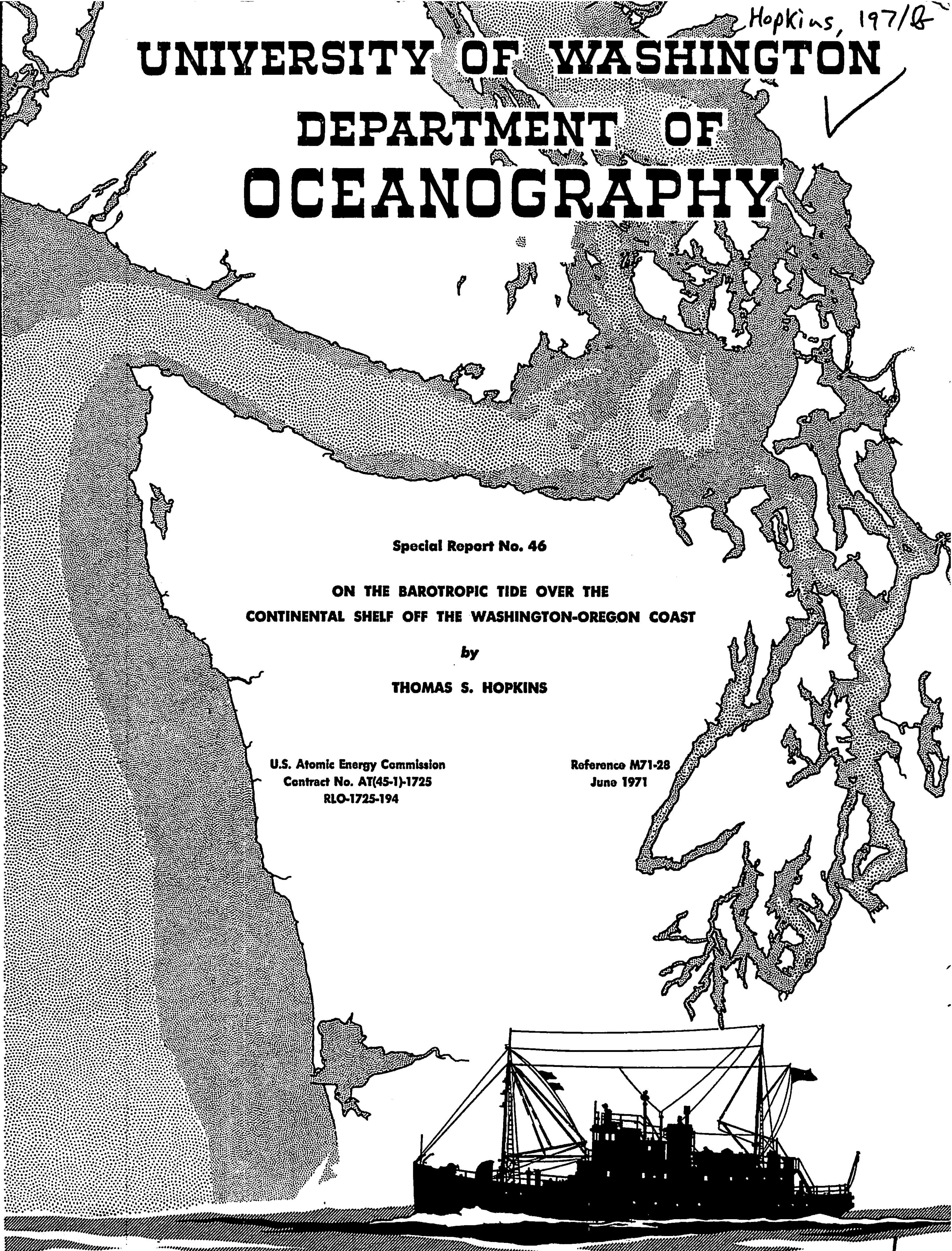
Hopkins, 1971b



UNIVERSITY OF WASHINGTON
DEPARTMENT OF
OCEANOGRAPHY

Special Report No. 46

ON THE BAROTROPIC TIDE OVER THE CONTINENTAL SHELF OFF THE WASHINGTON-OREGON COAST

by

THOMAS S. HOPKINS

U.S. Atomic Energy Commission
Contract No. AT(45-1)-1725
RLO-1725-194

Reference M71-28
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ABSTRACT

This report treats the tides along the Washington-Oregon coast and the variations with latitude of the amplitude and phase of the major tidal constituents. Surface elevations obtained from pressures recorded from 1967 to 1969 at a fixed location (46°25'N 124°20'W) approximately 35 km off the Columbia River mouth and 80 m depth are compared with predicted values. Tidal velocity components computed from direct current observations at the above location are also compared with computed values. The program of harmonic analysis and the tide filter used in the analysis are discussed.

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INTRODUCTION

Present knowledge of tides and of tide-induced motions over continental shelves is so scant that in treating the circulation, it is usual to ignore them completely or to use only rough approximations. Nevertheless a rigorous oceanographic description of a region demands a good working knowledge of the tide. This report notes a few of the problems associated with coastal tides and presents briefly some approaches that might be used in treating them.

The Department of Oceanography at the University of Washington made a series of velocity and pressure measurements over the continental shelf near the Columbia River mouth from 1967 to 1969, and these measurements are used in part as the material for this report. Some aspects of the circulation have been treated by Hopkins (1971a) and the observations have been summarized by Hopkins (1971b). The current velocities were measured with Braincon Type 316 and 381 histogram current meters, and temperatures and pressures were measured with Braincon Type 531 temperature-depth recorders. These instruments record integrated (20-min.) sensor outputs on film that must be read and then digitized to recover the data. A section of the shelf near the Columbia River mouth and the location of the observations are shown in Fig. 1. Hopkins (1971b) presents the data from this location and gives a discussion of the data quality.

The Tidal Current Tables 1971 (ESSA, 1970) describe the tidal currents at the Columbia River Lightship as being clockwise rotary and weak, characterized by 0.3 kt flow directed 020°T on flood and 200°T on ebb. At this position a strong nontidal component of the current, apparently associated with the Columbia River, masks the weaker tidal flow. Hopkins (1971a) demonstrated that large nontidal components associated with wind-induced motion exist over the shelf away from the Columbia River mouth. Collins (1968) statistically analyzes current velocities at the tidal frequencies, and Mooers (1970) comments on the baroclinic tidal components from velocity measurements taken over the continental shelf off Newport, Oregon.

The approximate magnitudes of the tidal currents and their rotation can be seen from current records during quiet periods, Fig. 2. At other times the tidal fluctuations are completely masked by nontidal components (note the V component in Fig. 3); in such instances tidal currents probably interact with the mean current. One apparent result of persistent tidal movement is the presence of a permanent boundary layer above bottom, of thickness proportional to the square root of the eddy viscosity divided by the frequency.

In analyzing water movement at the subtidal or so-called nontidal frequencies, tidal motions first must be removed from the observed data. One straightforward method of separation is that of frequency-centered filtering (discussed in a later section), which can be applied twice, say, at the semidiurnal and diurnal frequencies. Unfortunately these frequencies are not necessarily free of nontidal energy; in fact, diurnal energy in the local wind (e.g. Enfield, 1970) will appear in the wind-induced components of water velocity.

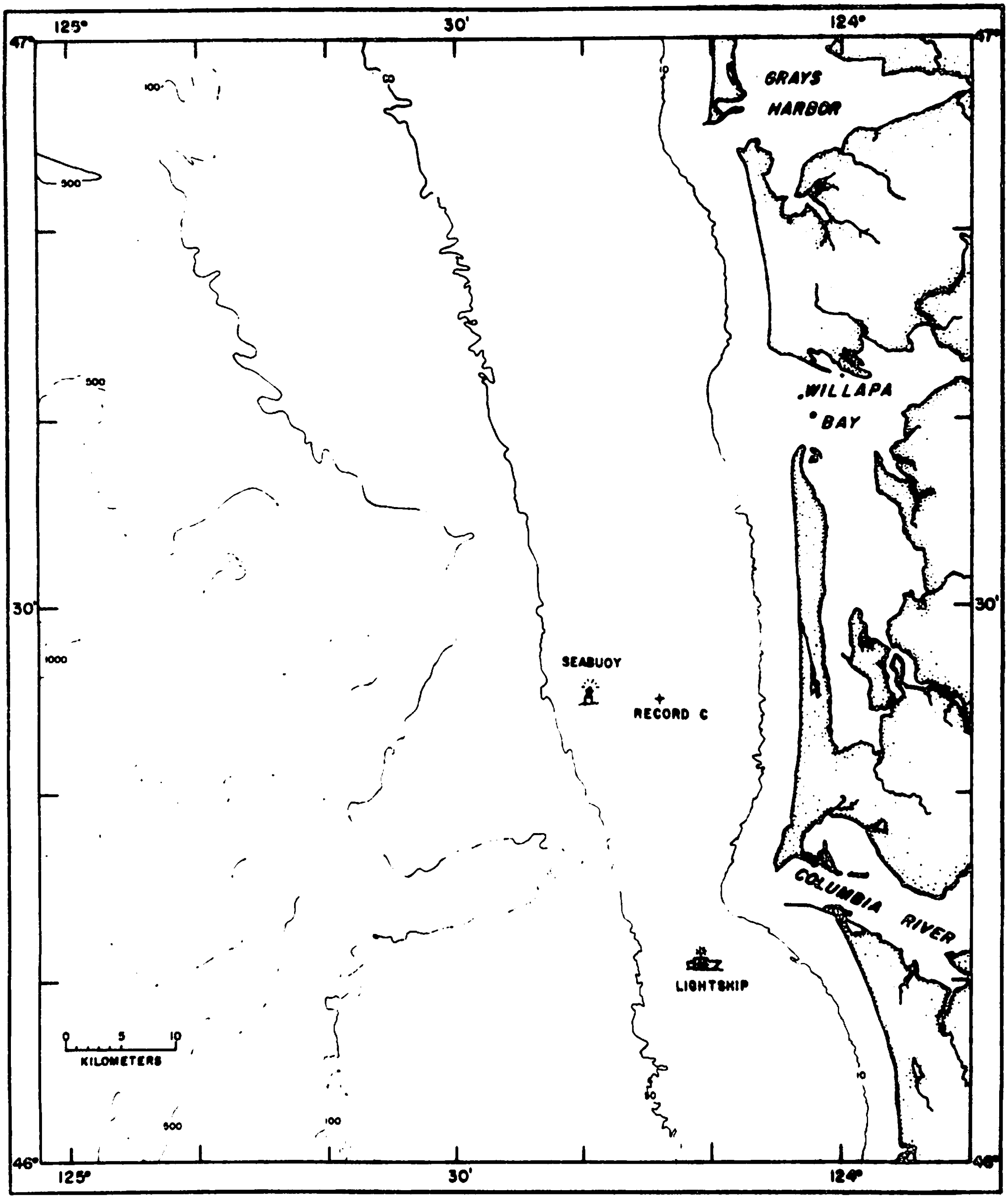


Fig. 1. Location of the various mooring installations (after Hopkins 1971a).

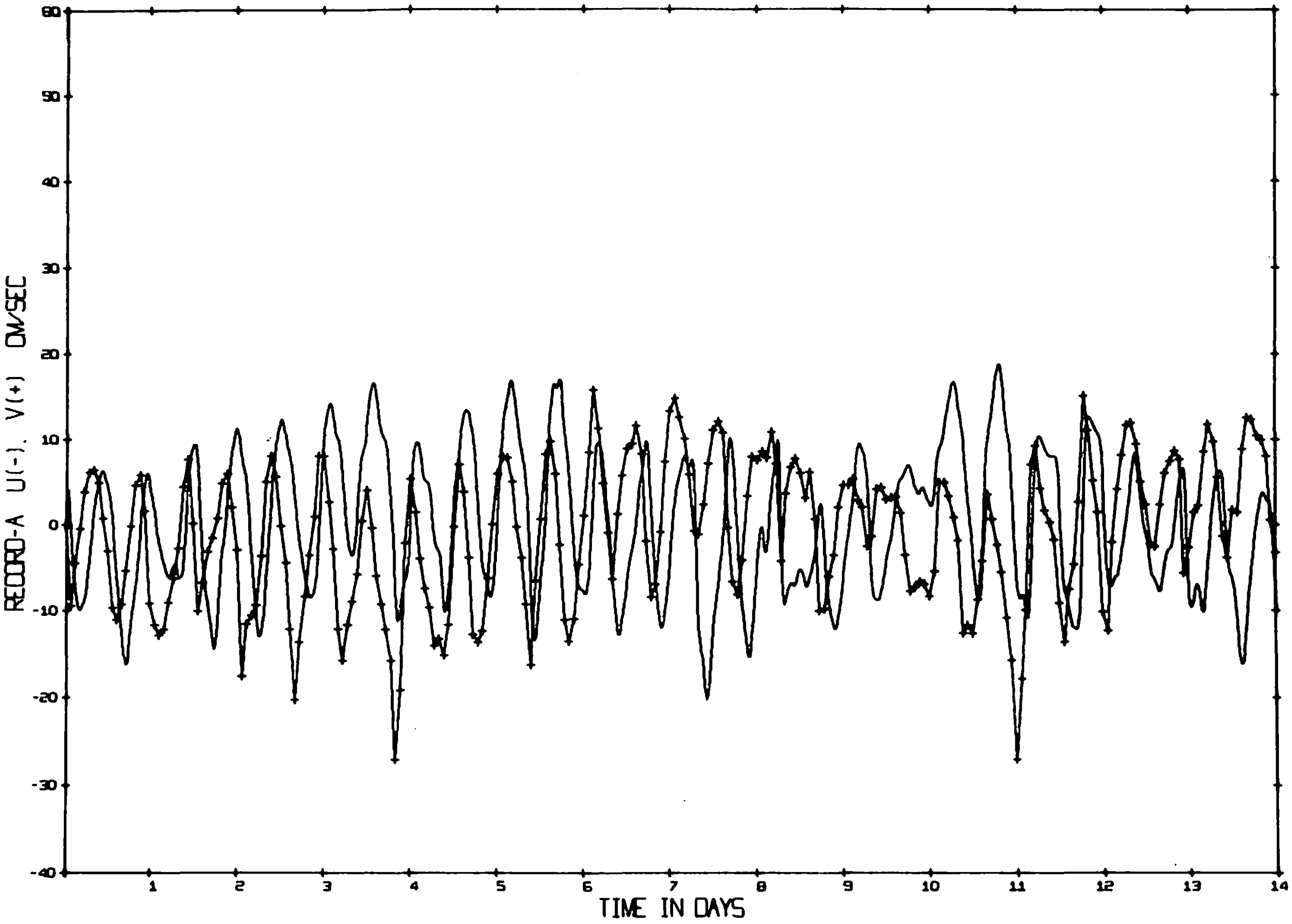


Fig. 2. Record A time series. Start time: 1600 11 July 1967.

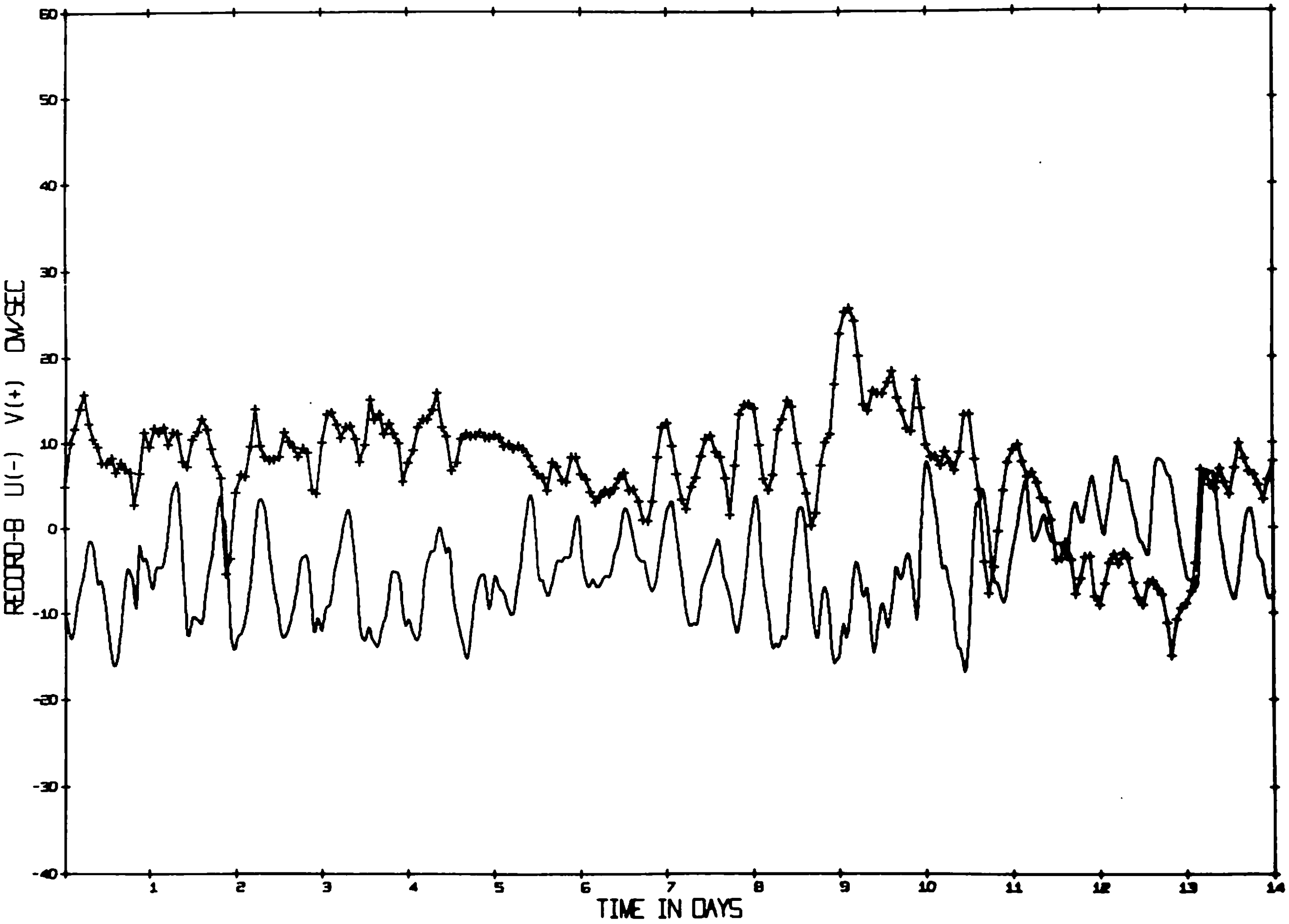


Fig. 3. Record B time series. Start time: 1600 1 September 1967.

Significant tidal motions complicate oceanographic measurement in a number of ways. Without tidal information for making corrections a tidal range of 3 m can give an annoying uncertainty in measurements made with respect to the sea surface. Furthermore it is difficult to make meaningful current measurements from shipboard if the tidal velocity component is not known. Duxbury and McGary (1967) describe how tidal displacement for a gradient at a boundary between different waters can affect the interpretation of oceanographic properties measured at fixed locations. The measurement and interpretation of oceanographic parameters are also complicated by tide-generated internal waves which may cause vertical fluctuations of two to three times those of the surface mode and give oscillating current shears across the pycnocline.

The general solution to the offshore tidal problem is limited by topographic complexities and too few measurements in the open ocean or on the shelf. For a specific location the tide may be measured and predicted by traditional methods of tidal analysis; however, evidence from this study indicates the futility of predicting the tidal velocity component separate from the rest of the velocity field. Munk and Cartwright (1966) present a "response method" for tide prediction, i.e., the empirically derived response function for a given locality is convoluted with the known tidal forcing function to give the tidal response. Water motions on the middle and outer shelf probably result from co-oscillations with the ocean tide, and suffer little interference from shallow water constituents. Available tidal information, however, is primarily for harbors located in bays and estuaries, where shallow water distortions are significant. For example the M_4 constituent at Coos Bay entrance is only 1.8% of the M_2 constituent, whereas 7 mi upstream at Marshfield the corresponding percentage is 13. Some tidal information for the Oregon-Washington coast is given in Tables I, II, and III. Note here Table II in particular, which gives the percent of diurnal range that the primary tide comprises for the various locations along the coast.

In considering co-oscillations in the coastal domain, a primary concern is how the tide varies in the onshore direction. In order to estimate the ranges and times of high water, Redfield (1958) treated the Atlantic coast as a series of narrow gulfs of unit width co-oscillating with the ocean tide. In this case the amplification experienced over the shelf is related to width and depth of the shelf as these parameters affect the travel time of a tidal wave across the shelf. The closer the travel time approaches a quarter of a tidal period, the greater the amplification. Other factors influencing the amplitude at the coast are the amplitude of the oceanic tide, its angle of approach, its period, and the shelf topography including that of the bays and estuaries where the tide is observed.

Both the semidiurnal and the diurnal tides change little in phase along the Oregon-Washington-Vancouver Island coasts (Table I). In both cases the tide occurs later to the north indicating that the tidal wave approaches the slope obliquely (from the southwest), so that the larger normally incident component is reflected at the slope. The tide moves across the shelf and is either reflected or absorbed at the coast, depending in part on the local bathymetry and configuration of the coastline.

TABLE I

AMPLITUDE (FEET) AND PHASE OF MAJOR TIDAL CONSTITUENTS OF ANALYZED STATIONS

Station	*Lat*	*Long*	M_2	S_2	N_2	K_2	K_1	O_1	P_1
Brookings	42-	124-	2.399	0.615	0.512	0.158	1.319	0.808	0.397
Oregon	02.6	17.1	324.8	346.1	298.4	344.5	102.9	88.2	97.3
Port Orford	42-	124-	2.451	0.625	0.515	0.160	1.402	0.866	0.413
Oregon	44.4	29.9	327.7	350.9	303.1	347.9	107.3	90.9	102.6
Bandon	43-	124-	2.404	0.613	0.496	0.156	1.221	0.762	0.372
Oregon	07.3	24.8	335.3	000.3	310.2	351.3	112.4	97.6	108.6
Coos Bay Entrance	43-	124-	2.449	0.638	0.486	0.176	1.250	0.763	0.358
Oregon	20.9	19.3	339.6	3.8	314.0	353.6	112.5	98.1	111.9
Marshfield	43-	124-	2.433	0.536	0.436	0.152	1.148	0.658	0.315
Oregon	23.0	13.1	19.1	55.4	3.1	43.9	136.7	124.1	136.6
Gardiner	43-	124-	2.322	0.523	0.445	0.167	1.176	0.681	0.323
Oregon	44.0	06.7	7.8	40.0	345.9	20.5	130.6	116.8	130.0
Florence	43-	124-	2.220	0.517	0.422	0.155	1.162	0.648	0.312
Oregon	58.0	06.3	003.4	34.0	344.3	17.6	128.2	114.8	124.1
Waldport	44-	124-	2.607	0.669	0.516	0.181	1.314	0.773	0.387
Oregon	26.1	03.5	353.9	23.2	330.8	17.2	120.7	105.1	117.8
Newport	44-	124-	2.778	0.728	0.566	0.190	1.386	0.843	0.426
Oregon	37.6	03.3	346.9	14.8	323.0	12.3	116.3	99.9	110.5
Astoria, Youngs Bay	46-	123-	3.129	0.746	0.586	0.216	1.326	0.798	0.346
Oregon	10.3	50.6	11.9	44.4	348.5	26.9	130.2	115.6	125.0

TABLE I (Continued)

Station	*Lat*	*Long*	M_2	S_2	N_2	K_2	K_1	O_1	P_1
Astoria, Tongue Point	46-	123-	2.976	0.681	0.556	0.219	1.244	0.727	0.337
Oregon	12.5	46.0	19.8	52.4	358.0	43.6	135.3	121.2	133.1
Raymond	46-	123-	3.503	0.902	0.686	0.192	1.405	0.828	0.417
Washington	41.0	45.3	15.6	49.0	352.8	34.6	133.1	118.4	128.0
Toke Point	46-	123-	3.147	0.813	0.635	0.235	1.383	0.841	0.430
Washington	42.4	57.9	5.9	35.9	340.5	24.0	126.7	110.8	122.5
Aberdeen	46-	123-	3.418	0.856	0.672	0.252	1.336	0.790	0.394
Washington	58.0	51.2	15.0	52.0	353.1	49.0	132.2	118.4	129.6
Neah Bay	48-	124-	2.668	0.749	0.566	0.173	1.598	0.980	0.501
Washington	22.1	37.0	355.8	22.2	330.8	11.2	122.6	105.6	117.7
Clayoquot	49-	125-	3.26	0.949	0.651	0.254	1.273	0.798	0.398
British Columbia	09.0	55.0	347.4	15.7	321.3	1.5	113.7	100.1	112.4

TABLE II

COMPUTED PERCENT OF DIURNAL RANGE BY CONSTITUENT

Station	Diurnal Range	M_2	S_2	N_2	K_1	O_1	P_1	Total of Percentage
		% of Diurnal Range						
Brookings*	6.9	34.8	8.9	7.4	19.1	11.7	5.8	87.8
Port Orford*	7.3	33.6	8.6	7.1	19.2	11.8	5.7	86.0
Bandon*	6.8	35.4	9.0	7.3	17.8	11.2	5.5	86.2
Coos Bay*	7.0	35.0	9.1	7.0	17.9	10.9	5.1	85.0
Marshfield	7.3	33.4	7.4	6.0	15.7	9.0	4.3	75.8
Gardiner*	6.7	34.7	7.8	6.7	17.6	10.2	4.8	81.8
Florence*	6.6	33.7	7.8	6.4	17.6	9.8	4.7	80.0
Waldport*	7.7	33.9	8.7	6.7	17.1	10.0	5.0	81.4
Newport*	8.0	34.7	9.1	7.1	17.4	10.5	5.3	84.1
Astoria Y. B.	8.6	36.4	8.7	6.8	15.4	9.3	4.0	80.6
Astoria T. P.	8.2	36.3	8.3	6.8	15.2	8.9	4.1	79.6
Raymond	9.9	35.4	9.1	6.9	14.2	8.4	4.2	78.2
Toke Point*	8.9	35.4	9.1	7.1	15.6	9.5	4.8	81.5
Aberdeen	9.9	34.5	8.7	6.8	13.5	8.0	4.0	75.5
Neah Bay	7.9	33.8	9.5	7.2	20.2	12.4	6.3	89.4
Clayquot*	8.8	37.1	10.8	7.4	14.5	9.1	4.5	83.4
Averages								
*More-open coast		34.83	8.89	7.02	17.38	10.47	5.12	83.72
All		34.88	8.78	6.92	16.75	10.04	4.88	82.27

TABLE III Amplitude and Phase of Major Constituents

		M_2	S_2	N_2	K_1	O_1	P_1
Clayoquot		96.5	27.2	20.8	34.8	23.2	3.7
LSQ(58 da)		338	27	319	99	90	111
Clayoquot		99.4	28.9	19.8	38.8	24.3	12.1
tide		347	16	321	114	100	112
Record AD		87.0	17.7	32.8	53.8	24.2	6.4
(29 da)		351	43	336	120	106	183
Record AF		74.6	13.8	19.4	36.4	26.1	17.2
(29 da)		347	4	342	107	103	144
Record AG		74.4	17.9	24.8	40.5	24.4	9.2
(29 da)		329	330	350	105	92	117
Record AH		76.5	28.2	18.9	46.5	24.6	20.4
(58 da)		34	55	2	139	123	134
Record A	u	6.61	0.81	1.49	.75	.63	.87
(29 da)		300	251	291	60	42.5	141.4
	v	5.31	0.26	1.11	2.52	1.46	1.04
		236	135	250	185	168	317
Record B	u	2.44	0.62	0.95	1.39	0.53	1.52
(58 da)		295	359	189	105	53	93
	v	0.74	0.09	1.59	2.84	1.24	1.48
		167	38	119	179	165	164
Record M	u	2.86	2.24	0.34	1.32	0.66	1.70
(28 da)		249	258	62	220	325	171
	v	1.40	0.76	1.14	2.32	1.93	1.97
		222	166	294	92	166	62
Record N	u	5.6	1.22	0.16	1.85	0.58	3.21
(29 da)		258	269	147	89	269	72
	v	2.90	0.63	1.59	4.83	2.28	2.98
		218	65	285	209	169	206

TABLE III (Continued)

		M_2	S_2	N_2	K_1	O_1	P_1
Record O	u	3.16	0.75	0.96	6.86	2.29	5.47
(29 da)		284	37	357	109	314	265
	v	1.08	0.13	1.31	4.86	2.13	6.17
		208	184	297	43	215	181
Record S	u	4.16	0.58	2.36	1.65	0.76	2.23
(29 da)		201	49	77	227	92	85
	v	1.29	1.31	1.89	0.29	1.15	1.54
		93	311	343	323	163	193
Record V	u	4.95	3.01	.45	3.79	1.81	3.16
(29 da)		259	306	339	106	92	308
	v	2.95	2.06	0.89	1.88	2.60	4.72
		201	252	345	328	116	158

The shelf is too narrow to provide any resonant amplification. The travel time across the shelf can be approximated from the following:

$$T = L/\int_0^L \frac{dx}{\sqrt{gh(x)}} \approx 33 \text{ min., where } h = 0.004x, \quad L = 4(10^6),$$

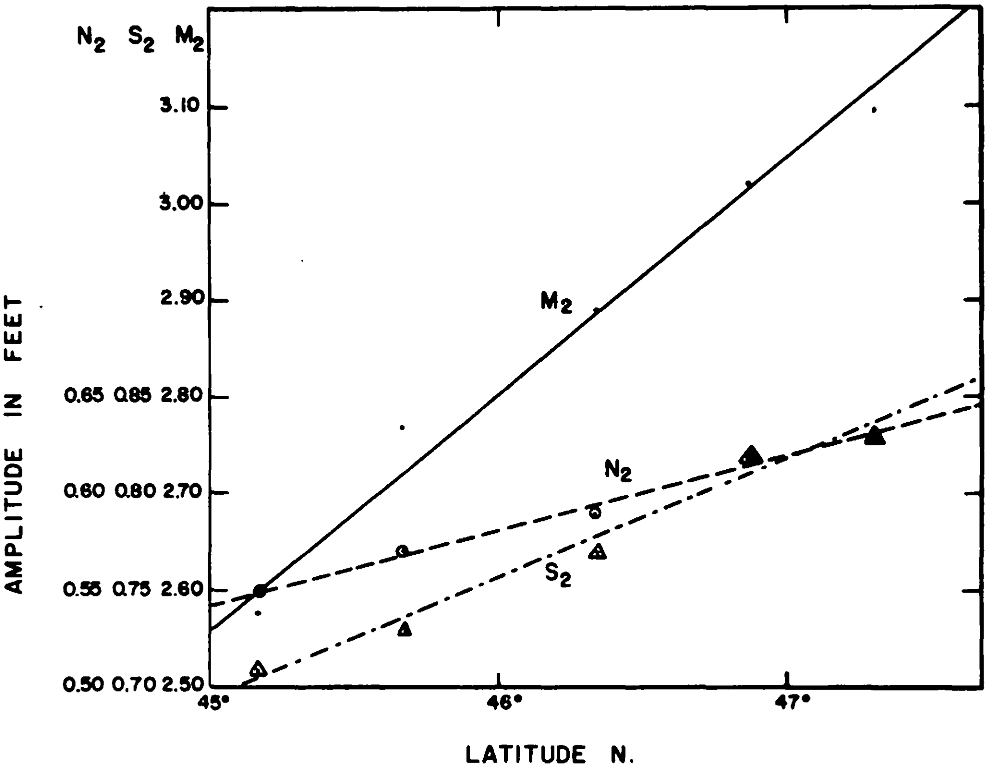
which is a small fraction of the period.

At the shore, wave setup also contaminates the measurement of sea level. Stewart (1961), in discussing wave setup, comments ". . .[it] can amount to the order of a metre, but even the sign of such effects is extremely difficult to predict or to calculate, since it depends upon the proportion of wave energy lost by breaking or by partial reflection. Correcting for them would seem to be difficult in the extreme." This would favor the making of water level measurements outside the nearshore region, i.e., deeper than 50 m. Runoff and its associated hydraulic and isosteric anomalies will further complicate the interpretation of water level measurements at the coast. Additional water level measurements are much needed at offshore locations. For relatively short-period phenomena such as tides, shelf waves, etc., changes in relative slope can be determined using several recorders suitably installed in the offshore direction. Pressure devices can be used but would need to be securely affixed to the bottom to prevent movement.

Improved tidal predictions are needed. Thorough knowledge of the tidal behavior would assist in short-time period sampling, would facilitate in trawling and other fishing operations, and would provide a more precise base for analyzing the nontidal portions of the current and their mutual interactions. As a step towards improving tide predictions the tidal problem is treated briefly from three approaches: by computing the offshore tide, by analyzing the observed tide, and by statistically filtering the tide.

On the Oregon-Washington coast the tides have been analyzed only in various bays and estuaries. The amplitudes and phases of the major constituents are given in Table I. Most of these tidal values reflect shallow water distortion, some more than others. An empirical approach was used to minimize this error. The ratio of constituent amplitude to diurnal range changes but little, e.g., see Table II. It was assumed that deviations were caused by the stronger shallow water components. The tide and diurnal range are given at a number of substations along the coast. The amplitudes of the various constituents were computed using the amplitude/diurnal range ratios, and were plotted against latitude (Fig. 4). The phase at the substations was approximated by adjusting the high water times and speed of the constituent. Since the phase angles seemed to change little with latitude, the phase gradients were set to zero. The values used for Long Beach, Washington were:

	M_2	S_2	N_2	K_1	O_1	P_1
amplitude (cm)	88.0	23.4	18.0	39.3	24.4	12.2
phase	348°	037°	319°	119°	101°	114°
amplitude (10^7) gradient	6.74	1.70	1.10	0.96	0.55	0.14



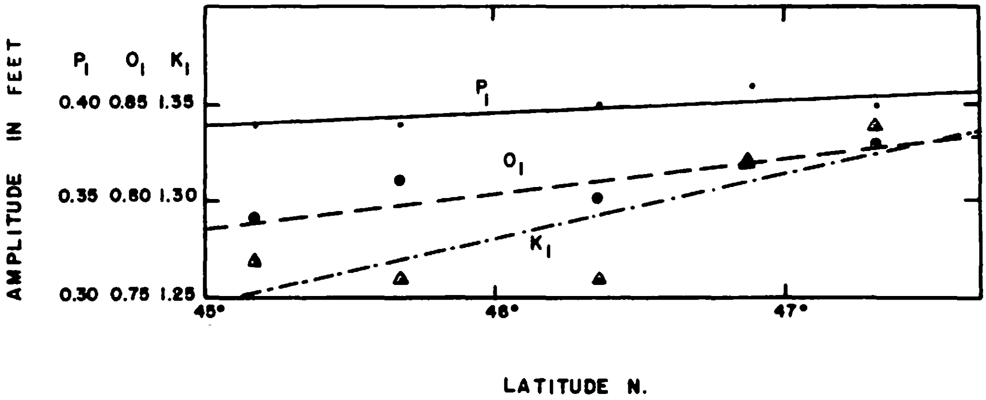


Fig. 4. Approximated constituent amplitude versus latitude.

The surface elevation is well predicted by this scheme (see Figs. 5 and 6), essentially because there is so little change in amplitude and phase over the narrow shelf. The tidal oscillations of the major constituents dominate the pressure records. There are some lower amplitude low-frequency changes most likely due to wind setup.

The predicted and observed tidal velocities differ substantially as shown in Fig. 7. This portion of Record A was chosen because the velocity was predominantly tidal. The v component of the predicted tide is generally larger than the u component, whereas in the records of observed velocity the opposite is true. The amplitude and phase in the true records vary considerably with time. Part of the phase discrepancy in Fig. 7 arises from the wide filter used (see below) to obtain the observed tidal velocities. Reasonable values for the friction parameter failed to alter the predicted tide in any significant way because the frictional time constant is at least an order of magnitude longer than the tidal period.

HARMONIC ANALYSIS

Several analytical methods are now being used for tidal analysis and prediction. Zetler and Lennon (1967) have compared some of these by observing the amount of tidal energy remaining in the residual spectrum after applying various techniques to the time series of data. One of the methods tested was the Harris-Pore-Cummings (1963) least-square method that has been accepted for general use by the Coast and Geodetic Survey to replace their long-used mechanical method. Improvements have been made on the method by Zetler, Schuldt, Whipple, and Hicks (1965) to permit analysis of data randomly spaced in time, and by Zetler and Cummings (1966) to include as many as 114 constituents. The current version of the program was obtained via the courtesy of the tides section of the Oceanography Division of Environmental Sciences Services Administration, Rockville, Maryland.

The program fits in a least-squared sense a set of frequencies to the data time series. Time, longitude, constituent speeds, equilibrium arguments, and node factors are used as input and give the local amplitude and phase as output.

Table III lists values of amplitude and phase of the six major constituents for various records of this study. The tides and their analysis by this method at a known station (Clayoquot) are given for comparison. The pressure records are far less noisy and more nearly stationary, and therefore give more reliable results. Phase discrepancies may occur because of uncertainty in start times. The two simultaneous records AF and AG agree quite well.

The velocity records give variable results, reflecting a nonstationary tidal response. Some trends are worth noting. The u component of the M_2 constituent leads the v component by 2.5 to 3 hrs, whereas the pressure leads the u component by 3 to 5 hrs. The amplitude of the v component of the M_2 constituent is consistently less than that of the u component. The

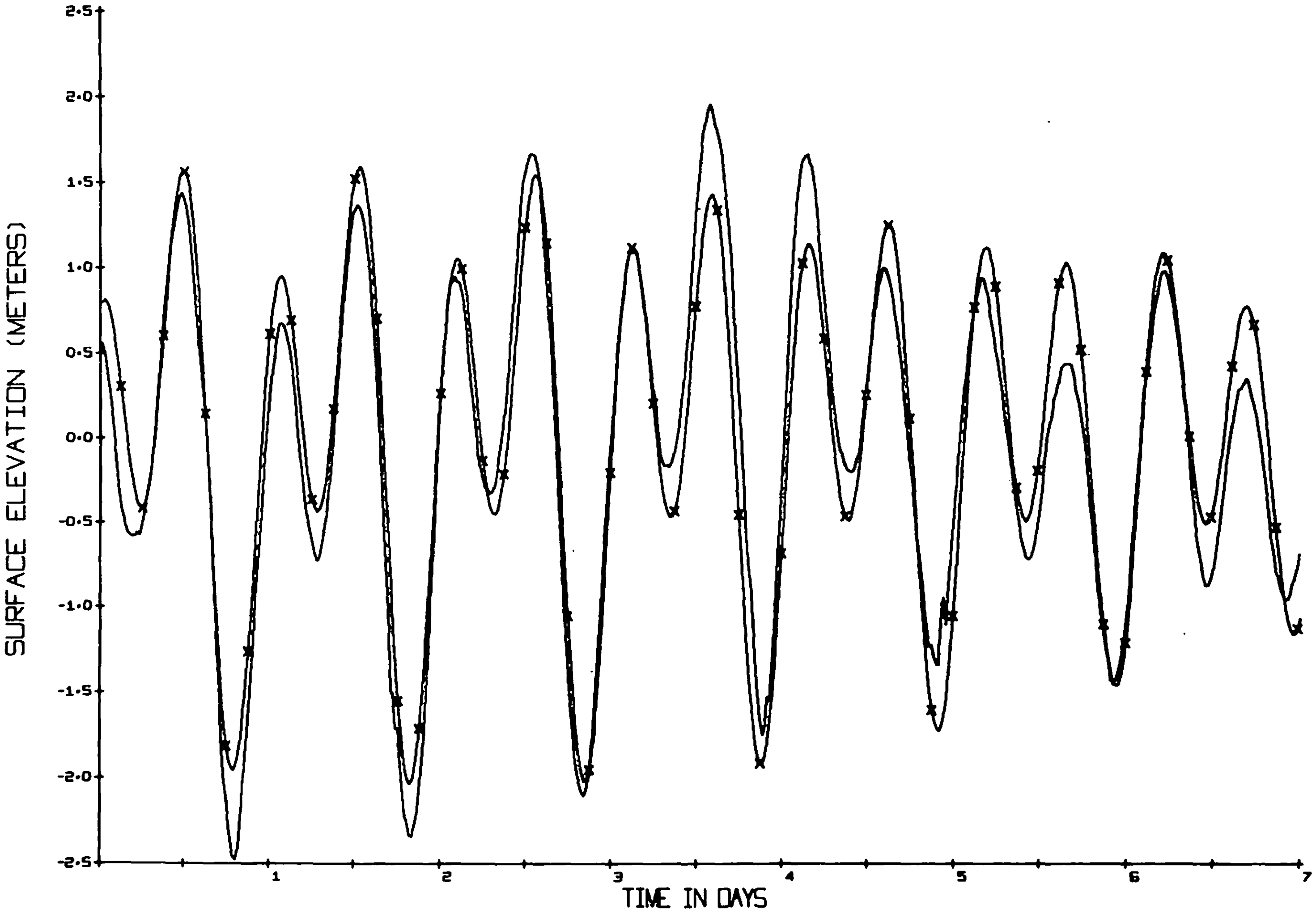


Fig. 5. Pressure Record AD, solid line, compared with predicted surface elevation. Start time: 1630 26 December 1968.

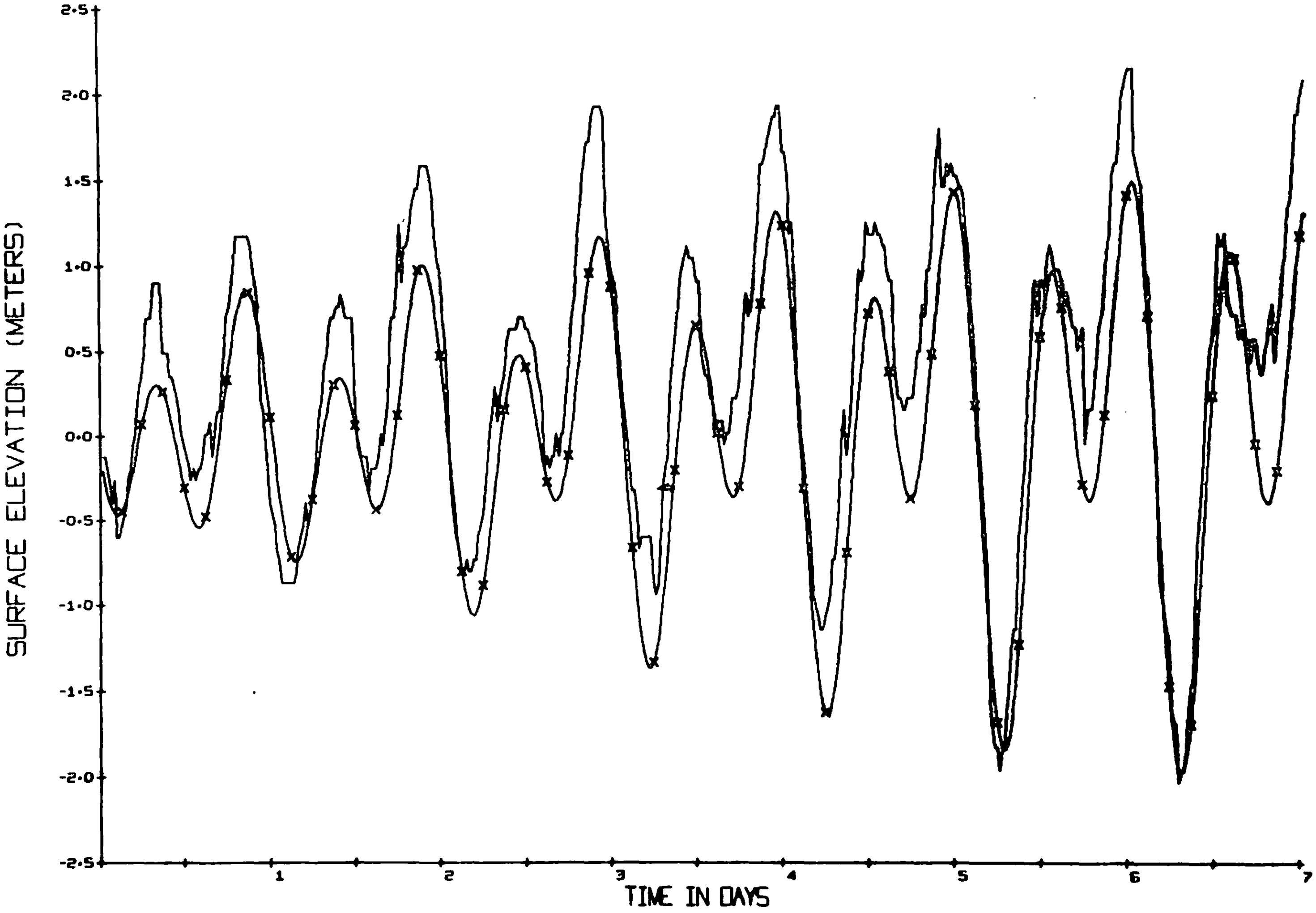


Fig. 6. Pressure Record AF, solid line, compared with predicted surface elevations. Start time: 1810 1 June 1969.

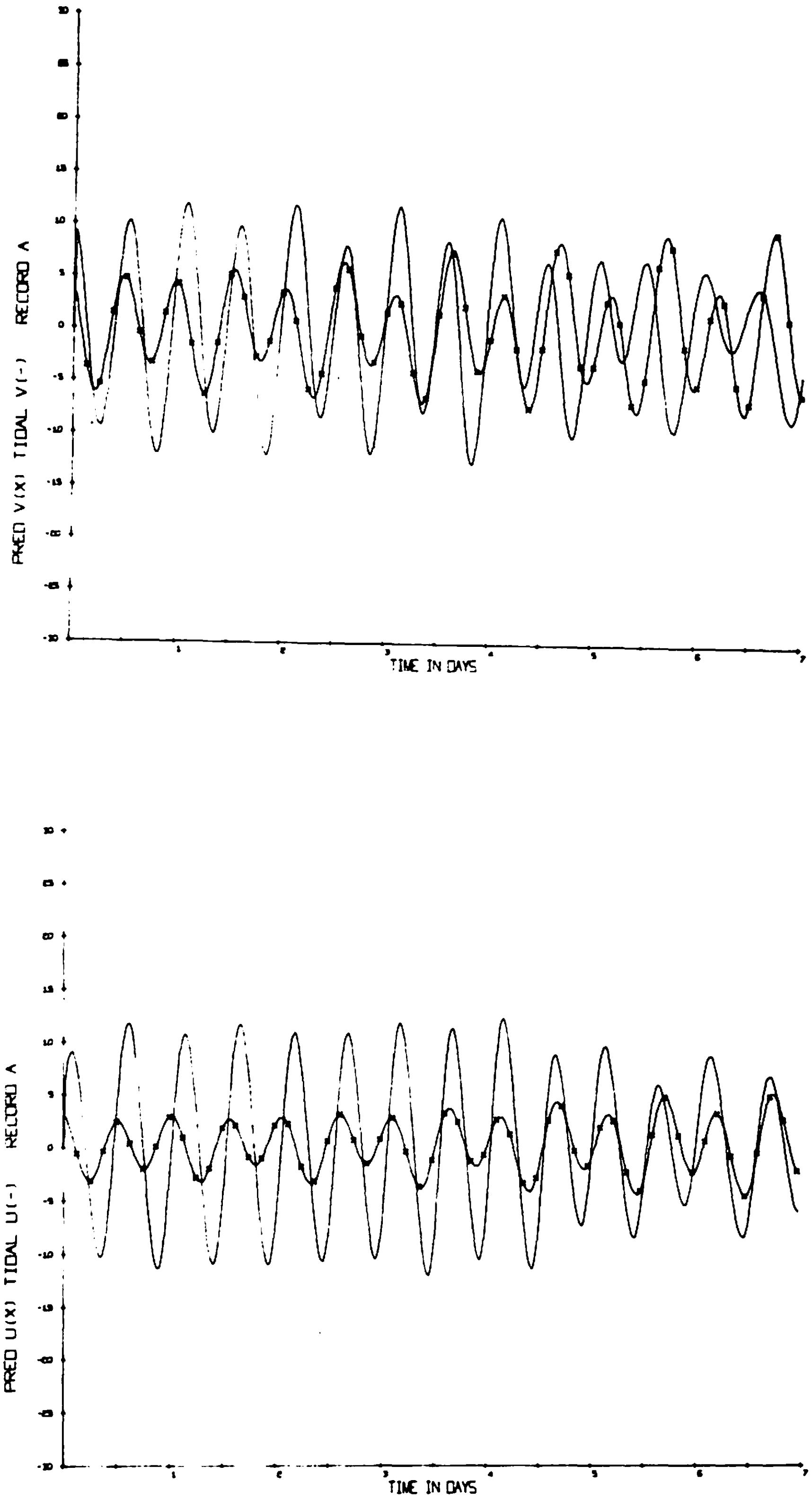


Fig. 7. Predicted tidal velocity components compared with those observed in Record A. Start time: 1630 15 July 1967.

The diurnal constituents tend to be more for active records (Record O) and less for inactive records (Record A) with the opposite true for the semidiurnal constituent. The two vertical pairs (M/N and S/V) show a vertical phase lag in the M_2 constituent.

TIDE FILTER

The tide filter used consisted of the inverse transformation of the Fourier coefficients for a given time series in which the coefficients at the tidal frequencies had been replaced by zeros. The Fourier coefficients were generated using the Fast Fourier Transform algorithm. The particular program used was authored by J. W. Cooley and is described by Cooley and Tukey (1965). Subsequent modifications have been made by J. R. Wilson of the University of British Columbia, and by J. G. Dworski of the University of Washington.

The band width chosen for the analysis was sufficient to include the energy spread about the central frequency. Unfortunately there is a time variable continuum of nontidal energy at these frequencies, and there is a time variable transfer of tidal energy out of these frequencies. Both of these important processes decrease the exactness of the filtered energy. The actual periods encompassed by the filter were from 10.5 to 14.5 hrs for the semidiurnal and from 22 to 26 hrs for the diurnal.

Two examples of tidally filtered records are given in Figs. 8 and 9. The first is Record A, which had relatively large tidal amplitudes and the second is Record B, which had relatively more energy in the lower frequencies. Considerable energy at the quarter-diurnal frequency contributes to the apparent high frequency noise. The observed tide used in Fig. 7 was generated by subtracting the tide-filtered series from the original series. The amplitude variations at the tidal frequencies can be seen by inspecting the tidal residuals for a more active record; two weeks of the residuals are shown in Fig. 10.

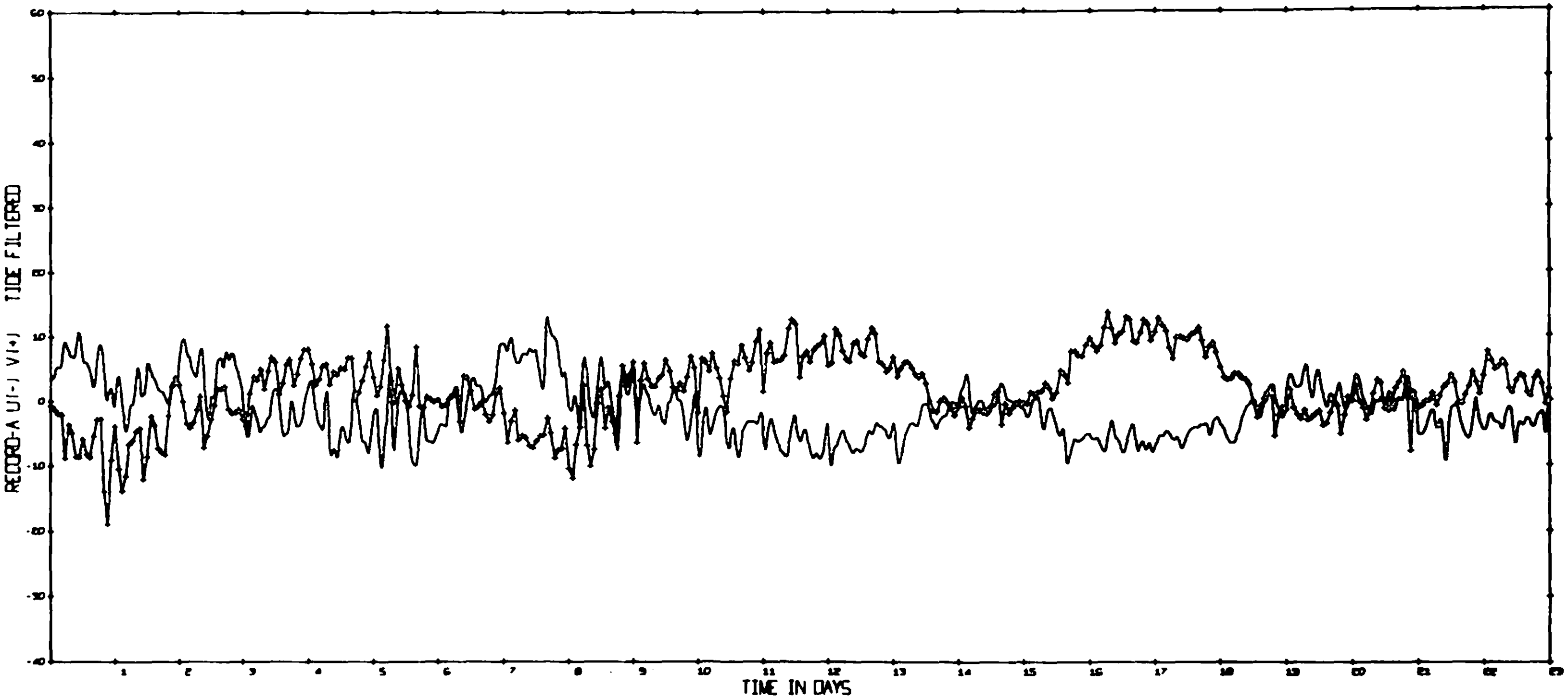


Fig. 8. Tide filtered velocity components from Record A.

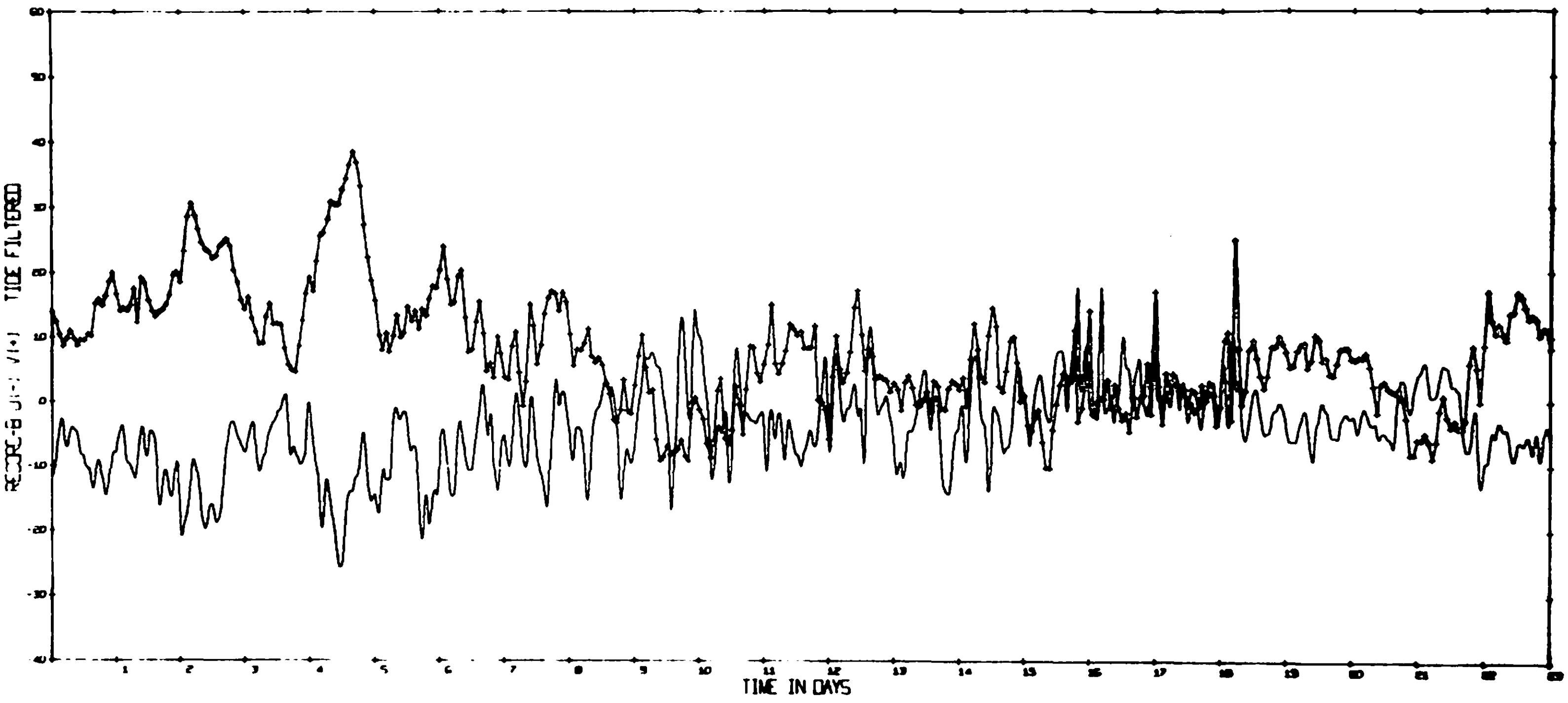


Fig. 9. Tide filtered velocity components from Record B.

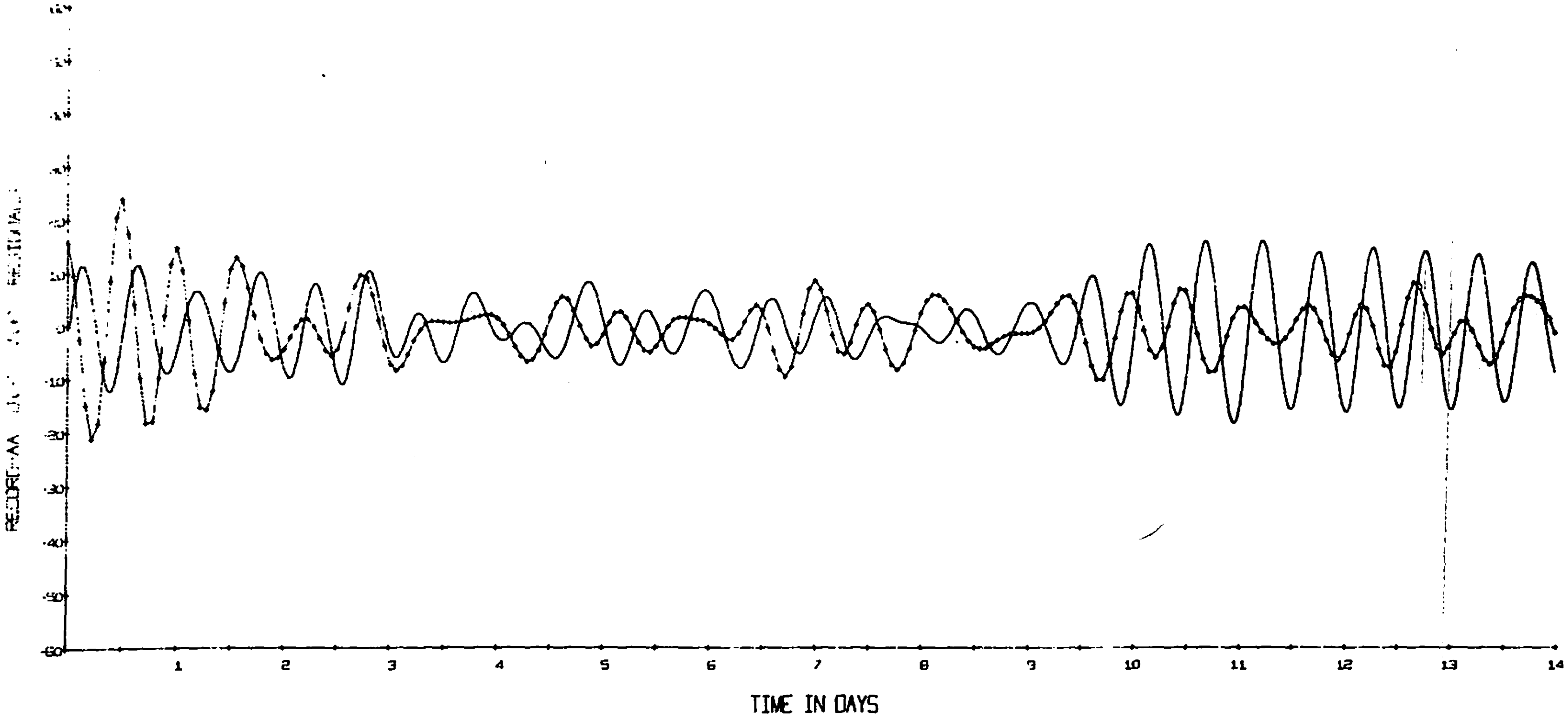


Fig. 10. Tide residuals Record AA.

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