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USE OF LONG-RANGE WEATHER FORECASTS IN SHIP ROUTING

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ABSTRACT:

This report presents an operational computer program for the calculus of variations method of minimal-time routing of single ships. Although written specifically for VC2AP3 and VC2AP2 vessels operating in a described area of the north Pacific ocean, the program can be modified easily to provide routes for other type vessels in any ocean area of the northern hemisphere. An improved method is used for varying time-extremal ship tracks toward admissibility, which requires only 30 seconds per track iteration, and which gives the desired route in about 3 minutes without convergence difficulties. The method of incorporating weather forecasts into the preparation of minimal-time ship routes is described, and possible future developments are discussed.

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Use of Long-Range Weather Forecasts in Ship Routing

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ABSTRACT

Two advances in the calculus of variations method for minimal-time ship routing are described. The first is a scheme for constructing ocean wave field forecasts which may be expected to have considerable skill for perhaps 8 days. The second is an improved technique for varying time-extremal ship tracks toward admissibility. Both ideas are illustrated by calculating the optimum track ship route of a VC2AP3 vessel on a trans-Pacific voyage. Possible future developments are discussed.

1. Introduction

The use of calculus of variations methods in computing minimal time ship routes has been restricted severely in the past by the unavailability of ocean wave field forecasts for extended periods. In an initial attempt to remedy this situation it is proposed here that the wave forecasts now available for periods up to two days from the Fleet Numerical Weather Facility may be extrapolated with considerable skill for 6 more days by using certain 5-day and 30-day forecasts now available from the U. S. Weather Bureau. Bleick and Faulkner (1965) gave a method of computing minimal-time ship routes by varying time-extremal ship tracks toward the admissibility of reaching a desired terminal point. Their scheme of extremal variation is refined here so that rapid convergence of the track iteration process is assured. An example of wave field construction and extremal variation is given for a Pacific voyage.

2. Wave Field Construction

The scheme of incorporating weather forecasts into the construction of a 10-member computer-stored time series of wave fields for the numerical example of a trans-Pacific voyage consists of the following parts:

a) The Fleet Numerical Weather Facility prepares wave analyses at 00Z and 12Z each day, as well as operational wave predictions at 12-hour intervals for periods up to 48 hours. The first 5 members of the time series consisted of the analysis at 12Z of 26 July 1966, and the predictions for 00Z and 12Z of 27 and 28 July.

b) The U. S. Weather Bureau's 5-day surface pressure forecast, issued every Monday, Wednesday and Friday, consisting of one sea-level pressure map per day at 1230Z, was used to construct the next 3 members of the time series. The last 3 maps of the forecast issued on Wednesday, 27 July 1966, were used to determine surface winds and, in turn, to calculate height, period and direction of the wind waves and swell. This data was used for time series members at 12Z of 29, 30 and 31 July.

c) The U. S. Weather Bureau's 30-day forecast was utilized for calculating the 9th and 10th members of the time series. Although not published for use outside the Weather Bureau, a copy of the 30-day predicted mean sea-level pressure map, centered at the middle of the month of August 1966, was obtained. Surface winds were estimated from this single map, and again wave conditions were calculated. The calculations were repeated on a daily basis using the same map. Since the same winds are used repeatedly, the forecast waves reach a steady state within a few days. The limited amount of computer core storage made it necessary to terminate the time series by using this data at 12Z on 1 and 2 August. The last member of the time series was used to satisfy any later need for wave fields.

The predicted 30-day mean pressure chart has relatively weak pressure gradients, as would be expected from the averaging process. In contrast, the individual daily charts which make up such a mean have strong gradients in general, particularly in the vicinity of migratory cyclones or low pressure areas. These systems have strong winds and high seas associated with them, which are reflected in the 30-day mean only in a very limited fashion. The forecast procedure did, however, show considerable skill over the use of long term monthly mean charts. Nevertheless it is desireable to seek additional ways, possibly more accurate, of providing wave estimates for the latter part of a voyage extending beyond 5 days. Possible future developments of this kind are discussed later.

3. Variation of Extremals

As in the previous work of Bleick and Faulkner (1965) let the differential equations of a ships motion in the stereographic plane be

$$\dot{x}=V\cos p, \quad \dot{y}=V\sin p. \tag{1}$$

It was shown that the ship track direction angle p on a time-extremal route is

$$p=\arctan(\mu/\lambda)+\arctan(V_p/V). \tag{2}$$

Here

$$\lambda=\lambda_1\cos\alpha+\lambda_2\sin\alpha \tag{3}$$

and

$$\mu=\mu_1\cos\alpha+\mu_2\sin\alpha \tag{4}$$

are linear combinations of the linearly independent solutions λ_1,μ_1 and λ_2,μ_2 of the adjoint system

$$\dot{\lambda}+V_x(\lambda\cos p+\mu\sin p)=0 \tag{5}$$

$$\dot{\mu}+V_y(\lambda\cos p+\mu\sin p)=0, \tag{6}$$

and α is approximately the departure angle between the ship track and the Ox coordinate axis at the t=0 initial point of the voyage. In the previous work on varying a time-extremal ship track toward the admissibility of reaching a desired terminal point the variation δp was considered to be dependent on the variation $\delta\alpha$ only. This is a convenient approximation to avoid mathematical complications, but its use may lead to a marked slowing down of the Newton-Raphson track iteration process. If this approximation is abandoned in computing the variations $\delta x,\delta y$ of a time-extremal ship track solution of (1) and (2), then the dependence of δp on all of the variations δx, δy, $\delta\lambda_1$, $\delta\lambda_2$, $\delta\mu_1$, $\delta\mu_2$ and $\delta\alpha$ must be considered. This complete variation δp is found from (2) to be

$$\delta p=[(V_p/V)_x\delta x+(V_p/V)_y\delta y+S^2(\lambda\delta\zeta-\mu\delta\xi+E\delta\alpha)]/D \tag{7}$$

where

$$\delta\xi=\delta\lambda_1\cos\alpha+\delta\lambda_2\sin\alpha, \tag{8}$$

$$\delta\zeta=\delta\mu_1\cos\alpha+\delta\mu_2\sin\alpha, \tag{9}$$

$$S^2=[1+(V_p/V)^2]/(\lambda^2+\mu^2), \tag{10}$$

$$D = 1+(V_p/V)^2-(V_p/V)_p, \tag{11}$$

$$E = \lambda_1\mu_2-\lambda_2\mu_1. \tag{12}$$

The variation of (1), the time differentiation of (8) and (9), and use of (5), (6) and (7) give the following non-homogeneous system of equations to solve for the desired variations $\delta x,\delta y$:

$$\delta\dot{x}=[V_x\cos p-\mu QW_x]\delta x+[V_y\cos p-\mu QW_y]\delta y+\mu S^2[Q(\mu\delta\xi-\lambda\delta\zeta)-E\delta\alpha], \tag{13}$$

$$\delta\dot{y}=[V_x\sin p+\lambda QW_x]\delta x+[V_y\sin p+\lambda QW_y]\delta y-\lambda S^2[Q(\mu\delta\xi-\lambda\delta\zeta)-E\delta\alpha], \tag{14}$$

$$-\delta\dot{\xi}=S^{-1}[V_{xx}+VD^{-1}W_x{}^2]\delta x + S^{-1}[V_{xy}+VD^{-1}W_xW_y]\delta y$$

$$+ [V_x\cos p-\mu QW_x]\delta\xi + [V_x\sin p+\lambda QW_x]\delta\zeta + QEW_x\delta\alpha, \qquad (15)$$

$$-\delta\dot{\zeta}=S^{-1}[V_{yx}+VD^{-1}W_yW_x]\delta x + S^{-1}[V_{yy}+VD^{-1}W_y{}^2]\delta y$$

$$+ [V_y\cos p-\mu QW_y]\delta\xi + [V_y\sin p+\lambda QW_y]\delta\zeta + QEW_y\delta\alpha, \qquad (16)$$

where $Q=VS/D$ and $W=V_p/V$. Equations (13) to (16) are integrated, with zero initial values at the $t=0$ initial point of the track and with $\delta\alpha=1$, to obtain the variations $\delta x(T)$ and $\delta y(T)$ at the $t=T$ terminal point. These variations are really the partial derivatives $\partial x(T)/\partial\alpha$ and $\partial y(T)/\partial\alpha$ since we have taken $\delta\alpha=1$. The Newton-Raphson equations for determining ΔT and $\delta\alpha$ on a varied time-extremal track, which attempt to reduce the terminal errors $\Delta x(T)$ and $\Delta y(T)$ of the previous extremal track, are then

$$\begin{aligned}\dot{x}(T)\Delta T+[\partial x(T)/\partial\alpha]\delta\alpha&=\Delta x(T)\\ \dot{y}(T)\Delta T+[\partial y(T)/\partial\alpha]\delta\alpha&=\Delta y(T).\end{aligned} \qquad (17)$$

In the numerical integration of (1), (5), (6) and (13) to (16) it is desirable to use a wave field interpolation formula which will guarantee as far as possible the continuity of all terms of these equations where any of x,y,t assume grid values. A method which achieves this when interpolating in the time dimension was given by Bleick and Faulkner (1965). The method given there for interpolating in the grid of the Oxy stereographic plane will not give the desired continuity of V_{xx}, V_{xy} and V_{yy} of (15) and (16). The 16-point interpolation formula used here to guarantee the continuity of V and all its first and second order partial derivatives with respect to x and y, except V_{xy}, is obtained from the 4×4 matrix $\underset{\sim}{F}(x,y)$, whose four rows and columns of function entries correspond to four successive x and y grid values respectively. The interpolation mesh cell is the central cell of the array, with x and y measured from the cell center, and with the mesh distance considered to be two units. The formula is

$$F(x,y) = \underset{\sim}{P}(x)\ \underset{\sim}{F}\ \underset{\sim}{P}'(y)/1024 \tag{18}$$

where the row matrix $\underset{\sim}{P}(x)=[P_1,P_2,P_3,P_4]$ has the elements

$$\begin{aligned} P_1&=(x^2-1)(x-1)^2(x+2),\\ P_2&=(1-x)(3x^4+3x^3-9x^2-7x+18),\\ P_3&=(x+1)(3x^4-3x^3-9x^2+7x+18),\\ P_4&=(x^2-1)(x+1)^2(2-x), \end{aligned} \tag{19}$$

and the prime indicates matrix transposition. This matrix type of interpolation gave excellent results in the numerical example which follows despite its inability to give continuity of V_{xy} at grid values of x or y. In contrast with the earlier work it was found desir able to evaluate the various derivatives of V=mv by explicit differentiation of the solution of the quadratic equation in v for the elliptical polar velocity diagram.

4. Numerical Example

Figure 1 illustrates the result of the new methods of wave field construction and time-extremal track variation in the case of a trans-Pacific voyage of a VC2AP3 vessel. The elliptical polar velocity diagram used was based upon the work of James (1959). The minimal-time track starts from 154E, 41N at 1200Z on 26 July 1966 and ends at 123W, 38N at 0828Z on 4 August, with circles indicating successive positions of the vessel at 8-hour intervals. The solid line is the great circle route obtained by integrating

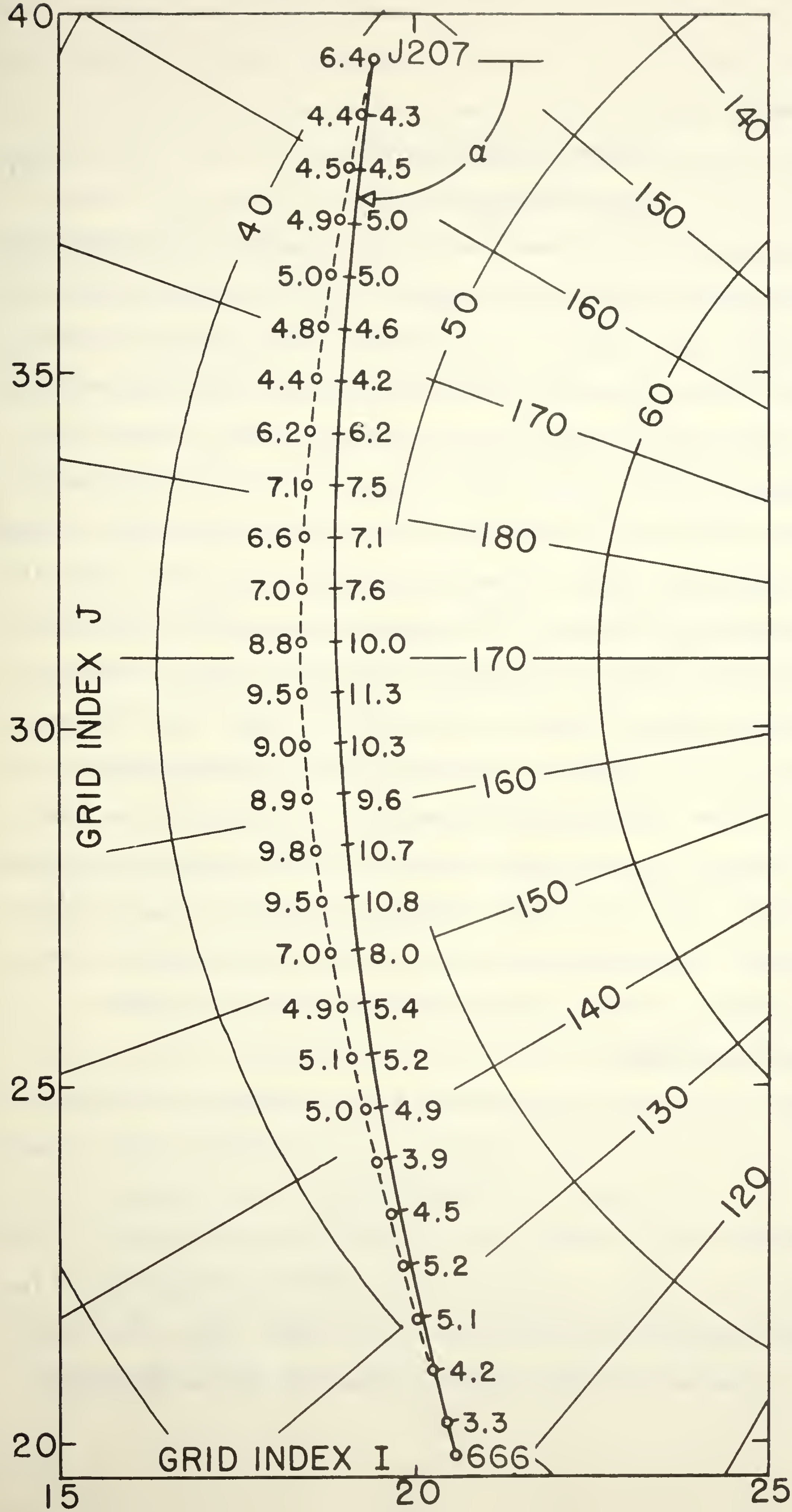

FIG. 1. Trans-Pacific voyages of a VC2AP3. Wave heights in feet every 8 hours on geodesic track (solid line) and minimal-time track (circles).

(I) using

$$\begin{aligned} \cos p &= n[(31-J)/31.205]+m \\ \sin p &= n[(I-31)/31.205]-l \end{aligned} \qquad (20)$$

where I,J are the Fleet Numerical Weather Facility stereographic plane grid indices, and l,m,n are the direction cosines of the normal vector to the great circle plane. These cosines are computed from the normalized cross product of the vectors from the earth's center to the initial and terminal points of the track. Because of the rather calm prevailing seas there was no significant time difference between the geodesic and minimal-time routes, but the latter did show a reduction in the wave heights encountered as indicated in Fig. 1. The example illustrates the advantage of the new method of extremal variation in that the Newton-Raphson Eqs. (17) were used as they stand without convergence difficulties, i.e. without resorting to the delayed approach to the limit scheme of using only some fraction of $\delta\alpha$ on the next track iteration. The new method also permitted the use of a rather large 4-hour time step in the numerical integrations, with consequent gain in the speed of the track iteration process. The Fortran computer program may be obtained from the authors.

5. Concluding Remarks

Another possibility for predicting wave fields for extended periods, which appears to have promise, is to utilize a wave climatology. This could consist of utilizing the wave analyses now being prepared daily at the Fleet Numerical Weather Facility to compute mean wave height, direction and period as a function of latitude and longitude for each month of the year. These data could then be compared with those derived from the Weather Bureau 30-

day sea level pressure forecasts in order to ascertain the best source of wave data for trans-oceanic ship routing. Such a wave climatology would have other applications in shipping operations. A further refinement in the development of such a wave climatology might consist of the preparation of mean wave characteristics not only as a function of latitude, longitude and month, but also separated according to weather type. The latter are determined largely according to the main storm tracks which vary from week to week as well as with season. Such a climatology would obviously take more effort to prepare, but would be a very valuable aid in ship routing.

Finally, it should be mentioned that a number of groups are experimenting with long-range weather prediction by numerical integration of the hydrodynamical equations. It is expected that eventually such predictions will show skill for perhaps several weeks, and thus day-by-day wave forecasts could be made available for the entire period of a trans-oceanic voyage.

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7. REFERENCES

Bleick, W. E. and F. D. Faulkner, 1965: Minimal-time ship routing. J. Appl. Meteor., 4, 217-221.

James, R. W., 1959: Application of wave forecasts to marine navigation. U. S. Navy Hydrographic Office, 85 pp.

8. Appendix:

Computer Program Input and Output

The program was written for the CDC 1604 computer in Fortran 1963. The magnetic tape input to the main program VC2AP3 of this appendix is from logical unit 1. This input tape was prepared by program TAPE of this appendix, and involves conversion of fixed-point data to floating-point data by the normalizing operation (addition to floating-point zero) of the CDC 1604. The first floating-point BCD record of the tape input to VC2AP3 contains the data required to plot the stereographic plane map grid of lines of longitude and circles of latitude by calling subroutine DRAW, described in Naval Postgraduate School Technical Report/ Research Paper No. 73. The second and last floating-point BCD record of the tape input to VC2AP3 contains the three 18×32×10 wave field time-series arrays XHT, CSK and SNK corresponding to the wave height H, and the wave direction cosines cosK and sines sinK described in the first reference. The dimensions 18 and 32 correspond to the FNWF stereographic plane grid point indices of $8 \leq I \leq 25$ in the direction of the 10E meridian and $16 \leq J \leq 47$ in the direction of the 100E meridian. The dimension 10 corresponds to the time series of wave fields described in Section 2. The VC2AP3 program will not work unless all points of a ship route, includ- the initial and terminal points, are <u>within</u> a smaller 16×30 rect- angle defined by $9<I<24$ and $17<J<46$. A local coordinate system is set up with the origin 0 at I=7 and J=15, with the 0x and 0y axes in the direction of increasing I and J respectively. The smallest values of x and y, corresponding to I=8 and J=16, are therefore x=1 and y=1. The punched card input to VC2AP3, immediately after the EXECUTER control card, contains the following data:

Card 1: First line of the TI=IT title in format (6A8/) for the map produced by subroutine DRAW in Statement 11. See example in the Fortran card listing of this appendix.

Card2: Format (8A8,I3) of which 6A8 is the second line of the map title TI. The remaining part of the format is A8 for the DATE=KATE of the routing computation, A8 for eight blank Hollerith characters for a null label AL=LA on the map grid plot, and I3 for the NST total number of ships to be routed. The DATE of the routing computation corresponds to the 12Z hour of the first member of the time series described in Section 2. See example in the Fortran card listing of this appendix.

Following these two input cards there a groups of either 6 cards or one card for each ship routed by VC2AP3, depending on whether or not the option to plot an earlier route of a particular ship is elected.

Card 3: Format (A4,2A8,F3.0,F6.1,F5.1,F6.1,F5.1,F3.0,I1,2I2,I1, F8.5,F6.3) with example in the Fortran card listing of this appendix. The first A4 is the GL=LG ship identification number with column 1 of the card blank, used by subroutine DRAW to label the terminal point of a ship route. The first A8 is the DATEX=KATEX date on which the ship leaves the initial point of its route. The second A8 is the FL=LF Julian date of departure, with blanks in columns 17 to 20 inclusive, used by subroutine DRAW to label the initial point of a ship route. The F3.0 is the HR hour of ship departure from its initial point measured from 12Z on the DATE of routing, i.e. from the 12Z hour of hour of the first member of the wave field time series. The F6.1, F5.1, F6.1, F5.1 formats are the longitudes and latitudes of the initial and terminal points of theroute, XLG1, XLT1, XLG2, XLT2, with longitudes considered positive if east of the Greenwich meridian. The F3.0 format provides for the RMUL convergence factor which can be used to divide $\delta\alpha$ by RMUL before accepting it for the next track iteration. The Fortran card list of this appendix shows RMUL=1 indicating that there are no convergence difficulties in the present revision of VC2AP3. The I1 format provides for NN which is either 1 or zero according as the option to plot an earlier route of the ship is or is not elected. The first of the 2I2 format is for the NSTEP reciprocal of the time step used in the integration process, with 6 of the card listing indicating a step of 1/6 of a day. The second I2 format specifies the number LMAX of iterations allowed in determining the ship route. The remaining formats I1,F8.5, F6.3 provide for NP, PALF and PT described in NPS Tech. Report/Res.Paper 73, but found unnecessary in present revision of VC2AP3 with consequent blanks in the card listing.

Card 3 is followed by 5 cards punched out by the statements on cards 337 to 341 of an earlier use of VC2AP3 if the option NN=1 to plot an earlier track of the ship has been elected. If NN=0 on card 3, the remaining data cards of the input deck refer to other ships to be routed.

The output of VC2AP3 contains a map grid for each vessel routed, shown in Fig.1, produced by the CALL DRAW of statement 11. If the option NN=1 has been elected, statements 16 to 18 plot an earlier route of the ship using plus signs for daily positions and an identifying Julian day mark for the initial point. Statements 19 to 44 cause a geodesic route to be computed and plotted as a solid line as shown in Fig.1 where the approximate initial angle of departure ALF=α, measured from the Ox axis, is indicated also. The terminal point of the geodesic route is marked by the GL=LG identification number of the ship. One purpose of the geodesic route computation is to find first approximations to the time T and departure angle ALF used in the LMAX iterations toward a minimal-time track of statements 45 to 69. Another purpose is to provide a standard of comparison for the effectiveness of the minimal-time routing. The geodesic route computation is abandoned if any point of the route falls outside of the rectangle $9<I<24$ and $17<J<46$, but the route within this rectangle is plotted on the map grid. The minimal-time route computation is initiated by statement 45 only if the entire geodesic route has been computed successfully. The format of statement 71 is printed if the LMAX iterations result in a terminal point more than 100 nautical miles from the desired destination, together with advice about how to improve convergence. Experience to date on trans-Pacific routes indicates that it is desireable to use LMAX=10 and RMUL=1. The tabulated daily position, wave height and direction for the last of the LMAX iterations are printed under the format of statements 73 and 74, with example on the following page. Five cards, shown on the following page, are punched under the formats of statements 76 and 78, which may be used for some later plot of the track if the NN=1 option of card 41 of VC2AP3 is elected in a later routing of the ship. The statement of card 342 of VC2AP3 causes the daily track positions to be plotted on the map grid as in Fig.1, with the LF =FL Julian day identification of the initial point. Statement 80 continues the M=1,NST loop for the routing of the next ship.

PRINT output for J207 route of ship 666

```
TOTAL NUMBER OF VC2AP3 SHIPS ROUTED =    1
ON JUL26,66 FROM 12Z TO 24Z, AND ON FOLLOWING DAY FROM 00Z TO 11Z

ROUTE OF SHIP  666 BEGINS ON JUL26,66, JULIAN DATE = J207,
  0 HOURS AFTER 1200Z ON JUL26,66
 FROM LONGITUDE =   154.0 AND LATITUDE =    41.0
   TO LONGITUDE = -123.0 AND LATITUDE =    38.0

RMLL=    1    LMAX=10    NSTEP= 6    NN=0    NP=0
```

L	N1	ALF	T	X(N1)	XFIN	Y(N1)	YFIN
0	55	-1.72471	8.856	13.620	13.620	4.869	4.869
1	55	-1.72471	8.856	14.112	13.620	5.020	4.869
		-1.78100	8.855				
2	55	-1.78100	8.855	13.915	13.620	4.960	4.869
		-2.30819	8.850				
3	49	-2.30819	8.000	2.343	13.620	7.467	4.869
		-1.49355	7.587				
4	47	-1.49355	7.587	16.950	13.620	9.125	4.869
		-2.29251	8.649				
5	49	-2.29251	8.000	2.516	13.620	7.408	4.869
		-1.42639	7.614				
6	45	-1.42639	7.167	16.915	13.620	10.077	4.869
		-2.01005	8.787				
7	52	-2.01005	8.500	8.146	13.620	5.007	4.869
		-1.80262	8.497				
8	52	-1.80262	8.497	13.544	13.620	5.713	4.869
		-1.82049	8.852				
9	55	-1.82049	8.852	13.501	13.620	4.831	4.869
		-1.81506	8.853				
10	55	-1.81506	8.853	13.623	13.620	4.869	4.869
		-1.81522	8.853				

DAYS OF TRAVEL	LONGI -TUDE	LATI- TUDE	WAVE HEIGHT	WAVE DIRECTION FROM NORTH
0	154.0	41.0	6.39	221
1.00	162.9	43.3	4.93	224
2.00	172.4	45.0	4.43	186
3.00	-177.8	46.0	6.64	202
4.00	-167.8	46.2	9.52	257
5.00	-157.8	45.8	9.81	251
6.00	-148.0	44.9	4.92	234
7.00	-138.6	43.3	3.93	188
8.00	-129.9	40.7	5.14	338
8.85	-123.0	38.0	2.81	331

```
GRAPH TITLED
    JOB C574           ELEICK          BOX 6
    VC2AP3             APRIL 14        1967
HAS BEEN PLOTTED.
```

PUNCH output for J207 day route of ship 666

```
 666     J207     10
10.1210.1110.2510.5410.9711.5812.3913.3414.3415.30 666       J207       1
    0    0    0    0    0    0    0    0    0    0 666       J207       2
21.9719.6817.4415.2513.1010.99 8.93 6.91 4.88 3.15J207       666        1
    0    0    0    0    0    0    0    0    0    0J207       666        2
```

```
-COOP,BOX6, BLEICK,I/1/0/49/S/56/57/E/45=54,15,10000,0, VC2AP3 - 14 APR 67.
-BINARY,56.
(RELOCOM.
-FTN,L,A,E.
      PROGRAM VC2AP3
C  YVARS(1)=LAMBDA1  YVARS(2)=MU1    YVARS(3)=LAMBDA2    YVARS(4)=MU2
C  YVARS(5)=X        YVARS(6)=Y      YVARS(7)=S OR VARX  YVARS(8)=VARY
C  YVARS(9)=VARXI   YVARS(10)=VARZETA
      DIMENSION X(900),Y(900),RX(10,90),RY(10,90),IT(12),TI(12),C(4),
     +          AK(4,10),DY(10),D(20)
      COMMON    YC(10),LR,A,B,CC,H,CK,SK
      COMMON/L1/XHT(5760),CSK(5760),SNK(5760),TC
      COMMON/L5/COST,SINT,V,CAPV,CAPVX,CAPVY,CAPVXX,CAPVXY,CAPVYY,
     +          VPBVX,VPBVY,DIV,RBV,CAPVP
      COMMON/L6/YVARS(10),XK,XLG,XLT
      EQUIVALENCE (IT,TI),(LA,AL),(KATE,DATE),(LP,PL),(LG,GL),(LF,FL),
     +             (X,RX),(Y,RY),(KATEX,DATEX)
      REWIND 1
      C(1) = 0.0
      C(2) = 0.5
      C(3) = 0.5
      C(4) = 1.0
C READ MAP GRID DATA FOR DRAW SUBROUTINE, AND WAVE FIELD ARRAYS
      READ(1,3) (X(I),I=1,390),(Y(I),I=1,390)
    3 FORMAT (17F7.3)
      READ(1,4) XHT,CSK,SNK
    4 FORMAT (13F9.5)
C  READ MAP TITLE, DATE OF ROUTING COMPUTATION, MAP GRID PLOT LABEL,
C       AND TOTAL NUMBER OF SHIPS ROUTED
      READ(50,1) TI,DATE,AL,NST
    1 FORMAT (6A8/8A8,I3)
      WRITE(51,2) NST,KATE
    2 FORMAT(39H1TOTAL NUMBER OF VC2AP3 SHIPS ROUTED = I3/1X3HON A8,54H
     +FROM 12Z TO 24Z, AND ON FOLLOWING DAY FROM 00Z TO 11Z/)
      REWIND 1
      DO 80  M=1,NST
      IF (M-1)  10,11,10
C  READ MAP GRID DATA FOR DRAW SUBROUTINE
   10 READ(1,3) (X(I),I=1,390),(Y(I),I=1,390)
      REWIND 1
C  DRAW MAP GRID
   11 CALL DRAW (386,X,Y,1,0,LA,IT,2.,2.,0,0,2,2,9,15,0,LAST)
C  READ SHIP IDENTIFICATION NUMBER, DATE AND HOUR OF DEPARTURE, COORDINATES
C       OF TRACK END POINTS, CONVERGENCE FACTOR, OPTION TO PLOT EARLIER
C       TRACK, TIME STEP RECIPROCAL, AND NUMBER OF ITERATIONS
      READ(50,14) GL,DATEX,FL,HR,XLG1,XLT1,XLG2,XLT2,RMUL,NN,NSTEP,LMAX,
     + NP,PALF,PT
   14 FORMAT (A4,2A8,F3.0,F6.1,F5.1,F6.1,F5.1,F3.0,I1,2I2,I1,F8.5,F6.3)
      RSTEP = NSTEP
```

```
   WRITE(51,15) LG,KATEX,LF,HR,KATE,XLG1,XLT1,XLG2,XLT2,RMUL,LMAX,
  + NSTEP,NN,NP
15 FORMAT(15HOROUTE OF SHIP A4,11H BEGINS ON A8,16H, JULIAN DATE = A4
  +,1H,/1XF3.0,22H HOURS AFTER 1200Z ON A8/19H  FROM LONGITUDE = F6.1
  +,16H AND LATITUDE = F6.1/19H    TO LONGITUDE = F6.1,16H AND LATITU
  +DE = F6.1//6H RMUL=F5.0,3X5HLMAX=I2,3X6HNSTEP=I2,3X3HNN=I1,3X3HNP=
  +I1//)
CHECK ON OPTION TO PLOT EARLIER TRACK
   IF (NN)  16,19,16
16 READ(50,17) GL,PL,NK
17 FORMAT (2A8,I2)
   READ(50,29) (X(I),I=1,20), (Y(I),I=1,20)
29 FORMAT (10F5.2)
   CALL DRAW (NK,X,Y,2,2,LP,IT,2.,2.,0,0,2,2,9,15,0,LAST)
   WRITE(51,18) LG,LP
18 FORMAT(23HOEARLIER ROUTE OF SHIP A8,15H ON JULIAN DAY A4/66H  HAS
  +BEEN PLOTTED USING PLUS SIGNS FOR SUCCESSIVE DAILY POSITIONS/)
COMPUTATION OF GEODESIC TRACK
19 ARG = (XLG1-10.)/57.29577951
   COSLG1= COSF(ARG)
   SINLG1= SINF(ARG)
   ARG = (XLG2-10.)/57.29577951
   COSLG2= COSF(ARG)
   SINLG2= SINF(ARG)
   ARG = XLT1/57.29577951
   COSLT1= COSF(ARG)
   SINLT1= SINF(ARG)
   ARG = XLT2/57.29577951
   COSLT2= COSF(ARG)
   SINLT2= SINF(ARG)
   EL = SINLT2*COSLT1*SINLG1 - COSLT2*SINLT1*SINLG2
   EM =-SINLT2*COSLT1*COSLG1 + COSLT2*SINLT1*COSLG2
   EN =(SINLG2*COSLG1-COSLG2*SINLG1)*COSLT1*COSLT2
   ROOT = SQRTF(EL*EL + EM*EM + EN*EN)
   EL = EL/ROOT
   EM = EM/ROOT
   EN = EN/ROOT
   PR1= 31.205*COSLT1/(1.+SINLT1)
   X1 = PR1*COSLG1
   Y1 = PR1*SINLG1
   PR2= 31.205*COSLT2/(1.+SINLT2)
   X2 = PR2*COSLG2
   Y2 = PR2*SINLG2
   DELX = X2 - X1
   DELY = Y2 - Y1
   S12  = SQRTF(DELX*DELX + DELY*DELY)
   ARC= S12
   IF (XLG2-XLG1) 20,21,20
20 ARG= ABSF(EN/62.41)
   ARC= ASINF(ARG*S12)/ARG
```

```
21 COSA = -EN*Y1/31.205 + EM
   SINA =  EN*X1/31.205 - EL
   IF (COSA)  23,22,23
22 ALF = SIGNF(1.5707963268,SINA)
   GO TO 27
23 ALF = ATANF(SINA/COSA)
   IF (COSA)  24,27,27
24 IF (SINA)  26,25,25
25 ALF = ALF + 3.1415926536
   GO TO 27
26 ALF = ALF - 3.1415926536
27 N3 = 0
   X(1) = X1 + 24.
   Y(1) = Y1 + 16.
   XFIN = X2 + 24.
   YFIN = Y2 + 16.
   LR = 0
   STEP = 1.0/RSTEP
   TAU  = 0.0
    S   = 0.0
   TVAR = HR/24.
   YVARS(5) = X(1)
   YVARS(6) = Y(1)
   YVARS(7) = 0.0
   N1 = 1
   N2 = 1
   DO 40  K=2,900
   DO 32  I=1,4
   TC = C(I)*STEP + TVAR
   DO 31  J=5,7
31 YC(J) = C(I)*AK(I-1,J) + YVARS(J)
   IF (ABSF(YC(5)- 9.5)- 7.5) 97,38,38
97 IF (ABSF(YC(6)-16.5)-14.5) 98,38,38
98 CALL TERP
   CALL AP3
   COSP = (16.-YC(6))*EN/31.205 + EM
   SINP = (YC(5)-24.)*EN/31.205 - EL
   COST =  COSP*CK + SINP*SK
   SINT =  SINP*CK - COSP*SK
   CALL VDERIV
   DY(5)= CAPV*COSP
   DY(6)= CAPV*SINP
   DY(7)= CAPV
   DO 32  J=5,7
32 AK(I,J) = STEP*DY(J)
   DO 33  J=5,7
33 YVARS(J) = ( AK(1,J)+2.*AK(2,J)+2.*AK(3,J)+AK(4,J) )/6. + YVARS(J)
   TVAR = TVAR + STEP
   X(K) = YVARS(5)
   Y(K) = YVARS(6)
```

```
      N1  = K
      N2 = K
     IF (YVARS(7)-ARC)  35,34,34
 34  RAT = (ARC-S)/(YVARS(7)-S)
     T = STEP*RAT + TAU
     X(K) = (X(K)-X(K-1))*RAT + X(K-1)
     Y(K) = (Y(K)-Y(K-1))*RAT + Y(K-1)
      N2 = K+1
     X(N2) = XFIN
     Y(N2) = YFIN
     GO TO 41
 35   S = YVARS(7)
     TAU= TAU + STEP
     IF (K-900)  36,38,38
 36  IF (ABSF(X(K)- 9.5)- 7.5) 37,38,38
 37  IF (ABSF(Y(K)-16.5)-14.5) 40,38,38
 38   T = TAU
     WRITE(51,39)  LG
 39  FORMAT(61HOMORE THAN 899 INTEGRATION STEPS OR WAVE DATA FIELD EXCE
    +EDED./21H OTS ROUTING OF SHIP A4,4X39HABANDONED BUT GEODESIC TRACK
    + IS PLOTTED/)
     N3 = 1
     GO TO 41
 40  CONTINUE
 41   L = 0
     WRITE(51,42)
 42  FORMAT(4X1HL4X2HN16X3HALF7X1HT7X5HX(N1)4X4HXFIN5X5HY(N1)4X4HYFIN/)
C    PRINT WEIGHTING FACTOR ALPHA AND TIME T OF GEODESIC TRACK
     WRITE(51,43) L,N1,ALF,T,X(N1),XFIN,Y(N1),YFIN
 43  FORMAT (I5,I6,F11.5,5F9.3)
C    ROTATE AND TRANSLATE AXES TO PLOT GEODESIC TRACK ON MAP GRID
     DO 44  I=1,N2
     TEMP = .97780241408*X(I) - .20952908873*Y(I) + 3.0032502718
     Y(I) = .20952908873*X(I) + .97780241408*Y(I) - 4.4699538929
 44  X(I) = TEMP
     CALL DRAW (N2,X,Y,N3+2,0,LG,IT,2.,2.,0,0,2,2,9,15,0,LAST)
     IF (N3)  80,45,80
C    PREPARE FOR LMAX ITERATIONS TOWARD MINIMAL-TIME TRACK
 45  TC = HR/24.
     X(1) = X1 + 24.
     Y(1) = Y1 + 16.
     YC(5) = X(1)
     YC(6) = Y(1)
     CALL TERP
     DO 9  I=2,399
     X(I) = 0.0
  9  Y(I) = 0.0
     X(101) = H
     YVARS(5) = X(1)
     YVARS(6) = Y(1)
```

```
      CALL ANGLE
      Y(101) = XK
      X(201) = XLG1
      Y(201) = XLT1
      LR = 1
      IF (NP) 81,82,81
 81   ALF = PALF
       T  = PT
      COSA = COSF(ALF)
      SINA = SINF(ALF)
 82   DO 69  L=1,LMAX
      TVAR = HR/24.
      TAU = 0.0
      N1 = XINTF(RSTEP * T)
      XN1 = N1
      STEP1 = 1.0/RSTEP
      FSTEP = -XN1/RSTEP + T
      N1 = N1 + 2
      DO 46  I=1,10
 46   YVARS(I) = 0.0
      YVARS(1) = 1.0
      YVARS(4) = 1.0
      YVARS(5) = X(1)
      YVARS(6) = Y(1)
      NK = 1
      DO 66 K=2,N1
      STEP = STEP1
      IF (K-N1)  48,47,48
 47   STEP = FSTEP
 48   DO 52  I=1,4
      TC = C(I)*STEP + TVAR
      DO 49  J=1,10
 49   YC(J) = C(I)*AK(I-1,J) + YVARS(J)
      IF (ABSF(YC(5)- 9.5)- 7.5) 99,65,65
 99   IF (ABSF(YC(6)-16.5)-14.5)100,65,65
100   XLAM = YC(1)*COSA + YC(3)*SINA
      XMU  = YC(2)*COSA + YC(4)*SINA
      CLAM = SQRTF(XLAM*XLAM + XMU*XMU)
      CALL TERP
      CALL AP3
      ABS = (XLAM*CK + XMU*SK)*A/CLAM
      ORD = (XMU *CK -XLAM*SK)*B/CLAM
      HYP = SQRTF(ABS*ABS + ORD*ORD)
      VMAJ= A*ABS/HYP - CC
      VMIN= B*ORD/HYP
        V = SQRTF(VMAJ*VMAJ + VMIN*VMIN)
      COST= VMAJ/V
      SINT= VMIN/V
      COSP= CK*COST - SK*SINT
      SINP= SK*COST + CK*SINT
```

```
      CALL VDERIV
      FAC1 = YC(1)*COSP + YC(2)*SINP
      DY(1)= -CAPVX*FAC1
      DY(2)= -CAPVY*FAC1
      FAC2 = YC(3)*COSP + YC(4)*SINP
      DY(3)= -CAPVX*FAC2
      DY(4)= -CAPVY*FAC2
      DY(5)= CAPV * COSP
      DY(6)= CAPV * SINP
      DET = YC(1)*YC(4) - YC(2)*YC(3)
      QUO = RBV/CLAM
      FAC1=CAPV*QUO*VPBVX/DIV
      FAC2=CAPV*QUO*VPBVY/DIV
      FAC3= CAPV*QUO*QUO*QUO/DIV
      FAC4=CAPV*DET*QUO/DIV
      D(1) = CAPVX*COSP - XMU*FAC1
      D(2) = CAPVY*COSP - XMU*FAC2
      D(3) = XMU * XMU*FAC3
      D(4) = -XLAM*XMU*FAC3
      D(5) = -XMU* DET*FAC3
      DY(7) = D(1)*YC(7) + D(2)*YC(8) + D(3)*YC(9) + D(4)*YC(10) + D(5)
      D(6) = CAPVX*SINP + XLAM*FAC1
      D(7) = CAPVY*SINP + XLAM*FAC2
      D(9) = XLAM*XLAM*FAC3
      D(10)= XLAM* DET*FAC3
      DY(8) = D(6)*YC(7) + D(7)*YC(8) + D(4)*YC(9) + D(9)*YC(10) + D(10)
      D(11)= (-CAPV*VPBVX*VPBVX/DIV - CAPVXX)/QUO
      D(12)= (-CAPV*VPBVX*VPBVY/DIV - CAPVXY)/QUO
      D(15)= -VPBVX*FAC4
      DY(9) =D(11)*YC(7) +D(12)*YC(8) - D(1)*YC(9) - D(6)*YC(10) + D(15)
      D(17)= (-CAPV*VPBVY*VPBVY/DIV - CAPVYY)/QUO
      D(20)= -VPBVY*FAC4
      DY(10)=D(12)*YC(7) +D(17)*YC(8) - D(2)*YC(9) - D(7)*YC(10) + D(20)
      DO 52  J=1,10
   52 AK(I,J) = STEP * DY(J)
      DO 53  J=1,10
   53 YVARS(J) = ( AK(1,J)+2.*AK(2,J)+2.*AK(3,J)+AK(4,J) )/6. + YVARS(J)
      TVAR = TVAR + STEP
      TAU  = TAU + STEP
      IF (N1-K)  54,56,54
   54 IF (LMAX-L)  62,55,62
   55 IF ((K-1)/NSTEP+1-NK)  62,62,56
   56 NK = NK + 1
      YC(5)= YVARS(5)
      YC(6)= YVARS(6)
      LR = 0
      CALL TERP
      CALL AP3
      LR = 1
      IF (LMAX-L)  61,60,61
```

```
60 X(NK) = YVARS(5)
   Y(NK) = YVARS(6)
   X(NK+100) = H
   X(NK+300) = TAU
   CALL ANGLE
   Y(NK+100) = XK
   X(NK+200) = XLG
   Y(NK+200) = XLT
61 IF (N1-K)  62,67,62
62 DELX = YVARS(5) - X(1)
   DELY = YVARS(6) - Y(1)
   IF (DELX*DELX + DELY*DELY - S12*S12) 63,65,65
63 IF (ABSF(YVARS(5)- 9.5)- 7.5) 64,65,65
64 IF (ABSF(YVARS(6)-16.5)-14.5) 66,65,65
65 N1 = K
   T  = TAU
   GO TO 56
66 CONTINUE
C  PRINT ALPHA, T, X, AND Y AT END OF EACH ITERATION
67 WRITE(51,43) L,N1,ALF,T,YVARS(5),XFIN,YVARS(6),YFIN
   XLAM = YVARS(1)*COSA + YVARS(3)*SINA
    XMU = YVARS(2)*COSA + YVARS(4)*SINA
   CLAM = SQRTF(XLAM*XLAM + XMU*XMU)
   ABS = (XLAM*CK +  XMU*SK)*A/CLAM
   ORD = ( XMU*CK - XLAM*SK)*B/CLAM
   HYP = SQRTF(ABS*ABS + ORD*ORD)
   VMAJ= A * ABS/HYP - CC
   VMIN= B * ORD/HYP
   DELX = YVARS(5) - 24.
   DELY = YVARS(6) - 16.
   EMFI = (DELX*DELX + DELY*DELY + 973.75)/1043.638743
   XDOT= (CK*VMAJ-SK*VMIN)*EMFI/8.5660416667
   YDOT= (SK*VMAJ+CK*VMIN)*EMFI/8.5660416667
   DIFX = XFIN - YVARS(5)
   DIFY = YFIN - YVARS(6)
   DET = XDOT*YVARS(8) - YDOT*YVARS(7)
   DIFT= (YVARS(8)*DIFX - YVARS(7)*DIFY)/DET
   DIFA= (XDOT*DIFY - YDOT*DIFX)/DET
    T   = DIFT + T
   ALF  = DIFA/RMUL + ALF
   COSA = COSF(ALF)
   SINA = SINF(ALF)
C  PRINT NEW VALUES OF ALPHA AND T
   WRITE(51,50) ALF,T
50 FORMAT (11XF11.5,F9.3)
69 CONTINUE
   IF (DIFX*DIFX + DIFY*DIFY - EMFI*EMFI*.2366)  72,72,70
70 WRITE(51,71) LG
71 FORMAT(20H0 OTS ROUTE OF SHIP A4,47H MORE THAN 100 MILES FROM DEST
  +INATION BUT TRACK/69H  IS PLOTTED. INCREASE RMUL OR LMAX, OR BOTH,
```

```
   + TO IMPROVE CONVERGENCE.)
C  TABULATE FINAL TRACK DAILY POSITION, WAVE HEIGHT AND DIRECTION
 72 WRITE(51,73)
 73 FORMAT (1H0/4X4HDAYS7X5HLONGI4X5HLATI-5X4HWAVE5X14HWAVE DIRECTION/
   +2X9HOF TRAVEL4X5H-TUDE4X4HTUDE5X6HHEIGHT6X10HFROM NORTH/)
    WRITE(51,74)(X(K+300),X(K+200),Y(K+200),X(K+100),Y(K+100),K=1,NK)
 74 FORMAT (F9.2,F11.1,F8.1,F9.0,F14.0)
C  ROTATE AND TRANSLATE AXES FOR PLOT OF DAILY POSITIONS
    DO 75  I=1,NK
    TEMP = .97780241408*X(I) - .20952908873*Y(I) + 3.0032502718
    Y(I) = .20952908873*X(I) + .97780241408*Y(I) - 4.4699538929
 75 X(I) = TEMP
C  PUNCH 11 CARDS USEABLE FOR A LATER PLOT OF TRACK
    WRITE(52,76) LG,LF,NK
 76 FORMAT (2A8,I2,61X1H )
    WRITE(52,78) (((RX(I,J),I=1,10),LG,LF,J),J=1,2),
   +             (((RY(I,J),I=1,10),LF,LG,J),J=1,2)
 78 FORMAT (10F5.2,2A8,I2,11X1H )
    CALL DRAW (NK,X,Y,3,4,LF,IT,2.,2.,0,0,2,2,9,15,0,LAST)
    WRITE(51,93)
 93 FORMAT (1H1)
C  PROCEED TO COMPUTE THE ROUTE OF NEXT SHIP
 80 CONTINUE
    STOP
    END
    SUBROUTINE TERP
    DIMENSION HT(4,4),CT(4,4),ST(4,4),P(4),Q(4),PX(4),QY(4),PXX(4),QYY
   +(4),HD(4),CD(4),SD(4),HS(4),CS(4),SS(4),HP(4),CP(4),SP(4),HXS(4),
   +CXS(4),SXS(4),HPX(4),HPY(4),HPXX(4),HPXY(4),HPYY(4),CPX(4),CPY(4),
   +CPXX(4),CPXY(4),CPYY(4),SPX(4),SPY(4),SPXX(4),SPXY(4),SPYY(4),C(4)
    COMMON    YC(10),LR,A,B,CC,H,CK,SK
    COMMON/L1/XHT(5760),CSK(5760),SNK(5760),TC
    COMMON/L2/HX,HY,HXX,HXY,HYY
    COMMON/L3/DKX,DKY,DKXX,DKXY,DKYY
    DTC = 2.*TC
     L = XINTF(DTC)
    IF (L-3)  1,1,7
  1 TT = (-INTF(DTC)+DTC)*2. - 1.
    TP1= TT + 1.
    TM1= TT - 1.
    T2M= TP1*TM1
    IF (L)  2,2,3
  2 K4 = 3
    TM3= TT - 3.
    C(1)= TM1*TM3/8.
    C(2)=-TP1*TM3/4.
    C(3)= T2M/8.
    GO TO 16
  3 K4 = 4
    IF (L-2)  4,4,6
```

```
4    G = (3.*TT+2.)*TT - 9.
     F = -4.*TT + G
   C(1)= -T2M*TM1/16.
   C(2)= G*TM1/16.
 5 C(3)= -F*TP1/16.
   C(4)= T2M*TP1/16.
   GO TO 15
 6 C(1)= -T2M*TM1/16.
   C(2)=((2.*TT+1.)*TT-7.)*TM1/12.
   C(3)=((1.-TT)*TT+4.)*TP1/8.
   C(4)= T2M*TP1/48.
   GO TO 15
 7  L = XINTF(TC-2.) + 4
   IF (L-10)  9,8,8
 8 K4 = 1
    L = 9
   C(1)= 1.
   GO TO 16
 9 TT = (-INTF(TC)+TC)*2. - 1.
   TP1= TT + 1.
   TM1= TT - 1.
   T2M= TP1*TM1
     G = (3.*TT+2.)*TT - 9.
     F = -4.*TT + G
   C(1)= -T2M*TM1/16.
   IF (L-9)  11,10,8
10 K4 = 2
   C(2)= (G*TM1 + (T2M-F)*TP1)/16.
   GO TO 15
11 C(2)= G*TM1/16.
   IF (L-8)  13,12,10
12 K4 = 3
   C(3)= (T2M-F)*TP1/16.
   GO TO 15
13 K4 = 4
   IF (L-5)  14,5,5
14 C(1)= -T2M*TM1/6.
   C(2)=((5.*TT+2.)*TT-11.)*TM1/16.
   C(3)=((-5.*TT+4.)*TT+13.)*TP1/24.
   C(4)= T2M*TP1/16.
15  L = L-1
16  M = XINTF(YC(5)) - 2
    N = XINTF(YC(6)) - 2
   XX = (-INTF(YC(5))+YC(5))*2.0 - 1.
   YY = (-INTF(YC(6))+YC(6))*2.0 - 1.
   XP1= XX + 1.0
   XM1= XX - 1.0
   YP1= YY + 1.0
   YM1= YY - 1.0
   X2M= XP1*XM1
```

```
      Y2M= YP1*YM1
      P(1) = (XX+2.)*X2M*XM1*XM1/32.
      P(2) = ((((-3.*XX*XX+12.)*XX-2.)*XX-25.)*XX+18.)/32.
      P(3) = (-XX*XX+9.)/8. - P(2)
      P(4) = (-XX+2.)*X2M*XP1*XP1/32.
      Q(1) = (YY+2.)*Y2M*YM1*YM1/32.
      Q(2) = ((((-3.*YY*YY+12.)*YY-2.)*YY-25.)*YY+18.)/32.
      Q(3) = (-YY*YY+9.)/8. - Q(2)
      Q(4) = (-YY+2.)*Y2M*YP1*YP1/32.
      PX(4)= ((-5.*XX+10.)*XX-3.)*XP1*XP1/16.
      PX(1)=  XX/2. - PX(4)
      PX(2)=(((-15.*XX*XX+36.)*XX-4.)*XX 25.)/16.
      PX(3)= -XX/2. - PX(2)
      QY(4)= ((-5.*YY+10.)*YY-3.)*YP1*YP1/16.
      QY(1)=  YY/2. - QY(4)
      QY(2)=(((-15.*YY*YY+36.)*YY-4.)*YY 25.)/16.
      QY(3)= -YY/2. - QY(2)
       IF (LR) 17,18,17
17    PXX(4)=((-5.*XX*XX+6.)*XX+1.)/2.
      PXX(1)= 1. - PXX(4)
      PXX(2)=((-15.*XX*XX+18.)*XX-1.)/2.
      PXX(3)= -1. - PXX(2)
      QYY(4)=((-5.*YY*YY+6.)*YY+1.)/2.
      QYY(1)= 1. - QYY(4)
      QYY(2)=((-15.*YY*YY+18.)*YY-1.)/2.
      QYY(3)= -1. - QYY(2)
18    DO 27  K=1,K4
      HP(K) = 0.0
      CP(K) = 0.0
      SP(K) = 0.0
      HPX(K)= 0.0
      HPY(K)= 0.0
      CPX(K)= 0.0
      CPY(K)= 0.0
      SPX(K)= 0.0
      SPY(K)= 0.0
       IF (LR) 19,20,19
19    HPXX(K) = 0.0
      HPXY(K) = 0.0
      HPYY(K) = 0.0
      CPXX(K) = 0.0
      CPXY(K) = 0.0
      CPYY(K) = 0.0
      SPXX(K) = 0.0
      SPXY(K) = 0.0
      SPYY(K) = 0.0
20     KK = ((K+L)*32+N)*18 + M - 594
      DO 23  J=1,4
      HD(J) = 0.0
      CD(J) = 0.0
```

```
   SD(J) = 0.0
   HS(J) = 0.0
   CS(J) = 0.0
   SS(J) = 0.0
   IF (LR) 21,22,21
21 HXS(J) = 0.0
   CXS(J) = 0.0
   SXS(J) = 0.0
22  JJ = J*18 + KK
   DO 23  I=1,4
    II = I + JJ
   HT(I,J) = XHT(II)
   CT(I,J) = CSK(II)
23 ST(I,J) = SNK(II)
   DO 25  I=1,4
   DO 25  J=1,4
   HD(I) = Q(J)*HT(I,J) + HD(I)
   CD(I) = Q(J)*CT(I,J) + CD(I)
   SD(I) = Q(J)*ST(I,J) + SD(I)
   HS(I) = P(J)*HT(J,I) + HS(I)
   CS(I) = P(J)*CT(J,I) + CS(I)
   SS(I) = P(J)*ST(J,I) + SS(I)
   IF (LR) 24,25,24
24 HXS(I)=PX(J)*HT(J,I) + HXS(I)
   CXS(I)=PX(J)*CT(J,I) + CXS(I)
   SXS(I)=PX(J)*ST(J,I) + SXS(I)
25 CONTINUE
   DO 27  I=1,4
   HP(K) = HD(I)*P(I) + HP(K)
   CP(K) = CD(I)*P(I) + CP(K)
   SP(K) = SD(I)*P(I) + SP(K)
   HPX(K)=HD(I)*PX(I) + HPX(K)
   CPX(K)=CD(I)*PX(I) + CPX(K)
   SPX(K)=SD(I)*PX(I) + SPX(K)
   HPY(K)=HS(I)*QY(I) + HPY(K)
   CPY(K)=CS(I)*QY(I) + CPY(K)
   SPY(K)=SS(I)*QY(I) + SPY(K)
   IF (LR)26,27,26
26 HPXX(K)= HD(I)*PXX(I) + HPXX(K)
   HPXY(K)=HXS(I)* QY(I) + HPXY(K)
   HPYY(K)= HS(I)*QYY(I) + HPYY(K)
   CPXX(K)= CD(I)*PXX(I) + CPXX(K)
   CPXY(K)=CXS(I)* QY(I) + CPXY(K)
.  CPYY(K)= CS(I)*QYY(I) + CPYY(K)
   SPXX(K)= SD(I)*PXX(I) + SPXX(K)
   SPXY(K)=SXS(I)* QY(I) + SPXY(K)
   SPYY(K)= SS(I)*QYY(I) + SPYY(K)
27 CONTINUE
    H  = 0.0
    CK = 0.0
```

```
      SK  = 0.0
      HX  = 0.0
      HY  = 0.0
     CKX  = 0.0
     CKY  = 0.0
     SKX  = 0.0
     SKY  = 0.0
     IF (LR)  28,29,28
  28 HXX  = 0.0
     HXY  = 0.0
     HYY  = 0.0
     CKXX= 0.0
     CKXY= 0.0
     CKYY= 0.0
     SKXX= 0.0
     SKXY= 0.0
     SKYY= 0.0
  29 DO 31  K=1,K4
      H   = C(K)*HP(K) + H
     CK   = C(K)*CP(K) + CK
     SK   = C(K)*SP(K) + SK
      HX  = C(K)*HPX(K)  + HX
      HY  = C(K)*HPY(K)  + HY
     CKX  = C(K)*CPX(K)  + CKX
     CKY  = C(K)*CPY(K)  + CKY
     SKX  = C(K)*SPX(K)  + SKX
     SKY  = C(K)*SPY(K)  + SKY
     IF (LR)  30,31,30
  30 HXX  = C(K)*HPXX(K)  + HXX
     HXY  = C(K)*HPXY(K)  + HXY
     HYY  = C(K)*HPYY(K)  + HYY
     CKXX= C(K)*CPXX(K)  + CKXX
     CKXY= C(K)*CPXY(K)  + CKXY
     CKYY= C(K)*CPYY(K)  + CKYY
     SKXX= C(K)*SPXX(K)  + SKXX
     SKXY= C(K)*SPXY(K)  + SKXY
     SKYY= C(K)*SPYY(K)  + SKYY
  31 CONTINUE
     RAD  = SQRTF(CK*CK + SK*SK)
     CK   = CK/RAD
     SK   = SK/RAD
     DKX  = CK*SKX  - SK*CKX
     DKY  = CK*SKY  - SK*CKY
     IF (LR)  32,33,32
  32 DKXX= CK*SKXX-SK*CKXX
     DKYY= CK*SKYY-SK*CKYY
     DKXY= CK*SKXY-SK*CKXY + CKY*SKX - SKY*CKX
  33 RETURN
     END
```

```
      SUBROUTINE ANGLE
      COMMON    YC(10),LR,A,B,CC,H,CK,SK
      COMMON/L6/YVARS(10),XK,XLG,XLT
      DELX = YVARS(5) - 24.
      DELY = YVARS(6) - 16.
      COSXK= -DELX*CK - DELY*SK
      SINXK=  DELX*SK - DELY*CK
      IF (COSXK)  2,1,2
    1 XK = SIGNF(90.,SINXK)
      GO TO 6
    2 XK = ATANF(SINXK/COSXK)*57.29577951
      IF (COSXK)  3,6,6
    3 IF (SINXK)  5,4,4
    4 XK = XK + 180.
      GO TO 6
    5 XK = XK - 180.
    6 IF (XK)  7,8,8
    7 XK = 360. + XK
    8 XT = DELX*.98480775 - DELY*.17364818
      YT = DELX*.17364818 + DELY*.98480775
      RAD= SQRTF(XT*XT + YT*YT)
      IF (XT)  10,9,10
    9 XLG = SIGNF(90.0,YT)
      GO TO 14
   10 XLG = ATANF(YT/XT)*57.29577951
      IF (XT)  11,14,14
   11 IF (YT)  13,12,12
   12 XLG = XLG + 180.
      GO TO 14
   13 XLG = XLG - 180.
   14 XLT = -ATANF(RAD/31.205)*114.591559 + 90.0
      RETURN
      END
      SUBROUTINE VDERIV
      COMMON    YC(10),LR,A,B,CC,H,CK,SK
      COMMON/L3/DKX,DKY,DKXX,DKXY,DKYY
      COMMON/L4/AX,AY,BX,BY,CX,CY,AXX,AXY,AYY,BXX,BXY,BYY,CXX,CXY,CYY
      COMMON/L5/COST,SINT,V,CAPV,CAPVX,CAPVY,CAPVXX,CAPVXY,CAPVYY,
     +          VPBVX,VPBVY,DIV,RBV,CAPVP
      SIN2T = 2.*SINT*COST
      COS2T = 2.*COST*COST - 1.
      DELX = YC(5) - 24.
      DELY = YC(6) - 16.
      EMFI = (DELX*DELX + DELY*DELY + 973.75)/1043.638743
      EMFIX= DELX/521.8193715
      EMFIY= DELY/521.8193715
      AMCX = A*AX - CC*CX
      AMCY = A*AY - CC*CY
      AMC2 = A*A - CC*CC
```

```
      BCA2 = B*B - AMC2
      BCASN2= BCA2*SIN2T
      BCACS2= BCA2*COS2T
      ROOT = SQRTF((B*B + AMC2 + BCACS2)/2.)
      BCACOS= B*CC*COST/A
      BCASIN= B*CC*SINT/A
      REC = BCACOS + ROOT
       FP = .5*BCASN2/ROOT + BCASIN
      VPBV  = FP/REC
      IF (LR) 2,1,2
    1  V  = (B*AMC2/REC)/A
    2 VBR = V/8.5660416667
      CAPV = VBR*EMFI
       FX = (CC*BX + B*CX - B*CC*AX/A)/A
       FY = (CC*BY + B*CY - B*CC*AY/A)/A
       RX = AMCX*SINT*SINT + B*BX*COST*COST + .5*BCASN2*DKX
       RY = AMCY*SINT*SINT + B*BY*COST*COST + .5*BCASN2*DKY
      RECX= FX*COST + BCASIN*DKX + RX/ROOT
      RECY= FY*COST + BCASIN*DKY + RY/ROOT
      FACX= 2.*AMCX/AMC2 + BX/B - AX/A - RECX/REC
      FACY= 2.*AMCY/AMC2 + BY/B - AY/A - RECY/REC
      CAPVX = (FACX*EMFI + EMFIX)*VBR
      CAPVY = (FACY*EMFI + EMFIY)*VBR
      IF (LR)  4,3,4
    3 CAPVP = VPBV * CAPV
      RETURN
    4 AMCXY = AX*AY - CX*CY + A*AXY - CC*CXY
      AMCXX = AX*AX - CX*CX + A*AXX - CC*CXX
      AMCYY = AY*AY - CY*CY + A*AYY - CC*CYY
      FXY=(CC*BXY + B*CXY - B*CC*AXY/A + BX*CY + CX*BY-(B*CY+CC*BY)*AX/A
     +    -CC*BX*AY/A - B*CX*AY/A + (2.*B*CC*AX*AY/A)/A)/A
      FXX=(CC*BXX + B*CXX - B*CC*AXX/A + 2.*BX*CX - (B*CX+CC*BX)*2.*AX/A
     +    +(2.*B*CC*AX*AX/A)/A)/A
      FYY=(CC*BYY + B*CYY - B*CC*AYY/A + 2.*BY*CY - (B*CY+CC*BY)*2.*AY/A
     +    +(2.*B*CC*AY*AY/A)/A)/A
      BCAX = B*BX - AMCX
      BCAY = B*BY - AMCY
      RXY = AMCXY*SINT*SINT + (BCAX*DKY+BCAY*DKX)*SIN2T - BCACS2*DKX*DKY
     +       (BX*BY+B*BXY)*COST*COST + .5*BCASN2*DKXY
      RXX = AMCXX*SINT*SINT + (2.*BCAX*SIN2T-BCACS2*DKX)*DKX
     +       (BX*BX+B*BXX)*COST*COST + .5*BCASN2*DKXX
      RYY = AMCYY*SINT*SINT + (2.*BCAY*SIN2T-BCACS2*DKY)*DKY
     +       (BY*BY+B*BYY)*COST*COST + .5*BCASN2*DKYY
      RECXY = FXY*COST + (FX*DKY+FY*DKX)*SINT - BCACOS*DKX*DKY
     +         BCASIN*DKXY + ((-RX*RY/ROOT)/ROOT+RXY)/ROOT
      RECXX = FXX*COST + (2.*FX*SINT-BCACOS*DKX)*DKX
     +         BCASIN*DKXX + ((-RX*RX/ROOT)/ROOT+RXX)/ROOT
      RECYY = FYY*COST + (2.*FY*SINT-BCACOS*DKY)*DKY
     +         BCASIN*DKYY + ((-RY*RY/ROOT)/ROOT+RYY)/ROOT
      FACXY = (-2.*AMCX*AMCY/AMC2+AMCXY)*2./AMC2 + (-BX*BY/B+BXY)/B
```

```
+          (AX*AY/A-AXY)/A + (RECX*RECY/REC-RECXY)/REC
 FACXX = (-2.*AMCX*AMCX/AMC2+AMCXX)*2./AMC2 + (-BX*BX/B+BXX)/B
+          (AX*AX/A-AXX)/A + (RECX*RECX/REC-RECXX)/REC
 FACYY = (-2.*AMCY*AMCY/AMC2+AMCYY)*2./AMC2 + (-BY*BY/B+BYY)/B
+          (AY*AY/A-AYY)/A + (RECY*RECY/REC-RECYY)/REC
 CAPVXY = ((FACX*FACY+FACXY)*EMFI + FACX*EMFIY + FACY*EMFIX)*VBR
 CAPVXX = ((FACX*FACX+FACXX)*EMFI +2.*FACX*EMFIX+.001916371938)*VBR
 CAPVYY = ((FACY*FACY+FACYY)*EMFI +2.*FACY*EMFIY+.001916371938)*VBR
 FPX = ((-.5*BCASN2*RX/ROOT)/ROOT + BCAX*SIN2T - BCACS2*DKX)/ROOT
+        FX*SINT - BCACOS*DKX
 FPY = ((-.5*BCASN2*RY/ROOT)/ROOT + BCAY*SIN2T - BCACS2*DKY)/ROOT
+        FY*SINT - BCACOS*DKY
 VPBVX = (-FP*RECX/REC + FPX)/REC
 VPBVY = (-FP*RECY/REC + FPY)/REC
 RECP= -.5*BCASN2/ROOT - BCASIN
 FPP = ((.25*BCASN2*BCASN2/ROOT)/ROOT + BCACS2)/ROOT + BCACOS
 VPBVP = (-FP*RECP/REC + FPP)/REC
 DIV = VPBV*VPBV - VPBVP + 1.
 RBV = SQRTF(VPBV*VPBV + 1.)
 RETURN
 END
 SUBROUTINE AP3
 COMMON    YC(10),LR,A,B,CC,H,CK,SK
 COMMON/L2/HX,HY,HXX,HXY,HYY
 COMMON/L4/AX,AY,BX,BY,CX,CY,AXX,AXY,AYY,BXX,BXY,BYY,CXX,CXY,CYY
 R1 = SQRTF((.062760850324*H-.60018313990)*H+4.7014047597)
 VF = 0.021541997619*H + 19.278272298 - R1
 R2 = SQRTF((.060104035000*H-.96636105838)*H+6.1294779871)
  B = -0.12663045716*H + 19.585778258 - R2
 DVFM= (-.062760850324*H+.30009156995)/R1
 DVF = DVFM + .021541997619
 DBM = (-.060104035000*H+.48318052919)/R2
  DB = DBM - 0.12663045716
 D2VF= (DVFM*DVFM - .062760850324)/R1
 D2B = (DBM * DBM - .060104035000)/R2
 IF (H-17.)  1,1,2
1 R3 =SQRTF((.083601632403*H-1.3340008783)*H+7.1705253492)
 VH = -0.24791650490*H + 19.793624009 - R3
 DVHM= (-.083601632403*H+.66700043915)/R3
 DVH = DVHM - 0.24791650490
 D2VH= (DVHM*DVHM - .083601632403)/R3
 GO TO 3
2 R4 =SQRTF((.055777533214*H-3.0851911409)*H+45.698170763)
 VH = -0.31013284648*H + 14.848653764 + R4
 DVHM= ( .055777533214*H-1.54259557045)/R4
 DVH = DVHM - 0.31013284648
 D2VH= (-DVHM*DVHM+ .055777533214)/R4
3  A = (VF+VH)*.5
 CC = A-VH
 DA =(DVF+DVH)*.5
```

```
      DC =DA-DVH
      AX = DA*HX
      AY = DA*HY
      BX = DB*HX
      BY = DB*HY
      CX = DC*HX
      CY = DC*HY
      IF (LR)  4,8,4
    4 XX = HX*HX
      XY = HX*HY
      YY = HY*HY
      D2A =(D2VF+D2VH)*.5
      D2C = D2A - D2VH
      AXX= DA*HXX + D2A*XX
      AXY= DA*HXY + D2A*XY
      AYY= DA*HYY + D2A*YY
      BXX= DB*HXX + D2B*XX
      BXY= DB*HXY + D2B*XY
      BYY= DB*HYY + D2B*YY
      CXX= DC*HXX + D2C*XX
      CXY= DC*HXY + D2C*XY
      CYY= DC*HYY + D2C*YY
    8 RETURN
      END
          END
          FINIS
EXECUTER.
OB 0574          BLEICK           BOX 6
C2AP3            APRIL 14         1967             JUL26,66            1
666JUL26,66J207     00. 154.0 41.0-123.0 38.0  10 610


COOP, BOX 6, BLEICK ,I/1/0/2/S/56/57,5,10000,0, TAPE - 14 APR 67.
BINARY,56.
RELOCOM.
FTN,L,A,E.
      PROGRAM TAPE
      DIMENSION ND(3969)
      COMMON     X(390),Y(390),MD(63,63),
     +           XHT(18,32,10),CSK(18,32,10),SNK(18,32,10)
      EQUIVALENCE (MD,ND),(ID,ARG),(IH,H)
      REWIND 1
      REWIND 2
      ISCALE = 2000000000000000B
  READ COORDINATES FOR MAP GRID OF DRAW SUBROUTINE
      READ(50,1) (X(I),I=1,390), (Y(I),I=1,390)
    1 FORMAT (15F5.3)
      WRITE(2,7) X,Y
    7 FORMAT (17F7.3)
      IF (IOCHECK,2) 2,4
```

```
  2 WRITE(51,3)
  3 FORMAT (37H0  PARITY ERROR OCCURRED ON X,Y WRITE/)
  4 DO 43  K=1,10
C  READ WAVE DIRECTION FROM FLEET NUMERICAL WEATHER FACILITY TAPE
    BUFFER IN(1,2) (ND(1),ND(3969))
  5 IF(UNIT,1) 5,14,8,10
  8 WRITE(51,9) K
  9 FORMAT (44H0  DIRECTION EOF OR EOT ERROR OCCURRED ON K=I3/)
    GO TO 6
 10 WRITE(51,11) K
 11 FORMAT (49H0  DIRECTION PARITY OR LENGTH ERROR OCCURRED ON K=I3/)
    M = LENGTHF(1)
    IF (M-3969) 12,14,12
 12 WRITE(51,13) M
 13 FORMAT (28H0  DIRECTION BUFFER LENGTH =I6/)
C  COMPUTE COSINE AND SINE OF WAVE DIRECTION K MEASURED FROM X AXIS
 14 DO 17  I=1,18
    DELX = I-24
    DO 17  J=1,32
    DELY = J-16
    ROOT = SQRTF(DELX*DELX + DELY*DELY)
     ID = MD(I+8,J+16)/2048 + ISCALE
    ARG = (ARG + 0.0)*11.17010721
    COS = COSF(ARG)
    SIN = SINF(ARG)
    CSK(I,J,K) =(-DELX*COS - DELY*SIN)/ROOT
 17 SNK(I,J,K) = (DELX*SIN - DELY*COS)/ROOT
C  READ WAVE PERIOD FROM FLEET NUMERICAL WEATHER FACILITY TAPE (NOT USED)
    BUFFER IN(1,2) (ND(1),ND(3969))
 15 IF(UNIT,1) 15,24,18,20
 18 WRITE(51,19) K
 19 FORMAT (41H0  PERIOD EOF OR EOT ERROR OCCURRED ON K=I3/)
    GO TO 6
 20 WRITE(51,21) K
 21 FORMAT (46H0  PERIOD PARITY OR LENGTH ERROR OCCURRED ON K=I3/)
    M = LENGTHF(1)
    IF (M-3969) 22,24,22
 22 WRITE(51,23) M
 23 FORMAT (25H0  PERIOD BUFFER LENGTH =I6/)
C  READ WAVE HEIGHT H FROM FLEET NUMERICAL WEATHER FACILITY TAPE
 24 BUFFER IN(1,2) (ND(1),ND(3969))
 25 IF(UNIT,1) 25,34,28,30
 28 WRITE(51,29) K
 29 FORMAT (41H0  HEIGHT EOF OR EOT ERROR OCCURRED ON K=I3/)
    N1 = K
    GO TO 16
 30 WRITE(51,31) K
 31 FORMAT (46H0  HEIGHT PARITY OR LENGTH ERROR OCCURRED ON K=I3/)
    M = LENGTHF(1)
    IF (M-3969) 32,34,32
```

```
32 WRITE(51,33) M
33 FORMAT (25H0  HEIGHT BUFFER LENGTH =I6/)
34 DO 43  I=1,18
   DO 43  J=1,32
    IH = MD(I+8,J+16)/2048 + ISCALE
43 XHT(I,J,K) = (H + 0.0)*64.
   REWIND 1
   WRITE(2,47) XHT,CSK,SNK
47 FORMAT (13F9.5)
   IF(IOCHECK,2) 44,46
44 WRITE(51,45)
45 FORMAT (45H0  PARITY ERROR OCCURRED ON XHT,CSK,SNK WRITE/)
46 END FILE 2
   N1 = 10
16 WRITE(51,27) (((XHT(I,J,K),I=1,17),J=1,31,5),K=1,N1)
27 FORMAT (17F7.2/)
 6 REWIND 2
   STOP
   END
   END
      FINIS
ECUTER.
78   9781746117461  978   978 2070 4931 4133 3388 2698 2065 1491  978  978ABS 1
91 2064 2697 5198 4550 3956 3418 2937 2515 2152 1851 1612 1435 1321 1271ABS 2
84 1361 1501 1704 1969 2296 2684 3130 3635 4197 4814 5484 6205 6976 7794ABS 3
64 9841 8966 8144 7378 6669 6021 5437 4917 4465 4082 3769 3528 3359 3262ABS 4
40 3290 3414 3611 3879 4219 4628 5106 5651 6259 6931 766110146 9307 8535ABS 5
34 7207 6658 6188 5800 5496 5278 5146 5102 5145 5275 5491 5793 6179 6647ABS 6
96 7821 8520 929110128110281198713000140621746117461164771552314600137l4ABS 7
6812067113121060 8 9957 9363 8827 8353 7942 7596 7316 7104 6960 6885 6880ABS 8
44 7078 7280 7550 7886 8288 8753 9279 98651050711204119511274615672 14829ABS 9
2513265125511188711277107231022 7 9793 9422 9116 8877 8705 8601 8567 8601ABS10
05 8877 9116 9422 97931022710723112771188712551132651402614829156731 6551ABS11
6117461166631589715167144751382513220126641215911708113111097310694 10475ABS12
1810224101931022410318104751069410973113111170812159126641322013825 14475ABS13
6715897166631746117461168271622115645151001459014117136821328812936 12628ABS14
3612149119791185811785117601178511858119791214912366126281293613288 13682ABS15
171459 15100156451622116827174611746116989165391611315712153881499114674ABS16
8714131139081371713560134381335013297132791329713350134381356013717 13908ABS17
3114387146741499115338157121611316539169891746117461171501685516577 16317ABS18
7415851156471546215299151561503514935148571480114768147571476814801 14857ABS19
3515035151561529915462156471585116074163171657716855171501746117461 17312ABS20
7217041169191680616702166081652316448163821632716281162461622016205 16200ABS21
051622 16246162811632716382164481652316608167021680616919170411717217312ABS22
6117461167221527717461174611366511824174611746 1 9667 70621746117461 3797ABS23
78   9781746117461  978   9781746117461  978   9781746117461  978   97817461ABS24
61   978   9781746117461  978   9781746117461  978   9781746117461 2520 5878ABS25
6117461 86421099117461174611304014870174611746116537                    ABS26
292870528705  629   629 2224  629   629 1612 2637 3700 4797 5927 70852532ORD 1
8027609287052870527721267032565524578234782235721217200631889817725165470RD 2
```

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15368141921302211861107l3 9580 8467 7377 6312 5275 4271 3302 2369 1478  629ORD
  629 1408 2242 3127 4061 5039 6059 7116 8207 93281047311640128241402015224ORD
1643217639188412003321211223712350724617256952673927743287052870527772267830RD
257422465523528223642117119953187181747016216149621371412478112611O067 8903ORD
 7774 6686 5645 4654 3720 2846 2037 1297  629  629  976 1379 1844 2372 2958ORD
 3601 4298 5046 5842 6682 7562 8480 943110410114151244013481145331559316656ORD
177161877 198132084121849228322378824710255972644327246280012870528705281630RD
275642691126207254562466023825229532205021118201641919018203172051620315202ORD
14204132171224311288l0357 9453 8582 7746 6951 6200 5496 4843 4244 3702 3219ORD
 2797 4582 5005 5483 6013 6593 7220 7890 8602 935010132109431178012638135140RD
144031530116204171061800418893197692062721464222762305723806245172518725814ORD
263942692427402278252605225660252272475624248237052313022525218932123720559ORD
198621914918424176891694816204154591471813983132581254511849111701O514 9882ORD
 9277 8702 8159 7651 7180 6747 6355 8154 8507 8887 9294 97261018110657111540RD
116681219912744133011386914445150281561516204167921737917962185381910619663ORD
202082073921254217502222622681231132352023900242532236022060217432141221067ORD
207092033819957195661916618757183421792117496170671663616204157711534014911ORD
144861406513650132421284112450120691169811340109951066410347100471222212442ORD
126671289713133133721361613864141151437014627148861514715410156741593816204ORD
164691673316997172601752117781180381829218543187911903519275195101974019966ORD
201852726128705287052522423685287052870522466214622870528705206081986428705ORD
287052792919200185942555823357180311750021277192781698916491173271539415997ORD
15499134481145914991l4464 9395 72161390713309 4876 23181265511926  629  629ORD
1109310117  629  629 8938 7461  629  629 5521 2814  629                  ORD
```

```
      SUBROUTINE AP2
      COMMON    YC(10),LR,A,B,CC,H,CK,SK
      COMMON/L2/HX,HY,HXX,HXY,HYY
      COMMON/L4/AX,AY,BX,BY,CX,CY,AXX,AXY,AYY,BXX,BXY,BYY,CXX,CXY,CYY
      R1 = SQRTF((.041783709356*H-.42321401072)*H+2.2342337579)
      VF = -.028281950577*H + 17.494735347 - R1
      R2 = SQRTF((.058458667266*H-.90729449065)*H+6.4033842487)
       B = -0.14520001518*H + 18.530490911 - R2
      DVFM= (-.041783709356*H+.21160700536)/R1
      DVF = DVFM - .028281950577
      DBM = (-.058458667266*H+.45364724533)/R2
       DB = DBM - 0.14520001518
      D2VF= (DVFM*DVFM - .041783709356)/R1
      D2B = (DBM * DBM - .058458667266)/R2
      IF (H-15.)  1,1,2
    1 R3 =SQRTF(( .23341292994*H-3.1096617758)*H+29.275404601)
      VH = -0.25152614353*H + 21.408836894 - R3
      DVHM= ( -.23341292994*H+1.5548308879)/R3
      DVH = DVHM - 0.25152614353
      D2VH= (DVHM*DVHM -  .23341292994)/R3
      GO TO 3
    2 R4 =SQRTF(( .14668786198*H-6.8828319323)*H+105.12448592)
      VH = -0.36970234218*H + 11.346369501 + R4
      DVHM= ( 0.14668786198*H - 3.44141596615)/R4
```

```
      DVH = DVHM - 0.36970234218
      D2VH= (-DVHM*DVHM + .14668786198)/R4
3     A = (VF+VH)*.5
      CC = A-VH
      DA =(DVF+DVH)*.5
      DC =DA-DVH
      AX = DA*HX
      AY = DA*HY
      BX = DB*HX
      BY = DB*HY
      CX = DC*HX
      CY = DC*HY
      IF (LR)  4,8,4
4     XX = HX*HX
      XY = HX*HY
      YY = HY*HY
      D2A =(D2VF+D2VH)*.5
      D2C = D2A - D2VH
      AXX= DA*HXX + D2A*XX
      AXY= DA*HXY + D2A*XY
      AYY= DA*HYY + D2A*YY
      BXX= DB*HXX + D2B*XX
      BXY= DB*HXY + D2B*XY
      BYY= DB*HYY + D2B*YY
      CXX= DC*HXX + D2C*XX
      CXY= DC*HXY + D2C*XY
      CYY= DC*HYY + D2C*YY
8     RETURN
      END
```

List of cards requiring changes if the geometric dimensions and/or origin, or time dimension of the XHT, CSK and SNK arrays are changed:

<u>VC2AP3</u>: 2,3,4,7,15,27,44,94 to 97,113,114,117,118,146,147,162,163, 168,169,212,213,291,292,306,307,334,335,339 to 341

<u>TERP</u>: 5,6,38,40,50,55,121,133

<u>ANGLE</u>: 1 to 4

<u>VDERIV</u>: 1,8,9

<u>AP3 (and substitutableAP2)</u>: 1

<u>TAPE</u>: 2,3,8,15,27 to 30,32,61 to 63,72,73

Some unnecessary remnants of experimentation remain to be cleaned up as follows:

<u>TERP</u>: When LR=0 only H, CK and SK need be computed before returning to the main VC2AP3 program

<u>AP3 and AP2</u>: When LR=0 only A, B and CC need be computed before returning to the main VC2AP3 program

<u>VDERIV</u>: When LR=0 only CAPV need be computed before returning to the main VC2AP3 program

Glossary (For omissions consult pages 9 and 10)

VC2AP3

X(900),Y(900)	= Storage for map grid data, and temporary storage for output data
IT(12)	= Title for map produced by DRAW subroutine
C(4)	= Runge-Kutta integration weighting factors
AK(4,10)	= Data used in finding four YC(10) intermediate ordinates in one Runge-Kutta integration step
DY(10)	= Time derivatives in the 10 differential equations
D(20)	= Store used in integrating eqs. for $\delta x, \delta y, \delta \xi, \delta \zeta$
LR	= Index to denote a geodesic track (LR=0) or a minimal-time track (LR=1)
A,B,CC	= Parameters for elliptical polar velocity figure
H,CK,SK	= Wave height and wave direction cosine cosK and sine sinK relative to Oxy axes
XHT,CSK,SNK	= Wave field arrays with 18×32×10 or 5760 elements
COST,SINT	= $\cos\theta$, $\sin\theta$ of the polar velocity diagram
V	= Speed in knots on earth's surface
CAPV	= Speed in grid units per day in stereographic plane
CAPVX to CAPVYY	=Partial derivatives of CAPV
VPBVX to VPBVY	= Partial derivatives of V_p/V
DIV	= $(V_p/V)^2-(V_p/V)_p+1$
RBV	= $[(V_p/V)^2+1]^{\frac{1}{2}}$
YVARS(10)	= $\lambda_1, \mu_1, \lambda_2, \mu_2, x, y$, geodesic arc length or $\delta x, \delta y, \delta \xi$, and $\delta \zeta$ at end of each integration step
XK,XLG,XLT	= Wave direction from north, longitude and latitude produced by ANGLE subroutine for printed output tabulation by statements 72 to 74 of VC2AP3
RSTEP	= Floating-point value of NSTEP
COSLG1,SINLG1	= Cosine and sine of longitude of initial point
COSLG2,SINLG2	= Cosine and sine of longitude of terminal point
COSLT1,SINLT1	= Cosine and sine of latitude of initial point
COSLT2,SINLT2	= Cosine and sine of latitude of terminal point
EL,EM,EN	= Direction cosines (later normalized) of normal vector to great circle track plane
X1,Y1,X2,Y2	= Coordinates of initial and terminal points of track relative to North Pole in grid units
S12	= Straight-line distance from X1,Y1 to X2,Y2
ARC (Card 81)	= Great-circle distance from X1,Y1 to X2,Y2
ALF	= α = Departure angle of ship track at initial point relative to Oxy axes as in Figure 1(approx.)
COSA,SINA	= Cosine and sine of ALF
XFIN,YFIN	= Coordinates of desired terminal point relative Oxy
STEP	= Time integration step in units of days
TAU	= Time in days from beginning of track
S	= Arc length on geodesic track
TVAR	= Time in days from first member of time series
TC	= Intermediate values of TVAR in one integration step
N1	= Index for number of integration steps
N2	= Index used in plotting a geodesic track
N3	= Index used to indicate whether a complete geodesic track can be computed

T	= Time in days to complete geodesic track or any time-extremal iterated track
XN1	= Floating-point value of N1
FSTEP	= Final Runge-Kutta process time increment on a time-extremal track, with STEP1 used otherwise
XLAM	= $\lambda = \lambda_1 \cos\alpha + \lambda_2 \sin\alpha$
XMU	= $\mu = \mu_1 \cos\alpha + \mu_2 \sin\alpha$
CLAM	= $\Lambda = [\lambda^2 + \mu^2]^{\frac{1}{2}}$
COSP,SINP	= Direction cosines of CAPV relative to Oxy axes
FAC1 to FAC4	= Temporary storage
DET	= $\lambda_1\mu_2 - \lambda_2\mu_1$
EMFI	= Ratio of a differential distance in stereographic plane to corresponding distance on earth's surface
XDOT,YDOT	= $\dot{x}$ and $\dot{y}$
DIFT,DIFA	= ΔT and $\delta\alpha$
NK	= Index for daily position point plot

TERP

C(4)	= Weighting factors for interpolation in the time dimension between K4 ordinates
L	= Index to pick out member of wave field time series
TT	= t of Eq.(29) of NPS Tech.Report/Res.Paper No. 46
M,N	= Indicies to pick out x,y grid point data
XX,YY	= x,y of equation (18) of this report
P(1) to P(4)	= P_1 to P_4 of equation (19) of this report
Q(1) to Q(4)	= Elements of P'(y) matrix of Eq.(18) of this report
PX,QY,PXX,QYY	= Partial derivatives of P(1 to 4) and Q(1 to 4)
H	= Interpolated wave height in feet
CK,SK	= Interpolated (and later normalized) cosK and sinK
HX to SKYY	= Partial derivatives of H, cosK and sinK
DKX to DKXY	= Partial derivatives of the wave direction angle K

AP3, AP2 and VDERIV

VF	= Ship speed in knots in presence of following waves
VH	= Ship speed in knots in presence of head waves
A,B,CC	= Parameters for elliptical polar velocity diagram
AX to CYY	= Partial derivatives of A, B and CC
SIN2T,COS2T	= $\sin 2\theta$, $\cos 2\theta$
EMFIX,EMFIY	= Partial derivatives of EMFI
VBR	= Ship speed V in knots, multiplied by 24 hours, and divided by stereographic plane mesh size of 205.585 nautical miles at 60N latitude
VPBVP	= $(V_p/V)_p$

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13. ABSTRACT

This report presents an operational computer program for the calculus of variations method of minimal-time routing of single ships. Although written specifically for VC2AP3 and VC2AP2 vessels operating in a described area of the north Pacific ocean, the program can be modified easily to provide routes for other type vessels in any ocean area of the northern hemisphere. An improved method is used for varying time-extremal ship tracks toward admissibility, which requires only 30 seconds per track iteration, and which gives the desired route in about 3 minutes without convergence difficulties. The method of incorporating weather forecasts into the preparation of minimal-time ship routes is described, and possible future developments are discussed.

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