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AN EMPIRICAL MODEL FOR TIDAL CURRENTS IN

PUGET SOUND, STRAIT OF JUAN DE FUCA, AND SOUTHERN STRAIT OF GEORGIA

by

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ABSTRACT

An empirical model for tidal currents in Puget Sound, the Strait of Juan de Fuca, and the Southern Strait of Georgia was constructed in support of trajectory modelling and surface drifter analyses of the MESA Puget Sound Project. The model uses NOS tidal constituents for current measurements from 157 stations from the region and interpolates among them to represent the spatial variation of the region. The spatial interpolation is based on previous identification of areas or family groups of grid points expected to have similar temporal behavior. No mean currents are modelled.

Five detailed studies of test cases were performed for locations around the domain. The model underestimates the magnitude of the velocity by about 20% and quality of performance varies from place to place.

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ACKNOWLEDGEMENTS

Several people associated with the then Numerical Studies Group at Pacific Marine Environmental Laboratory (PMEL) helped to construct the data arrays relating the base grid to the tidal current stations. These people included J. A. Galt, A. S. Galt, J. E. Overland, D. L. Payton and C. M. Fridlind. S. A. Schoenberg helped to extend the arrays for Puget Sound and to convert the original grid assignments to a single grid base. P. LaNore helped with the computing.

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SECTION 1

INTRODUCTION

A computer model of tidal currents in Puget Sound, Strait of Juan de Fuca, southern Strait of Georgia, and connecting channels was developed in response to a need for tidal current input to pollutant trajectory models and surface drifter analyses. These applications required tidal current information on a variety of spatial and temporal scales, and over a region of complex topography. Since the purpose of the algorithm was to provide estimates of tidal currents for assessment problems and not the study of tidal physics, an empirically based modelling method was chosen over a theoretically based method. The model described herein was the result of a multiyear effort, with much of its design and functional characteristics resulting from its historical association with other studies (Pease et al., 1979; Cannon et al., 1978; Smyth, 1978; and Overland, Hitchman, and Han, 1979). This report documents the model derivation and some associated analysis products.

The tidal currents in the Puget basin are strongly influenced by the geography. The region is dominated by a mixed semidiurnal tide which intricately weaves its way among the channels. The tide in the Strait of Juan de Fuca is characterized as a progressive wave, converting smoothly in the region of the San Juan Islands to nearly a standing wave in the Strait of Georgia (Parker, 1977; Thomson, 1975a-d). The tide in Puget Sound also exhibits standing wave properties, although they are not as pronounced as in the Strait of Georgia (NOS, 1977). Eddies formed in the lee of spits and headlands are a common, time-varying feature of the tidal currents in the region. The largest of these occurs on flood in the embayment formed between Race Rocks and Victoria. No major eddy is seen to form on ebb in this area so the tidal current is rectified toward the southwest along the coast. Another major rectification occurs around Vashon Island. On flood the current is directed south along the east side of the island while the west side has weak flow. On ebb the current is directed north along the west side of the island while the east side has weak flow. The net effect is a clockwise, tidally induced circulation about Vashon Island (McGary and Lincoln, 1977). Although the eddy by Victoria and the circulation about Vashon Island are among the largest asymmetries in the region, there are other smaller eccentricities exhibiting horizontal scales equivalent to the size of geographic features forming them.

Despite these obvious exceptions, the tidal current over the basin is generally symmetric in speed between ebb and flood, and the ebb and flood are separated by 180° in direction. Although there is a rotary nature to the tidal cycle, most tidal currents of the region except in the eastern Strait of Juan de Fuca, exhibit a dominant major axis oriented parallel with the geographic axis of the channels. The M_2 component is the strongest, and the axial orientation of the observed currents is strongly correlated with the M_2 major axis orientation over most of the basin.

The National Ocean Survey (NOS) completed a series of current measurements in Puget Sound, Strait of Juan de Fuca, southern Strait of Georgia, and their connecting channels. Tidal analyses for 90 stations taken since 1973 in the northern portion of this region were reported by Parker (1977).

Another 38 stations were analyzed recently for Puget Sound proper and were made available by NOS for this study. To supplement these current data in areas where modern measurements were sparse or not yet available, standard harmonic constants for prediction of currents were obtained from NOS for six reference stations in the region. These were extrapolated for an additional 23 subordinate stations in Hood Canal and southern Puget Sound based on velocity ratios and time differences published annually in the NOS Tide Current Tables (1977). Thus a total of 157 tidal current stations comprised the available basis for the construction of the tide current model. The model reference number, the location, and the source for each current station are listed in Table 1.

The study region was bounded by 47° and 49°N latitude and 122°10' and 125°10'W longitude parallels. The size of this square was chosen for compatability with other models, principally meteorological (Pease et al., 1978 and Overland, Hitchman, and Han, 1979). However, the western limit of the tide information available was approximately 124°30'W longitude. No attempt was made to acquire tidal current information for the Pacific Coast. So the model nominally treated this western belt as out-of-bounds, although the regional umbrella was designed so that the model could include data for this region if it were desirable later.

SECTION 2

CONCLUSIONS

An empirical tide model based on 157 NOS tidal current stations was constructed by defining a 223^2 regional base grid divided into 760 groups of similar tidal velocity and direction and subjectively assigning interpolation coefficients for up to three current stations for each group. These interpolation coefficients and station numbers are read by a FORTRAN tide library which can then calculate tidal current velocities for specified times on demand. The actual major axis constituent phases and amplitudes for the current stations are held in data statements within the library.

The model was exercised for each of the 760 groups through a program which generated time series for any particular place within the domain. Five of these case studies were compared in detail to tide current predictions from NOS Tide Current Tables 1978; Pacific Coast of North America and Asia. The model mimicked the phase information and distribution of the semidiurnal characteristics of the NOS predicted current. The model typically underestimated the magnitude of the velocity by about 20%. A few percent of this error could possibly be due to the limitation of the constituent sums to the five largest contributing components. The NOS tables include an estimated mean surface current and the model did not, which led to some difficulties in comparing model performance to table predictions.

SECTION 3

RECOMMENDATIONS

The model could be improved by a number of modifications. The most critical to the technique would be to reassign interpolation coefficients for current stations based on an explicit hydrodynamic model of tidal currents instead of subjective criteria. Some streamlining of the FORTRAN library could be achieved by eliminating arbitrary current station numbers and substituting sequential station numbers to avoid searching algorithms. The model could be extended to full tidal elliptical format by including minor axis information for the constituents. The model could be extended to include ebb directions as independent variables from flood so that asymmetric flows could be modelled. The node factors (long-period lunar factors) could be allowed to vary in time by adding a subroutine which would calculate the node factors from sinusoids with a period of 8.85 years instead of specifying them in a data statement. If the model were to be used for assessment or prediction studies, several of these changes should be considered.

SECTION 4

MODEL STRUCTURE

There are several tacks one could take in spatially interpolating time dependent current information. These possibilities include assuming the tidal current at the desired location is: (1) exactly the current at the nearest station chosen by virtue of shortest distance (Smyth, 1978); (2) the linear sum of three stations where the model weights coefficients by the relative distance of each station (Mofjeld, 1975); or (3) a fixed relation to predetermined current stations where the model reads the relationships from a table. All three options work easily on regions of simple geometry (no islands, peninsulas, etc.) where the currents are well behaved (smoothly varying). Difficulties arise in applying these methods when the geometry is complex, when the current data is considerably sparser than the details in the flow, and when the flow is not well behaved spatially. The third interpolating option can be forced to conform to complex regions with the additional constraint that the direction of flow is a specified parameter and not a variable dependent on the interpolation. This latter method was chosen to be applied to the Puget Sound region for this project because of the extreme complexity of the basin.

The interpolation scheme involved assigning current meters and coefficients and current directions to all parts of a regional grid. Rather than carry coefficients for a vast number of locations, we decided on a two-layered approach: (1) a location matrix which would organize the grid into groups of like tidal characteristics; and (2) an array of interpolation assignments for these groups.

The study region was gridded into 223 segments on a side, where the segments are nominally 1 km and can be considered to be roughly the resolution of the model. Thus the base grid contains 223^2 or just slightly less than 50,000 boxes. Many of these are over land or are outside the data base of the model. An array (ILOC) was constructed which delineated boxes over land (or the Pacific belt) from boxes over water in the Puget basin system. Boxes with comparable tidal phases, velocities, and flood directions were grouped into families. These 760 families contained from one to about 50 boxes depending on the local complexity of the basin geometry. The location array ILOC was assigned a dummy integer value of -99 if the box were over land or out-of-range and a positive integer representing specified family number if the box were over water. The southwest or lower left corner is location 1,1 in this array, and the I,J pair are the east, north components. For purposes of the tide model the array is stored as a mass storage, random access file where J is the line number and I is the word number in the line. This storage method is superior to sequential file structure because any independent record may be retrieved without lengthy sorts of sequential data and because this eliminates holding the 5000-word location array in core during model runs.

The next consideration was the interpolation scheme for the current meter data to the families. Each family was assigned one to three current meter stations which would be interpolated to find appropriate tidal velocities. Each assigned current meter received a weighting coefficient signifying its relative importance to the group. The weightings were made on a scale of 0.1 to 1.0 (10 to 100%) on the subjective basis of proximity, streamline dependence, and cross-sectional area of the channel. Typically a family which contained a tidal station was related only to that one station with an assigned weighting of 1.0 (100%). The M_2 flood direction was ascertained for each group by comparing directions from McGavy and Lincoln (1977), the NOS charts (1973a, b) and actual current meter records. The ebb direction was assumed to be opposite the flood direction and the elliptical or rotary behavior of the current was ignored. Hence, seven integer numbers (3 meter numbers, 3 weighting factors, and 1 flood direction) were stored in a second array (ISTA). This array was also constructed as a mass storage, random access file for model use where the group number is the line number and the line contains seven words of station information. The assigned flood directions are depicted in figure 1.

The tidal current model was constructed as a library containing subroutines and functions which are meant to be accessed directly by the user's assessment model or analysis scheme. The functional dependence of the various routines in the library is outlined in figure 2. Subroutines TIDES, JULIAN, and LOCALE are the user accessible routines in the library, while STATS, TIMER, and real function SPEED are meant to be transparent to the user. TIDES acts as the main vehicle for controlling the computation of the tidal velocities. JULIAN converts calendar dates to number of days begun since the new year which is only necessary if the user's model carries Roman calendar dates. LOCALE converts latitude and longitude to grid locations so that the I, J values can be transparent to the user. STATS stores and retrieves phase and amplitude information for the tidal current stations. TIMER calculates the time elapsed since the base date of the algorithm. The base date was arbitrarily fixed at 00Z on 1 January 1978 and all phases (or epoches) are related to this date. This choice is transparent to the user and would only affect someone adding or changing tide station data to the model. SPEED actually computes the current speed for a particular current station and time. The overall library is called PSTIDE3 in card image format and PSTIDE in compiler-dependent, library format. These are included in the program directory in Appendix 1, and the card images are listed in full in Appendix 2.

SECTION 5

MODEL NUMERICAL FORMULATIONS

The current speed at a given time at a particular current station is given by

$$V = \sum_{i=1}^{5} f_i \, A_i \cos(\sigma_i t_{pst} + \alpha_i)$$

where f_i, A_i, σ_i, and α_i are the node factor, amplitude, frequency (constituent speed), and phase relative to time on the local Meridian 000 PST 1 January 1978. The frequencies were taken from Shureman (1958). The node factors vary slowly in time, but they were fixed at 1978 values from Shureman (1958) for this application. The constituent amplitudes in cm s^{-1} were taken from the data sources listed in Section 1. The phases were derived by

$$\alpha_i = \text{Greenwich } (V_o + u)_i - K'_i$$

where the Greenwich $(V_o + u)_i$ is the Greenwich equilibrium argument for each constituent from Shureman (1958) and K'_i is the principal axis phase lag for each constituent from the data sources listed in Section 1. Late in the model development process, it was decided that the tide library needed to process GMT rather than PST time. The time Meridian was changed in the TIDE subroutine rather than by modifying the array containing the phase information. Time then was returned to GMT before returning to the user's program,

$$\text{entry: } t_{PST} = t_{GMT} - (8 \text{ hrs.}),$$

$$\text{exit: } t_{GMT} = t_{PST} + (8 \text{ hrs.}).$$

The contribution of a particular current station to the current speed at a random location is given by

$$V_j = W_{K(j)} \, V_{K(j)}, \quad j \in \{1,2,3\}$$

where W_K and $K(j)$ are the weight factor and station number for each preselected station described in Section 4. Grid position is calculated from decimal latitude and longitude via a pair of equations

$$I = \text{INTEGER } \left(\frac{\xi_w - \xi}{\xi_w - \xi_e} \cdot \frac{1}{N_{we}}\right) + 1$$

$$J = \text{INTEGER } \left(\frac{\phi - \phi_s}{\phi_n - \phi_s} \cdot \frac{1}{N_{ns}}\right) + 1$$

where ξ_w, ξ_e, ξ, ϕ_n, ϕ_s, ϕ, N_{we}, N_{ns} are the longitude limits of the grid and longitude of the point, the latitude limits of the grid and latitude of the point, and the number of divisions of the grid by longitude and latitude.

The group number and station data relationships can be symbolized by

$$\text{STATION DATA}_j = (j,\ \text{ILOC}(I,J)), \quad i \in \{1,\ldots,7\}$$

where for $j = 1,2,3$, $S.D._j$ is equivalent to $K(j)$ of above and for $j = 4,5,6$, $S.D._j$ is equivalent to $W(j)$ of above, and $S.D._7$ is the direction of the tide at flood, presumed to be the major axis flood direction of the M_2 component.

Lastly the u and v components of the tide at an arbitrary point are computed by

$$u = \sum_{j=1}^{3} V_j \sin\theta, \quad \begin{array}{ll} \theta = \theta_f, & V_j \leqq 0 \\ \theta = \theta_f - 180°, & V_j < 0 \end{array}$$

$$v = \sum_{j=1}^{3} V_j \cos\theta, \quad \begin{array}{ll} \theta = \theta_f, & V_j \leqq 0 \\ \theta = \theta_f - 180°, & V_j < 0 \end{array}$$

SECTION 6

USER'S GUIDE

The following section addresses the form of the actual subroutines and functions within the tidal current library. Some of the information presented here is duplicated in APPENDICES I and II which constitute a program directory and listing.

A. Subroutine TIDES (I,J,DATE,U,V)

This routine controls the computation of the tidal current velocities. If the user calls this routine with grid location and time information it will return tidal velocity. The argument list includes:

I - integer east-west grid value (1-223) required by TIDES.

J - integer north-south grid value (1-223) required by TIDES.

DATE - integer 5-word array containing GMT time and date information (seconds, minutes, hour, Julian day, two-digit year) required by TIDES. Julian day is the number of days initiated since 00Z of the new year.

U - real value of east-west velocity (cm s^{-1}, oceanographic convention) returned by TIDES. If I, J are out of area or on land, TIDES will return U = 9999.

V - real value of north-south velocity (cm s^{-1}, oceanographic convention) returned by TIDES. If I, J are out of area or on land, TIDES will return V = 9999.

There is a common statement in TIDES which carries some extra information on current direction which may be of help to the user. This takes the form

```
COMMON/TIDDAT/DIR,RAD
```

where the operating variables have the following definitions:

DIR - real value of flood direction only, in decimal degrees from true north (oceanographic convention).

RAD - real value of present current direction, in radians from true north (oceanographic convention).

Discussion of possible structural modifications to the model are included in the model introduction in APPENDIX II, Section A6. This routine reads the location and station interpolation arrays discussed earlier, although this function should be transparent to the user.

B. Subroutine STATS (DATE,STN,CURRENT,IERR)

This routine stores and retrieves information on current amplitudes, node factors, constituent speeds, and current phases. It also calls TIMER, invokes function SPEED, and returns current magnitude to TIDES. The argument list includes:

DATE - integer 5-word array containing PST time and date information (seconds, minutes, hour, Julian day, two-digit year) required by STATS.

STN - integer station number (11-990, intermittant cardinals) required by STATS.

CURRENT - real value of velocity magnitude, positive if flood and negative if ebb, (cm s^{-1}) returned by STATS.

IERR - integer variable returned by STATS which is set to 1 if STN is a valid request and set to 2 if STN is invalid.

This subroutine contains no common statements. There are no external reads or writes, as all the station data arrays are initiated through data statements. This simplifies model interaction for an arbitrary user, although modifications to the station list (Table 1) are cumbersome at best. The fact that the tidal stations were entered into the tide station interpolation array (TIDDAT2) as arbitrary station numbers in the early phases of the work dictated that STATS be able to sort station numbers. A butterfly sort technique developed by Smyth (1978) was adapted for use in STATS. This entire process plus an array of 157 words containing the station numbers could be eliminated if the data files were reformatted to use simple sequential integers.

C. Subroutine TIMER (BDATE,DATE,TIME)

This routine calculates the number of elapsed hours between two times of the same form and time zone. It is valid for any dates not spanning an even century (e.g., not spanning the years 1900 or 2000) as it contains no provision for correcting for the lack of leap year on even centuries. The argument list includes:

BDATE - integer 5-word array of seconds, minutes, hour, Julian day, and year for some specific time zone, required by TIMER.

DATE - another integer 5-word array of time and date related to the same time zone as BDATE, required by TIMER.

TIME - real number of hours elapsed between BDATE and DATE, returned by TIMER. TIME is positive if BDATE precedes DATE and negative if DATE precedes BDATE.

There are no common statements in this routine, nor are there any external reads or writes. TIMER stores no data and is generalized within the limits described above.

D. Real Function SPEED (AMP,FAC,FREQ,PHAS,T,N)

This function calculates current magnitude for a given set of constituent amplitudes, node factors, frequencies, and phases applied at a given time. The argument list includes:

AMP - real N-word array containing the current amplitudes for the various constituents required by SPEED.

FAC - real N-word array containing the node factors for the various constituents required by SPEED.

FREQ - real N-word array containing the frequencies or phase speeds of the various constituents required by SPEED.

PHAS - real N-word array containing the phases (equilibrium argument minus epoch or phase lag) of the various constituents required by SPEED.

T - real variable of time in hours since the base date related to the phases required by SPEED.

N - integer number of constituents to be summed over, required by SPEED.

Since SPEED is a function, the real value is self-assigned and will have the units of the variable AMP. There are no common statements, external reads or writes, nor data storage within SPEED.

E. Subroutine JULIAN (MM,MD,MY,JULDAY)

This routine will return the Julian (or sequential) day of the year to the user given the month, day, and year. The routine will check for leap years, but will not check for lack of leap years in even centuries. The arguments list includes:

MM - integer number of the month (1-12) required by JULIAN.

MD - integer number of the day of the month (1-28,29,30,31) required by JULIAN.

MY - integer number for the year (1-99) required by JULIAN.

JULDAY - integer number of the Julian day (1-365,366) returned by JULIAN.

This routine has no common statements nor external reads or writes. It does not call any other routine nor is it called by any other routine in the tide library.

F. Subroutine LOCALE (LAT,LONG,I,J)

This routine chooses tide grid coordinates for latitude and longitude values within 47.° and 49.°N latitude and 122°10' and 125°10'W longitude. The routine does not check for out-of-bounds latitude or longitude values. If latitude is south of 47.°, the J value will be negative. If latitude is north of 49.°, the J value will be greater than 223. If longitude is west of 125°10', then the I value will be negative. Finally, if longitude is east of 122°10', then the I value will be greater than 223. The argument list includes:

LAT - real variable expressing latitude in positive decimal degrees, required by LOCALE.

LONG - real variable expressing longitude in positive decimal degrees, required by LOCALE.

I - integer word for the east-west component of the tide grid location returned by LOCALE.

J - integer word for the north-south component of the tide grid location returned by LOCALE.

This routine has no common statements nor external reads or writes. It does not call any other routine nor is it called by any other routine in the tide library.

SECTION 7

APPLICATION OF THE MODEL

As a preliminary verification of the tide model function, case studies were made throughout the Strait of Juan de Fuca and Puget Sound. One case study was run for each of the 760 family groups of the tide grid using the computer program described under PSTIME in Appendices I (A10) and II (A10). Of these cases, five were chosen for detailed comparison to NOS Tidal Current Tables 1978. The selection was essentially random; only the thought of spreading the detailed cases over the basin entered into the selection. These five studies are highlighted on the map in figure 3 and form the basis of the discussion of applications of the model.

After a tide series was calculated and plotted for each of the cases, the tidal current tables were consulted for the nearest reference or subordinate station in the NOS prediction tables. The times from the tables were adjusted to GMT, time differences for slack water and maximum current for subordinate NOS stations were added in, velocity ratios for correcting subordinate NOS stations were accounted for, and the current velocities were converted to cm s^{-1}. The results of these calculations were dotted in for the first 90 hours of each tide model plot and are displayed in figures 4 through 8. The first thing that is apparent is that the model agrees with the NOS predictions with respect to phasing and the relative timing of the components of the diurnal inequality. The most obvious difference between the modeled currents and the currents from the tide tables is that the flood values are reduced in the tables and the ebb values enhanced relatively in each case because the tables add an assumed mean velocity in the ebb direction. Another feature in two of the plots (figures 5 and 7) is that there are significant velocity scaling differences between the model and the tables which are best discussed on a case-by-case basis.

Case 1 (figure 4) near the entrance of the Strait of Juan de Fuca is 6.25 km from station 815 in the tide tables. The model calculation is based mainly on Parker's station 4 (Table 1). There is approximately a 25 cm s^{-1} shift in the tide table values toward the ebb as a mean current which leaves the modelled current amplitudes at about 0.8 of the values in the tables.

Case 2 (figure 5) in the lee of Race Rocks is about 12.5 km from station 830 in the tide tables. The model calculation is based mainly on Parker's station 18 (Table 1). There is approximately a 15 cm s^{-1} shift in the tide table values toward the ebb, as a mean current. Thus the net modelled current amplitudes are about 0.8 of the table values except on the modelled weaker ebb tide. Here the modelled values are about 0.25 of the table values indicating that the model is using different constituent sums. This may be due in part to the fact that Parker's station 18 is further north and inshore thus seeing a different constituent amplitude.

Case 3 (figure 6) near Smith Island in the eastern Strait of Juan de Fuca is 5.5 km west of station 925 in the tide tables. The model calculation is dependent on fractions of stations 39 and 40 from Parker (Table 1). There is about a 5 cm s^{-1} shift in the tide table values toward the ebb, as a mean current. Thus the modelled current amplitudes are about the same as the tide table values, except on the weaker maximum current, particularly ebb current. For the weak ebbs, the modelled values are about 0.5 table values.

Case 4 (figure 7) near Olele Point in northern Puget Sound is about the same position as station 1030 in the tide tables. The model calculation is based mainly on Parker's station 37 (Table 1). Even accounting for an apparent shift toward the ebb of roughly 10 cm s^{-1} in the table values, the modelled current amplitudes are about half again as large as the tide table values. This is the only example known where the model gives larger than otherwise predicted or observed currents. Other experience with the model (Pease et al., 1979) and all the other details cases in this study have led to the conclusion that the model estimates are usually low, as in cases 1 and 2, or tending toward similar magnitudes as otherwise measured or predicted, as in case 3. It would be most reasonable for the model to underpredict since the model velocity series truncates after the five larger constituents. In other respects, the current seems well represented in the model run for case 4.

Case 5 (figure 8) near Restoration Point in central Puget Sound is 4 km north of station 1160 in the tide tables. The model calculation is based on C156 and C166 from the new NOS Puget Sound stations. There is about an 8 cm s^{-1} shift toward the ebb in the current tables. Thus the modelled current amplitudes are about 0.75 of the table values and consistent for this case.

The similarity of predictions in the tide tables and the empirical tidal model in this analysis may be misleading. Since both rely on some of the same station data and since both rely on the NOS interpretation of current records which disregards asymmetrics in the field and other problems, both may have the same deficiencies. What we have attempted to show here is that they are comparable and that the model can be used with certain limitations to reliably estimate tidal currents in the Puget Sound basin.

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TABLE 1

Tidal Reference Stations Which Serve as a Basis for the Tide Velocity Predictions

Sequence Number	Model Station Number	Latitude North	Longitude West	Source[1]	Source Reference Number	M2 Flood Direction (degrees)
1	11	48°26.30'	124°46.50'	1	1	095
2	15	48°01.8'	122°38.2'	3	1015	180
3	21	48°33.30'	124°44.60'	1	2	115
4	31	48°24.90'	124°34.20'	1	3	138
5	41	48°30.30'	124°32.20'	1	4	110
6	51	48°24.90'	124°16.30'	1	5	104
7	60	47°49.'	122°41.'	3	1060	220
8	61	48°15.10'	124°06.30'	1	6	099
9	65	47°42.'	122°46.'	3	1065	185
10	70	47°32.'	123°02.'	3	1070	225[2]
11	71	48°17.95'	124°04.90'	1	7	119
12	75	47°21.'	123°02.'	3	1075	050
13	81	48°21.20'	124°03.20'	1	8	110
14	91	48°11.43'	123°39.75'	1	9	063
15	101	48°17.15'	123°38.43'	1	10	087
16	111	48°10.62'	123°32.06'	1	11	101
17	120	47°38.'	122°35.'	3	1120	360
18	121	48°14.03'	123°33.55'	1	12	077
19	125	47°42.'	122°36.'	3	1125	360[2]
20	131	48°14.3'	123°32.'[3]	1	13	091
21	141	48°16.85'	123°32.60'	1	14	090
22	151	48°08.13'	123°25.00'	1	15	278
23	161	48°08.15'	123°17.45'	1	16	091
24	171	48°15.70'	123°20.00'	1	17	090
25	181	48°22.42'	123°26.13'	1	18	056
26	185	47°34.'	122°36.'	3	1185	225[2]
27	191	48°24.52'	123°24.48'	1	19	120

Sequence Number	Model Station Number	Latitude North	Longitude West	Source[1]	Source Reference Number	M2 Flood Direction (degrees)
28	195	47°34.'	122°37.'	3	1195	325
29	200	47°36.'	122°40.'	3	1200	330
30	201	48°11.23'	123°09.50'	1	20	065
31	205	47°32.'	122°30.'	3	1205	135[2]
32	211	48°14.90'	123°12.10'	1	21	068
33	220	47°21.'	122°29.'	3	1220	350
34	221	48°19.40'	123°15.03'	1	22	064
35	231	48°23.45'	123°16.96'	1	23	075
36	240	47°18.'	122°33.'	3	1240	135
37	241	48°26.35'	123°12.30'	1	24	342
38	251	48°27.10'	123°09.40'	1	25	000
39	261	48°23.13'	123°09.66'	1	26	031
40	265	47°15.'	122°35.'	3	1265	275[4]
41	270	47°17.'	122°39.'	3	1270	300
42	271	48°26.60'	123°00.03'	1	27	346
43	280	48°22.25'	123°01.20'	1	28	039
45	290	47°09.'	122°30.'	3	1290	215[4]
46	291	48°19.40'	122°59.30'	1	29	060
47	301	48°16.62'	122°58.40'	1	30	081
48	305	47°13.'	122°43.'	3	1305	205
49	311	48°10.95'	122°55.60'	1	31	087
50	321	48°06.45'	122°57.45'	1	32	100
51	331	48°05.62'	122°53.93'	1	33	132
52	340	47°10.'	122°54.'	3	1340	315[4]
53	341	48°08.90'	122°44.60'	1	34	134
54	350	47°13.'	122°55.'	3	1350	320
55	351	48°09.28'	122°41.42'	1	35	137
56	355	47°11.'	122°55.'	3	1355	285
57	361	48°06.66'	122°36.92'	1	36	194
58	365	47°12.'	122°58.'	3	1365	285
59	370	47°12.'	123°02.'	3	1370	285

Sequence Number	Model Station Number	Latitude North	Longitude West	Source[1]	Source Reference Number	M2 Flood Direction (degrees)
60	371	48°01.35'	122°39.50'	1	37	189
61	381	48°14.30'	122°48.60'	1	38	171
62	391	48°17.66'	122°52.03'	1	39	082
63	401	48°18.45'	122°45.47'	1	40	039
64	410	48°16'	122°32.'	3	1410	060
65	411	48°21.45'	122°50.10'	1	41	067
66	421	48°23'90'	122°56.50'	1	42	044
67	430	48°24'	122°38.'	3	1430	090
68	431	48°25.93'	122°56.45'	1	43	354
69	441	48°24.30'	122°46.50'	1	44	046
70	451	48°21.63'	122°41.30'	1	45	019
71	461	48°24.06'	122°41.03'	1	46	345
72	470	48°27.53'	122°46.75'	3	1470	335
73	471	48°27.53'	122°46.77'	1	47	355
74	481	48°31.35'	122°44.09'	1	48	354
75	491	48°31.32'	122°42.13'	1	49	038
76	501	48°31.43'	122°37.88'	1	50	078
77	511	48°33.90'	122°39.60'	1	51	005
78	521	48°33.65'	122°44.85	1	52	344
79	531	48°37.65'	122°36.00'	1	53	056
80	541	48°40.50'	122°36.05'	1	54	331
81	551	48°38.58'	122°38.75'	1	55	318
82	561	48°40.65'	122°42.42'	1	56	342
83	571	48°40.98'	122°46.50'	1	57	287
84	581	48°44.90'	122°46.77'	1	58	342
85	591	48°44.20'	122°48.12'	1	59	343
86	601	48°44.25'	122°53.80'	1	60	083
87	611	48°45.30'	122°51.80'	1	61	009
88	621	48°47.10'	122°51.60'	1	62	322
89	631	48°49.42'	122°49.08'	1	63	323
90	641	48°51.47'	122°45.95'[5]	1	64	313

Sequence Number	Model Station Number	Latitude North	Longitude West	Source[1]	Source Reference Number	M2 Flood Direction (degrees)
91	651	48°53.30'	122°53.50'	1	65	315
92	660	48°28.'	122°57.'	3	1660	010
93	661	48°50.47'	122°58.05'	1	66	344
94	671	48°55.60'	123°05.00'	1	67	328
95	681	48°50.80'	123°10.07'	1	68	312
96	691	48°56.85'	123°05.62'	1	69	301
97	701	48°54.60'	123°09.47'	1	70	310
98	711	48°52.85'	123°12.75'	1	71	313
99	721	48°46.48'	123°00.13'	1	72	014
100	731	48°46.65'	122°55.30'	1	73	027
101	741	48°45.23'	122°58.47'	1	74	008
102	751	48°40.67'	122°59.95'	1	75	023
103	761	48°41.00'	123°25.00'	1	76	080
104	771	48°35.35'	123°13.47'	1	77	355
105	781	48°30.97'	123°09.57'	1	78	306
106	791	48°37.38'	123°04.17'	1	79	064
107	801	48°35.37'	123°02.63'	1	80	325
108	811	48°33.98'	123°00.57'	1	81	309
109	815	48°27.'	124°35.'	3	815	115
110	821	48°31.25'	122°56.47'	1	82	003
111	831	48°27.70'	122°57.00'	1	83	350
112	841	48°35.43'	122°59.80'	1	84	250
113	851	48°35.32'	122°54.75'	1	85	284
114	861	48°35.75'	122°50.92'	1	86	014
115	871	48°36.00'	122°48.20'	1	87	117
116	878	48°08.90'	122°44.25'	1	C078	131
117	881	48°35.45'	122°48.55'	1	88	064
118	891	48°31.65'	122°48.37'	1	89	272
119	901	48°28.80'	122°49.15'	1	90	253
120	930	48°06.67'	122°36.92'	2	C130	194
121	931	48°01.35'	122°39.50'	2	C131	189

Sequence Number	Model Station Number	Latitude North	Longitude West	Source[1]	Source Reference Number	M2 Flood Direction (degrees)
122	932	48°01.63'	122°38.30'	2	C132	167
123	934	48°06.60'	122°44.05'	2	C134	146[6]
124	935	48°09.20'	122°37.97'	2	C135	113[6]
125	936	47°55.65'	122°38.00'	2	C136	145
126	937	47°53.75'	122°36.08'	2	C137	165[6]
127	938	47°56.85'	122°34.82'	2	C138	128
128	939	47°57.55'	122°34.50'	2	C139	130
129	940	47°57.80'	122°33.53'	2	C140	126
130	943	47°55.27'	122°27.30'	2	C143	163[6]
131	944	47°54.50'	122°21.23'	2	C144	009
132	945	47°57.18'	122°20.00'	2	C145	012
133	947	48°00.88'	122°21.00'	2	C147	347
134	948	48°04.95'	122°20.30'	2	C148	332
135	949	48°04.87'	122°26.08'	2	C149	328
136	950	48°10.20'	122°33.37'	2	C150	341
137	951	47°52.68'	122°24.70	2	C151	121
138	952	47°48.50'	122°26.97'	2	C152	190
139	954	47°42.35'	122°26.57'	2	C154	233
140	955	47°34.33'	122°31.83'	2	C155	318
141	956	47°34.90'	122°26.87'	2	C156	221
142	959	47°30.15'	122°26.30'	2	C159	183
143	960	47°30.45'	122°24.28'	2	C160	154
144	961	47°23.38'	122°21.40'	2	C161	186
145	962	47°43.18'	122°33.34'	2	C162	210
146	963	47°19.30'	122°31.25'	2	C163	295
147	964	47°21.23'	122°32.33'	2	C164	030[6]
148	965	47°18.60'	122°33.43'	2	C165	160
149	966	47°39.00'	122°27.70'	2	C166	178
150	967	47°27.25'	122°24.28'	2	C167	152
151	976	47°07.10'	122°42.30'	2	C176	281
152	977	47°11.40'	122°43.83'	2	C177	192

Sequence Number	Model Station Number	Latitude North	Longitude West	Source[1]	Source Reference Number	M2 Flood Direction (degrees)
153	978	47°10.08'	122°47.37'	2	C178	332
154	979	47°09.93'	122°51.73'	2	C179	236[6]
155	980	47°13.85'	122°50.12'	2	C180	343
156	981	47°18.07'	122°51.70'	2	C181	229
157	990	48°06.'	122°41.'	3	990	120

1. Numbers in this column reference:
   1. Parker (1977), northern stations
   2. NOS unpublished, southern stations
   3. NOS standard stations
2. Flood direction inferred from continuity.
3. Location taken from figure 17 in Parker (1977).
4. Flood direction assumed to be (180° - ebb direction).
5. Correct longitude taken from figure 17 in Parker (1977).
6. Flood direction corrected by 180° from Ellipse data set.

Figure 1. Plot of modelled tide current flood direction without scaling considerations.

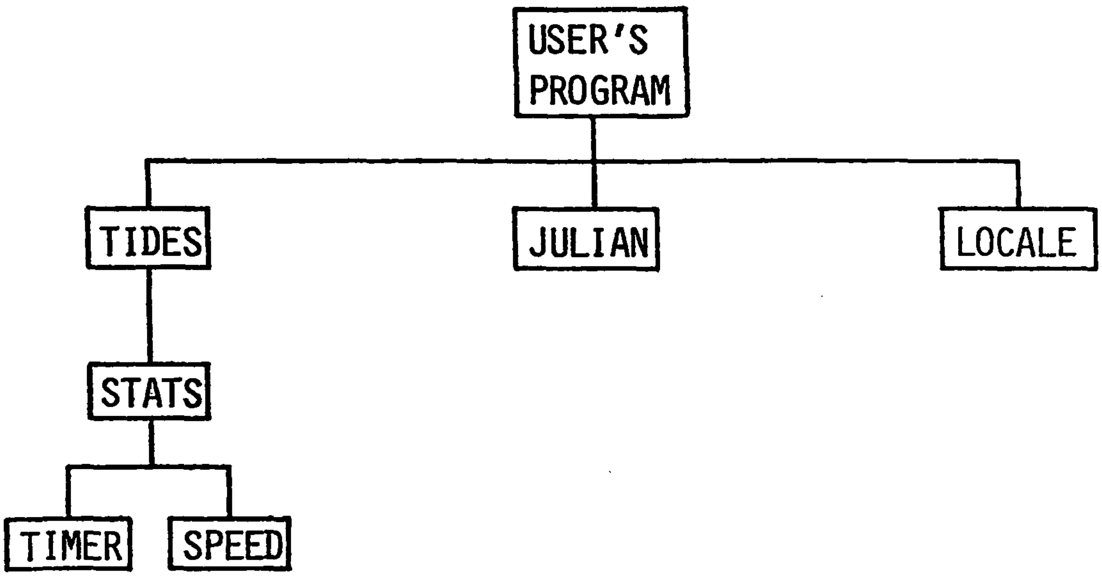


Figure 2. Diagram of functional relationship of Tide library routines.

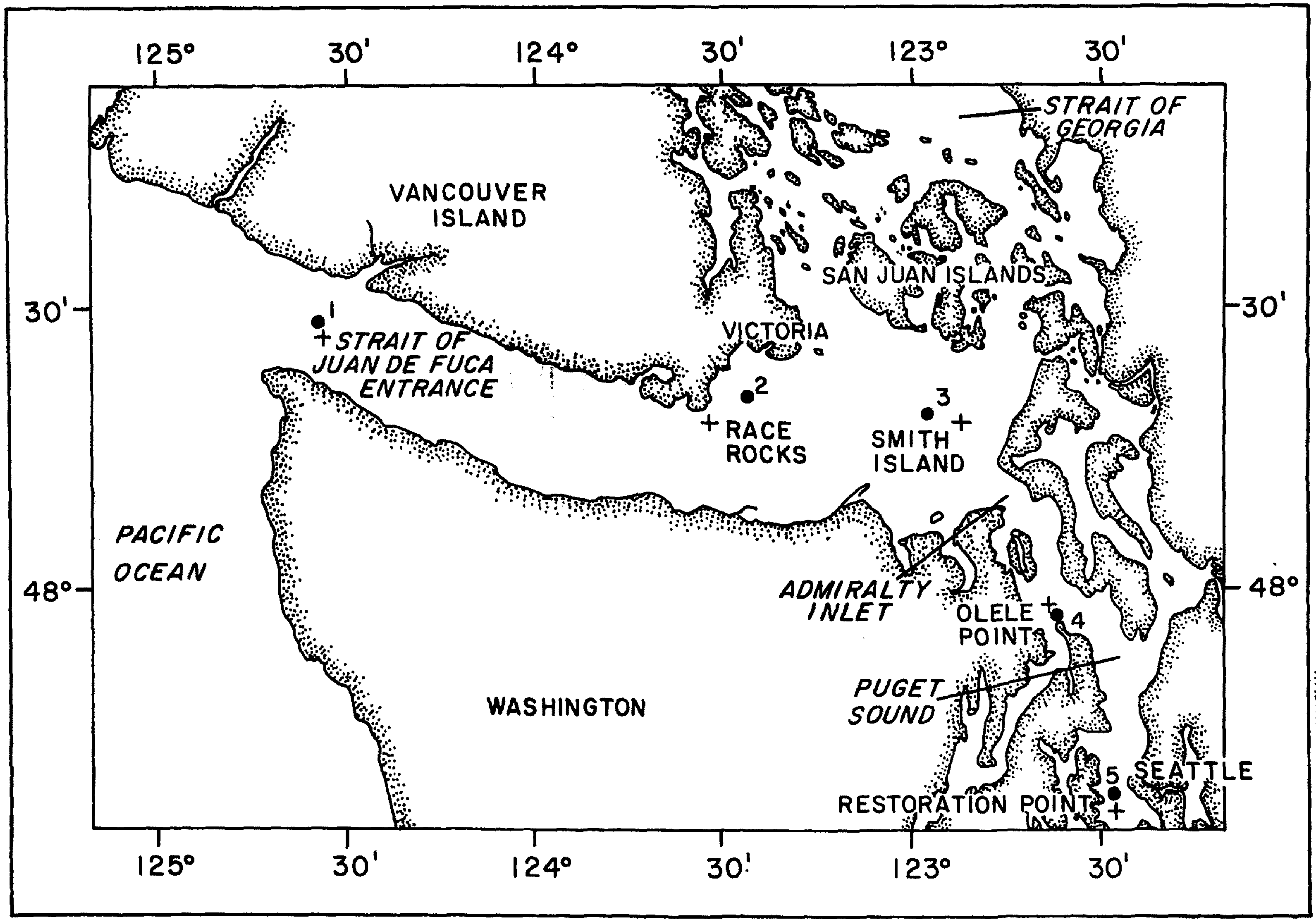


Figure 3. Chart of 5 case study locations (.) and the closest reference or subordinate station for each case (+) from Tidal Current Tables 1978; Pacific Coast of North America and Asia.

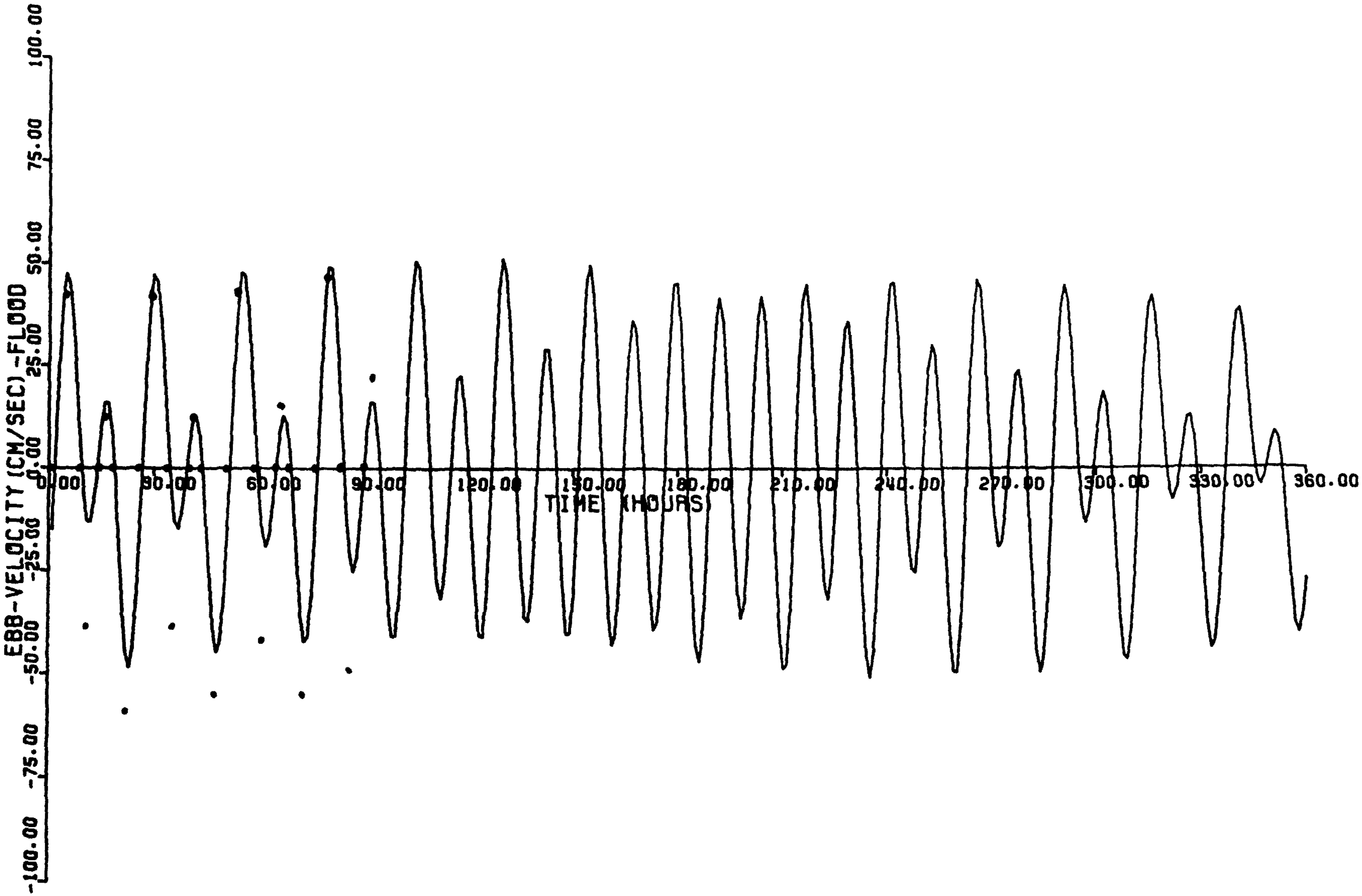


Figure 4. Time series of modelled tidal current (+flood, -ebb) for case study 1 (48°28.8'N, 124°39.3'W) compared to NOS predicted tidal currents from the Entrance to Juan de Fuca Strait (48°27.'N, 124°35.'W) beginning at 00Z on 31 March 1978.

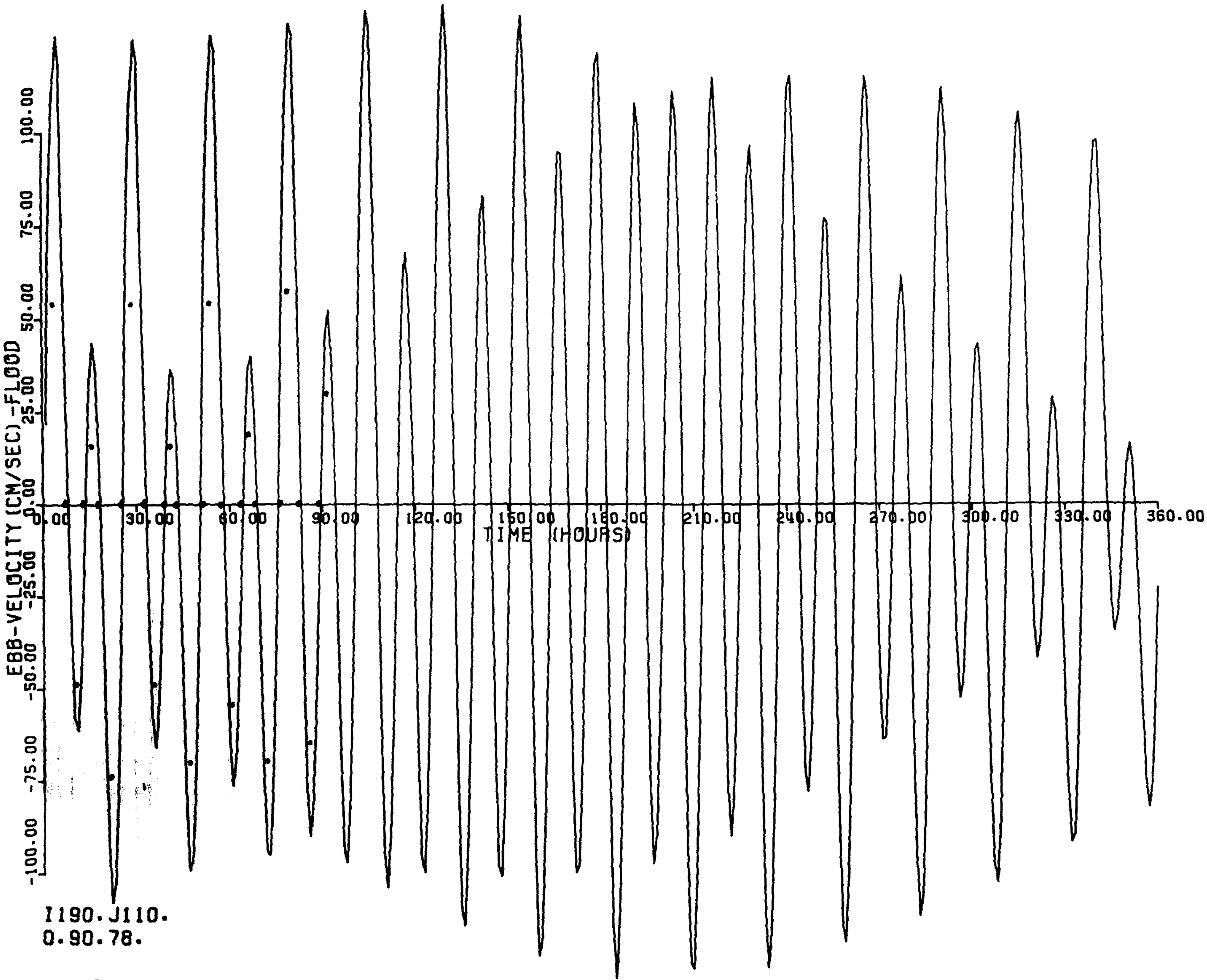


Figure 5. Time series of modelled tidal current for case study 2 (48°20.3'N, 123°26.7'W) compared to NOS predicted tidal currents near Race Rocks (48°14.'N, 123°21.'W) beginning at 00Z on 31 March 1978.

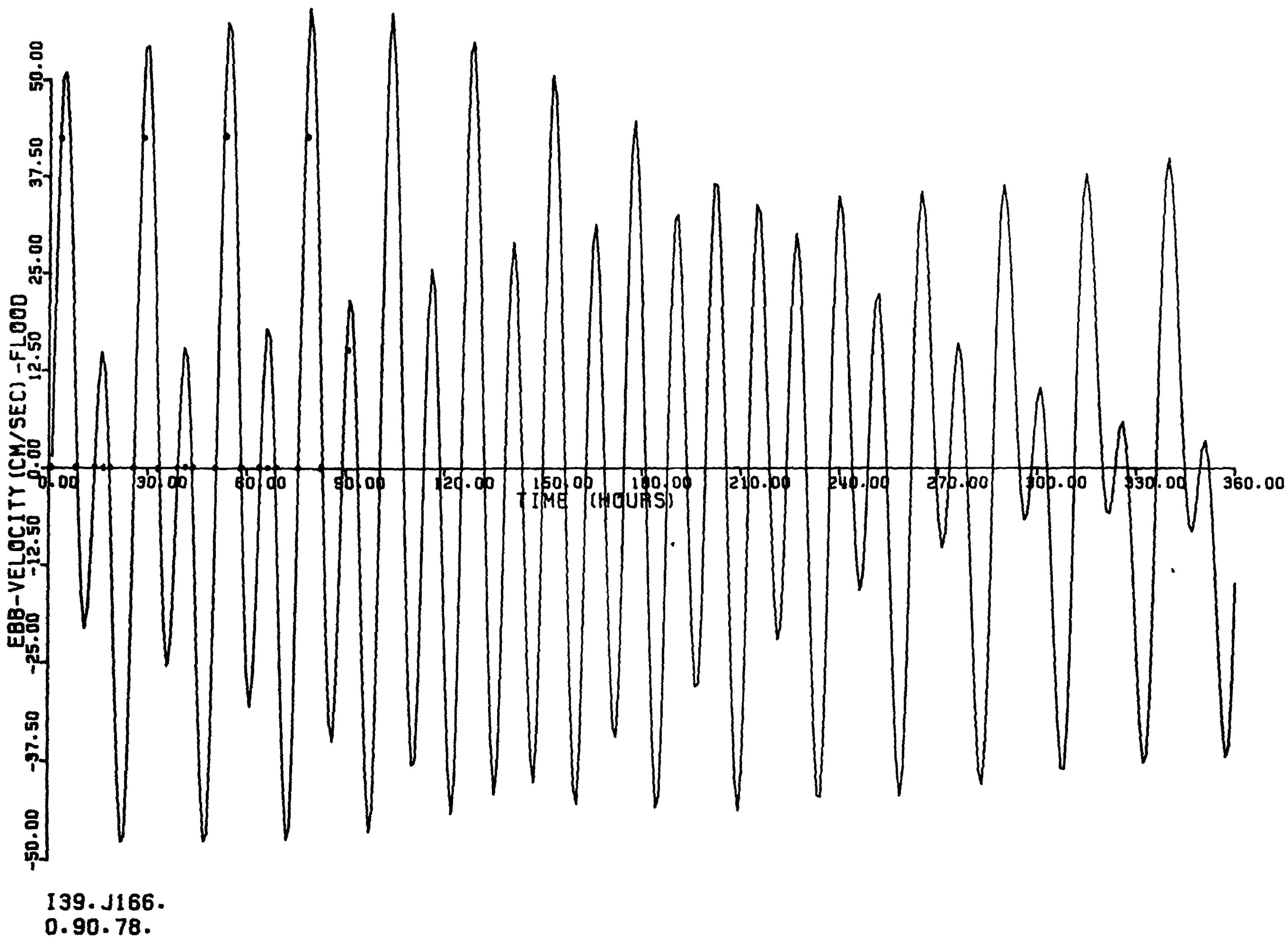
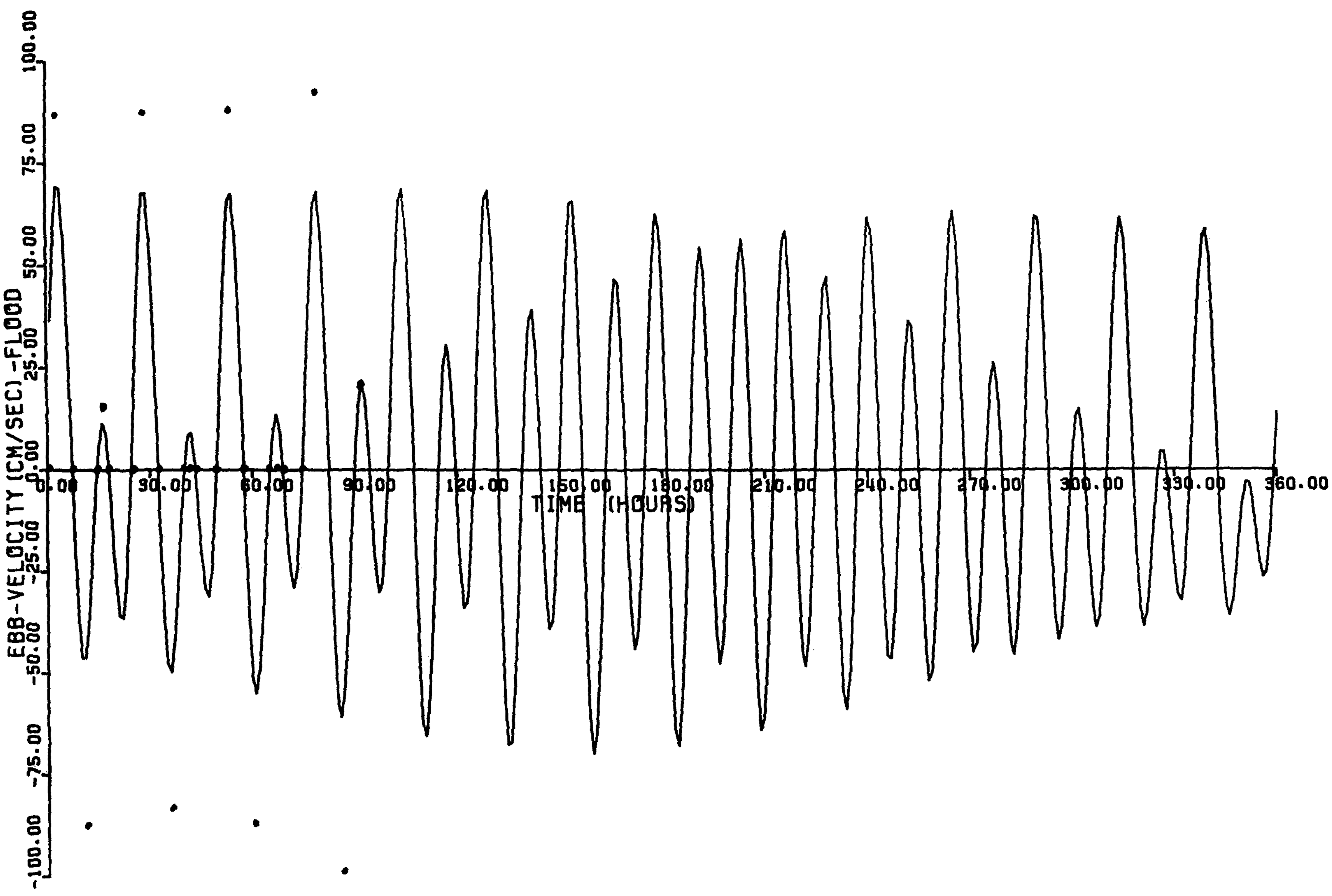


Figure 6. Time series of modelled tidal current for case study 3 (48°18.6'N, 122°57.6'W) compared to NOS predicted tidal currents near Smith Island (48°18.'N, 122°51.'W) beginning at 00Z on 31 March 1978.



I129.J154.
0.90.78.

Figure 7. Time series of modelled tidal current for case study 4 (47°58.6'N, 122°37.4'W) compared to NOS predicted tidal currents near Olele Point (47°59.'N, 122°38.'W) beginning at 00Z on 31 March 1978.

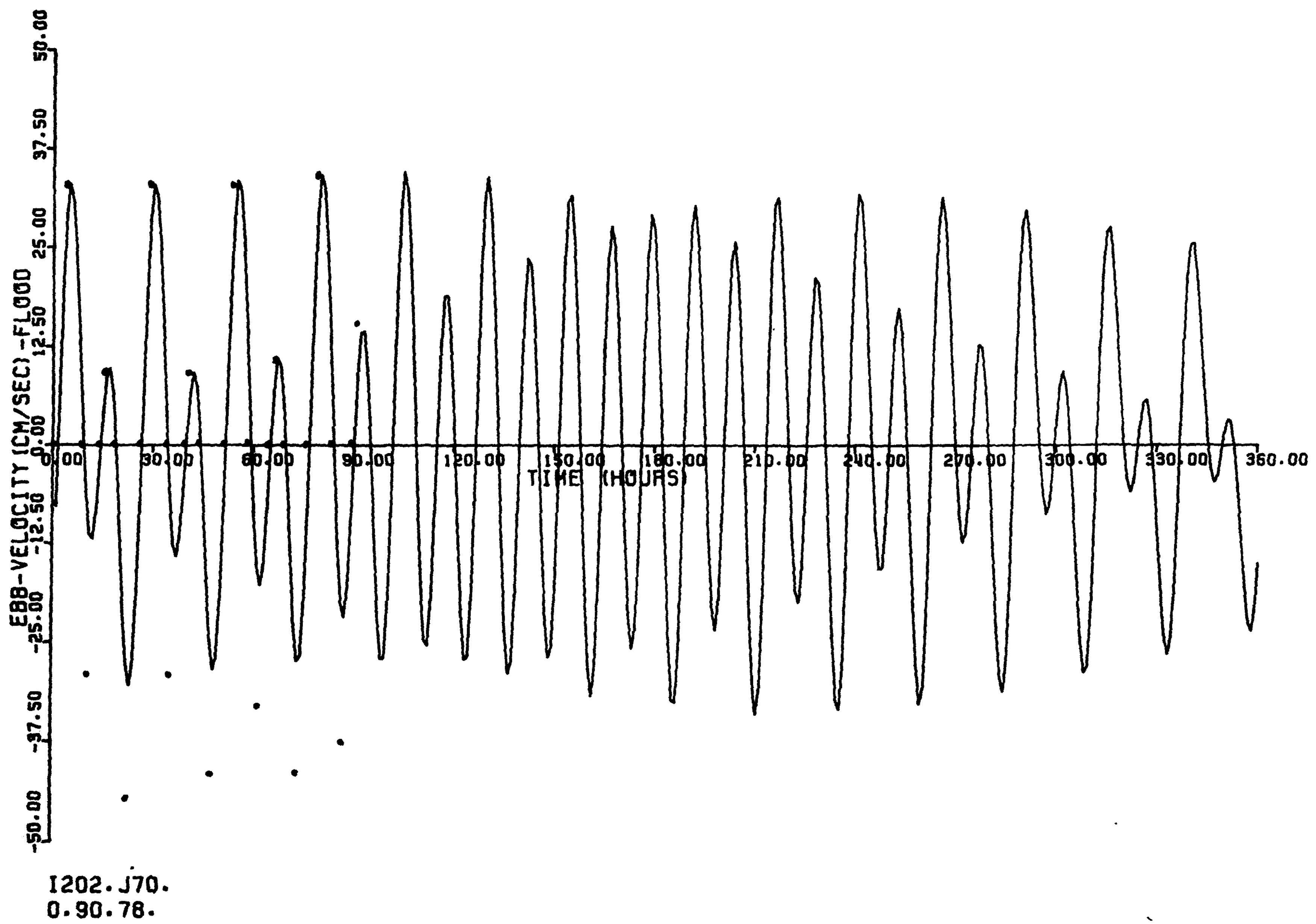


Figure 8. Time series of modelled tidal current for case study 5 (47°37.1'N, 122°27.8'W) compared to NOS predicted tidal currents near Restoration Point (47°35.'N, 122°28.'W) beginning at 00Z on 31 March 1978.

APPENDIX I

DIRECTORY OF THE TIDE LIBRARY AND SUPPORT PROGRAMS AND FILES

A. <u>Puget Sound Tide Files</u>

1. TIDDAT2: Card image, indirect access, tide field and station data. Two sequential fields: 1) location matrix, 2) station data. May be edited.

2. ILOC2: Mass storage, direct access, tide data: location matrix only.

3. ISTA2: Mass storage, direct access, tide data: station array only.

4. MASTOR1: Card image, indirect access FTN routine to convert tide field data from card image to mass storage. Needs TIDDAT2 and creates ILOC2 and ISTA2. Must be rerun fro TIDDAT2 edits.

5. RUNMAS2: Card image, indirect access procedure file to run MASTDR1.

6. PSTIDE3: Card image, indirect access FTN tide library. Needs ILOC2 and ISTA2. May be edited.

7. PSTIDE: Compiled library, indirect access version of PSTIDE3. Needs ILOC2 and ISTA2. Must be regenerated for PSTIDE3 edits.

8. PLOTMAP: Card image, indirect access, FTN routine which plots arrows representing direction of tide at flood and the appropriate background. Uses ILOC2, ISTA2, CALCOMP LIB, and Puget background from CMF.

9. RUNMAP: Card image, indirect access, procedure file which runs PLOTMAP.

10. PSTIME: Card image, indirect access, FTN routine which interogates the tide model for developing a velocity time series at a point. Needs PSTIDE, ILOC2, ISTA2 and a dummy file with certain input information. Creates an output file called OUTPSTM.

11. RUNPSTM: Card image, indirect access, procedure file which runs PSTIME.

12. OUTPSTM: Card image, indirect access, velocity time series data for tides at a point.

13. PSTPLOT: Card image, indirect access, FTN routine which plots tide velocity time series. Needs OUTPSTM and CALCOMP library.

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14. RUNPSPT: Card image, indirect access procedure file for running PSTPLOT.

B. Puget Sound Wind Files

1. PUGDATA: Packed card image file, indirect access, contains wind field data files: PUGSE1, PUGSE2, PUGS, PUGSW, PUGW, PUGNW, PUGN, PUGSB; these may be retrieved via GTR commands.

2. PSWLOC: Mass storage, direct access, wind data: location matrix only.

3. PSWVEL: Mass storage, direct access, wind data: velocity fields only.

4. REMODEL: Card image, indirect access, FTN routine to convert wind field data from card image to mass storage. Needs PUGDATA and creates PSWLOC and PSWVEL.

5. RUNWMOD: Card image, indirect access, procedure file to run REMODEL.

6. WINDS: Card image, indirect access, FTN wind library. Needs PSWLOC and PSWVEL. May be edited.

7. WINDLIB: Compiled library, indirect access, version of WINDS. Needs PSWLOC and PSWVEL. Must be regenerated for WINDS edit.

8. WINDPIC: Card image, indirect access, FTN routine which cycles through all possible calls to WINDLIB to check data and file operation. Needs PSWLOC, PSWVEL and WINDLIB.

9. RUNWIND: Card image, indirect access, procedure file to run WINDPIC.

C. Puget Sound Current Analyses

1. STRAIT1, STRAIT2, STRAIT3: Card image, indirect access, current meter velocity files corresponding to Holbrook's east straits current meters 11, 12, 13 during Aug. 1978.

2. CURANL2: Card image, indirect access FTN routine which compares Holbrook's CM data to tide model results; needs ILOC2, ISTA2, any of the STRAITn files, PSTIDE; and creates CURn files.

3. RUNANAL: Card image, indirect access, procedure file to run CURANL2.

4. CUR1, CUR2, CUR3: Card image, indirect access; velocity data files.

5. HOLPLOT: Card image, indirect access FTN routine which plots time series comparisons of velocity data on CURn files. Needs CURn and CALCOMP library.

6. RUNHOLP: Card image, indirect access, procedure file to run HOLPLOT.

7. HOLVECT: Card image, indirect access FTN routine which plots progressive vectors from velocity data in CURn files. Needs CURn and CALCOMP library.

8. RUNHOLV: Card image, indirect access, procedure file to run HOLVECT.

9. DATASET: Card image, indirect access, FTN routine which prepares current meter, model, or difference velocity data sets for input compatability with R2SPEC, a spectral analysis routine for tide data maintained by Carl Pearson of the PMEL Coastal Physics Group. Needs CURn files and creates METERn, MODELn, or DIFFn files.

10. RUNDATS: Card image, indirect access procedure file to run DATASET.

11. SCATTER: Card image, indirect access, FTN routine which computes scatter diagrams on the DIFFn files and creates a CALCOMP plot of the results. Needs DIFFn files and CALCOMP Library.

12. RUNSCAT: Card image, indirect access, procedure file to run SCATTER.