*16*)]. To find the shortest distance route, the route that would be chosen in the absence of the current information, simply set all $\mathrm{Vc}_{ij} = 0$ and run the same computer programs used to find the minimum time route.

A network was used in which 21 arcs fanned out from each tail node (beginning with the origin node), connecting head notes that were 0.5° longitude toward the destination from the tail node and separated by 0.1° latitude increments from 1.0° north of the tail node to 1.0° south of the tail node. To test the accuracy of this discretized representation of the ocean, shortest-path distances through the network between origins and destinations were determined and compared with great circle distances computed by substituting the coordinates of the origin-destination pairs in Equation 1. The network distances were longer, as would be expected, but within 0.2 percent of the great circle distances. The distances would be longer on both the minimum time and minimum distance paths analyzed, reducing any effect of the discrete approximation.

Performance Measure

The impact of the spatial aggregation was indicated by the relative fuel savings achieved when using current estimates in route selection. Letting $\mathrm{FC_w}$ and $\mathrm{FC_{wo}}$ represent, respectively, the fuel consumed on a specific passage when using currents in choosing the route and the fuel consumed on the passage when not using currents, the relative fuel savings, RFS, on a specific passage can be written as

$$\mathrm{RFS} = 1 - (\mathrm{FC_w}/\mathrm{FC_{wo}}) \tag{3}$$

To determine the ratio between $\mathrm{FC_w}$ and $\mathrm{FC_{wo}}$ in Equation 3, the relation given by Jansson and Shneerson (*17*) that approximates the rate of fuel consumed as varying with the third power of the velocity $\mathrm{Vr}(t)$ of the ship relative to the water at that time. The fuel consumed during time T, then, would be

$$\mathrm{FC} = \int_0^T k[\mathrm{Vr}(t)]^3 dt \tag{4}$$

where k is a constant depending on the ship considered.

As mentioned earlier, the time T in the study region was assumed to be the same for the routes analyzed when using the currents as inputs to route selection and when not using them as inputs. Because the effect was analyzed on the same ship for two routes, k was also constant. Finally, because the ship was assumed to travel at constant velocity through the water, $\mathrm{Vr}(t) = \mathrm{Vr}$. With these assumptions, substituting Equation 4 in Equation 3 and simplifying,

$$\mathrm{RFS} = 1 - (V_{\mathrm{r,w}}/V_{\mathrm{r,wo}})^3 \tag{5}$$

where $V_{\mathrm{r,w}}$ and $V_{\mathrm{r,wo}}$ are the constant speeds relative to the water on the minimum-time route (that taken when using currents as inputs to route selection) and the minimum-distance route (that taken when not using currents as inputs), respectively. In the study, $V_{\mathrm{r,wo}}$ was 16 knots (the same Vr value used to determine the minimum time route), and $V_{\mathrm{r,w}}$ was the velocity along the minimum-time route that ensured arriving at time T.

The minimum time route was determined with Vr = 16 knots. There is no guarantee that the minimum-time route identified with $\mathrm{Vr} = V_{\mathrm{r,w}}$ would be the same route. However, $V_{\mathrm{r,w}}$ never differed by more than 0.5 knot from the assumed 16-knot velocity, and Lo et al. (*3*) obtained the same minimum-time routes whether 16 knots or $V_{\mathrm{r,w}}$ was used. (Also, as proven by Lo et al. (*3*), when the two minimum-time routes are identical, the route identified with this procedure is guaranteed to be the minimum-fuel-consumption route.)

RESULTS

In order to determine origin-destination pairs, the current study area was laid over trans-Atlantic trade routes found by U.S. Department of Transportation (*18*) and four locations on the west wall and four locations on the east wall were selected on the basis of where the routes entered and left the area. The coordinates of these locations are shown in Figure 5. Then, analyzing 16 eastbound routes formed by using each of the four western wall locations as origins and each of the four eastern wall locations as destinations, RFS in Equation

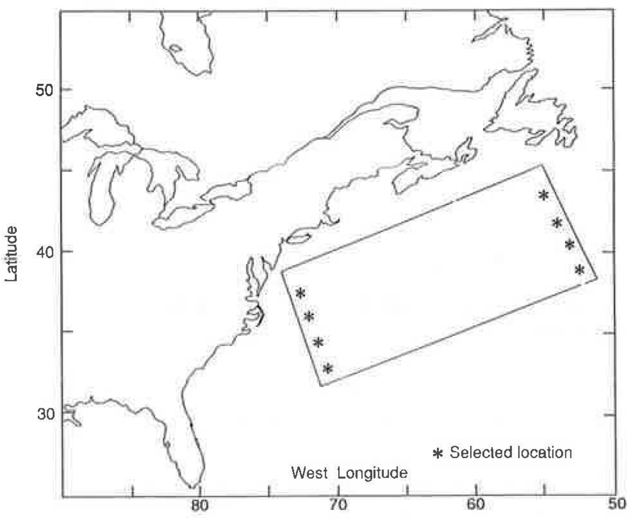

FIGURE 5 Location of points serving as origins and destinations.

5 was determined for each. The 16 westbound routes formed by using each of the four eastern wall locations as origins and each of the four western wall locations as destinations were also analyzed.

As mentioned earlier, two 5-week periods of Harvard model outputs, i.e., 70 daily current patterns, were accessible. From these data, six different dates were chosen for analysis. McCord and Lo (*4*) found that the Gulf Stream reaches about 75 percent of its 6-month variability in current activity after approximately 14 days. Therefore, model outputs separated by 14 days or more could be considered relatively independent. The five dates analyzed were Oct. 28, 1987; Nov. 11, 1987; Nov. 25, 1987; April 20, 1988; May 4, 1988; and May 18, 1988.

For each date and each resolution level, an average fuel savings of the 16 eastbound routes and an average fuel savings of the 16 westbound routes were determined. The impacts of the spatial averaging are presented in Tables 2 and 3. As expected, the performance is best for finest resolution (0.1 × 0.5) and consistently degrades, with minor exceptions, as the resolution becomes coarser. The 5.0 × 5.0 resolution, that consistent with available pilot chart data, would be of little use in strategic routing. The average savings are only 0.1 and 0.5 percent on westbound and eastbound routes, respectively, with several dates offering zero or negative route-averaged savings.

More positively, three of the resolutions consistent with satellite sampling—0.3 × 1.5, 0.5 × 2.5, and 0.6 × 3.0—performed well, always producing positive fuel savings. Moreover, these resolutions, especially the 0.3 × 1.5, produced savings close to the maximum possible savings, those obtained from the true 0.1 × 0.5 resolution. The coarse GEOSAT resolution, 1.0 × 5.0, did not perform as well, but still produced an average 3 percent fuel savings on eastbound routes and 1 percent fuel savings on westbound routes.

The impacts of sampling only along ground tracks before averaging are presented in Tables 4 and 5. GEOSAT gound tracks were averaged to 0.3 × 1.5 and 0.5 × 2.5 resolution and the more spatially separated TOPEX ground tracks to 0.6 × 3.0 resolution. Comparing Tables 4 and 5 with Tables 2 and 3, the savings decreased when sampling along ground tracks. Still, all of these samples produced routes with positive fuel savings compared with the shorter great circle routes. They also produced averages higher than those found in the evaluation studies (*3,4*).

From Tables 2–5, the fuel savings were generally higher when using the April and May data than when using the October and November data. This agrees with Lo et al. (*3*), who found that warmer months performed, on average, better than colder months. This is of practical interest, because route analysts say that business declines as the summer approaches and the weather improves. They hope to use timely current estimates as an additional product to keep more business during this period.

Regardless of the season, though, better fuel savings were obtained by averaging over smaller spatial areas. The type of resolution available with satellite altimeters performed relatively well, however, even when sampling only along ground tracks. The resolution provided by presently available pilot charts did not perform well, at least in the spatially variable Gulf Stream region.

DISCUSSION

These results were pleasantly surprising. The poor performance of the 5.0 × 5.0 resolution was not particularly astonishing. Practitioners do not place much confidence in pilot chart data that are averaged to this resolution. Lo et al. (*3*) mentioned that pilot chart data would probably wash out

TABLE 2 FUEL SAVINGS (%) OF EASTBOUND CURRENT-BASED ROUTES RELATIVE TO NONCURRENT-BASED (GREAT CIRCLE) ROUTES BY CURRENT RESOLUTION AND DATE

Resolution (degrees lat. × degrees long.)	Date 10/28/87	11/11/87	11/25/87	04/20/88	05/04/88	05/18/88	Avg.
0.1 × 0.5	9.8	7.2	8.0	9.6	10.1	8.7	8.9
0.3 × 1.5	7.8	5.4	6.2	7.7	8.9	7.7	7.3
0.5 × 2.5	6.3	4.3	4.6	5.9	5.8	5.4	5.3
0.6 × 3.0	6.0	3.0	3.4	6.4	7.1	4.7	5.1
1.0 × 5.0	3.9	−0.2	1.9	3.6	4.6	4.2	3.0
5.0 × 5.0	0.2	0.4	0.0	0.3	1.5	0.6	0.5

TABLE 3 FUEL SAVINGS (%) OF WESTBOUND CURRENT-BASED ROUTES RELATIVE TO NONCURRENT-BASED (GREAT CIRCLE) ROUTES BY CURRENT RESOLUTION AND DATE

Resolution (degrees lat. × degrees long.)	Date 10/28/87	11/11/87	11/25/87	04/20/88	05/04/88	05/18/88	Avg.
0.1 × 0.5	5.1	6.0	5.6	8.3	5.9	6.6	6.3
0.3 × 1.5	4.4	5.0	4.7	7.3	4.7	5.9	5.3
0.5 × 2.5	2.9	3.9	3.4	5.4	3.0	4.2	3.8
0.6 × 3.0	2.9	3.1	2.1	4.5	1.9	3.5	3.0
1.0 × 5.0	−0.6	1.8	0.6	2.3	0.7	1.8	1.1
5.0 × 5.0	0.2	0.8	−0.2	0.2	0.0	0.0	0.1

TABLE 4 FUEL SAVINGS (%) OF EASTBOUND CURRENT-BASED ROUTES RELATIVE TO NONCURRENT-BASED (GREAT CIRCLE) ROUTES BY GROUND TRACK SAMPLE AND DATE

Ground Track Sample	Date						
	10/28/87	11/11/87	11/25/87	04/20/88	05/04/88	05/18/88	Avg.
GEOSAT averaged to 0.3 × 1.5	7.8	5.1	5.1	6.6	8.2	7.4	6.7
GEOSAT averaged to 0.5 × 2.5	6.6	4.3	4.3	5.6	6.1	5.7	5.4
TOPEX averaged to 0.6 × 3.0	3.5	1.7	3.4	5.8	7.0	2.5	4.0

TABLE 5 FUEL SAVINGS (%) OF WESTBOUND CURRENT-BASED ROUTES RELATIVE TO NONCURRENT-BASED (GREAT CIRCLE) ROUTES BY GROUND TRACK SAMPLE AND DATE

Ground Track Sample	Date						
	10/28/87	11/11/87	11/25/87	04/20/88	05/04/88	05/18/88	Avg.
GEOSAT averaged to 0.3 × 1.5	4.1	4.8	3.9	6.3	3.8	5.1	4.7
GEOSAT averaged to 0.5 × 2.5	3.2	3.8	2.1	5.1	2.7	3.9	3.5
TOPEX averaged to 0.6 × 3.0	2.5	1.7	1.6	3.5	1.4	2.9	2.3

much of the spatial variability in current patterns that could be advantageous in strategic routing. The results support this claim. What was surprising was the good performance of those resolutions compatible with planned altimeter missions, and especially the fact that sampling only along ground tracks performed so well. The study was limited to an area encompassing only a small percentage of global ocean areas because of a lack of data outside this area. However, results in other areas would be similar or better, because of the recognized spatial variability in this area of the Gulf Stream (*12,13*). Moreover, the Gulf Stream and its eddies are spatially similar to the Kuroshio current, and together these are two of the most studied currents, in part because of their spatial properties, as well as their overall importance (*19,20*).

Although encouraging, the results should be interpreted carefully. They indicate that even in the variable Gulf Stream area, the spatial sampling parameters of satellite coverage can lead to positive fuel savings in a static world. However, currents are dynamic, and the ground tracks shown in Figure 1, and those in the TOPEX mission, can be covered only progressively in time. For example, GEOSAT repeated its entire coverage every 17 days, with only one-seventeenth of the tracks of Figure 1 being covered each day (*21*). McCord and Lo (*4*) found that 17-day coverage does not seem frequent enough to obtain viable estimates, and that an interpolation model or a second altimeter would be needed. TOPEX will have a 10-day repeat cycle, but its temporal resolution is of concern and its impact for strategic routing is being investigated.

Even if the temporal resolution and its combined effect with spatial resolution turns out to be troublesome, the results presented are still encouraging. Options for overcoming limited altimeter resolution include the development of an interpolation model and the supply of more than one altimeter. Interpolation models are being examined. The results presented here indicate that the coverage of the model (both inputs and outputs) could be limited to the ground tracks or to grid size resolutions on the order of those that performed well. This would represent sizable savings in computer storage and computational time. On the supply side, several satellites are expected to carry altimeters in the late 1990s. However, the missions will be under the jurisdiction of different agencies and even different governments. If the commercial routing community could access this data, and more optimistically, if the missions could somehow be coordinated, the temporal resolution would be greatly improved, and the promising results obtained here might be realized in practice.

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