GREENWOOD, M. R.
1958. Bottom trawling explorations of southeastern Alaska, 1956-1957. Commer. Fish. Rev. 20(12):9-21.
HOMANS, R. E. S., AND V. D. VLADYKOV.
1954. Relation between feeding and the sexual cycle of the haddock. J. Fish. Res. Board Can. 11:535-542.
HUGHES, S. E., AND N. B. PARKS.
1975. A major fishery for Alaska. Natl. Fisherman 55(13):34-40
JONES, W. G.
1977. Emerging bottomfish fisheries - potential effects. Alaska Seas Coasts 5:1-5.
KETCHEN, K. S.
1961. Observations on the ecology of the Pacific cod (*Gadus macrocephalus*) in Canadian waters. J. Fish. Res. Board Can. 18:513-558.
MITO, K.
1974. Food relation in demersal fishing community in the Bering Sea - walleye pollock fishing ground in October and November 1972. Master's Thesis, Hokkaido Univ., Hakodate, 86 p.
MOISEEV, P. A.
1953. [Cod and flounders of far-eastern waters.] Izv. Tikhookean. Nauchno-Issled. Inst. Rybn. Khoz. Okeanogr. 40:1-287. (Tranl. 1956, Fish Res. Board Can. Transl. Ser. 119, 576 p.)
1960. On the habits of the cod-fish *Gadus morhua macrocephalus* Tilesius in different zoogeographical regions. [In Russ., Engl. summ.] Zool. Zh. 39:558-562.
POWLES, P. M.
1958. Studies of reproduction and feeding of Atlantic cod (*Gadus callarias* L.) in the southwestern Gulf of St. Lawrence. J. Fish. Res. Board Can. 15:1383-1402.
RAE, B. B.
1967. The food of cod in the North Sea and on the west of Scotland grounds. Dep. Agric. Fish. Scotl, Mar. Res. 1967(1), 68 p.
RONHOLT, L. L.
1963. Distribution and relative abundance of commercially important pandalid shrimps in the northeastern Pacific Ocean. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 449, 28 p.
SUYEHIRO, Y.
1942. A study on the digestive system and feeding habits of fish. Jpn. J. Zool. 10:1-303.
WIGLEY, R. L.
1956. Food habits of Georges Bank haddock. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish 165, 26 p.
WIGLEY, R. L., AND R. B. THEROUX.
1965. Seasonal food habits of Higlands Ground haddock. Trans. Am. Fish. Soc. 94:243-251.

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A COMPUTER SOFTWARE SYSTEM FOR OPTIMIZING SURVEY CRUISE TRACKS[1]

Since 1972, the Southeast Fisheries Center, National Marine Fisheries Service, NOAA, has been conducting resource assessment surveys for groundfish in the northern Gulf of Mexico. Random sampling stations were selected and cruise tracks plotted by hand requiring several man-days of effort without assurance than an optimum cruise track had been chosen. Consequently, a computer routine was developed at the NMFS National Fisheries Engineering Laboratory, Bay Saint Louis, Miss., to satisfy two requirements: Generate a set of randomly selected sampling stations from a preestablished station grid and minimize the distance the vessel must travel to sample each station once. This paper presents the resultant routine, a comparison of results with actual cruises, and a discussion of other possible applications of the program.

Background

The problem of determining the optimum cruise track to sample a given set of stations can be restated as, "determining the shortest route from one point to another which allows a vessel to visit every station once." This problem is similar to one in the field of operations research generally referred to as "the traveling salesman problem." The original formulation of the problem was to minimize the time required by a traveling salesman to visit a number of cities and return home (Bellmore and Nemhauser 1968). Several algorithms have been developed which solve the problem exactly; however, computer storage and running time increase exponentially with the number of points to be visited. Because the groundfish surveys normally deal with station numbers in excess of 100, an heuristic method of solving the problem was selected. Lin and Kernighan (1973) at the Bell Telephone Laboratories (BTL) developed an approximate procedure for solving traveling salesman problems with large number of visitation points which appeared applicable to cruise track optimization.[2] The National Fisheries Engineering Laboratory obtained

[1]Contribution No. 78-19F from the Southeast Fisheries Center, National Marine Fisheries Service, NOAA, NSTL Station, MS 39529. MARMAP Contribution No. 154.
[2]To develop a feeling for the complexity of these problems, it should be noted that for a given number of stations, n, there are

a FORTRAN program from BTL and converted it to operate on a Univac[3] 1108 system at the National Aeronautics and Space Administration Computer Complex, Slidell, La.

Modifications to the BTL algorithm were made to satisfy requirements of the groundfish survey program. Most internal modifications were fairly general so that the program could be used for other areas and purposes. Specifics of grid locations and random selection requirements were stored on magnetic tape in a separate master file. The program, as presently configured, can handle up to 150 stations; however, 300 stations could be handled using extended core storage.

Algorithm Description

Assume a number of stations (n) have been selected, either randomly or specifically. There are a total of $n(n-1)/2$ links between the n stations. The object is to find an n-subset of these links such that (a) each station is sampled exactly one time, and (b) the total distance traveled is a minimum. A sequence of links satisfying (a) is called a tour; if it also satisfies (b), it is the optimum tour.

The optimization algorithm begins by computing all $n(n-1)/2$ distances and storing them in a matrix. A completely random tour is generated to use as a starting point. An attempt is then made to find two sets of links $X = x_1, x_2 \ldots x_k$ *and* $Y = y_1, y_2 \ldots y_k$ such that if the links in X are replaced with the links in Y, the result gives a tour of a shorter distance. This is done by identifying x_1 and y_1 as the "most-out-of-place" pair, setting them aside, then proceeding with x_2 and y_2, x_3 and y_3, and so on.

A criterion is then used to determine how many pairs of links are to be exchanged. This criterion can be explained as follows: Let the length of x_i and y_i be dx_i and dy_i, and $g_i = dx_i - dy_i$. This determines the gain (shorter distance) by exchanging x_i with y_i. After examining a sequence of proposed exchanges $x_1, x_2 \ldots x_k$ and $y_1, y_2 \ldots y_k$ with their corresponding gains $g_1, g_2 \ldots g_k$, the actual value of k that defines the number of sets to exchange is the one for which $g_1 + g_2 + \ldots + g_k$ is always zero or negative. This indicates the solution is a local optimum based on the fact that if a sequence of numbers has a positive sum, there is a cyclic permutation of these numbers such that every partial sum is positive. Hence, the algorithm looks for sequences of g_i's whose partial sum is always positive, reducing the number of sequences that need to be examined. This means that the value of k, which gives the number of links to be exchanged, is determined when $G^* = \sum_{j=1}^{k} g_j \leq 0$, i.e., when the partial sum of the gains fails to remain positive. These links are then exchanged and the process of selecting new links to be exchanged begins again at $i = 1$. When all possibilities have been tried, the tour length is recorded. The program generates a new random initial tour and the entire process begins again. Eleven distinct solutions are produced in this manner, and the tour with the shortest length is considered the optimum solution. Program operation can best be understood by a simple example.

Assume that n stations are selected and a random tour generated (Figure 1a5. The black dots represent the stations and the circle represents the random tour. Any station S_1 is selected and S_2 is designated as an adjacent station in the tour. The link connecting the two stations is designated

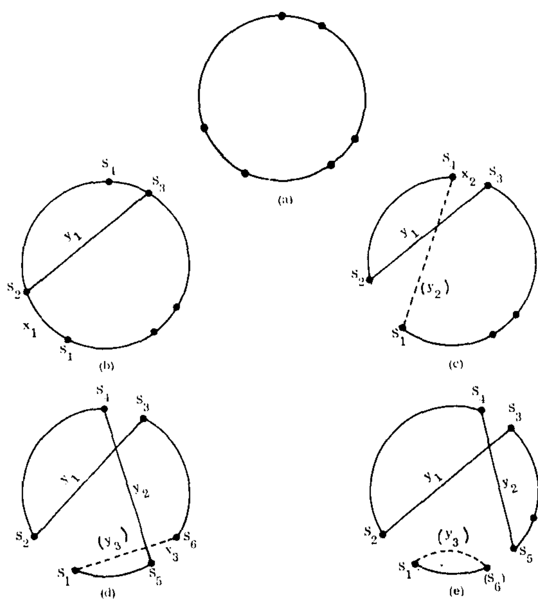

FIGURE 1.—Example of the algorithm operation (modified from Lin and Kernighan 1973).

(n − 1) factorial possible cruise tracks that satisfy the criterion of sampling all stations once and returning to starting position (e.g., if $n = 101$, the number of possible solutions is 9.3326×10^{157}).

[3]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

as x_1 as shown schematically in Figure 1b. The station closest to S_2 is designated as S_3 and y_1 is the link joining S_2 and S_3. The link y_1 is not permitted to be either of the links already connected to S_2. The gain criterion is then calculated as $g_1 = dx_1 - dy_1$. If this is negative, S_2 is designated as the other neighbor of S_1 in the tour. If g_1 is positive, S_4 is designated as one of the tour neighbors of S_3 as shown in Figure 1c. If y_2 were chosen to join S_4 with S_1, the result would be a tour. The gain criterion is then calculated as $g_2 = dx_2 - dy_2$. If $g_1 + g_2 > 0$, the original tour could be improved by exchanging x_1 and x_2 with y_1 and y_2, respectively. This potential improvement, which results from closing up the tour immediately ($G^* = g_1 + g_2$), is then stored. Now S_5 is chosen as the nearest neighbor of S_4, and y_2 is designated as the link connecting the two stations. Station S_5 is not permitted to be either of the stations already connected to S_4. Figure 1d shows there is only one choice for station S_6 and the link x_3 such that if S_6 is connected to S_1, a tour remains. If S_6 were chosen as the other neighbor of S_5 in the original tour, closing up S_6 to S_1 would result in a tour of two disconnected pieces (Figure 1e). The gain associated with closing up immediately (connecting S_6 with S_1) is then compared with that obtained by joining S_4 to S_1 (G^*). The link connecting S_6 to S_1 is designated as y_3. The gain criterion is then calculated as $g_3 = dx_3 - dy_3$. If $g_1 + g_2 + g_3 \leq G^*$ (G^* is the best improvement thus far), there is no improvement, so the number of links (k) to be profitably exchanged is defined as $k = 2$. If $g_1 + g_2 + g_3 > G^*$, however, a new station S_7 and link x_4 are selected and the process is continued.

A limited backtracking feature of the program is included for the case when $G^* = 0$ (i.e., no improvement can be made). The link y_2 was chosen (Figure 1d) to join S_5 to S_4 as the closest station to S_4. When no improvement is made at some stage ($G^* = 0$), new links y_2 are considered in order of increasing length to a maximum of five choices. If still no improvement is found, the five y_1 links are examined in order of increasing length. When G^* cannot be improved, and the value k determined, a new initial station S_1 is selected and the process repeated. The procedure ends when all n stations have been examined. A new random tour is generated, and each station is examined as an S_1 again in the same manner. This limited backtracking significantly increases program effectiveness.

The computational procedure has other features that improve the calculations and reduce running time; such as limited foresight to the next links to be broken, allowance for nonsequential link exchanges, and elimination from computation of those links previously recorded in good tours. For a more complete description of the algorithm, see Lin and Kernighan (1973).

Results

Station Description

Separate station grids lere used for areas east and west of the Mississippi River Delta. A station consisted of a rectangle, lat. 2′30″ by long. 2′30″, within which three trawl tows were made. Stations were identified and located at the center point of the rectangle.

The station grid for the West Delta area consisted of an area extending from long. 89°30′W to 91°30′W (Figure 2). The station grid for the East Delta area consisted of a primary and secondary zone extending between long. 88°00′W and 89°30′W and long. 79°30′W and 88°00′W (Figure 3). Each area was limited by the 9.2-m (5-fm) and 92-m (50-fm) depth contours. Stations were excluded from random selection in both areas because of navigation and trawling hazards, and areas of known low groundfish densities.

Random Selection

Station number, latitude, and longitude were stored in a master grid file for each area. Input to station selection for the West Delta region was the number of stations to be sampled. This region had 780 stations. For the East Delta area, the number of stations must be specified separately for the primary and the secondary zones—there were 555 stations in the primary zone and 139 in the secondary region. Station selection was performed by a random number generator which selected stations based on the number required for each area.

Cruise Track Optimization

Requirements for an optimized cruise track were different for the areas east and west of the delta. A round-trip track was desired for the West Delta area, while a one-way calculation was desired for the East Delta area. The latter consisted of the shortest route from a designated starting point near Pascagoula. Miss., through each selected station and ending at a point near the mouth of the Mississippi River.

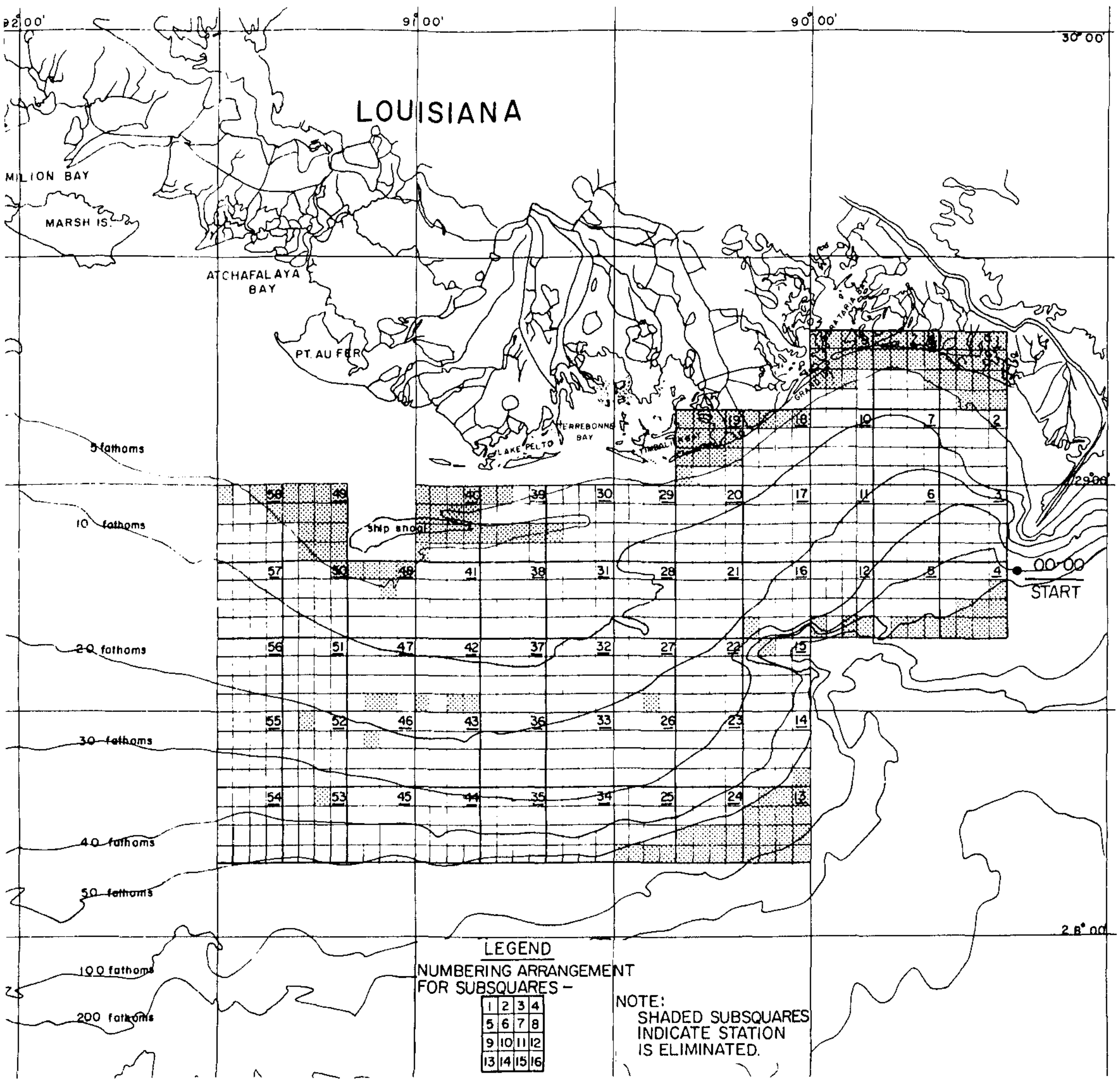

FIGURE 2.—Master station grid for groundfish survey sampling in northern Gulf of Mexico - West Delta area. Dot labeled 00-00 is start and end point for round-trip cruise track optimization.

Since the grid used in the calculations was square, a coefficient was included to account for differences in absolute distance for one unit of longitude vs. one unit of latitude. The coefficient used for optimizing groundfish survey tracks is 52.10/59.85, which is the ratio of the distance in nautical miles for 1° of longitude to that for 1° of latitude at lat. 30°N. All longitudinal Cartesian coordinate distances were multiplied by this coefficient before calculations began.

For the West Delta area, the cruise track was optimized from a point located just east of the primary survey area (Pascagoula station number 00-00) through all randomly selected stations, returning to the starting point. The optimization program computed 11 solutions and the best route in terms of the shortest distance was selected. Output consisted of a listing of stations in proper sampling order, and a plot of the stations and optimum cruise track with every fifth station labeled.

The starting point of the cruise track was south of Pascagoula for the East Delta area. Optimization was done for a cruise track that visited all randomly selected primary and secondary stations and terminated at a point near the Mississippi River Delta designated 99-99 (Figure 3). Outputs were the same as for the West Delta except for treatment of the stations randomly selected which appear in blocks 45, 46, 47, and 48. These were not included in the optimized cruise track, but were listed at the end of the optimized cruise track listing. The stations in these blocks were added to the end of the optimized cruise track and plotted as individual points labeled with their Pascagoula number.

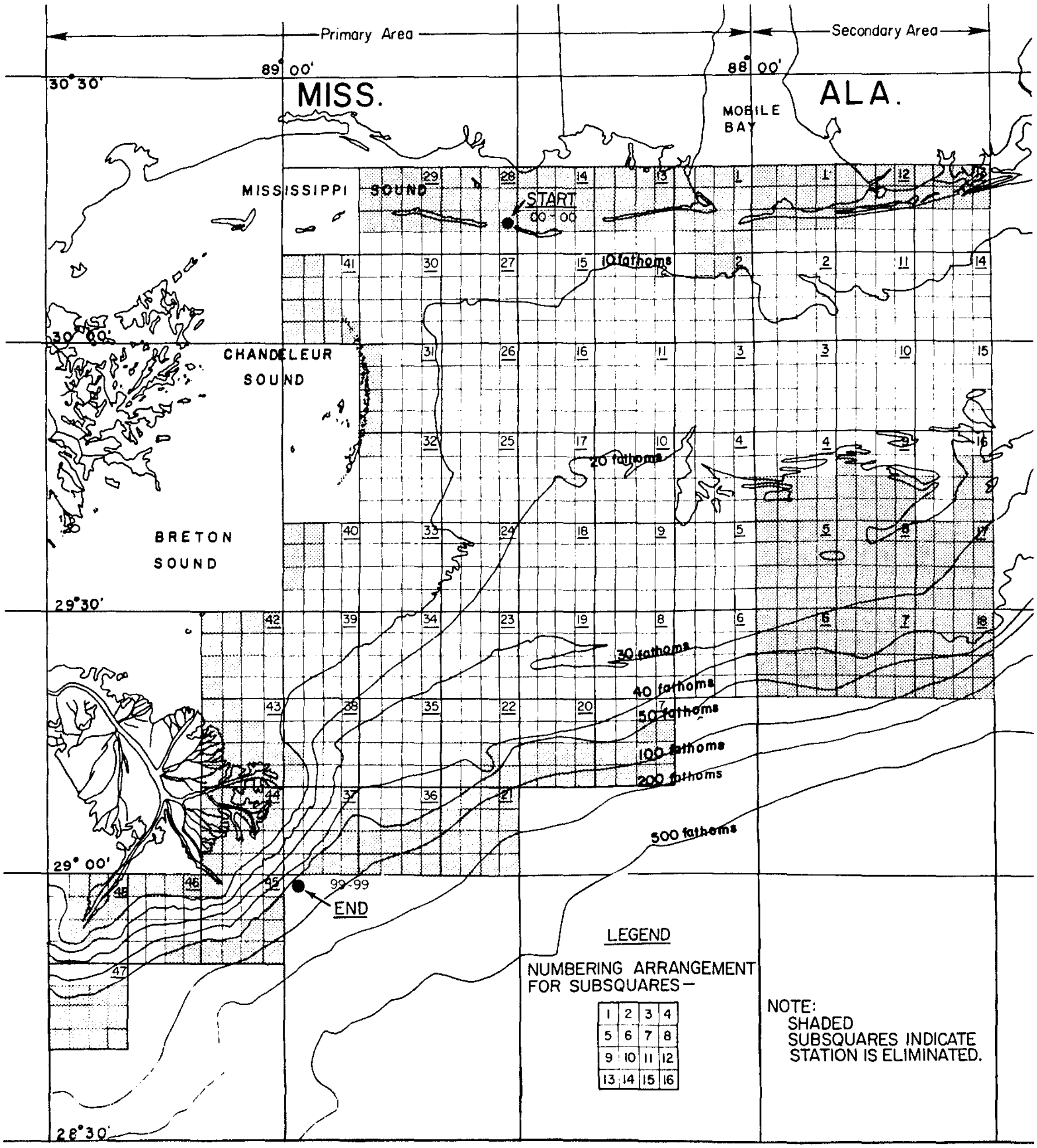

FIGURE 3.—Master station grid for groundfish survey sampling in northern Gulf of Mexico - East Delta area. Dot labeled 00-00 is starting point and dot labeled 99-99 is end point for one-way cruise track optimization. Primary and secondary areas are indicated by arrows at top of figure.

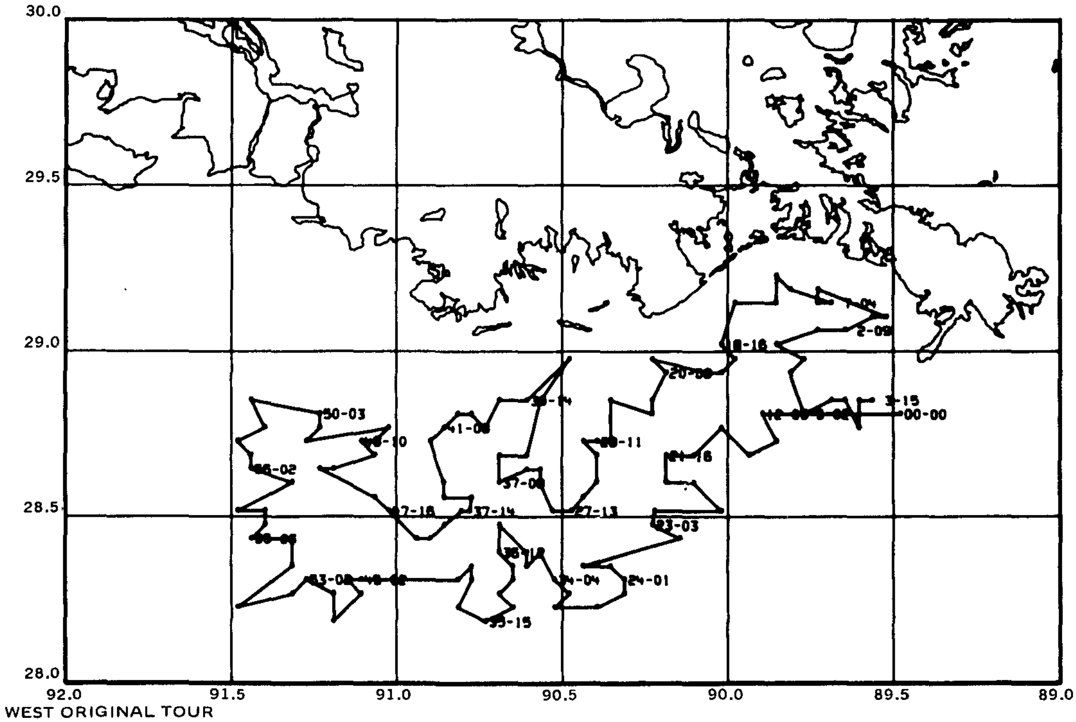

FIGURE 4.—Actual cruise track followed for West Delta area, FRV *Oregon II* cruise 55. Every fifth station is labeled.

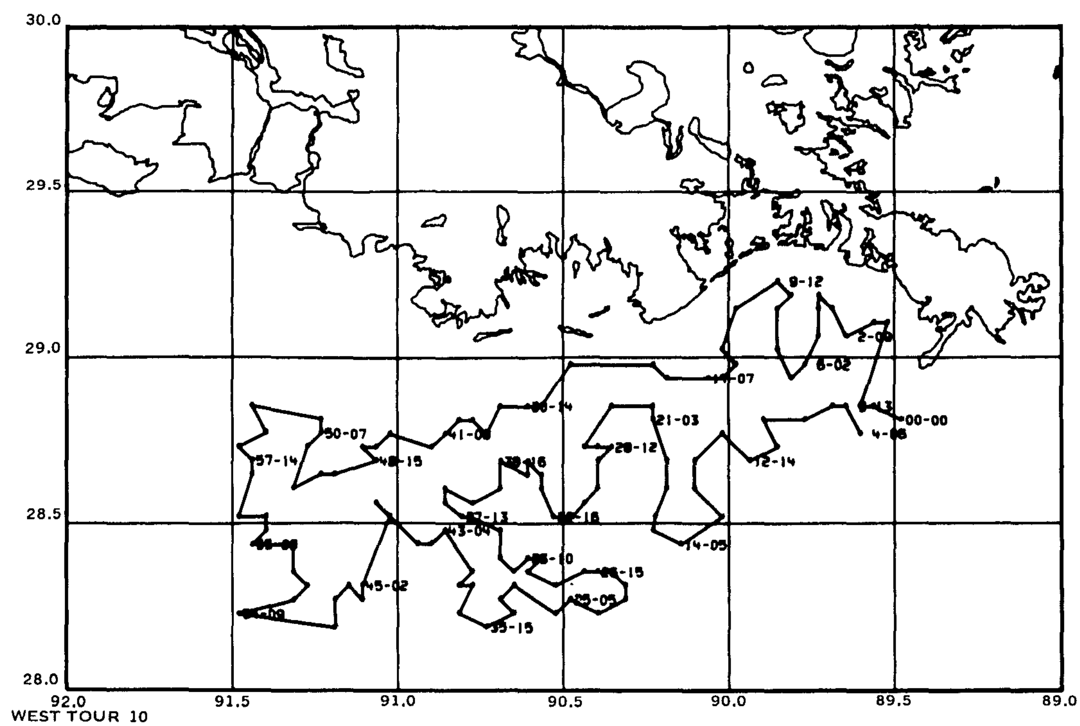

FIGURE 5.—Optimized cruise track for West Delta area, FRV *Oregon II* cruise 55. Every fifth station is labeled.

Test Case and Sample Products

The optimization program was tested to compare computational results with a cruise track actually followed during a survey—FRV *Oregon II* cruise 55, 5-29 November 1974.

West Delta

The 126 stations sampled during cruise 55 for the West Delta area were entered in the order they were sampled (Figure 4), and the total distance (in grid units) was calculated to be 254. Each grid unit was equivalent to approximately 4.6 km; thus, the total distance was about 1,176 km.

Eleven computations were performed on these stations by the optimization program, and a minimum length of 233 grid units (approximately 1,078 km) occurred three times. It can be said with confidence the optimum tour (Figure 5) represented an 8.3% improvement over the actual cruise track. Distances were calculated from the center of each subsquare; therefore, the actual dis-

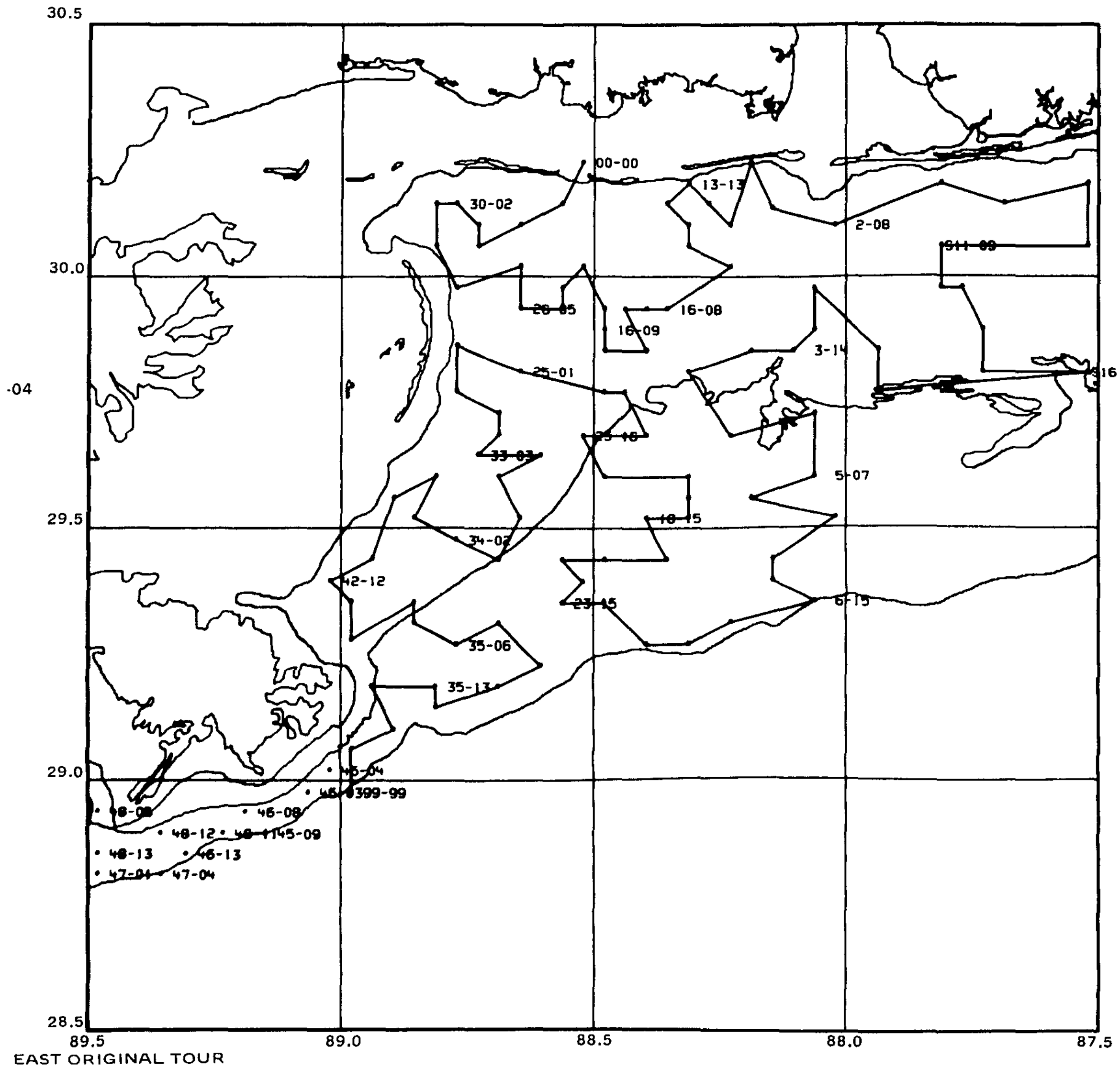

FIGURE 6.—Actual cruise track followed for East Delta area, FRV *Oregon II* cruise 55. Every fifth station is labeled. Station numbers listed at lower left are those not included in optimization calculations.

tance would be decreased by the vessel cutting corners of the subsquares. Calculations for the 126 stations on the Univac 1108 system used about 60K of core storage and required 2 min of Central Processing Unit (CPU) time.

East Delta

Cruise 55 was used to test the program for the East Delta area also. Of 116 stations sampled, 105 were included in the computation of an optimum one-way cruise track. The other 11 stations were located in blocks 45, 46, 47, and 48. They were, however, added to the end of the optimized listout, plotted, and labeled on the cruise track plot. The actual cruise track distance for the 105 stations was 229 grid units (approximately 1,061 km) (Figure 6). The optimized one-way path was calculated to be 216 grid units (1,000 km), an improvement of 5.8% (Figure 7). Calculations for the 105 stations used 60K of core storage and required 66 s of CPU time.

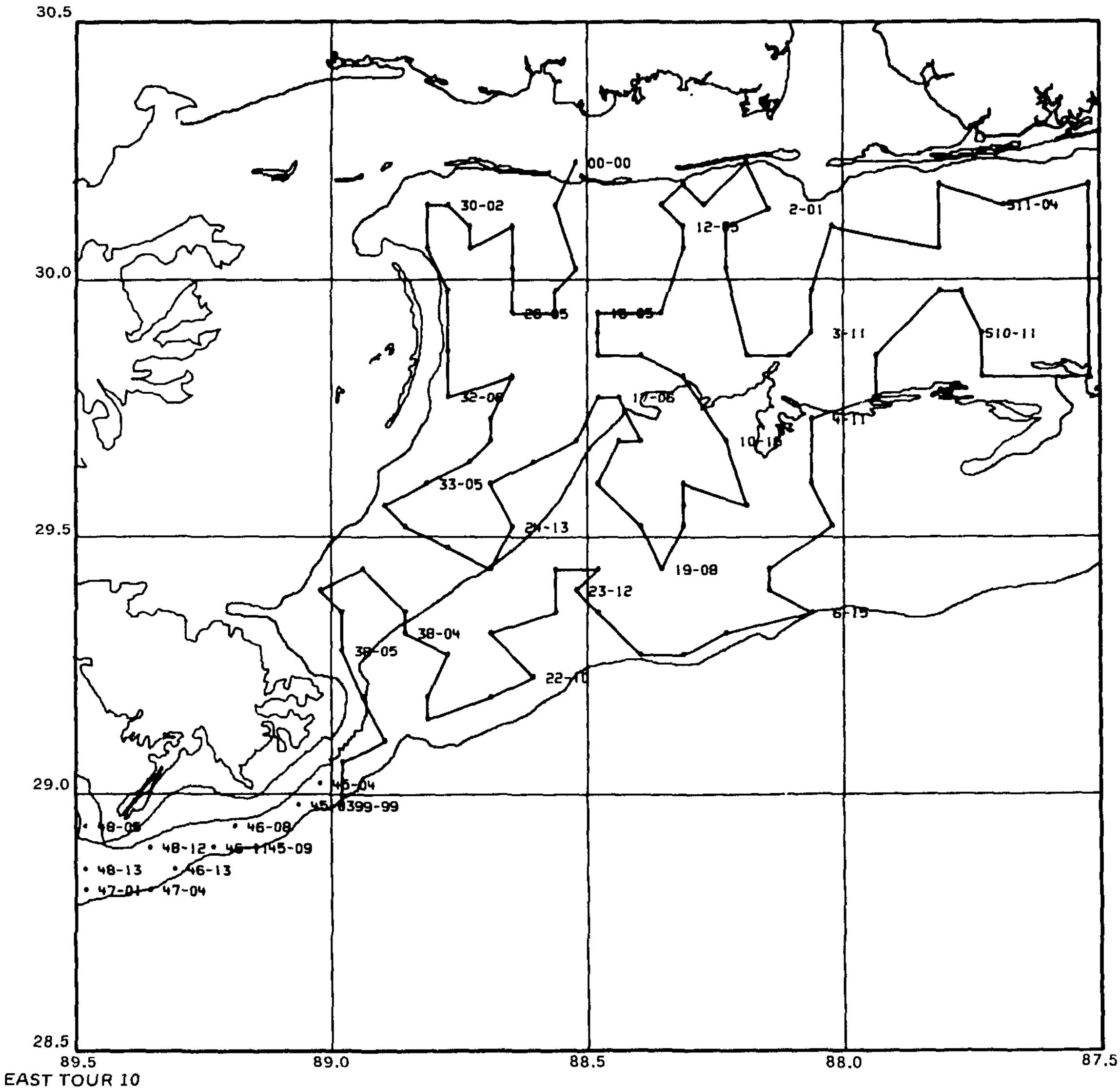

FIGURE 7.—Optimized cruise track for East Delta area, FRV *Oregon II* cruise 55. Every fifth station is labeled. Station numbers listed at lower left are those not included in optimization calculations.

Discussion

The basic optimization program has the capability and inherent versatility to be utilized for a wide range of applications. The round-trip capability can be modified to a one-way path calculation as was done for the East Delta portion of the groundfish survey by manipulating the distance matrix. Cartesian integrity of the start-stop points is kept intact but the distance between the two stations is set equal to zero in the distance matrix. The program then calculates the optimum tour as if the start-stop points were very close together when, in fact, they are not.

There is no requirement that distance be the optimization parameter. Factors such as cost, time, or suitable weighted combinations of other variables could be used to compute a cruise track considered optimum for specific user requirements. Also, there is no requirement that the problem be symmetric or Cartesian in nature. For example, the distance (cost, time, etc.) in going from station A to station B need not be equal to that from station B to station A. Applications of these characteristics and other distance matrix manipulations include:

1) The "cost" in going from station to station in the presence of strong currents, such as the Gulf Stream, could be adjusted. "Downstream" directions from station to station would be given preferential status for computing the optimum cruise track.
2) In some situations, it may be desirable to group selected stations to be sampled preferentially as a subset or subsets of the total station pattern. This might occur if certain sampling areas had a higher priority than others because of biological and/or environmental considerations.
3) Actual curvilinear distances between stations could be entered into the distance matrix when sampling in areas near the coast. This would be done for station pairs connected by a straight line that passes across land.
4) If the number of stations exceeds the present 150 maximum allowable (300 with extended core storage), and it is possible to divide them into subgroups, the problem is limited only by CPU restrictions.

Many variations of the optimum cruise track theme could be solved with this program and the requirements are usually unique to a particular problem or investigation.[4] The examples demonstrate the types of problems that could be solved. Simple problems, such as those solved for the groundfish survey, can be improved about 7% over manually produced cruise tracks.

Improvements obtained using the optimized cruise track for the cited application are not dramatic, but would be significant over a long time period and/or extensive cruising distance. The program eliminates selecting stations from random number tables and hand plotting the cruise track, which may require several man-days

Literature Cited

BELLMORE, M., AND G. L. NEMHAUSER.
1968. The traveling salesman problem: A survey. Oper. Res. 16:538-558.

LIN, S., AND B. W. KERNIGHAN.
1973. An effective heuristic algorithm for the traveling-salesman problem. Oper. Res. 21:498-516.

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