THE USE OF OCEAN TIDE RECORDS TO DETECT MOTIONS PREMONITORY TO A TECTONIC EVENT IN THE LONG BEACH, CALIFORNIA AREA

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THESIS

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EVENT IN THE LONG BEACH, CALIFORNIA AREA

by

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ABSTRACT

Marigram records of ocean tide fluctuations at three tide stations operating in the Santa Monica/Long Beach, California area at the time of the 10 March 1933 Long Beach earthquake (magnitude 6.3) were digitized onto magnetic tape. Time series of hourly instantaneous tide level observations were generated and processed under a least squares criterion to remove the effects of the nine most energetic lines of the ocean tide harmonic spectrum. The resulting residual series did not contain any anomalous premonitory motions indicated by another residual series previously analyzed at the National Center for Earthquake Research. Auto- and cross-correlations of the three residual series used revealed only two possibly significant auto-correlation peaks for two stations lagging themselves by 24 hours. Correlation confidence regions were not established due to an inability to establish sufficient independence between residual series. Ocean tide spectrum line amplitude analyses showed the O_1 and M_2 lines to have the greatest stability.

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I. INTRODUCTION

In general, studies of interaction between ocean tides and adjacent land masses fall into one of two classes of analysis--(1) frequency analysis and, (2) trend analysis. The data used for trend analysis have generally been observations of some mean ocean characteristic. The use of mean data, such as yearly mean sea levels, monthly mean sea levels, and daily mean sea levels, has dictated the use of lengthy epochs in order to gain sufficient data points to ensure the statistical significance of the results. This in turn has restricted the studies to long term trends. The use of more-frequent observations would enable one to study short-term trends not previously recognizable, due to masking by aggregation of data into means.

In 1964, sea level changes were recorded by tide gauges shortly after the 16 June Niigata, Japan earthquake (magnitude 7.5) [1]. The changes recorded were in directional agreement with the seismic uplift and tilting associated with the earthquake, and the tide level changes were readily visible over the twenty-eight day data streams from the tide gauges.

An implication was that frequent observations of ocean tides might enable one to detect not only post-seismic changes in tilt, but possibly pre-seismic changes as well, if indeed any existed. In addition, whereas longer-term

large scale tilts would be recognizable to a general populace due to changes in the flow characteristics of drainage and water supply facilities, short term (several hours to one day), smaller scale tilts premonitory to an event might go unnoticed. Yet these smaller scale changes might be detectable through analysis of frequent ocean tide observations.

It seemed that shallow focus earthquakes offered the best chance for the detection of such events due to the generally more explicit surface deformations associated with a shallow event of a given magnitude. A search was conducted for a large or moderate, shallow focus earthquake which occurred in reasonably close proximity to ocean tide recording stations for which the records were readily available. The 1755 (5:55 p.m.) 10 March 1933 Long Beach, California earthquake (magnitude 6.3) satisfied these restrictions.

Any changes in the sea level over a short period of time would be more easily discerned if the harmonic portions of the ocean tide fluctuations were removed from the ocean tide observations. The resulting observations would then be attributable to meteorological, geological, and tectonic factors. If the meteorological effects were additionally extracted, the resultant residual data would then reflect geological and tectonic movements, if any.

The goal of this research was to extract the most powerful harmonic portions of the ocean tides and the meteorological effects from series of ocean tide level observations from several stations to generate residual time series

reflecting geological and tectonic motions at the stations. Ocean tide records from Long Beach Inner Harbor were analyzed by Dr. M. D. Wood at the National Center for Earthquake Research (NCER) prior to this investigation. The residual tide series generated indicated anomalous tidal motions premonitory to the earthquake. These residual series "signals" were evident after removal of only the harmonic portions of the ocean tides and were well above the noise level of the residual series. It was hoped that the data analyzed in this investigation would contain similar pre-seismic "signals". These "signals" could then possibly be correlated between the stations and the epicenter of the event in some temporal or spatial aspect.

II. THE THEORY OF TIDES

The movements of all heavenly bodies in the solar system causes the gravitational forces exerted upon the earth to vary in time. Among these bodies, the sun and moon are dominant in their effects due to their masses and their proximities to the earth. The responses of the earth to these forces can be classed into three categories as follows: (1) a deflection of the vertical at a point of observation, (2) a deformation of the earth's body, and (3) a change in the radial force of gravity at a point. In this investigation the area of concern was limited to the third response class and the bodies of the sun and the moon.

At a point of observation the radial force of gravity varies in a cyclical manner, called earth tides, due to recurring relative relationships between the system bodies and a rigid earth. A frequency analysis of these gravity variations reveals that the motion is composed of a spectrum of harmonic motions - each line with its unique amplitude and frequency. The lines are clustered in groups and particular groups can be related to recurring relationships between specific bodies.

When the complex relationships between the moon and a rigid earth are considered, for example, these groupings of lines become meaningful. An idealized model of the earth - moon system is a moon moving around the earth in a circular

equatorial orbit at a constant velocity. This motion produces a semi-diurnal tide with a period equal to the lunar half-day of 12 hours 25 minutes and is described by the M_2 principal lunar wave which is the most energetic of the semi-diurnal waves.

When the declination of the lunar orbit is considered, the absolute distance between the moon and the observation point on the earth varies in time. For an equatorial observer, the effects of the lunar traverses in the northern and southern hemispheres are equal in magnitude. For the non-equatorial observer, however, the magnitude of the effects are unequal and are referred to as the diurnal inequality. The moon has an earth-orbital period of 27.55 days and the cyclical motion of the moon's declination causes an additional fortnightly modulation of the earth tides.

In reality, the orbit of the moon is an ellipse. Kepler's law states that for elliptical motion the revolving body sweeps out equal areas in equal times. This implies that there is an inverse relationship between the instantaneous velocity of the moon in its orbit and its instantaneous distance from the earth. These cyclical variations in the moon's velocity and distance from the earth cause all of the above principal motions' effects to be modulated in amplitude and phase.

Fundamental motions can be described as well for the movement of the sun in relation to the earth with a view toward a circular orbit, and declinational and elliptical properties of that orbit (Figure 1). Yet the frequency spectrum of the earth tides is not fully developed by

application of the above fundamental-motions approach. There also exist spectral lines that occur because of the beatings of the principal tidal lines. This causes additional variations at sum and difference frequencies which cannot be ignored.

Consider the principal solar demi-diurnal wave S_2 and the principal lunar semi-diurnal wave M_2. They beat between themselves at a difference frequency causing a fortnightly modulation. The M_2 wave beating against the N_2 lunar elliptical semi-diurnal wave causes a monthly modulation describing the eccentricity of the lunar orbit. The K_2 wave, with a period equal to the sidereal half-day, is composed of both lunar (68%) and solar (32%) components which are analytically inseparable. The K_1 wave is the analogous luni-solar diurnal declinational wave. A further beating with a lower frequency occurs between the ${}^{s}K_2$ and S_2 waves producing a solar semi-annual declinational wave. The amplitudes of all the long period, diurnal, and semi-diurnal waves are latitude dependent.

Other waves concerned with long period phenomena such as variations in orbital eccentricities and earth flattening also exist but were not of interest in this investigation.

The above waves are all constituents of the tides of a rigid earth (Table 1). The ocean masses of the earth are also subjected to, and in turn respond to, these forces. Certain other motions caused by the ability of the oceans to redistribute themselves in response to these forces must be harmonically described in order to adequately construct

theoretical ocean tides. The single component entered in this analysis to account for this fact was the M_4 lunar quarter-diurnal wave describing shallow water responses with a period of 6.21 hours. Other constituents were not considered to be of sufficient magnitude for inclusion in this analysis.

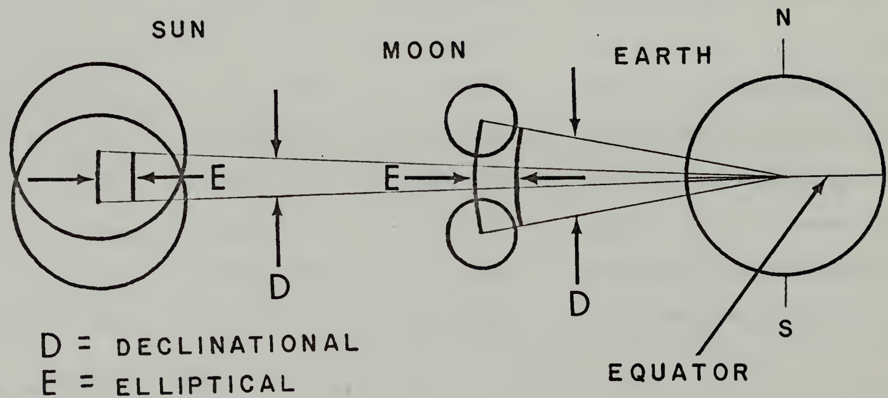

Figure 1. Lunar - Solar Orbital Motions

TABLE I. TIDAL CONSTITUENTS USED IN ANALYSIS

Classification	Symbol	Amplitude Coefficient (microgals)	Frequency (deg/solar day)	Wave Description
Diurnal	K_1	+53.050	15.041	Luni-Solar Declinational Wave
	O_1	+37.689	13.943	Lunar Declinational Wave
	P_1	+17.554	14.958	Solar Declinational Wave
	Q_1	+ 7.216	13.398	Lunar Elliptic Wave of O_1
Semi-Diurnal	M_2	+90.812	28.984	Lunar Wave-Circular Orbit
	S_2	+42.286	30.000	Solar Wave-Circular Orbit
	N_2	+17.387	28.439	Lunar Elliptic Wave of M_2
	K_2	+11.506	30.082	Luni-Solar Declinational Wave
Quarter-Diurnal	M_4	-	57.968	Shallow-Water Lunar Wave

(Adopted from Melchior, 1967)

III. DATA PROCESSING

A. DATA COLLECTION

1. Ocean Tide Records

All the ocean tide records used were in the form of paper strip chart records called marigrams. Each marigram was recorded by a standard U. S. Coast and Geodetic Survey automatic recording ocean tide gauge and was of approximately 30 days duration. The gauge was operated by a float moving up and down in a stilling well (designed to eliminate horizontal movements and attenuate rapid vertical movements) beneath the tide gauge station. The movement of the float and its suspension wire actuated a worm screw on the gauge which drove a pencil horizontally across the recording strip chart at a scale of one inch per one foot (30.48 centimeters) of vertical tide movement.

The strip chart was lead off of a supply roller, over the main recording roller, and onto a receiving roller. The chart was kept under spring tension on the supply roller to prevent its unrolling too rapidly. The paper was advanced continuously by the main roller under the recording pencil at a uniform rate of one inch per hour. The main roller was driven by a clock motor. The receiving roller maintained the strip chart under constant tension through the aid of a tensioned drum. In this manner, the strip chart record was recorded at a uniform rate and at a constant tension from

roller to roller. Hourly time marks were recorded on the chart by means of a trip mechanism and a continuous fiducial line was recorded.

The tide gauge contained both a motor clock and a time clock. When the gauge was inspected daily, with the exception of weekends, the two clocks' times were compared and entered on the marigram and the related point on the actual tide curve was marked in some manner. The gauge clocks were then adjusted as necessary. The clocks were eight-day clocks but were wound semi-weekly to ensure a uniform rate of tide recording. In some cases, Western Union time was used in lieu of time-clock time for the time comparison. Usually some weather conditions were also entered on the marigram with the time comparison note.

Two actual tide record tracings extracted from marigrams from Santa Monica and Los Angeles Inner Harbor are shown in Figure 2. It is apparent that the tide gauges were able to record even the higher-frequency tide motions resulting from meteorological effects such as wind. These samples were taken from recordings for 10 March 1933 spanning the occurrence of the earthquake at 1755 hours and even the shock response of the waters to the earthquake are visible in the records.

2. Station Selection

Ocean tide records from permanent U. S. Coast and Geodetic Survey automatic recording ocean tide gauges were readily available for analysis. These stations, all

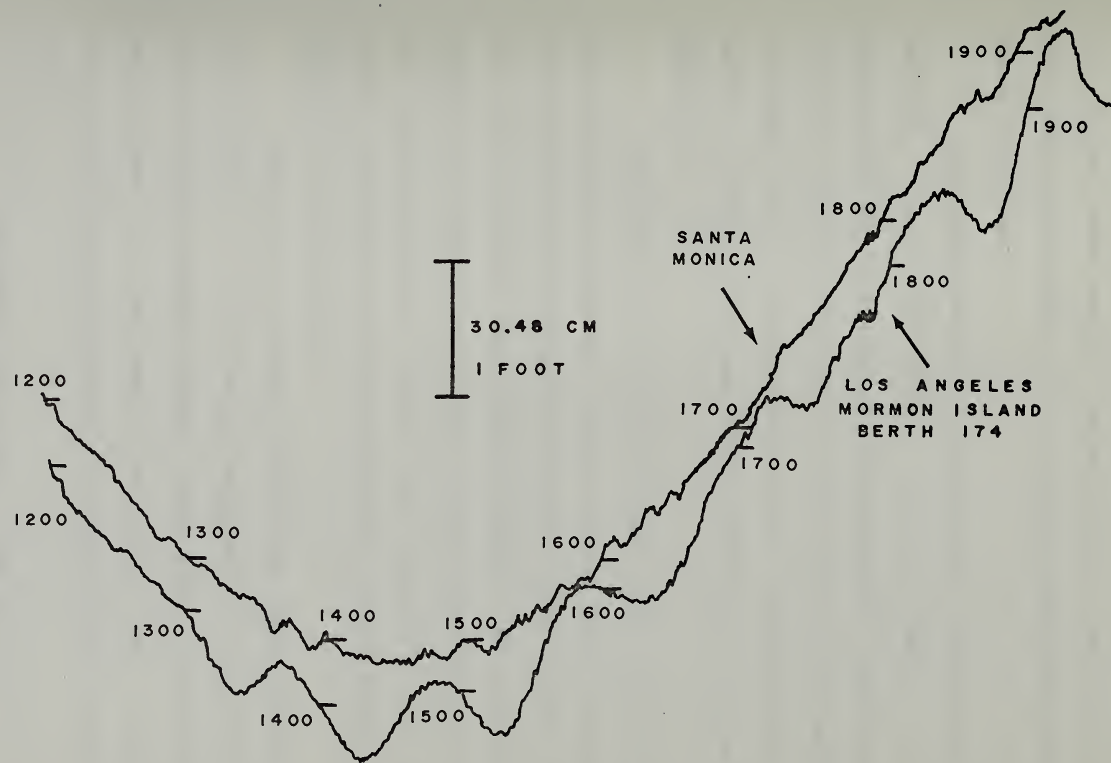

Figure 2. Marigram Record Tracings from 13 March 1933

operating at the time of the earthquake were: (1) Santa Monica pier, (2) Los Angeles Outer Harbor - Berth 60, (3) Los Angeles Inner Harbor - Mormon Island - Berth 174, (4) Long Beach Inner Harbor, and (5) Long Beach Outer Harbor, as shown in Figure 3.

The locations were spatially well suited in two respects. First, they varied in distance from 34 to 70 kilometers from the epicenter of the earthquake. Second, they varied in distance from the supposed trace of the Newport - Inglewood fault, although they were all to the western, or seaward, side of the trace. These distances are given in Table II.

Nicholson [2] in 1929 concluded from City of Los Angeles Harbor Department surveys that an active fault existed cutting across Terminal Island and Mormon Island, extending into Wilmington toward Redondo Beach. He found that the surveys indicated a fault scarp of 0.07 feet and cautioned that leveling surveys connected with determining sea level at the port should take this relative movement between bench marks into consideration.

Leypoldt [3] in 1938, using tide gauge records from five stations [(1) Los Angeles (Wilmington) Inner Harbor, (2) Los Angeles (Mormon Island) Inner Harbor, (3) Los Angeles Outer Harbor, (4) Long Beach Inner Harbor, and (5) Long Beach Outer Harbor] concluded that, for the Los Angeles gauges,

> "any marked variation in the relation between the elevations of mean tide level on the respective staffs is a

> measure of the movement of one staff in relation to the other, and not a variation of tidal regime."

He also concluded that the Los Angeles Outer Harbor tide gauge station remained relatively stable over time. Comparing the Wilmington and Los Angeles Outer Harbor gauges from 1921 to 1931, he found that Wilmington subsided uniformly from 1921 to 1928, at which time it commenced returning to its 1921 condition, which it reached in mid-1929. In 1931 the Wilmington relative subsidence again commenced.

A comparison of the Los Angeles Mormon Island and Outer Harbor gauges from 1931 to 1937 revealed a seven month periodicity in the relative uplift and subsidence of the stations. The Long Beach Inner and Outer Harbor gauges also were found to have relative motions when compared to the Los Angeles Outer Harbor gauge.

For the period February to April 1933 the relative movements between gauges varied between 0.03 and 0.08 feet, or a maximum of 2.4 centimeters. Due to working with monthly sea levels, however, the movements could not be pinpointed temporally in relation to the earthquake.

Gilluly and Grant [4] in 1949, considering comparisons of tide gauges from 1926 to 1945, as well as a number of leveling surveys conducted by various agencies, concluded that

> "intercomparisons of tide gauge records ...support the precise level data in showing subsidence."

In speaking of the Long Beach Outer Harbor tide gauge they

said,

> "It shows essential stability with reference to the standard tide gauge at Los Angeles Outer Harbor, Pier 60, up to 1937."

In their "Summary of Elevation Changes" their conclusions included (1)

> "The movements in the interval between the two surveys (1931-1932 and 1933-1934) which bracketed the Long Beach earthquake were irregular in the western part of the area, involving both uplift and depression..."

and (2)

> "The differential subsidence centering in the Wilmington oil field was trivial, if indeed it existed at all, prior to 1934."

No reference to the gauge at Santa Monica was found. One conclusion drawn from the above investigations was that the tide gauges were operating on a relatively stable areal base for the two months surrounding the earthquake. The largest effect of the earthquake recorded by the surveys was an uplift of 0.61 feet (18.6 centimeters). A change of this magnitude appeared to be readily detectable in the data analyses anticipated.

Leypoldt's assumptions that the tidal regime had approximately equal effects on the tidal records from Los Angeles was considered valid when using monthly mean sea levels and only two close stations, but had to be re-evaluated for this current work involving hourly instantaneous tide level observations and five tide stations.

The personnel who cared for the tide gauges and made the time comparisons were not the same for each tide gauge. Neither was a single individual responsible for even a majority of the stations. Thus, each gauge had associated with it a different standard of cleanliness and preservation. But since no human calculations were involved in the data collection, the effects from different caretaker personnel were assumed to be minimal.

As a first approximation, the Santa Monica, Los Angeles Outer Harbor, and Long Beach Outer Harbor gauges were considered as being on the coast open to the ocean, showing little, if any, seiche effects. However, the Los Angeles Inner Harbor and Long Beach Inner Harbor gauges were located in channels and might be subject to more energetic seiche effects. As shown by Figure 2, the Santa Monica data was generally smooth with some small scale perturbations. Los Angeles Berth 174 data, on the other hand, showed prominent seiches which varied in their perturbing effect upon the tide response curve (compare the interval 1200 to 1300 hours to the interval 1800 to 1900 hours).

Winds in the Los Angeles/Long Beach area were generally from the southwest. For the Santa Monica gauge this was a wind directly onshore. For the Los Angeles tide gauges the wind would effect both gauges in approximately equal numbers due to the wind being cross-channel to the Los Angeles main channel. For the Long Beach gauges, the effect would be unequal due to the Inner Harbor gauge's location in a channel

and the wind being generally aligned with the axis of the Long Beach back channel leading to the Inner Harbor. Thus, the tide level would tend to rise more at the inner gauge with respect to the outer gauge in response to wind.

Humidity conditions for the entire area of consideration were considered as approximately uniform at any given time, with the exception of any localized fog in the Los Angeles/Long Beach Harbor areas which might not affect the Santa Monica area. A fog would possibly cause a strip chart paper to become damp and make it susceptable to a slight stretching under the effect of the tensioned receiving roller. This stretching would cause an hour of tidal observations to encompass more than a linear inch of chart.

The tide gauges were all of the same type and, although in service for varying lengths of time, it was assumed that each was sufficiently accurate in recording of the tidal fluctuations in its stilling well.

The obvious conclusion was that any recorded movements between the various gauges could not be attributed solely to other than tidal regime effects in this investigation.

B. DATA REDUCTION

1. Digitization

The marigrams were digitized onto magnetic tape through the use of a strip chart digitizer, built by NCER, and a control Data Corporation CDC-1700 digital computer. The digitizer consisted of a flat metal plate with a pair of tensioned rubber pincher rollers mounted at each end of the

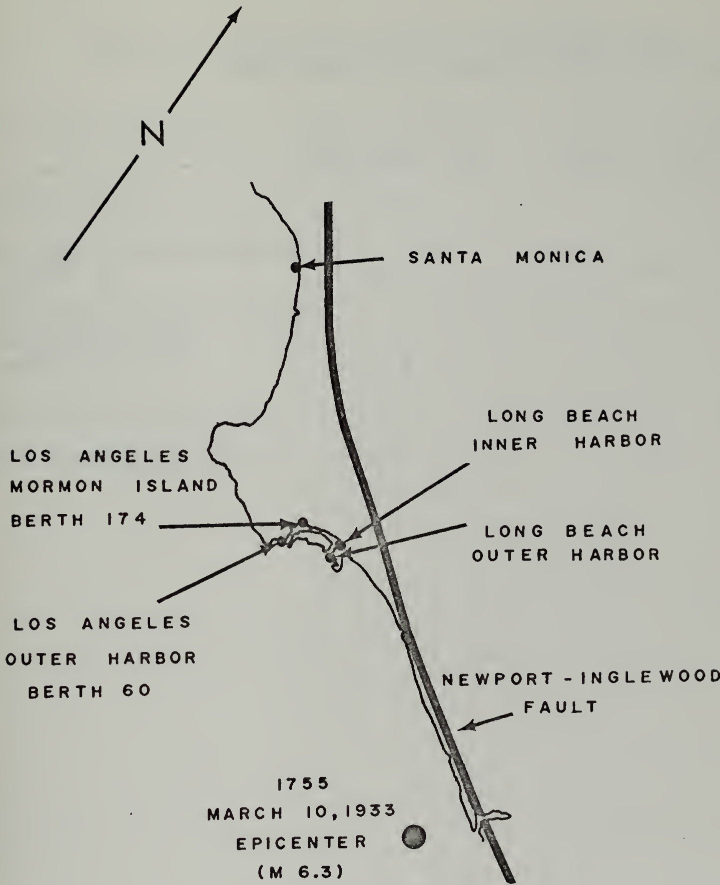

Figure 3. Tide Gauge Station Locations

TABLE II. TIDE GAUGE STATION DISTANCES FROM EPICENTER AND NEWPORT - INGLEWOOD FAULT

Tide Gauge Station	Distance From Epicenter (km)	Distance From Fault Trace (km)
Santa Monica	70.0	4.4
Los Angeles Outer Harbor Berth 60	32.7	10.8
Los Angeles Inner Harbor Mormon Island Berth 174	34.4	7.1
Long Beach Outer Harbor	30.5	3.6
Long Beach Inner Harbor	32.1	2.6

apparatus. One pair of rollers was connected by a chain drive to a variable speed electric motor. Mounted above and resting on the bed of the digitizer were a tracing cursor and a fiducial cursor. The marigrams were dragged under tension across the bed of the digitizer by the driven pincher rollers. During the digitizing operation the strip chart was allowed to wander back and forth across the width of the digitizer bed. Correction for this movement was made by maintaining the fiducial cursor on the marigram fiducial line. The other cursor was maintained on the trace of the tide response curve.

The motion sensor of the digitizer operated at a resolution of 0.01 inch in the X - Y plane (representing 0.01 hours along the X axis and 0.01 feet of vertical tide movement along the Y axis) of the digitizer bed. Whenever the computer sensed that a movement of this magnitude had occurred, the analog voltage difference between the tracing and fiducial cursors was sampled and an entry was made on the magnetic tape indicating a movement in one of five valid directions--(1) +Y, (2) +Y, +X, (3) +X, (4) -Y, +X, and (5) -Y. The +X direction corresponded to the positive time axis.

The variable speed of the driving motor permitted the operator to vary the speed of chart drag. When chart segments containing a greater degree of high frequency tide motion were encountered the speed of advance could be lowered. This ensured that the operator could comfortably follow the tide line trace with maximum accuracy, and yet it eliminated

a significant source of possible operator fatigue. This in turn maintained the accuracy with which the magnetic tape represented the actual tide response curve. Fatigue effects were further eliminated from the tape record through the use of either two or three operators. Whenever one operator began to feel fatigued, operators shifted. Digitization of one month of strip chart record generally involved a minimum of five changes of operator.

Separate tape records were commenced at all tide trace points at which a gauge time comparison was entered on the marigram. With this scheme the magnetic tape marigram records consisted of a large number of fixed- record-length records, each based upon a valid time mark. This caused any digitization errors due to a stretched strip chart to be confined to the day or weekend of magnetic marigram record in which the actual stretching took place at the time of recording the marigram. Whenever the operator made an error in digitizing, the then-current record was encoded on the tape as being invalid, and a new record was started at the last time comparison entry point on the tide trace.

Upon completion of digitization of a marigram, a sampling of the magnetic tape was conducted to determine the actual number of records written. This was compared with tabulations kept during the digitization and any discrepancies were resolved.

2. Raw Series Generation

As a preface to any analysis of the data written on the magnetic tape, the data had to be purified and certain parameters had to be ascertained. A preliminary reading of a tape consisted of sampling each record and tabulating the following data for each record: (1) the total number of 0.01-inch increments recorded in the +X (positive time) direction and (2) the vertical offset (+Y of -Y) of the record's last data point in reference to the record's initial point which was set as a zero reference point.

Due to the use of fixed record lengths in the digitization process, it frequently occurred that a single time segment of marigram data spanned two or more records on the magnetic tape. By comparing the tabulated data determined above with the records kept at the time of digitization, the invalid tape records could be located and the valid data segments could be identified where they spanned more than one record. In addition, the total time spanned by the marigram was compared with the time interval indicated on the tape by the summation of the number of 0.01-inch increments in the +X direction. Discrepancies between these two figures were common and were attributed to several factors. The first of these was the inability of the digitizer operator to split a time mark to the correct 0.01 inch, and the second was a past physical deformation of the marigrams.

The marigrams might have stretched or shortened as humidity varied when they were recorded or later analyzed. Too, some shrinkage might have taken place if the marigrams

were stored in a dry atmosphere. Some stretching may have taken place due to the digitizer, but attempts were made to keep tension used in digitization to the minimum levels required.

All of the marigrams used in this analysis showed that some net stretching had taken place. The usual error in digitization varied from 0.03 to 0.05 inch (representing 1.8 to 3.0 minutes) for a twenty four hour period and in no case did it exceed 0.10 inch (6 minutes) for a twenty four hour period. This indicated that errors in time due to stretching were consistently less than 0.45%.

The magnetic tape was read a second time, this time ignoring the invalid records and connecting all valid records end-to-end for analysis as a time stream of continuous data. The initial datum was referenced as zero and the data stream was sampled for vertical offset on the first hour and after each 1.00 inch of indicated time advance (one hour) thereafter. In this manner, a data stream of raw data, consisting of on-the-hour instantaneous tide level observations was generated. Had stretching errors been on the order of 1%, then the sampling interval would have been changed to 1.01 inch to avoid propagating an error to the last record or dropping data from individual records.

The generated data stream, referred to as the raw data series, was then plotted at a vertical scale of 1 inch equal to 30.48 centimeters (1 foot) and a horizontal scale of 1 inch equal to 48 hours (2 Julian days) as in Figure 4.

Visual inspection of these plots permitted an additional check for raw series integrity since any breaks in the data would be visible. These generated raw series then served as the data base for further analysis. In this investigation, four marigrams, three spanning the earthquake, were digitized. They were: (1) Santa Monica - 1 January to 1 March 1933, (2) Los Angeles - Berth 174 - 1 March to 1 April 1933, (3) Santa Monica - 1 March to 31 March 1933, and (4) Long Beach Outer Harbor - 17 February to 3 April 1933.

3. Residual Series Generation

The raw data series were each fit to the nine most energetic lines of the earth/ocean tide spectrum under a least squares criterion. The fitting was made simultaneously with a detrending of the series. The data were fit to the model:

$$H(t) = \sum_{i=1}^{N} A_n \cos(w_n t - \phi_n) + D(t) \qquad (1)$$

where

$H(t)$ is the theoretical tide,

A_n is the constituent amplitude,

w_n is the constituent frequency,

ϕ_n is the constituent phase at time zero,

N is the number of constituents used for analysis, and

$D(t)$ is a first order trend.

Removal of this theoretical tide from each observation of a raw series resulted in a residual time series as shown in Figure 5.

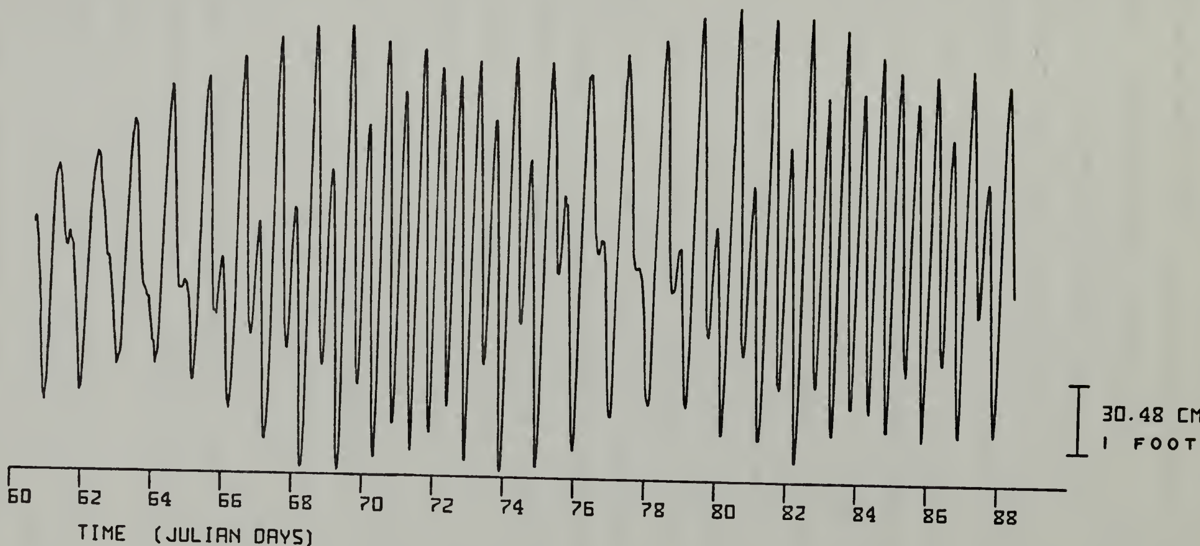

Figure 4. Raw Digitized Data Series

As mentioned earlier, the geographical area of consideration was relatively stable during the period of the marigrams analyzed, and so it would be assumed that the drift rates encountered in the raw series would be low. If the detrending of the data were accomplished prior to the fitting process, amplitude errors would result in the fitting analysis. These errors would arise from the fact that partial cycles of the harmonic frequencies considered would be contained in any finite length record with certainty. Detrending would be accomplished incorrectly due to the trending effects of the partial cycles upon the data. Once an incorrect trend were removed, it would be impossible to arrive at the correct amplitudes of the frequencies that comprised the data.

Infinite length records would allow amplitudes and phases of the considered frequencies to be determined exactly. The use of finite length records introduced an uncertainty into these determinations. There is, however, no certain method of determining the degree of contamination involved in separating two closely spaced frequencies in a finite record. The Doodson argument numbers presented by Melchior [5] indicated that the P_1 and K_1 lines (see Table I) were inseparable for a month of observations. Based upon the calculated phase differences between the P_1 and K_1 lines for the record lengths involved, the P_1 and K_1 lines were treated as separate lines in this analysis.

The shortest record was of 670 hours duration, which indicated a phase difference of 18.4% of a cycle, and the longest was of 1632 hours duration, which indicated a

difference of 40.8% of a cycle. Wood in [6] determined that, for his work with earth tides,

> "to achieve better than 0.1% in accuracy in amplitude determination for the theoretical data the minimum series length was determined to be 500 hours."

The record lengths involved limited this analysis to the nine frequencies shown in Table I.

The ability of a theoretical tide series to account for the actual tide series was measured by determining the percent of the original raw series' energy remaining in the residual series. The results obtained are shown in Table III. The energy remaining in the residual series is attributable to numerous factors. Most significant among these are meteorological effects, water basin resonances, and the method of analysis.

4. Program Calibration

The least squares analysis program was calibrated in its effectiveness at fitting by analyzing varying lengths of earth tide theoretical data. A year of hourly earth tide theoretical observations was generated at each of three locations in the Long Beach/Los Angeles/Santa Monica area. The locations were (1) Los Angeles Outer Harbor, (2) Los Angeles Berth 174, and (3) Santa Monica. The theoretical observations were computed in Ref. 7 using second and third order spherical harmonics and did not account for the effects of ocean tidal loading. These data then were noise free and were a suitable test of how much energy the analysis program could extract from a record using but nine of the available 79 tidal lines.

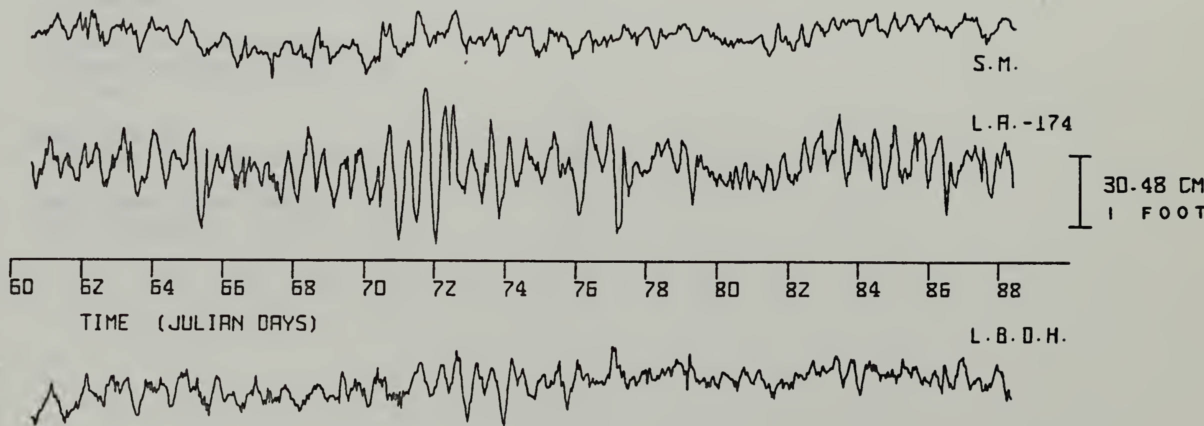

Figure 5. Residual Digitized Data Series

TABLE III. RESIDUAL ENERGY PERCENTAGES

Marigram	Record Length (Hours)	Energy in Residual Series (Percent)
Santa Monica 1 February - 1 March 1933	670	7.28
Los Angeles Inner Harbor Mormon Island - Berth 174 1 March - 1 April 1933	741	17.74
Santa Monica 1 March - 31 March 1933	673	10.18
Long Beach Outer Harbor 17 February - 3 April 1933	1632	8.13

The results of these analyses are shown in Table IV. They indicate that for the nine lines used in this analysis the minimum residual energy that could be expected in a residual series of a month's duration was an average of 6.13%. For a 60-day series the average minimum residual was 7.09%. The energy remaining in these residual series was due to the 70 tidal spectrum lines not used in the analysis. Comparison of the above minimum figures with the residuals obtained from analyses of ocean tide records showed that, with the exception of the Los Angeles Berth 174 marigram, the analysis program nearly reached the minimum expected residual energy levels. For all four marigrams the difference in residual energy between the average minimum expected and the observed value was considered as due not to the program, but entirely to physical factors. These differences are presented in Table V as a percentage of the energy contained in the raw generated series and as a percentage of the energy that could theoretically have been accounted for by using nine lines for the analyses.

TABLE IV. EARTH TIDE ANALYSES RESULTS

Location	Record Length (Hours)	Energy in Residual Series (Percent)	Average Energy In Residual Series (Percent)
Los Angeles Outer Harbor	8856 (1 year)	7.28	7.28
Los Angeles Inner Harbor Mormon Island	8856 (1 year)	7.28	7.28
Santa Monica	8856 (1 year)	7.29	7.28
Los Angeles Outer Harbor Days 1 - 90	2160 (3 months)	7.28	7.28
Los Angeles Outer Harbor Days 1 - 60	1440 (2 months)	6.70	7.09
Los Angeles Outer Harbor Days 31 - 90	1440 (2 months)	7.48	7.09
Los Angeles Outer Harbor Days 1 - 30	720	5.41	6.13
Los Angeles Outer Harbor Days 31 - 60	720	6.36	6.13
Los Angeles Outer Harbor Days 61 - 90	720	6.63	6.13

TABLE V. RESIDUAL ENERGY COMPARISONS

	Record Length (Hours)	(Energy In Residual - Average Minimum) / (Energy In Raw Series) (Percent)	(Energy in Residual - Average Minimum) / (Energy in Raw Series -Average Minimum) (Percent)
Santa Monica February 1 - March 1, 1933	670	1.15	1.22
Los Angeles Inner Harbor Mormon Island - Berth 174 March 1 - April 1, 1933	741	11.60	12.36
Santa Monica March 1 - March 31, 1933	673	4.05	4.31
Long Beach Outer Harbor February 17 - April 3, 1933	1632	1.04	1.12

IV. RESIDUAL SERIES ANALYSIS

A. SIGNAL DETERMINATION

Residual series data from Long Beach Inner Harbor constructed prior to this investigation by Dr. M. D. Wood at NCER (Figure 6) implied two ephemeral ground motions premonitory to the earthquake on Julian day 69. The motions were a subsidence of approximately 7 inches (18 centimeters) commencing 113 hours before the event and lasting 16 hours and an unwarp of approximately 14 inches (36 centimeters) commencing 48 hours before the event and lasting 20 hours. It was this type of "signal" that was expected in the residual series of the other tide station marigrams.

It was anticipated that upon completion of the residual series' generation, each residual series would be processed to determine the uniqueness of the "signal" which it contained. This would be accomplished by selecting a "window" of approximately 100 hours duration which encompassed the "signal." This segment would then be correlated against the entire length of the residual series by correlating it against the first 100 hours of the series and then advancing the "window" 1 hour. Another correlation would be performed and the "window" would be advanced again. The results of this "sliding window" approach would hopefully indicate a correlation spike only at the time that the signal was nearly coincident with itself. High correlations with other segments of the residual series would impute a non-uniqueness to the "signal."

As shown by Figure 5, these "signals" were not evident in the marigrams processed in this investigation. The data for the Long Beach Inner Harbor tide gauge were no longer available and it had to be assumed that the obvious "signal" in that data was a result of human errors in data processing.

B. CORRELATIONS

Correlation analyses were conducted on all possible pairs of residual series data. To ensure comparability of results, only those portions of the residual series were considered when all three marigrams encompassing the earthquake were being recorded. This trimmed each residual series to 668 observations, which occurred between the year's Julian hours of 1431 and 2098 inclusive. Serial auto- and cross-correlations from order 0 to 300 were calculated assuming series' means unequal to 0 according to the formula:

$$C_{j_{YZ}} = \frac{\sum_{t=j+1}^{N} (Y_{t+j} - \overline{Y})(Z_t - \overline{Z})}{\sqrt{\sum_{t=1}^{N} (Y_t - \overline{Y})^2}\sqrt{\sum_{t=1}^{N} (Z_t - \overline{Z})^2}} \qquad (2)$$

where

$C_{j_{YZ}}$ is the correlation of order j between the two series Y and Z,

j is the number of observations by which series Y lags series Z,

N is the total number of points in a series, and

$\overline{Y}$ and $\overline{Z}$ are the respective series' means.

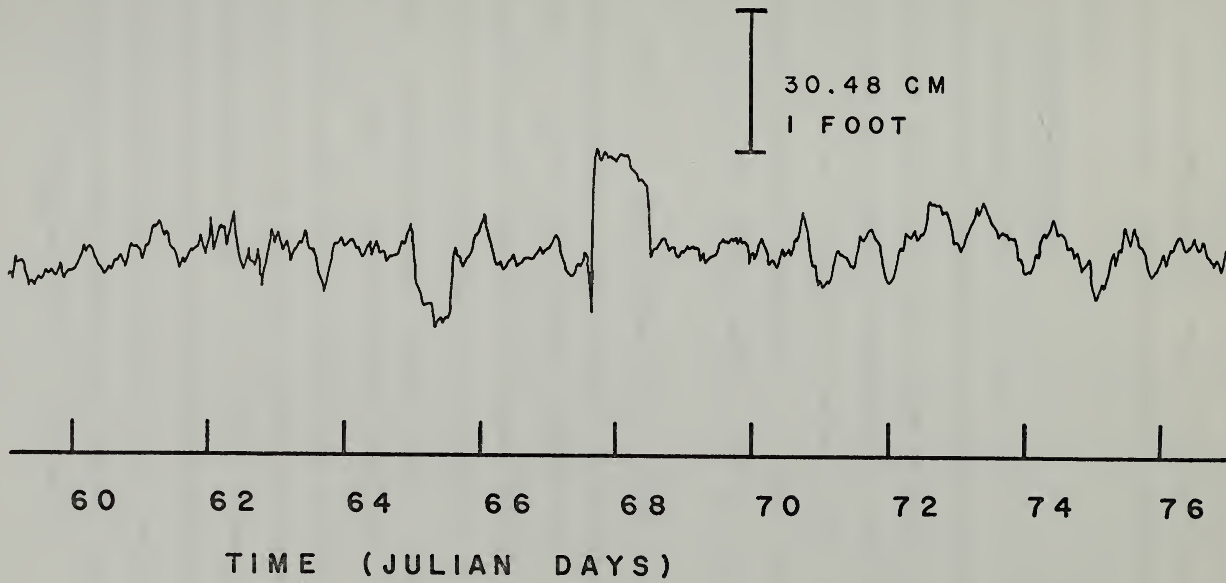

Figure 6. Long Beach Inner Harbor Residual Data Series (after Wood, NCER, personal communication)

Mathematically, correlations vary from +1.0, indicating perfect positive correlation, to 0.0, indicating no linear correlation, to -1.0, indicating perfect negative linear correlation.

1. Auto-Correlations

Auto-correlations of a series indicated the degree to which a series was capable of repeating its identical motion with an appropriate lag. These analyses would possibly bring to light low frequency resonances in a station's residual data due to meteorological or other causes. The auto-correlations are shown in Figures 7, 8, and 9 and the more notable peaks in correlation (above 0.20) are given in Table VI.

Although no significance levels could be set due to factors to be discussed later, several interesting, albeit questionably significant, results could be seen. Both the Santa Monica and Long Beach Outer Harbor residuals showed correlation peaks (the highest of each series) at a lag of 24 hours. Los Angeles Mormon Island, on the other hand, showed a possible 12 hour periodicity based upon the alternating positive and negative correlations with peaks at lags of 6, 13, 19, and 25 hours. After the first 24 hours, Santa Monica and Long Beach Outer Harbor showed an approximate 22 hour periodicity, whereas during the same period Los Angeles Mormon Island showed a 10 to 12 hour periodicity. No explanation for these results was reached, but this subject will be discussed later in this paper.

2. Cross-Correlations

Cross-correlations between pairs of residual series were investigated with a view toward detection of the movement of any general areal effect up or down the coast. A wave that travelled up the coast would be demonstrated by Santa Monica lagging both Long Beach Outer Harbor and Log Angeles Mormon Island. In addition, Los Angeles Mormon Island might lag Long Beach Outer Harbor by a short interval. The cross-correlations which checked for this movement are shown in Figures 10, 11, and 12 and the more notable peaks in correlation (above 0.20) are given in Table VII.

One possibly significant result occurred in the case of Santa Monica lagging Long Beach Outer Harbor by one hour. This might indicate an effect moving up the coast at a velocity of approximately 30 kilometers per hour, but this response was not reflected in the case of Los Angeles Mormon Island cross-correlated with Long Beach Outer Harbor at 0 hours lag. The other noticeable result is an apparent 23 hour periodicity, again in the case of Santa Monica lagging Long Beach Outer Harbor.

Effect waves that travelled down the coast would be demonstrated by motions at Santa Monica being lagged by Long Beach Outer Harbor and Los Angeles Mormon Island. The relationship between Long Beach Outer Harbor and Los Angeles Mormon Island could allow either to lag the other, dependent upon the causual phenomenon. The cross-correlations which checked this hypothesis are shown in Figures 12, 13, 14, and 15 and the more notable peaks in correlation (above 0.20)

are given in Table VIII. No apparently significant relations were found.

3. Statistical Confidence

No confidence limits were placed on the results of the auto- and cross-correlations to determine the statistical significance of the various correlation peaks. This was done due to the facts that the residual series were not independent and that the distribution of a series, as it stood, was of such a complex nature that it was of dubious value to construct it. As mentioned earlier, each residual series still contained the effects of weather upon the tides. Until these effects were removed from the series, they could in no way be considered as having any claim to statistical independence.

a. Meteorological Effects

The elements of weather which it was felt would most energetically effect tidal residuals were (1) wind, (2) barometric pressure, (3) rainfall, and (4) temperature. The response of the tides to these factors would vary, but for the wind and pressure variations the response would undoubtedly be in the form of seiches.

For wind, the seiches would normally be of a great enough frequency that the hourly readings would dampen out the effects of the surface waves generated. However, the typical winds of this area were from the southwest, arising during the mid-morning, and dying off during the later afternoon. The winds generally did not exceed 25 knots,

but a daily wind of this duration would tend to raise the level of the tide above the level which would otherwise be expected during the afternoon and early evening. This routine on a daily basis would introduce a certain periodicity into the marigrams, although tide gauges in channels, such as Los Angeles Mormon Island, might be affected by seiches of higher frequency than those gauges fronting the open ocean or the harbors. High velocity winds associated with storms, such as the 60 mile per hour winds on 11 Janaury 1933, would also likely introduce its effects into the residual series.

Seiches resulting from fluctuations in barometric pressure in the area would possibly influence the residual series with a period of approximately one hour, but the more energetic effect might be a fluctuation having a period of approximately five days - the approximate period for the passage of a weather front. References 8, 9, and 10 discuss the "inverted barometer" response of oceans to local barometric pressures. It appears that a similar response would be applicable when considering frontal passages in the Los Angeles area, although a simple mirror response would not be anticipated due to the action of the littoral areas on the water masses.

Rainfall would possibly have a small effect on the tide responses due to the currents connected with flow from a tributary opposing an onshore tide. Other possible effects would be a piling up of water in the area of a tributary's discharge and the water surface level gradient

due to an area of fresh water having a different density than the salt water surrounding the tributary outflow. In the Santa Monica / Long Beach area the only tributary is the Los Angeles river whose flow could be considered inconsequential due to its limited watershed.

Temperature variations of the coastal waters could possibly affect the tidal residuals due to the more shallow waters being warmed a relatively greater degree during the daylight hours, but this effect would be considered of low importance.

Unfortunately insufficient weather records were available for construction of time series of winds (velocity and direction), pressure variations, rainfall, and temperature. Nonetheless, rainfall can be excluded from this consideration due to the fact that in the spring of 1933 Southern California experienced a drought. In Los Angeles no measurable rain fell from 29 January to 26 April except for two light showers totaling 0.19 inch in March. From 29 January to 1 May the total precipitation was 0.75 inch, the smallest total in Los Angeles for that period in the station's 56 years of recording to that date. Of the remaining factors, wind would probably have affected the residuals to the greatest degree.

b. Meteorological Effect Transfer Function

If sufficient weather data had been available to construct the time series of data, a meteorological effect transfer function for each tide gauge station could have been determined for each of the factors (wind, pressure, and tem-

perature). The function would describe how a station responded to a given input factor and a separate function would be required for each factor for each station because, as stated previously, each station would be affected and respond in a different, although similar, manner. A transfer function would be developed through regression analysis of a factor's time series and a residual time series, after having assumed, at least initially, that interaction between factors was not significant in its effect on the residual.

After computation of all transfer functions, the effects of weather would be removed from the residual series to a large degree. New series of auto- and cross-correlations would then be generated. The assumptions would then be made that (1) for a given tide gauge station the hourly observations of the adjusted residual series were each independent of the other observations, and (2) that each observation was normally distributed about the mean of the series from which it was taken. Then in the consideration of a specific $C_{j_{YZ}}$ correlation coefficient the distribution of the correlation coefficient would be computed based upon the joint bivariate distribution of the (N-j) point pairs of the two series used in the computation. Once the distribution of the coefficient was determined for a given lag j, a confidence region of a desired degree would be established for each correlation point to determine whether the correlation at a given lag between two series was to be considered significant.

Correlation coefficient distributions could have been constructed based upon the previous assumptions to test

the significance of the original correlation series' peaks. This was not done because the assumption about independence of observations could not be justified and neither could normality of distribution about a series' mean. The energy in the residual series of Los Angeles Inner Harbor-Mormon Island-Berth 174 (Table III and V) was simply too high to ignore. An obvious possible explanation was wind effects in the Los Angeles main channel and the Inner Harbor. Were this residual energy ignored, the assumptions accepted, and the confidence regions constructed, the validity of any conclusions regarding the significance of correlations would be highly questionable.

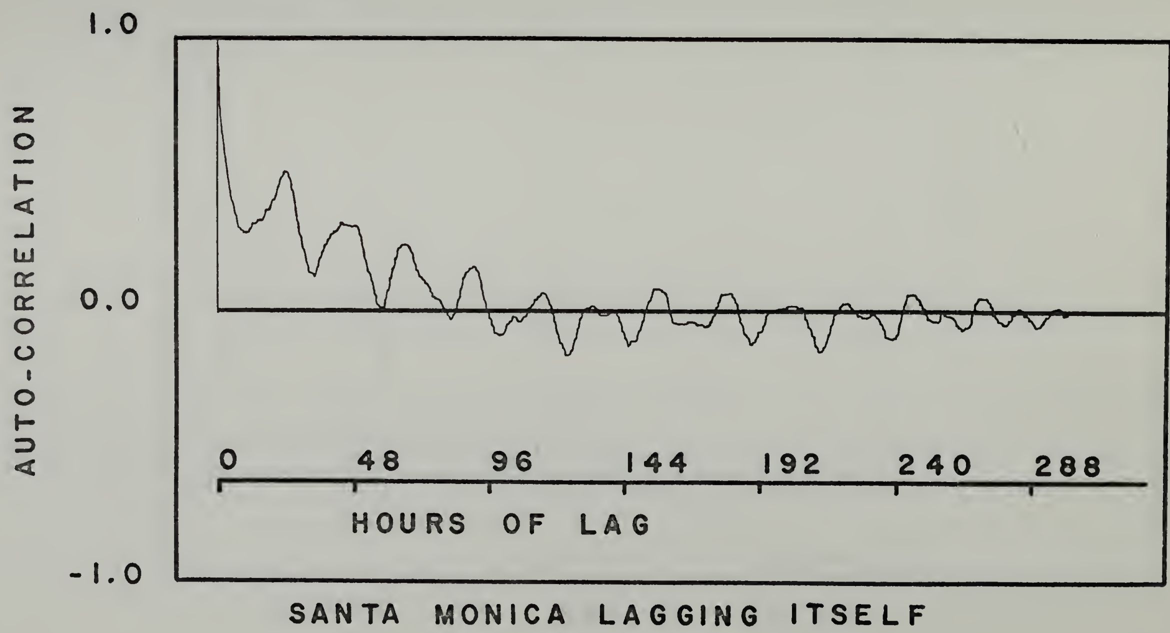

Figure 7. Auto-Correlation Santa Monica

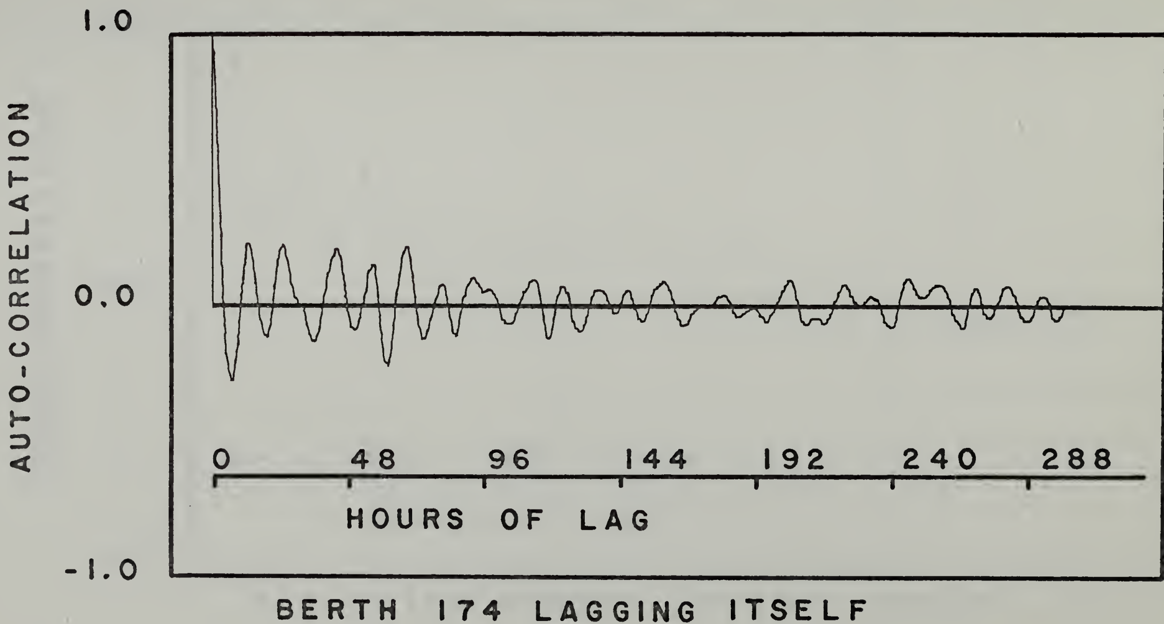

Figure 8. Auto-Correlation Los Angeles Berth 174

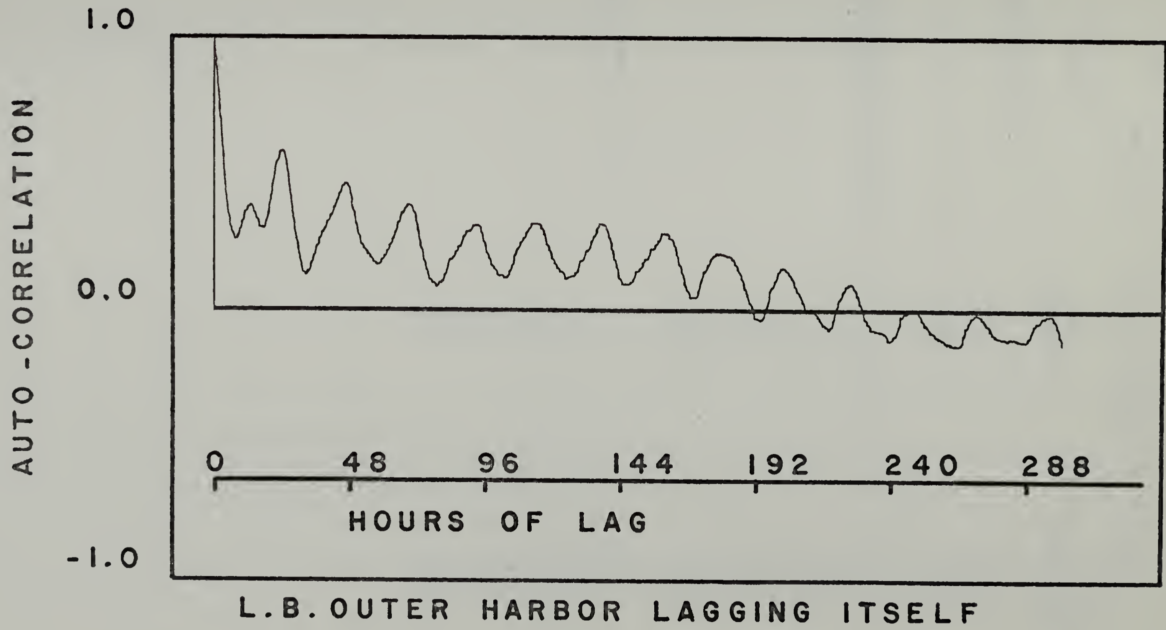

Figure 9. Auto-Correlation Long Beach Outer Harbor

TABLE VI. AUTO-CORRELATION PEAKS

Station	Lag (Hours)	Auto-Correlation (Percent)
Santa Monica	0	100
	24	50.7
	43	31.3
	65	24.2
	66	24.2
Los Angeles Mormon Island	0	100
	6	-28.2
	13	22.9
	19	-12.5
	25	22.4
	36	-14.1
	44	20.7
	56	15.2
	62	-23.2
	68	21.5
Long Beach Outer Harbor	0	100
	13	38.3
	24	58.1
	46	46.3
	68	38.4
	91	31.2
	114	32.1
	136	31.7
	160	28.7
	177	20.8

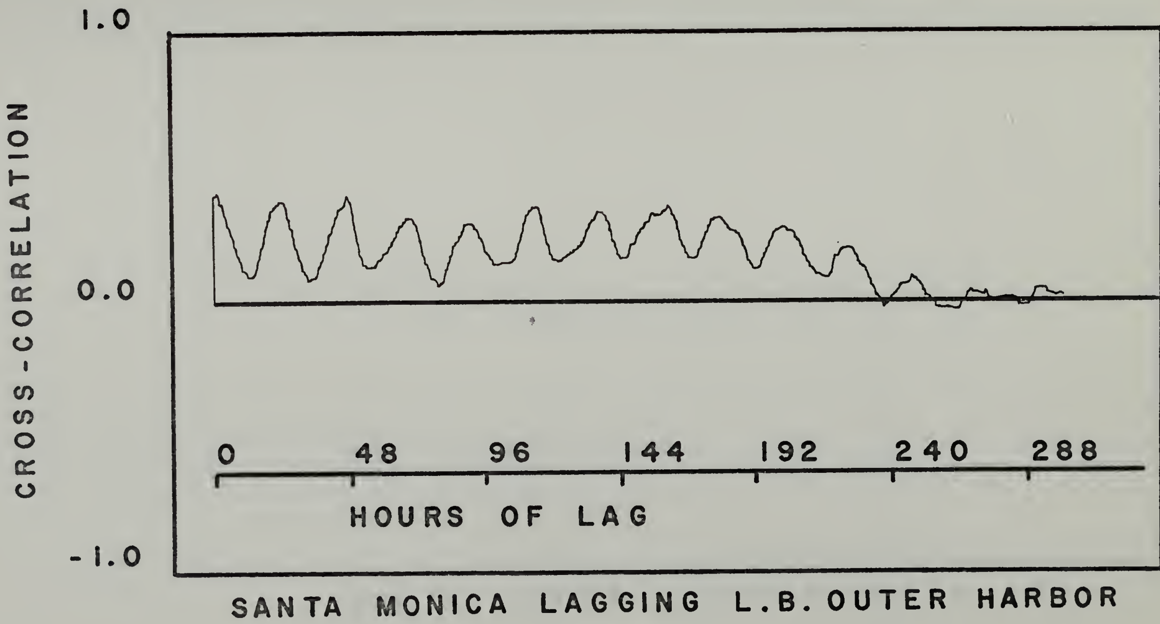

Figure 10. Cross-Correlation Santa Monica Lagging Long Beach Outer Harbor

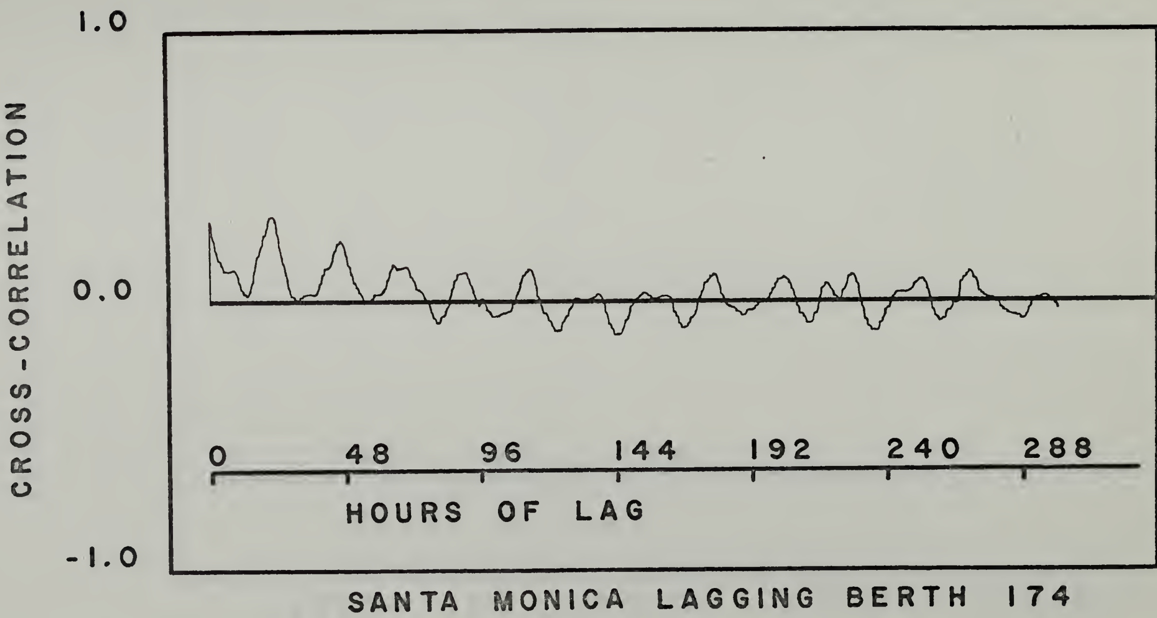

Figure 11. Cross-Correlation Santa Monica Lagging Los Angeles Berth 174

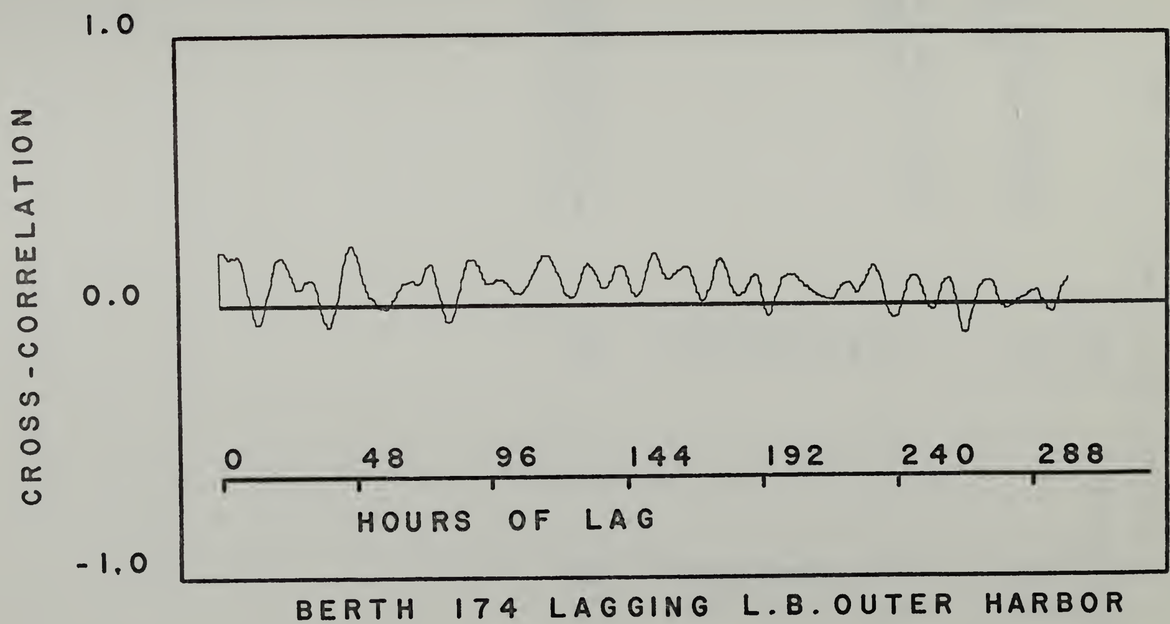

Figure 12. Cross-Correlation Los Angeles Berth 174 Lagging Long Beach Outer Harbor

TABLE VII. CROSS-CORRELATIONS GROUP I

	Lag (Hours)	Cross-Correlation (Percent)
Santa Monica Lagging Los Angeles Mormon Island	72	32.0
	46	22.3
Santa Monica Lagging Long Beach Outer Harbor	1	41.0
	23	37.4
	47	39.7
	68	31.6
	91	29.1
	114	36.1
	136	33.3
	137	33.3
	161	35.3
	177	31.6
	201	28.0
	224	20.7
Los Angeles Mormon Island Lagging Long Beach Outer Harbor	21	18.7
	47	22.5

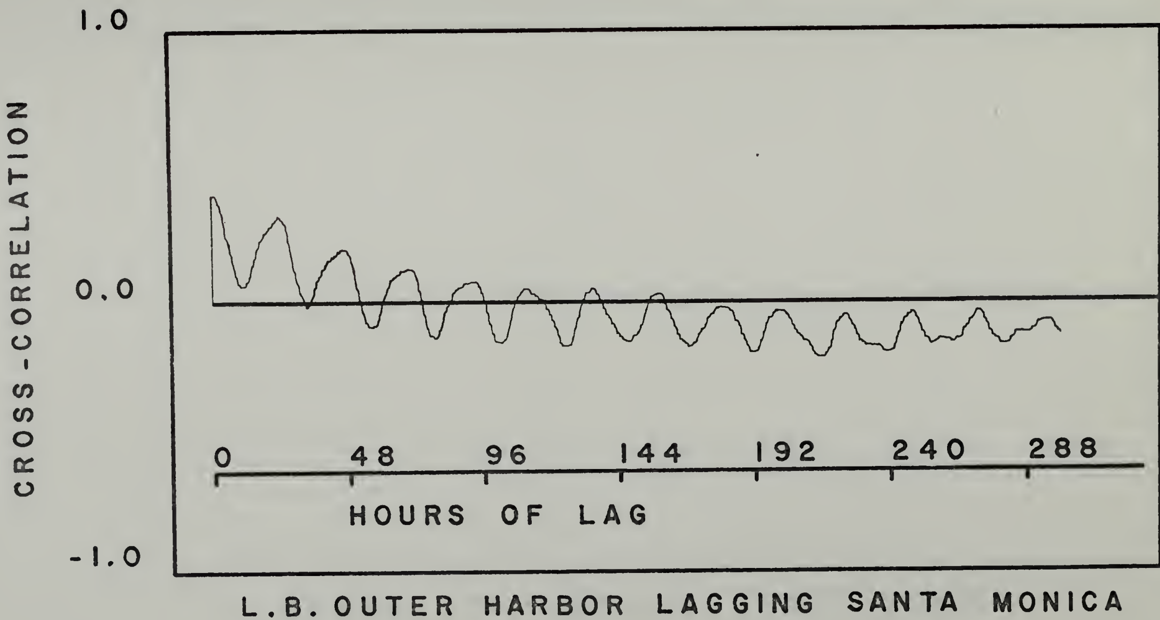

Figure 13. Cross-Correlation Long Beach Outer Harbor Lagging Santa Monica

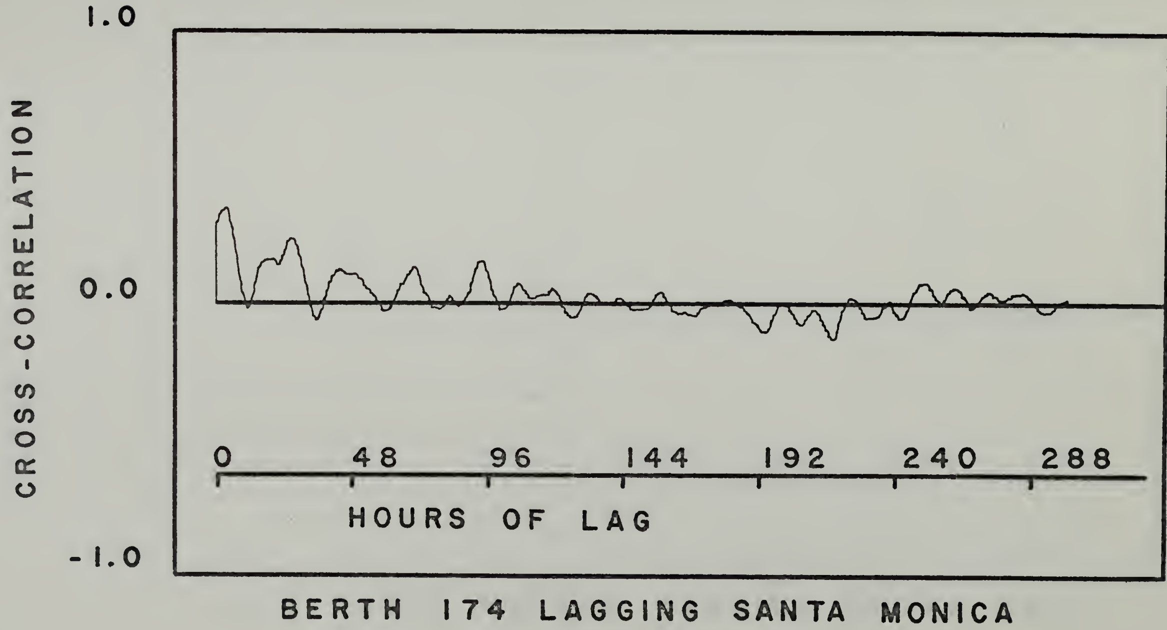

Figure 14. Cross-Correlation Los Angeles Berth 174 Lagging Santa Monica

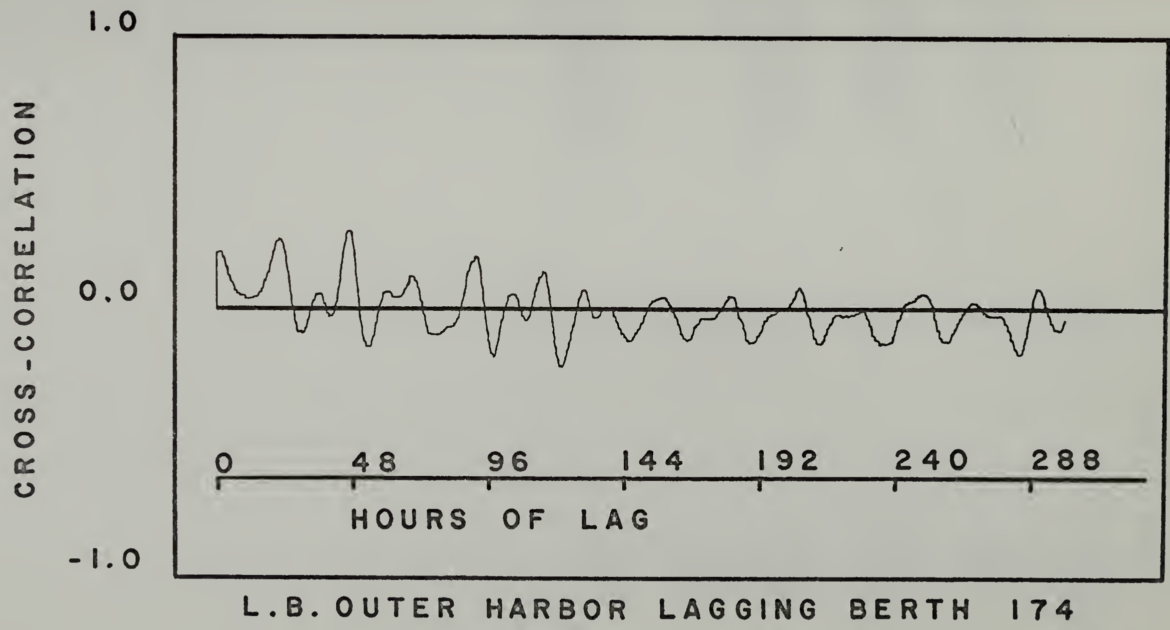

Figure 15. Cross-Correlation Long Beach Outer Harbor Lagging Los Angeles Berth 174

TABLE VIII. CROSS-CORRELATIONS GROUP 2

	Lag (Hours)	Cross-Correlation (Percent)
Long Beach Outer Harbor Lagging Santa Monica	23	31.8
	45	19.5
	215	-21.7
Los Angeles Mormon Island Lagging Santa Monica	3	35.2
	18	16.5
	27	24.0
Long Beach Outer Harbor Lagging Los Angeles Mormon Island	1	21.0
	22	25.4
	46	28.5
	91	19.2
	98	18.3
	122	-22.5
Los Angeles Mormon Island Lagging Long Beach Outer Harbor	21	18.7
	47	22.5

V. OCEAN TIDE CONSTITUENT AMPLITUDE ANALYSIS

An investigation of the amplitudes of the various tidal frequencies determined in the least squares program was conducted to determine the degree of agreement between ocean tide and earth tide responses to gravitational forces in the Long Beach area.

The principal lunar diurnal O_1 and semi-diurnal M_2 lines of the earth tide frequency spectrum are generally acknowledged to be the most reliable and invariant tidal lines due to their removal from the frequencies of solar effects. The stability of the M_2 line was confirmed in the amplitude output of the least squares analysis program.

The M_2 line amplitude (A_{M_2}) was chosen as a normalizing factor for computation of the theoretical tide line relative amplitudes shown in Figure 16. These normalized relative theoretical amplitudes were computed according to the formula:

$$(A_i^{\,r})_{th} = \left(\frac{A_i}{A_{M_2}}\right)_{th} \qquad (3)$$

where

$(A_i^{\,r})_{th}$ is the dimensionless theoretical relative amplitude, and

A_i is the theoretical tide constituent amplitude.

To allow for comparison of these ratios to the ocean tide line results, the above ratios were also computed using

the least-squares determined amplitudes. This gave a series of dimensionless experimental relative amplitudes $(A_i^r)_{ex}$ for each tidal line for each tide station marigram.

The relative ocean tide constituent amplitude factors were then computed according to the formula:

$$(G_i^r)_{oc} = \frac{(A_i \ / \ A_{M_2})_{ex}}{(A_i \ / \ A_{M_2})_{th}} \tag{4}$$

where

$(G_i^r)_{oc}$ is the ocean tide constituent relative amplitude factor, and

$(A_i \ / \ A_{M_2})_{ex}$ and $(A_i \ / \ A_{M_2})_{th}$ are the experimental and theoretical constituent relative amplitudes.

The results, which are given in Table IX are shown in Figure 17, indicated the stability and reproducibility of the various tidal constituents. The O_1 line had a standard deviation which was only 3.4% of the amplitude mean. By itself, the 1.76% standard deviation of the K_1 line indicated good stability. However, when considered in the light of the problem of separation of the K_1 and P_1 lines due to the close spacing of their frequencies, the 20.46% standard deviation of the P_1 line suggested that the lines' reproducibilities were questionable. No other lines had indicated standard deviations below 5%. This result confirmed the apparent stability of the O_1 line.

The anomalous apparent stability of the K_1 line in relation to the P_1 line was an intriguing but unexplained

result. One would have expected the relative instability of the two to be more evenly distributed.

For earth tides the factor analagous to that computed in equation (4) is called the relative Gravimetric factor which has a theoretical value between 1.00 and 1.01. The mean value of 0.9272 ± 0.0316 of the relative ocean tide constituent factor for the O_1 tide line is appealingly close to the mean relative Gravimetric factor of 0.926 ± 0.026 determined by Wood [11] for four stations in the San Francisco Bay area. Any conclusions drawn from this, however, would have to be examined by further data processing. No conclusions were drawn from this single analysis, except to say that for the Long Beach/Santa Monica area the O_1 and M_2 spectrum lines appeared to ellicit an ocean tide response quite similar to the response of the earth to the same gravitational factors.

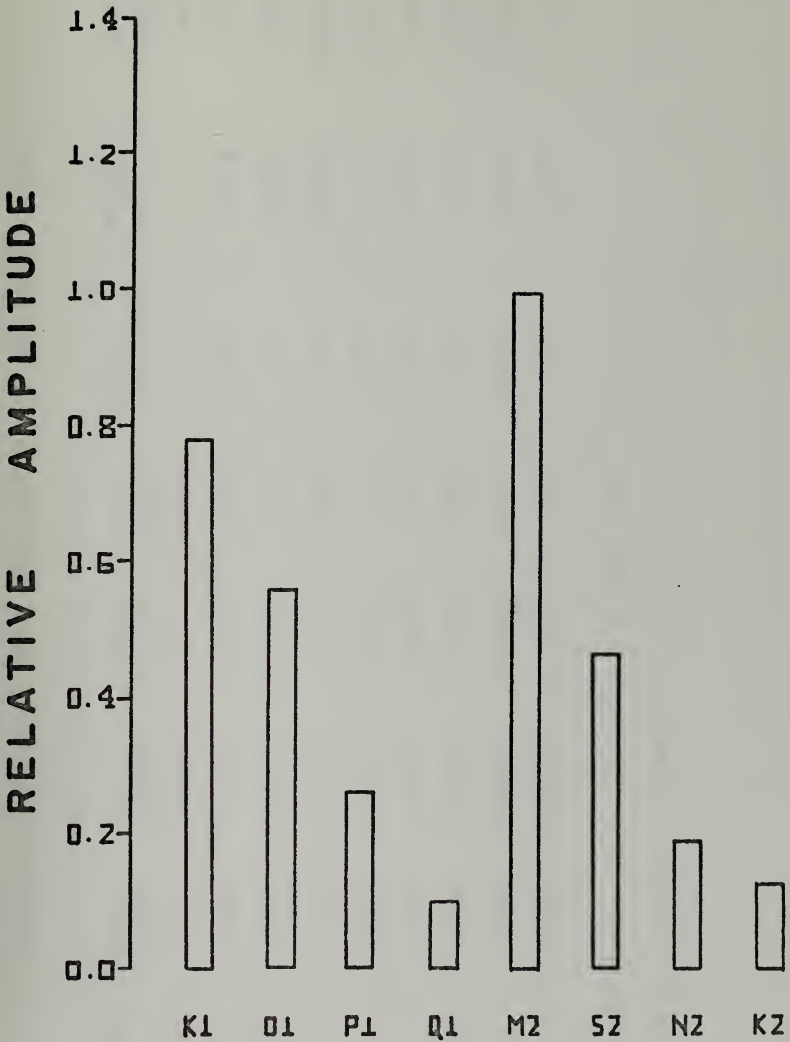

Figure 16. Earth Tide Constituent Amplitude Histogram, Normalized by M_2 Component

TABLE IX. RELATIVE OCEAN TIDE CONSTITUENT AMPLITUDE FACTORS

Tide Line	Relative Amplitudes				Mean Amplitude	Standard Deviation	Standard Deviation (Percent of Mean)
	Santa Monica (1)*	Los Angeles Mormon Island	Santa Monica (2)**	Long Beach Outer Harbor			
K_1	0.9864	0.9611	0.9939	1.0093	0.9877	0.0174	1.7625
O_1	0.9343	0.8737	0.9522	0.9487	0.9272	0.0316	3.4085
P_1	0.4710	0.7695	0.8213	0.8349	0.7242	0.1482	20.4629
Q_1	0.6991	0.5654	0.7423	0.7860	0.6982	0.0826	11.8337
M_2	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000
S_2	0.9707	0.8230	0.9345	0.8955	0.9059	0.0548	6.0449
N_2	1.0439	0.9896	1.0821	1.1498	1.0664	0.0583	5.4697
K_2	1.0548	1.2863	1.1067	1.2693	1.1793	0.1004	8.5130

* Santa Monica (1) - 1 February - 1 March 1933

** Santa Monica (2) - 1 March - 31 March 1933

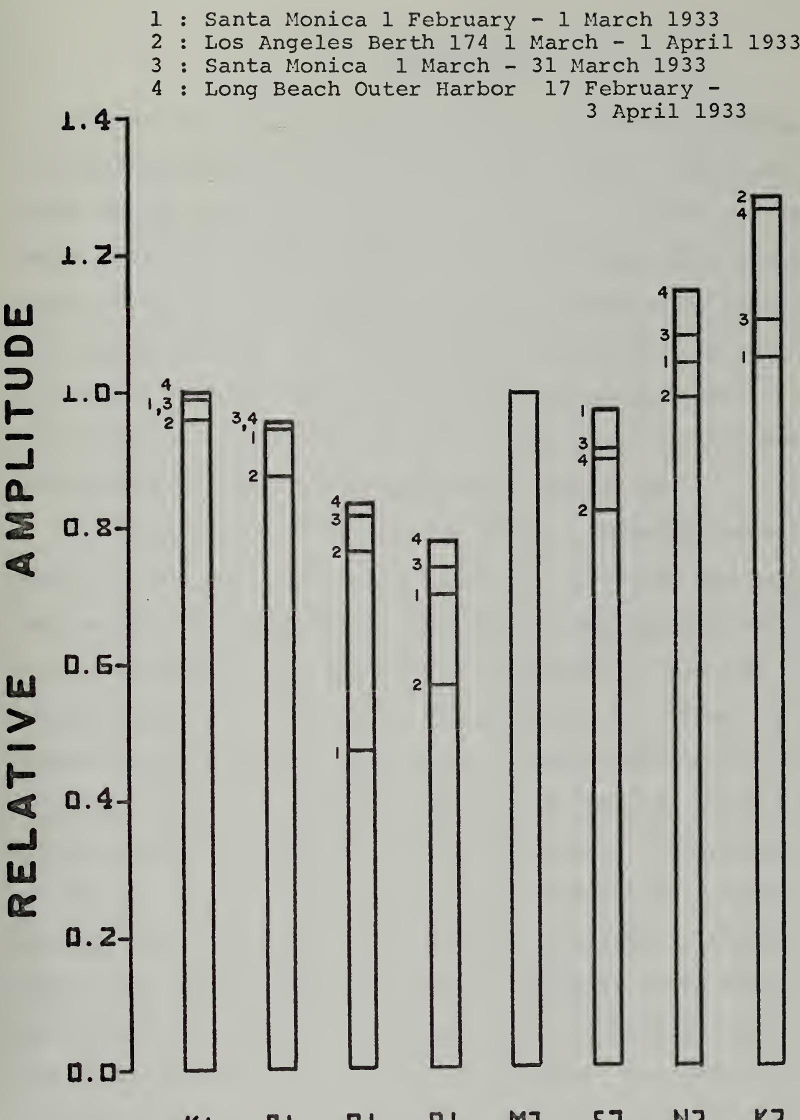

Figure 17. Relative Ocean Tide Constituent Amplitude Histogram, Normalized by M_2 Component

VI. CONCLUSIONS

Ocean tide fluctuations recorded on marigrams at three stations operating in Santa Monica, Los Angeles, and Long Beach at the time of the magnitude 6.3 1755 (5:55 p.m.) 13 March 1933 Long Beach earthquake were digitized onto magnetic tape. The data were sampled at hourly intervals to generate time series of hourly instantaneous tide levels. It was discovered that all the marigrams had undergone a net stretching since the time of their recording, but the resultant errors in time were consistently less than 0.45%.

By fitting nine of the most energetic principal constituents of the ocean tide spectrum to the generated raw data series under a least squares criterion simultaneously with a data detrending, the amplitudes and phases of the raw constituents were calculated. In addition, a residual data series was generated for each of the three stations by removing the theoretical tide series, composed of the nine constituents and the trend, from the raw generated series. The percent of the raw series' energy remaining in the residual series varied from 7.28% to 17.74%. However, analyses of theoretical earth tide series indicated that the spectral lines used could be expected to remove only 93% to 94% of the energy of the raw series when generating residual series. The additional remaining 1.22% to 12.36% residual energy was attributable to meteorological, reasonance, geological, and tectonic factors.

Subsidence and uplift "signals" premonitory to the tectonic event, and obvious in the residual series of Long Beach Inner Harbor processed prior to this study, were not noticeable in the generated residual series.

The tidal constituent amplitudes calculated through the least squares fitting showed the O_1 and M_2 spectral lines to consistently be the most invariant. The K_1 line appeared stable until compared with the P_1 line, this being the pair for which the accuracy of frequency separation was questionable. All other lines consistently had standard deviations of amplitudes greater than 5%.

Auto- and cross-correlations between all possible pairs of residual series were calculated for lags from 0 hours to 300 hours. This was done to determine whether there were any obviously apparent correlations. The auto-correlations might show meteorologically caused periodicities and the cross-correlations might detect areal effect waves moving up or down the coast. Santa Monica and Long Beach Outer Harbor showed possibly significant auto-correlations with a lag of 24 hours. No obvious areal effect waves were noted.

Statistical confidence regions for the correlations were not developed due to the interdependence of the residual series. Insufficient weather data was available to permit the formation of meteorological effect transfer functions. Without these functions the effects of weather could not be removed from the residual series. Confidence regions would be based upon the assumptions of independent normally

distributed hourly observations and independent residual series and neither of these assumptions could be justified for use with the available data.

The fact that the premonitory "signals" were not apparent in the residual series left several explanations plausible. First, they may not exist, but their non-existence was not proven. Second, they may exist but might be masked by the meteorological effect "noise" in the records. Third, they may exist but might be masked by the analysis method residual energy, even after removal of the meteorological noise. This latter would indicate that data from sequential marigrams would have to be joined to provide longer data streams for analysis, permitting the use of additional ocean tide spectral lines.

A point not to be overlooked is that even if the "signals" did not exist at all for this data, this study was still but an observation on a single earthquake in a single location. Other earthquakes, such as the 1906 San Francisco earthquake or the 1964 Alaska earthquake, might possibly give different results.

The methods of analysis employed in this investigation seem to be reasonable and still valid and the negative results arrived at are not at all conclusive.

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13. ABSTRACT

Marigram records of ocean tide fluctuations at three tide stations operating in the Santa Monica/Long Beach, California area at the time of the 10 March 1933 Long Beach earthquake (magnitude 6.3) were digitized onto magnetic tape. Time series of hourly instantaneous tide level observations were generated and processed under a least squares criterion to remove the effects of the nine most energetic lines of the ocean tide harmonic spectrum. The resulting residual series did not contain any anomalous premonitory motions indicated by another residual series previously analyzed at the National Center for Earthquake Research. Auto- and cross-correlations of the three residual series used revealed only two possibly significant auto-correlation peaks for two stations lagging themselves by 24 hours. Correlation confidence regions were not established due to an inability to establish sufficient independence between residual series. Ocean tide spectrum line amplitude analyses showed the O_1 and M_2 lines to have the greatest stability.

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