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Empirical Model for Tides in the Western North Atlantic Ocean

HAROLD O. MOFJELD

BOULDER, COLO.
OCTOBER 1975

U.S. DEPARTMENT OF COMMERCE
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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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EMPIRICAL MODEL FOR TIDES
IN THE
WESTERN NORTH ATLANTIC OCEAN

Harold O. Mofjeld

ABSTRACT

This report describes an empirical tide model for the western North Atlantic ocean which predicts the semi-daily and daily tides relative to mean sea level. The model interpolates harmonic constants from three reference stations on a Mercator projection to obtain constants at a given location, from which the tides are then computed. The geographic region over which the model predicts tides within a standard deviation of 5 cm was determined through a comparison with data from test tide stations. A set of FORTRAN subroutines and their use are described, allowing a user to implement the model. Minor modifications of two subroutines are required to extend the period of the model 1973-1978 to either earlier or later periods.

1. INTRODUCTION

This tide model, developed by the author under NASA Contract Number 369-07-01-17-53, is designed to provide sea-surface displacement information for tides in the western North Atlantic Ocean. The model is a set of computer subroutines which compute the tidal displacement from mean sea level, given the coordinates of the desired location and the desired date and time. It can be used to generate a time series at a given location, the geographical distribution of tidal height at a given instant, and/or the tidal height under a satellite as it passes over the model area. The model was developed in support of the GEOS-III satellite program to measure tides from space; the model area corresponds to part of the calibration area for this satellite.

The tidal displacement is computed from a set of harmonic constants which have been obtained by linear interpolation on a Mercator projection of harmonic constants at three reference stations. The latter constants were found through analysis of actual pressure or sea level observations. Figure 1 shows the western North Atlantic Ocean reference and test stations and a cross-hatched area indicating where the model is applicable as estimated from an accuracy criterion applied at test stations. Table 1 lists the locations of the reference stations, the periods over which the observations were made, the analysis method, literature references, and harmonic constants.

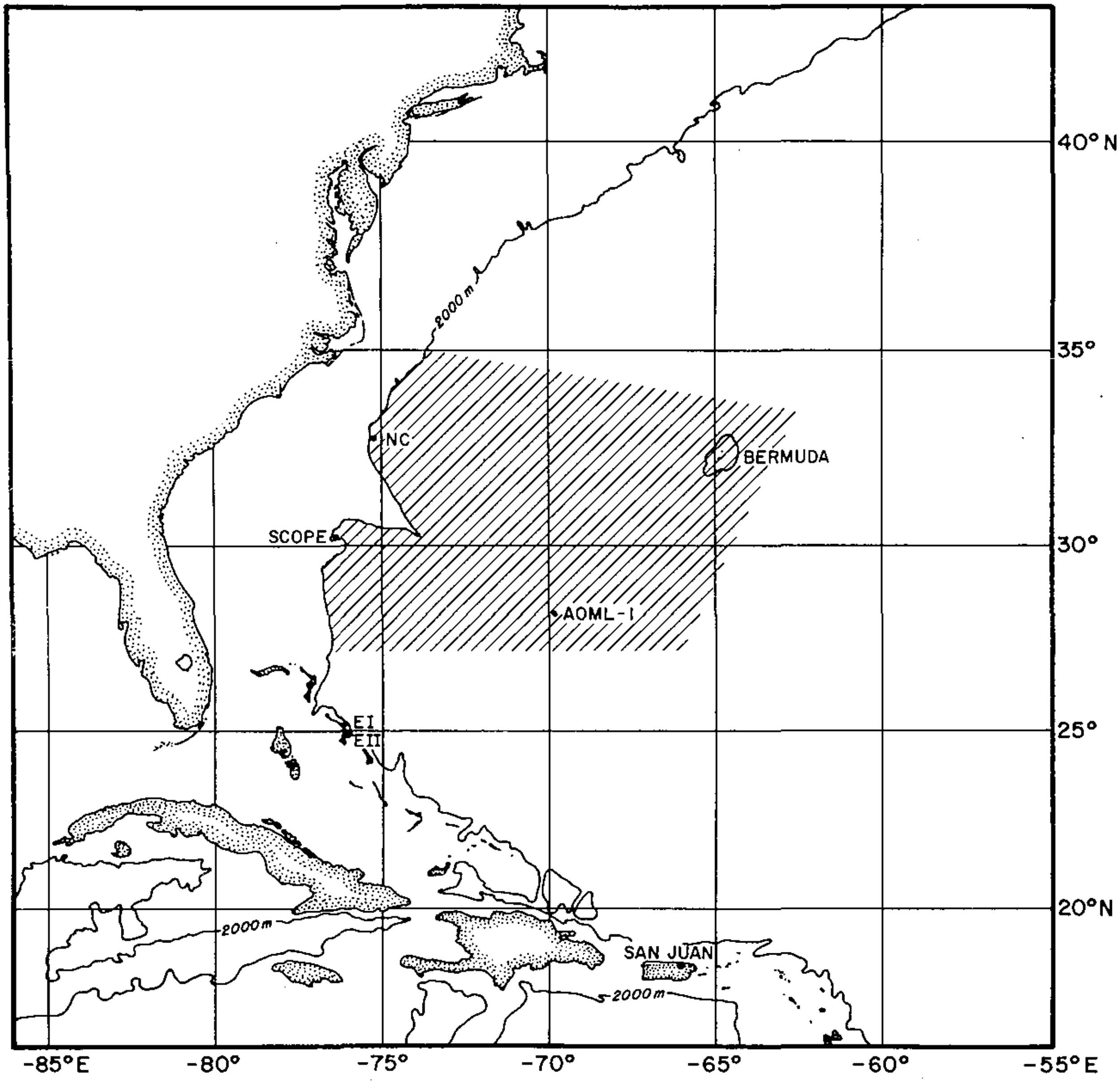

Figure 1. GEOS-III calibration area in the western Atlantic with reference and test stations and the geographical extent of the GEOS-III tide model as defined by the cross-hatched region.

Table 1. Reference Stations

Location	Bermuda 32°24N, -64°42E		MODE/AOML-1 28°08N, -69°45E		SCOPE 30°26N, -76°25E	
Gage type	Shore gage		Bottom pressure gage		Bottom pressure gage	
Observation period	1950-1951, 1953-1954, 1956-1957		11 Mar. - 29 June 1973		18 Sept. 1973 - 20 Mar. 1974	
Type of analysis	Response method		Response method		Response method	
References	Zetler *et al.* (1975)		Zetler *et al.* (1975)		Pearson (1975)	
Constituents	Amplitude (m)	Phase (°G)	Amplitude (m)	Phase (°G)	Amplitude (m)	Phase (°G)
M_2	0.356	358.3	0.345	0.6	0.434	357.6
N_2	0.082	337.7	0.080	339.8	0.106	335.7
S_2	0.081	24.2	0.071	30.8	0.082	23.1
K_2	0.021	22.7	0.019	29.9	0.018	(21.6)
K_1	0.066	187.0	0.077	194.7	0.096	189.8
O_1	0.053	192.1	0.061	197.6	0.073	194.3
P_1	0.020	187.8	0.024	195.2	0.032	189.8
Q_1	0.011	186.6	0.013	193.3	0.014	183.8

The accuracy of the model depends on several factors: How accurately the harmonic constants have been determined at the reference stations, how well the interpolation scheme follows the actual distribution of harmonic constants, and whether the limited number of harmonic constants used in the model adequately describe the tides. The goal of the model is to provide tidal displacements above mean sea level within ±5 cm standard deviation in the area shown in figure 1. Eight harmonic constants have been selected for the model: four daily constituents, K_1, O_1, P_1, Q_1; and four semi-daily constituents, M_2, N_2, S_2, K_2. These eight constituents contain almost all the energy in the daily and semi-daily tidal frequency bands.

Lower frequency, minor daily and semi-daily, and higher frequency sea-level fluctuations are not included in the model. A discussion of the excluded fluctuations and their behavior in the western Atlantic can be found in Zetler _et al_. (1975), and Brown _et al_. (1975). The observations at the reference stations are measurements of either bottom pressure or sea level. Such measurements do not include displacements of the sea surface caused by the vertical motion of the bottom; the model therefore does not contain earth tides.

A comparison of tidal heights as obtained from observations at the MODE/AOML-1 station with predictions of the model is shown in figure 2. The standard deviation of model from the observations for the duration of the AOML-1 record is 3.0 cm. The observations have been filtered to remove fluctuations at frequencies lower than tidal bands.

The area within which the model should meet the ±5 cm accuracy criterion was obtained through a study of tidal distributions for the Atlantic Ocean as given by Dietrich (1963) and through a comparison of harmonic stations at tide stations other than the reference stations. There is good agreement at the NC (North Carolina) station. The model's predictions should therefore be accurate as far north as 35°N, near the continental shelf.

The discrepancies at Eleuthera Island and Puerto Rico stations define the southern limit of the model as shown in figure 1. The differences in harmonic constants between the model and these latter stations, as given in table 2, result from changes in the tidal regime between the western and equatorial Atlantic Oceans and from more localized influences of tidal regimes behind the islands, extending through the passes between the islands. A clear example of variations in tides near passes can be seen in table 2 by comparing the two Eleuthera Island stations shown in figure 3. The tidal regime on the Bahama Banks influences the tides at both stations; Eleuthera I, to a greater extent with smaller tidal amplitudes and later phases, than Eleuthera II, which is farther from island passes. Neither station can be considered representative of the open ocean.

Through studies such as Redfield (1958), it is clear that, on the continental shelves, tidal amplitudes and phases change over distances which are short compared with distances over which amplitudes and phases vary in the western Atlantic

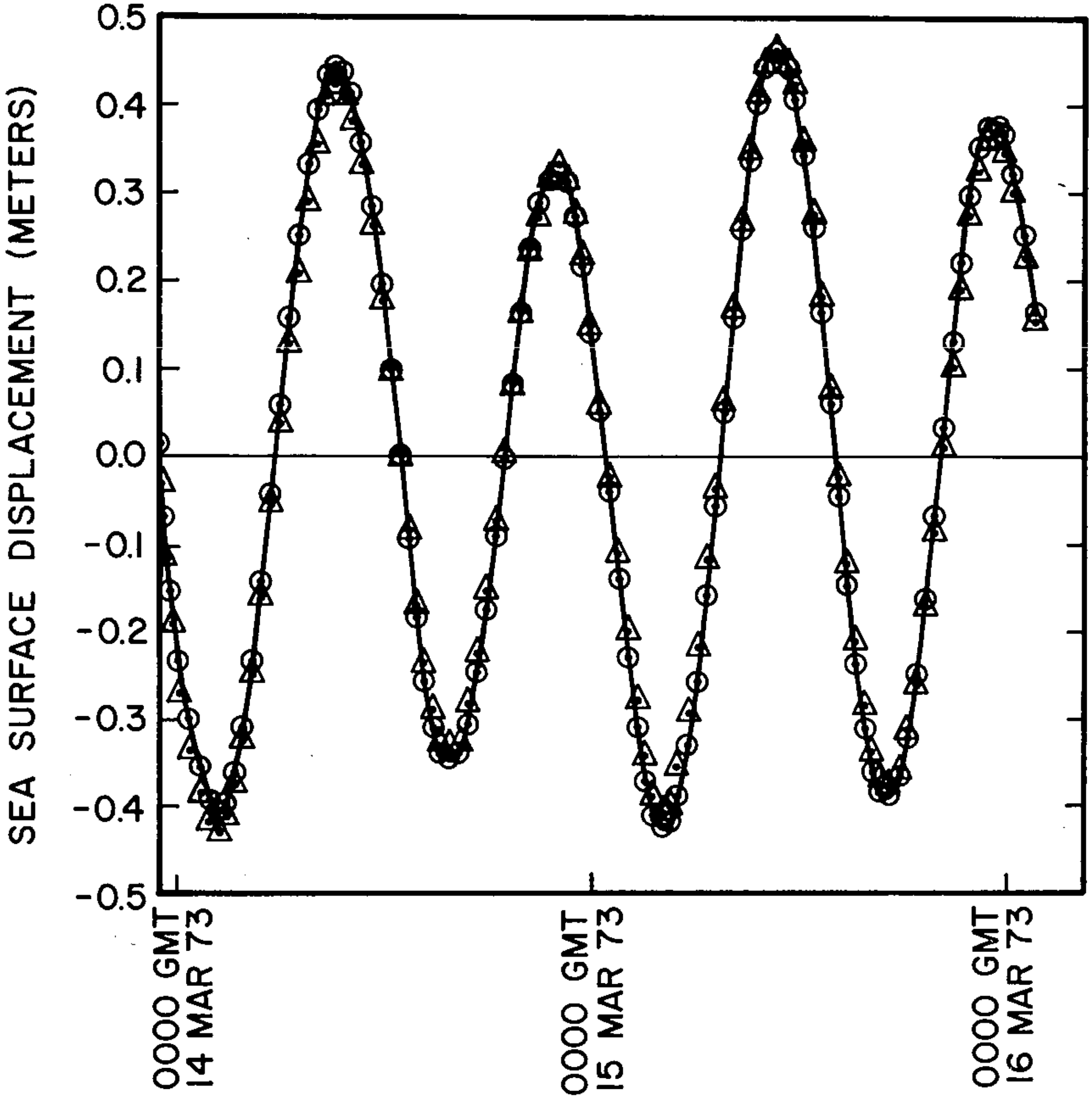

Figure 2. Comparison of observed and predicted sea-surface displacements at the MODE/AOML-1 reference station (28° 08N, -69° 45E) for the interval 18-21 Mar. 1973.

Table 2. Comparison of Model with Test Stations

Location	North Carolina Station 1 32°41.5'N, -75°37.5'E				San Juan, Puerto Rico, Station 18°29'N, -66°07'E			
Gage type	Bottom pressure gage				Shore gage			
Observation period	9 July - 6 Aug. 1972				1899; 191 1/2-day duration			
Type of analysis	Harmonic		Model		Harmonic		Model	
Reference	Mofjeld, 1972				USC&GS, 1942			
Constituents	Amplitude (m)	Phase ($^{\circ}$G)	Amplitude (m)	Phase ($^{\circ}$G)	Amplitude (m)	Phase ($^{\circ}$G)	Amplitude (m)	Phase ($^{\circ}$G)
M_2	0.481	356	0.4574	356	0.149	18	0.2021	16
N_2	0.093	339	0.1123	334	0.034	4	0.0409	2
S_2	0.072	27	0.0891	20	0.021	39	0.0518	65
K_2	(0.020)	(27)	0.0193	17	(0.006)	(38)	0.0187	54
K_1	0.101	185	0.0955	186	0.082	228	0.0680	216
O_1	0.077	192	0.0721	192	0.073	227	0.0551	211
P_1	(0.033)	(185)	0.0320	187	0.027	228	0.0191	220
Q_1	(0.015)	(185)	0.0135	179	0.015	227	0.0154	213

Table 2. Comparison of Model with Test Stations--(Continued)

Location	Eleuthera I (25°16.1'N, -76°17.2'E)				Eleuthera II (24°55.8'N, -76°09.2'E)			
Gage type	Shore gage				Shore gage			
Observation period	1-29 Sept. 1974				1946; 369-day duration			
Type of analysis	Harmonic		Model		Harmonic		Model	
Reference	Carrier (1975)				Goodman (1975)			
Constituent	Amplitude (m)	Phase (°G)	Amplitude (m)	Phase (°G)	Amplitude (m)	Phase (°G)	Amplitude (m)	Phase (°G)
M_2	0.344	6.7	0.367	1.2	0.321	20.3	0.361	1.5
N_2	0.096	346.7	0.087	339.7	0.071	0.3	0.080	340.1
S_2	0.058	29.5	0.067	34.2	0.052	48.3	0.066	35.2
K_2	0.016	29.5	0.016	34.8	0.013	39.0	0.016	35.8
K_1	0.076	213.8	0.093	197.5	0.084	209.0	0.093	198.0
S_1	0.061	204.8	0.072	199.8	0.065	212.3	0.072	200.2
P_1	0.025	213.8	0.030	197.2	0.026	213.8	0.030	197.8
Q_1	0.012	20.3	0.015	194.3	0.013	209.3	0.015	195.0

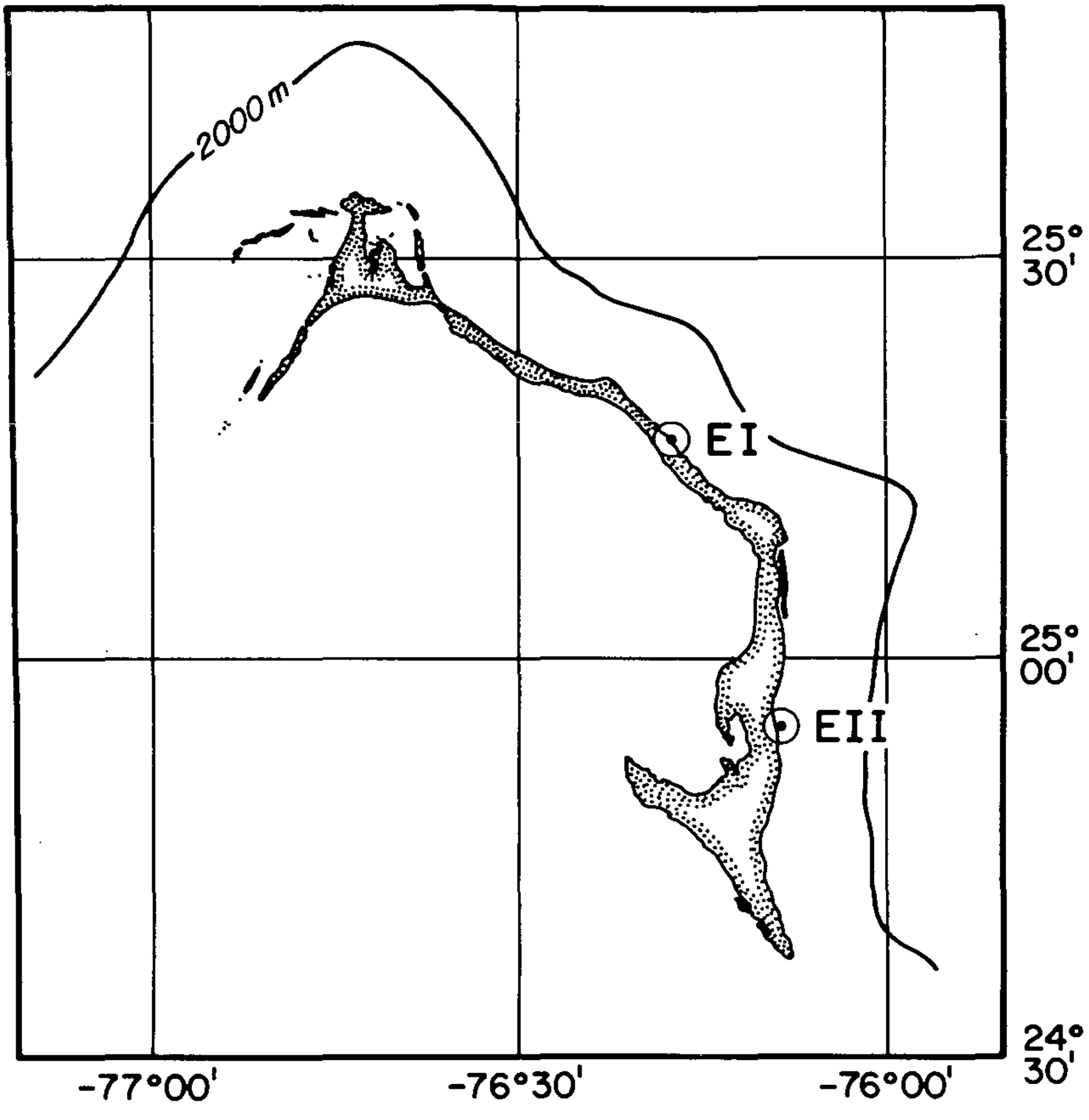

Figure 3. Tide stations Eleuthera I and Eleuthera II located in the Bahamas near passes between Eleuthera and adjacent islands.

Ocean. The GEOS-III tide model is based on harmonic constants from the open ocean and is applicable only where the tidal amplitude and phase variations have oceanic rather than shelf spatial scales. The model should be used seaward of the 2000-m depth contour. If extrapolated into shallower water, the model will underestimate the tidal amplitudes. The discrepancy increases rapidly shoreward of the 200-m depth contour.

While it is traditional in tidal prediction calculations to fix the node factors at a single set of values for time series up to 1 year in duration, the model computes the instantaneous node factors for each time. The more accurate procedure is used for two reasons: First, the operational period of the GEOS-III satellite coincides with a period in which the node factors are changing rapidly, and hence the fixed factors are likely to differ significantly from the correct values; and second, variable node factors allow direct comparisons between results of the model and observations obtained several years before the launch date of the satellite. The additional computer time required to compute the node factors is not significant.

Because of assumptions used in establishing the time base of the model and because of assumptions made about the functional dependence of the node factors on time, the model should be used only within the time period 1973-1978. Extending this period requires simple modifications of subroutines TIME and NODE.

In the open ocean the sea surface is fluctuating about a time-independent mean because of several processes of which ocean tides produce some of the largest displacements. In the GEOS-III calibration area, tidal displacements amount to about ±0.5 m. Other processes such as time-dependent currents, atmospherically induced, low frequency waves, seasonal heating and cooling (steric anomaly), and earth tides may produce displacements of perhaps ±0.1 m. The region of the Gulf Stream in the calibration area is subject to meanders of the current which can produce sea surface fluctuations as large as 1 m. If the altimeter of the GEOS-III is found to have sufficient resolution, these processes must be included in any analysis scheme to remove and/or study time-dependent sea surface fluctuations in the altimetry data.

2. FUNDAMENTAL FORMULAS

The sea surface displacement at a given time and location is computed using the expression

$$h = \sum_{i=1}^{8} f_i A_i \cos (\sigma_i t - \zeta_i) \ , \tag{1}$$

where f_i, A_i, σ_i, and ζ_i are the node factor, amplitude, frequency, and phase lag of the i-th tidal constitutent and t is the time relative to 0000 GMT 1 March 1975. The frequencies of the eight principal constituents are obtained from Schureman (1941); all other quantities are computed by the model.

The node factors f_i are computed from cubic polynomials, derived from Stirling's interpolation formula applied to values for the middle of each year 1973-1977, as found in Schureman (1941),

$$f_i = a_i + b_i\, u + c_i\, u^2 + d_i\, u^3 \;, \tag{2}$$

where a_i, b_i, c_i, and d_i are coefficients, and $u = t - t_o$, and t_o being the time lag in hours from the start time of the model to 0000 GMT 1 July 1975.

The amplitudes A_i and phase lags ζ_i are computed from the complex harmonic constants $H_i = H_i^{'}, H_i^{''}$,

$$A_i = \left({H_i^{'}}^{2} + {H_i^{''}}^{2} \right)^{1/2} \;, \tag{3}$$

and

$$\zeta_i = \arctan\left(H_i^{''} / H_i^{'} \right) \;. \tag{4}$$

The complex harmonic constants are computed at a given location by the linear polynomial

$$H_i = \left(H_{i,1} \right) x + \left(H_{i,2} \right) y + H_{i,3} \;, \tag{5}$$

where $H_{i,1}$, $H_{i,2}$, and $H_{i,3}$ are coefficients and x and y are the zonal and meridional Mercator coordinates, corresponding to the latitude θ and east longitude λ of the location, measured westward as a negative quantity from 0°E:

$$x = \pi\lambda \;, \tag{6}$$

and

$$y = \ln \left\{ \tan\left(45^{\circ} + \theta/2 \right) \right\} \;. \tag{7}$$

The coefficients $H_{i,j}$ are found by fitting equation (5) to complex harmonic constants (Greenwich phase adjusted to 0000 GMT 1 March 1975) at three reference stations, using the Mercator coordinates. Contour maps of the real and imaginary parts of the complex harmonic constants for M_2 and K_1 are shown in figure 4.

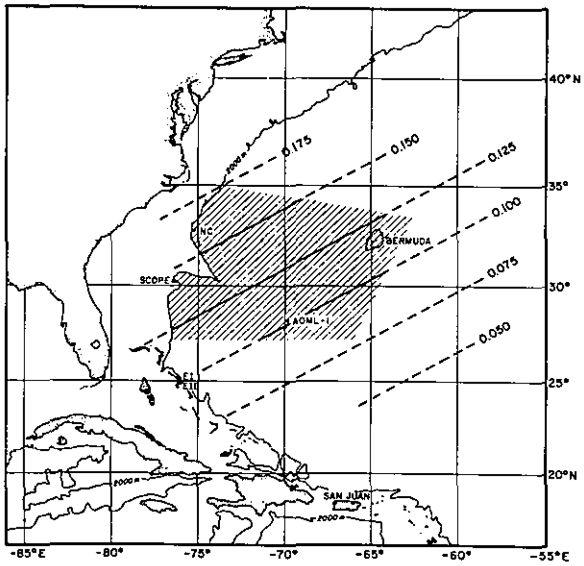

Figure 4a. Real part of the M_2 complex harmonic constant.

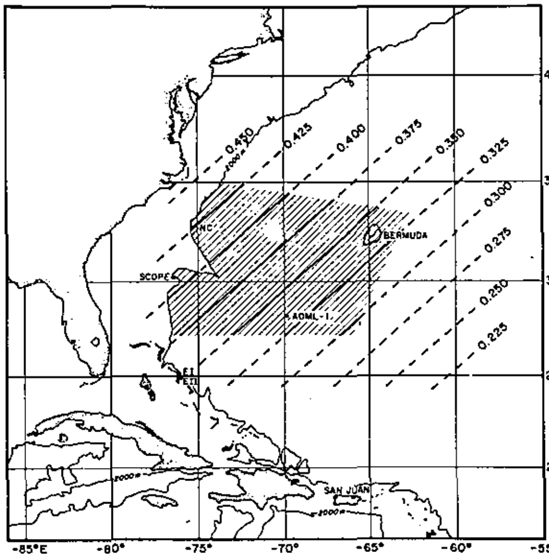

Figure 4b. Imaginary part of the M_2 complex harmonic constant.

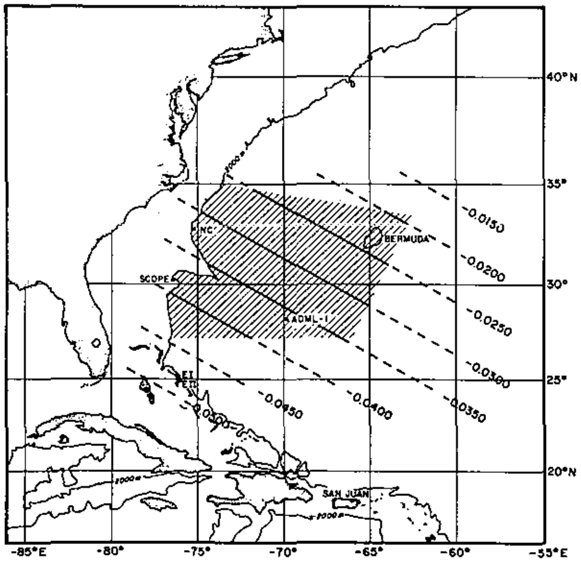

Figure 4c. Real part of the K_1 complex harmonic constant.

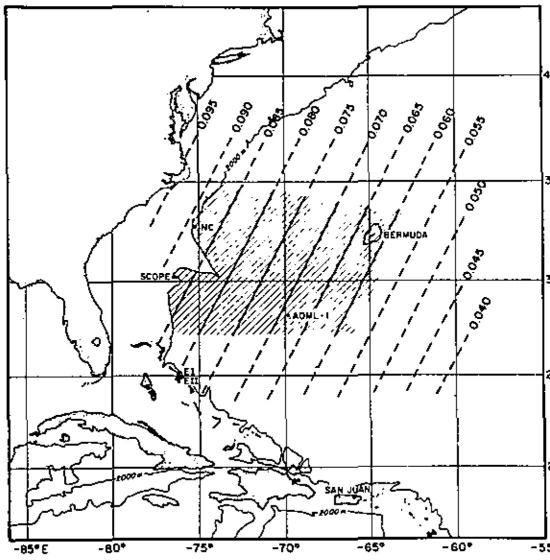

Figure 4d. Imaginary part of the K_1 complex harmonic constant.

3. USE OF THE MODEL

A straightforward application of the model would be to call TIME first to obtain the time T from the date and time in Greenwich Mean Time and then to call TIDE with T and the latitude THETA and longitude LAMBDA to obtain the sea surface displacement at that time and place. By repeating the TIDE call at different locations but using the same time T, the spatial distribution of the sea surface displacement at that instant can be obtained for the calibration area. Figure 5 gives contour maps of sea level during a semi-daily tidal cycle, using this procedure to generate the distributions over a grid at successive times. Contour maps of sea level within the model area are shown in figure 5 at 3-hr intervals, beginning 0000 GMT 1 March 1975. The maps illustrate the distribution of tidal deviation from mean sea level during a semi-daily tidal cycle. For a satellite passing over the calibration area in a time period which is short compared with the tidal periods, the displacement under the satellite may be obtained by fixing T and computing the displacements at a series of locations under the trajectory. Time series can be obtained by using the entry point TIDE1 in subroutine TIDE, as was done to generate the time series in figure 3. TIDE must be called once to establish the harmonic constants at the desired location, after which TIDE1 may be called in a DO loop to generate the time series.

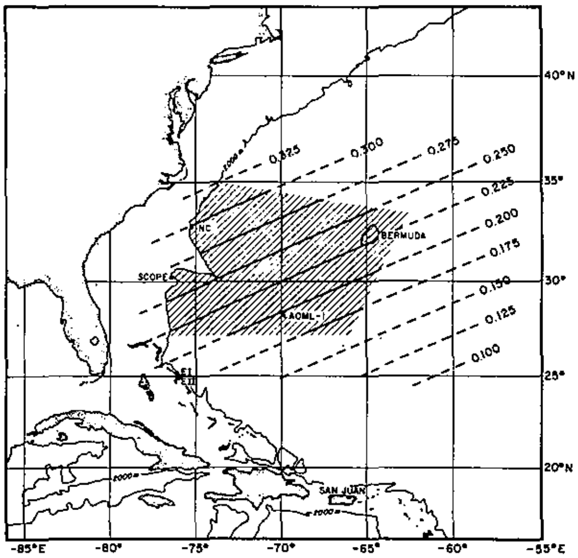

Figure 5a. Sea surface displacement at 0000 GMT 1 Mar. 1975.

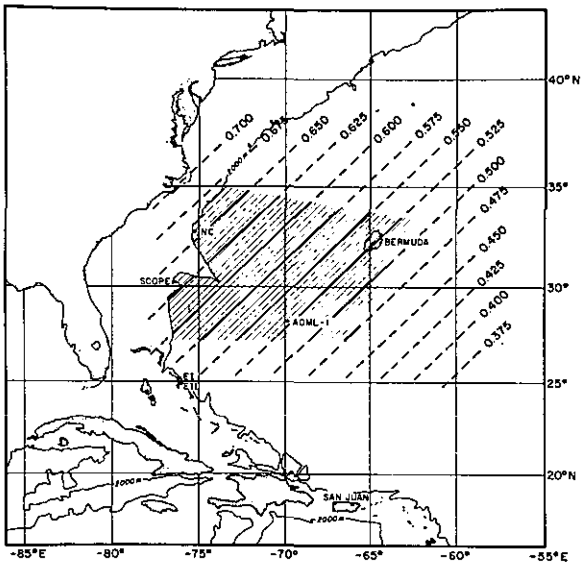

Figure 5b. Sea surface displacement at 0300 GMT 1 Mar. 1975.

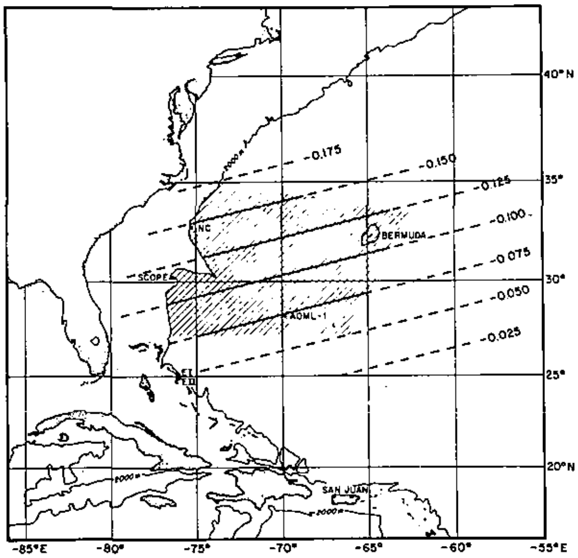

Figure 5c. Sea surface displacement at 0600 GMT 1 Mar. 1975.

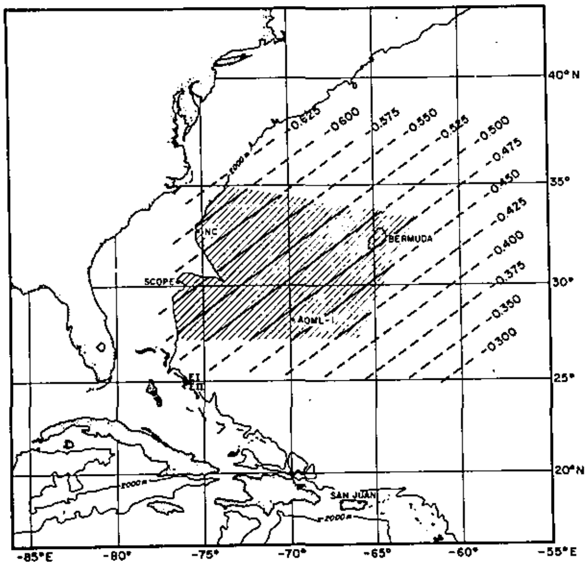

Figure 5d. Sea surface displacement at 0900 GMT 1 Mar. 1975.

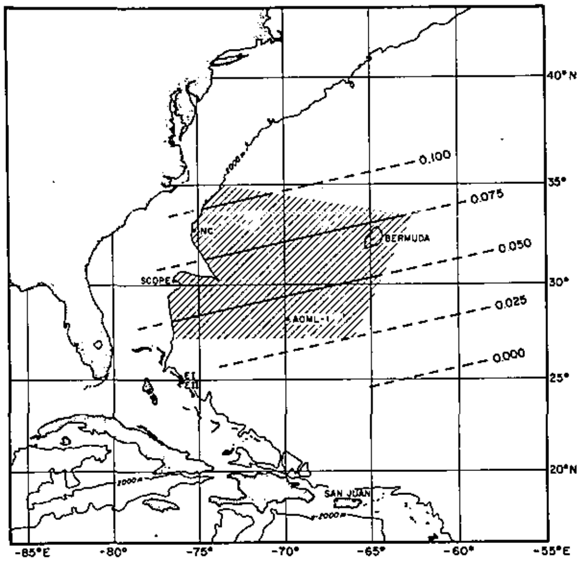

Figure 5e. Sea surface displacement at 1200 GMT 1 Mar. 1975.

4. COMPUTER SUBROUTINES AND FUNCTIONS

Following are descriptions of the subroutines and functions which comprise the tide model:

SUBROUTINE TIME (YEAR, MONTH, DAY, HOUR, MINUTE, SECOND, T)

Given the date in YEAR, MONTH (floating-point variable), and DAY and the time in HOUR, MINUTE (floating-point variable), and SECOND in Greenwich Mean Time, TIME computes the time elapsed in hours T since 0000 GMT 1 March 1975. This subroutine accounts for only 1 leap year 1976 and is valid only for the period 1 March 1972 - 29 February 1980.
Example: `CALL TIME (1975.0, 3.0, 1.0, 0.0, 0.0, 0.000, T)`

SUBROUTINE TIDE (THETA, LAMBDA, T, HEIGHT)

As input data, the user provides TIDE with the latitude THETA and east longitude LAMBDA (floating-point variable given as a negative quantity, measured westward from 0^{o}E), both in degrees, and the elapsed-time T in hours since 0000 GMT 1 March 1975 as obtained from TIME. TIDE then returns the sea surface displacement from the time mean in meters at that location and time.
Example: `CALL TIDE (28.00, -69.40, T, HEIGHT)`

ENTRY TIDE1 (T, HEIGHT)

This entry point in TIDE is used to produce time series at a given location whose harmonic constants need not be recomputed at each time step. TIDE must be called at least once to establish the harmonic constants after which TIDE1 may be used.
Example: `CALL TIDE1 (TO+FLOAT (IT), HEIGHT)` where IT is the index of a DØ loop and TO is the initial start time of the series.

SUBROUTINE CØNST (H)

CØNST contains the harmonic constants at the reference stations and equilibrium-phase information relative to 0000 GMT 1 March 1975. When called by TIDE, CØNST returns a complex array H(I,J) of coefficients that is used in subroutine AMPL to compute the harmonic constants at a given location. CØNST need be called only once.
Example: `CALL CØNST (H)`

SUBROUTINE LØCATE (THETA, LAMBDA, X, Y)

Using the latitude THETA in degrees and the east longitude LAMBDA (floating-point) in degrees, LØCATE returns the zonal and meridonal Mercator coordinates X and Y, respectively, where the origin is assumed to be 0^{o}N, 0^{o}E. This subroutine

neglects the earth's eccentricity in the computations of Y.
Example: CALL L0CATE (28.00, -69.40, X, Y)

SUBROUTINE AMPL (X, Y, H, A, Z)

From the Mercàtor coordinates X and Y, obtained from L0CATE, and the coefficient array H, obtained from C0NST, AMPL uses a linear interpolation scheme to compute the amplitudes A and phases Z, relative to 0000 GMT 1 March 1975, of the eight tidal constituents M_2, N_2, S_2, K_2, K_1, O_1, P_1, and Q_1.
Example: CALL AMPL (X, Y, H, A, Z)

SUBROUTINE N0DE (T, F)

Given the time T, N0DE returns an array F(I) of node factors which adjust the amplitudes of the harmonic constants for their 8.7 and 19-yr cycles.
Example: CALL N0DE (-2000.0,F)

FUNCTION SUM (F, A, Z, T)

Using the node factors F, the amplitudes A and phases Z of the eight principal tidal constituents and the time T, SUM computes the sea surface displacements caused by water tides in meters.
Example: HEIGHT = SUM (F, A, Z, T)

5. ACKNOWLEDGMENTS

The author would like to thank Lt. Carl Pearson (NOAA) for the use of the harmonic constants from the SCOPE reference station and Ms. Nancy Targett for her help in testing the model and preparing the examples. The author would also like to thank Mr. Bernard Zetler and Dr. Myrl Hendershott for their comments on the model and on the manuscript.

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7. APPENDIX

Listings of the model's FORTRAN subroutines are given below:

```
@ ELT TIME,1,750326, 40045

      SUBROUTINE TIME(    YEAR, MONTH, DAY, HOUR, MINUTE, SECOND, T )
C
C      GEOS-C TIDE MODEL
C      SUBROUTINE TO COMPUTE TIME T IN HOURS
C      T = 0 AT 0000Z 1 MARCH 75
C     SUBROUTINE WRITTEN BY H. MOFJELD, NOAA/AOML, MIAMI, FLA. 33149
C     SUBROUTINE REVISED 6 FEB 75
C
      REAL MONTH, MINUTE
      DIMENSION AM( 12 )
      DATA AM / 31.0, 28.0, 31.0, 30.0, 31.0, 30.0, 31.0, 31.0, 30.0,
     1  31.0, 30.0, 31.0 /
C
      TY = 8760.0 * ( YEAR - 1975.0 )
      IF( YEAR - 1976.0 ) 10,8,9
 8    IF( MONTH - 2.0 ) 10,10,9
 9    TY = TY + 24.0
 10   MAX = IFIX( MONTH - 0.999 )
      TM = 0.0
      IF( MAX .EQ. 0 ) GO TO 2
      DO 1 I = 1, MAX
 1    TM = TM + 24.0 * AM( I )
C
 2    T = TY + TM + 24.0 * DAY + HOUR + MINUTE / 60.0 + SECOND / 3600.0
     1  - 1440.0
 5     RETURN
      END
    2. LIST TIDE
```

```
@ ELT TIDE,1,750326, 40046

      SUBROUTINE TIDE( THETA, LAMBDA, T, HEIGHT )
C
C      GEOS-C TIDE MODEL FOR THE CALIBRATION AREA
C      SEA SURFACE HEIGHT COMPUTED FROM LATITUDE THETA, EAST LONGITUDE
C      LAMBDA, AND TIME T IN HOURS FROM 0000Z 1 MARCH 75
C      SUBROUTINE TIME IS CALLED BEFORE TIDE
C     SUBROUTINE WRITTEN BY H. MOFJELD, NOAA/AOML, MIAMI, FLA. 33149
C     SUBROUTINE REVISED 6 FEB 75
      REAL LAMBDA
      COMPLEX H( 3,8 )
      DIMENSION A( 8 ), Z( 8 ), F( 8 )
C
C      INITIAL SET-UP OF HARMONIC CONSTANTS
C
      IF( ITAG - 5 ) 10,20,10
 10   CALL CONST( H )
      PRINT 1, ( ( I,J, H(I,J),J=1,8), I=1,3 )
 1    FORMAT( 4H H( , I1, 1H,, I1, 4H ) =, 2F10.5  )
      ITAG = 5
 20   CONTINUE
C
      CALL LOCATE( THETA, LAMBDA, X, Y )
C
      CALL AMPL( X, Y, H, A, Z )
C
      ENTRY TIDE1( T, HEIGHT )
      CALL NODE( T, F )
      HEIGHT = SUM( F, A, Z, T )
C
      RETURN
      END
   3. LIST CONST
```

```
@ ELT CONST,1,750326, 40048

      SUBROUTINE CONST( H )
C
C      GEOS-C TIDE MODEL
C      SUBROUTINE TO COMPUTE THE COMPLEX COEFS FOR SUBROUTINE AMPL
C     START TIME 0000Z 1 MARCH 75
C      THE COMPLEX HARMONIC CONSTANTS ARE ASSUMED TO LIE ON PLANES
C     BETWEEN REFERENCE STATIONS
C      ORDER OF CONSTITUENTS M2, N2, S2, K2, K1, O1, P1, Q1
C      LONGITUDES EAST FROM GREENWICH
C     SUBROUTINE WRITTEN BY H. MOFJELD, NOAA/AOML, MIAMI, FLA. 33149
C     SUBROUTINE REVISED 6 FEB 75
C
      REAL L1, L2, L3
      COMPLEX H( 3,8 ), H1( 8 ), H2( 8 ), H3( 8 ), CEXP
      DIMENSION A1( 8 ), A2( 8 ), A3( 8 ), P1( 8 ), P2( 8 ), P3( 8 ),
     1V( 8 )
C
C     SCOPE BOTTOM STATION ( REF.  C. PEARSON, DEEP-SEA TIDE OBSERVATIONS OFF
C     THE SOUTHEASTERN UNITED STATES, IN PREPARATION )
C
      DATA T1, L1 / 30.43, -76.42/
     1 A1 / 0.434, 0.106, 0.082, 0.018, 0.096, 0.073, 0.032, 0.014 /
     2 P1 / 357.6, 335.7, 23.1, 21.6, 189.8, 194.3, 189.8, 183.8 /
C
C     BERMUDA ISLAND STATION ( REF.  ZETLER ET AL, MODE TIDES, JPO,
C     IN PRESS )
C
      DATA T2, L2 / 32.4, -64.7 /
     1  A2 / 0.356, 0.082, 0.081, 0.022, 0.066, 0.053, 0.020, 0.011 /
     2  P2 / 358.3, 337.7, 24.2, 22.7, 187.0, 192.1, 187.8, 186.6 /
C
C     MODE AOML-1 BOTTOM STATION ( REF.  IBID. )
C
      DATA T3, L3 / 28.14, -69.75 /
     1 A3 / 0.345, 0.080, 0.071, 0.019, 0.077, 0.061, 0.024, 0.013 /
     2  P3 / 0.6, 339.8, 30.8, 29.9, 194.7, 197.6, 195.2, 193.3 /
C
C     EQUILIBRIUM PHASES RELATIVE TO 0000 GMT 1 MAR 75
C
      DATA
     1  V / 287.3, 244.5, 0.0, 332.1, 76.4, 206.8, 291.9, 164.0 /
     2  PI / 1.7453293E-2 /
C
      DO 10 I = 1,8
      H1( I ) = A1(I) * CEXP( CMPLX( 0.0, PI*( P1(I)-V(I) ) ) )
      H2(I) = A2(I) * CEXP( CMPLX( 0.0, PI * ( P2(I)-V(I) ) ) )
   10 H3( I ) = A3(I) * CEXP( CMPLX( 0.0, PI * ( P3(I)-V(I) ) ) )
C
      CALL LOCATE( T1, L1, X1, Y1 )
      CALL LOCATE( T2, L2, X2, Y2 )
      CALL LOCATE( T3, L3, X3, Y3 )
C
      DET = X1*( Y2-Y3 ) + X2*( Y3-Y1 ) + X3*( Y1 - Y2 )
      DO 20 I = 1,8
```

```
      H(1,I) = H1(I)*( Y2-Y3) + H2(I)*( Y3-Y1 ) + H3(I)*( Y1-Y2 )
      H(2,I) = H1(I)*( X3-X2 ) + H2(I)*( X1-X3 ) + H3(I)*( X2-X1 )
      H(3,I) = H1(I)* ( X2*Y3-X3*Y2 ) + H2(I)*( X3*Y1-X1*Y3 )
     1  + H3(I) * ( X1*Y2-X2*Y1 )
C
      H(1,I) = H(1,I) / DET
      H(2,I) = H(2,I) / DET
 20   H(3,I) = H(3,I) / DET
C
      RETURN
      END
4. LIST LOCATE
```

```
    @ ELT LOCATE,1,750327, 44221

          SUBROUTINE LOCATE( THETA, LAMBDA, X, Y )
C          GEOS-C TIDE MODEL
C         SUBROUTINE TO COMPUTE MERCATOR COORDINATES FROM LAT AND LONG
C         ORIGIN AT 0 N  0 E
C         SUBROUTINE WRITTEN BY H. MOFJELD, NOAA/AOML, MIAMI, FLA. 3314
C         SUBROUTINE REVISED 25 MAR 75
C
          REAL LAMBDA
          DATA PI, E / 1.7453293E-2, 8.1819494E-2 /
          X = PI * LAMBDA
          Y1 = TAN( PI*( 45. + THETA/2. ) )
          Y=ALOG(Y1)
C
C
          RETURN
          END
   5. LIST AMPL
```

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```
@ ELT AMPL,1,750326, 40049

      SUBROUTINE AMPL( X, Y, H, A, Z )
C
C      GEOS-C TIDE MODEL
C      SUBROUTINE TO COMPUTE THE AMPLITUDES A AND GREENWICH PHASES Z
C     SUBROUTINE WRITTEN BY H. MOFJELD, NOAA/AOML, MIAMI, FLA. 33149
C     SUBROUTINE REVISED 6 FEB 75
C
      COMPLEX H( 3,8 ), HC
      DIMENSION Z( 8 ), A( 8 )
      DATA R / 1.7453293E-2 /
C
      DO 10 I = 1,8
      HC = H(1,I) * X + H(2,I) * Y + H(3,I)
      A( I ) = CABS( HC )
   10 Z( I) =    ATAN2( AIMAG( HC ), REAL( HC ) ) / R
C
      RETURN
      END
6. LIST NODE
```

```
@ ELT NODE,1,750326, 40050

                     SUBROUTINE NODE( T, F )
              C
              C      GEOS-C TIDE MODEL
              C      SUBROUTINE TO ADJUST AMPLITUDES FOR NODE FACTORS USING STIRLINGS
              C      INTERPOLATION FORMULA ON DATA FROM TABLE 14 OF P. SCHUREMAN,
              C      MANUAL OF HARMONIC ANALYSIS AND PREDICTION OF TIDES, DEPT. OF
              C      COMMERCE SPECIAL PUBL. NO. 98, 1941.
              C      ORDER OF CONSTITUENTS  M2, N2, S2, K2, K1, O1, P1, Q1
              C      SUBROUTINE WRITTEN BY H. MOFJELD / NOAA/ AOML/ MIAMI, FLA.
              C       30 JAN 75
              C
                     DIMENSION F( 8 )
                     U = ( T-2928.0 ) / 8760.0
                     F(1) = 1.020 + ( 0.0107 + ( -0.0015 - 1.7E-4 * U ) * U ) * U
                     F(2) = F(1)
                     F(3) = 1.000
                     F(4) = 0.871 + ( -0.0777 + ( 0.0095 + 0.0012 * U ) * U ) * U
                     F(5) = 0.951 + ( -0.0385 + ( 0.0025 + 0.001[illegible] * U ) * U ) * U
                     F(6) = 0.920 + ( -0.0619 + ( 0.0035 + 0.0014 * U ) * U ) * U
                     F(7) = 1.000
                     F(8) = F(6)
              C
                     RETURN
                     END
   7. LIST SUM
```

```
@ ELT SUM,1,750326, 40051

                   FUNCTION SUM( F, A, Z, T )
          C         GEOS-C TIDE MODEL
          C         FUNCTION TO COMPUTE THE SEA SURFACE DISPLACEMENT FROM
          C         HARMONIC CONSTANTS AND TIME
          C         ORDER OF CONSTITUENTS  M2, N2, S2, K2, K1, O1, P1, Q1
          C        SUBROUTINE WRITTEN BY H. MOFJELD, NOAA/AOML, MIAMI, FLA. 33149
          C        SUBROUTINE REVISED 6 FEB 75
          C
                   DIMENSION A( 8 ), Z( 8 ), S( 8 ), F( 8 )
                   DATA S / 28.984104, 28.439730, 30.0, 30.082137,
                  1  15.041069, 13.943056, 14.958931, 13.398661 /
                  2  R / 1.7453293E-2  /
                   SUM = 0.0
                   DO 100 N = 1,8
                   P = S(N) * T - Z(N)
                   IF( ITG .NE. 25 ) PRINT 1, P
              1    FORMAT( 16H PHASE FOR M2 =  , F20.5 // )
                   ITG = 25
              100  SUM = SUM + F(N)*A(N) * COS( R*P )
                   RETURN
                   END

END CUR LCC 1102-0038 L8
```