ANALYSIS OF TIDAL RECORDS OF THE 1964 ALASKAN TSUNAMI

Basil W. Wilson*, F.ASCE

abstract

The 8.5 magnitude Alaskan earthquake of March 27, 1964,generated a great tsunami in the Pacific Ocean. This paper presents results of energy spectrum analyses conducted on a sampling of 24 of the marigrams from some 105 tide-stations which recorded the waves. In the numerical digital procedure used, two important properties of the evolving energy spectra are invoked; the frequency resolution and statistical confidence. High confidence is obtainable only at the expense of poor resolution, and *vice versa.* Excessive resolution may give rise to physically unreal spectral peaks, just as excessive restrictions for confidence may cause blunting of the spectrum and possible loss of physically real spectral components. A trial-and-error compromise between these properties was sought by testing the effects on the energy spectra, for Hilo, Hawaii, of the parameters that control the digital process. An optimum selection of spectrum parameters was finally made so that the primary and secondary wave forms of components, identified by the analysis for the marigram of San Francisco, Calif., most closely agree with the corresponding wave forms obtained by use of Chrystal's (1904) graphical method of *residuation* analysis. Using the parameters so determined, and by application of band-pass filters in the digital analysis, the most prominent peaks of spectral energy in the marigrams of the 24 stations are isolated and their wave-forms computer-plotted. In all cases a recognizable long-period wave component is found having a frequency between 0.50 and 0.65 cy/hr (average period 1.73 hrs). General similarity of these primary wave forms as to period and shape of beats suggests their common origin at the source of the earthquake disturbance. The secondary wave forms of higher frequency (periods generally less than 40 mins) are ascribed to local free oscillations forced by the primary wave trains at the receiving stations. In some, but not all of the marigrams there is evidence of wave systems averaging 3.2 hrs in period. These are thought to be an independent wave-train originating at source.

1. INTRODUCTION

On March 27, 1964, a great earthquake in Prince William Sound, Alaska, (magnitude ≈ 8.5, Richter scale), generated a tsunami which swept the entire Pacific Ocean. Its coastal effects were recorded by some 105 tide-gauges at mainland and island stations throughout the area[1]. This paper reports on energy-spectrum analyses of the marigrams from a sampling of 24 represent-

* Consulting Oceanographic Engineer, Pasadena, California, U.S.A.

_ative stations distributed along the periphery of the Pacific Ocean and on islands within its circumference. Fig. 1, which is derived from the arrival times of the tsunami at coastlines and islands, and allows for the refraction of the wave-fronts in accord with the ocean depths, shows the advance of the front at hourly intervals and the locations of the tide-stations selected for marigram-analysis.

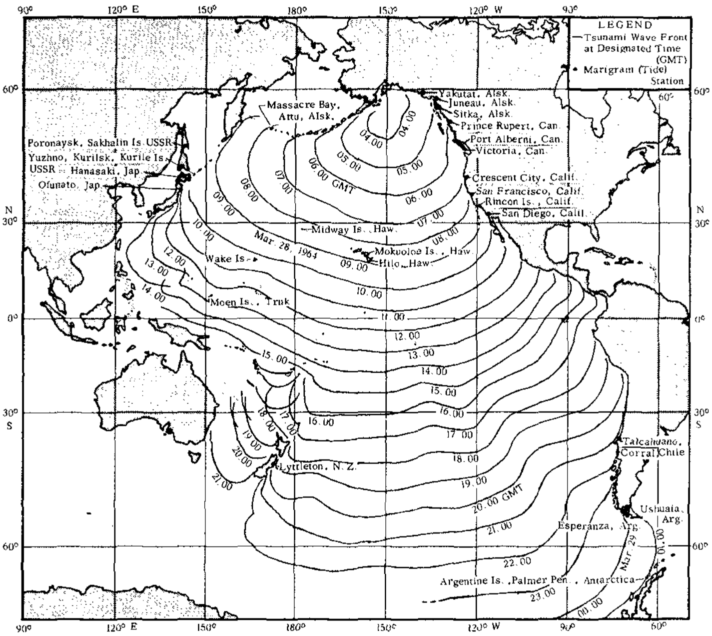

FIG. 1 - APPROXIMATE HOURLY (GMT) WAVE - FRONTS OF THE ALASKAN TSUNAMI OF MARCH 28-29, 1964. (Mercator projection).

A primary purpose of this investigation was to confirm of negate earlier analyses [2], undertaken during report preparation, (of necessity, hurriedly and at minimal cost), by use of Chrystal's graphical method of *residuation* [3]; thereby to verify the existence in the marigrams of exceptionally long-period wave systems, identified by those analyses, but hitherto unsuspected in tsunami occurrences (cf. Cox [4]). This paper summarizes a report of 1971 [5].

2. RESIDUATION VERSUS POWER-SPECTRUM ANALYSIS

Before numerical power-spectrum analysis had become one of the standard tools of oceanographic science in the 1950's [6,7,8], and preceded only by periodogram analysis [e.g. 9], (which in days before high-speed electronic computers was clumsy and time-consuming), Chrystal's method of *residuation* offered a relatively quick and easy way of interpreting the composition of wave or seiche records. The method follows sound theoretical principles on the precept that a wave record can be approximated by a discrete spectrum of sinusoidal wave components. The writer made extensive and effective use of the method in the period 1940-'67 [e. g., 10], and is not ashamed that this period was overlapped by the ascendancy of the modern method of continuous power-spectrum analysis. In referring to the Residuation method, the writer, at various times, has named it "subjective", in the sense that, initially, it relies on the personal judgements of an analyst as to the periods of the discrete components supposed to exist in a wave record. In point of fact, however, as Chrystal showed, the method can be as objective as the analyst will allow, simply by use of a process of successive approximations. In the writer's experience, it has seldom been necessary to invoke closer approximations than first estimates, because one or more shorter-period components in a wave record can usually be detected unambiguously as to periodicity. The very process of "residuating", or eliminating, a suspected sinusoidal component , tends to reveal lower-order components more distinctly, so that they too, in succession, can be subtracted out from the residual record by the graphical method.

While the Residuation method of wave analysis is hardly to be recommend-for modern usage, it seems pertinent to point out that the now popular power-spectrum analysis, by use of the Fourier Double Integral Theorem and auto-correlation techniques, of itself yields only an estimate of the composition of a wave record, and is thereby subject to varying degrees of reliability. This aspect has been fully discussed elsewhere [5, 11], and will therefore be only briefly alluded to here. The method, it turns out, is quite sensitive to certain parameters which enter into the mathematical systems used, and, of necessity, have to be selected by the wave analyst. These parameters are:

(a) the number of digitized data-points, N, in the length of a wave record, T_r
(b) the time increment, Δt, between adjacent data-points
(c) the number of lags, M, used for auto-correlation purposes
(d) the number of points, P, assigned to a numerical filter

Three important derivative parameters depend on the choice of (a), (b) and (c), namely:
(e) the frequency increment,or measure of *resolution*:

$$\left.\begin{array}{lll} \text{(i)} & \Delta\sigma = 2\pi(2\,\Delta t\,M)^{-1} & \text{radians-(time)}^{-1} \\ \text{or (ii)} & \Delta f = (2\,\Delta t\,M)^{-1} & \text{cycles-(time)}^{-1} \end{array}\right\} \quad (1)$$

(f) the frequency range, or Nyquist cut-off frequency:

$$\left.\begin{array}{lll} \text{(i)} & \sigma_n = 2\pi(2\,\Delta t)^{-1} & \text{radians-(time)}^{-1} \\ \text{or (ii)} & f_n = (2\,\Delta t)^{-1} & \text{cycles-(time)}^{-1} \end{array}\right\} \quad (2)$$

(g) the number of degrees of freedom, ν, or measure of *confidence*:

$$\nu = [N - M/4](M/2)^{-1} \approx 2N M^{-1} \quad \text{when } M \ll N \qquad (3)$$

It is anomalistic that in seeking high confidence of results in auto-correlation, the number of lags M in Eq.(3) should be chosen as small as possible, although, thereby, the frequency increment, $\Delta\sigma$ or Δf, in Eq.(1) is also rendered large, and the resolution of the power spectrum therefore low. Confidence and resolution, unfortunately, are two mutually antagonistic properties. Poor resolution of the spectral density estimates results in excessive blunting of spectral peaks in the spectrum. Too high resolution, on the other hand, inevitably lowers the confidence that spectral peaks of energy are real. The tendency in spectrum analysis seems to have been to lean towards high confidence rather than strong resolution, with the result that wave energy spectra often appear to be devoid of sharp peaks. A question of importance for this study was to know the best common meeting ground for good resolution and reasonable confidence in the estimates of spectral energy density of the tsunami records.

3. SPECTRUM PARAMETERS FOR THE MARIGRAMS OF HILO, HAWAII, AND SAN FRANCISCO, CALIFORNIA

To test the effects of different values of spectrum parameters on resulting spectra, two cases, Hilo, Hawaii, and San Francisco, California, were selected initially for analysis. Hilo was chosen as being one station for which it was contended by Van Dorn and Cox [12], on the basis of spectrum analyses made by Loomis [13], that the marigram showed no evidence of the presence of waves as long in period as 1.8 hrs. The writer on the other hand, using the Residuation process, had found them to be present [2], and desired verification.

The tide records were digitized on a trace follower and read directly on to magnetic tape, from which co-ordinates of points were then transferred to decks of punched cards. Counts were recorded at time intervals of 0.02 hr over record lengths of 36 hrs. Fig. 2(a) is a computer-plot of the original marigram

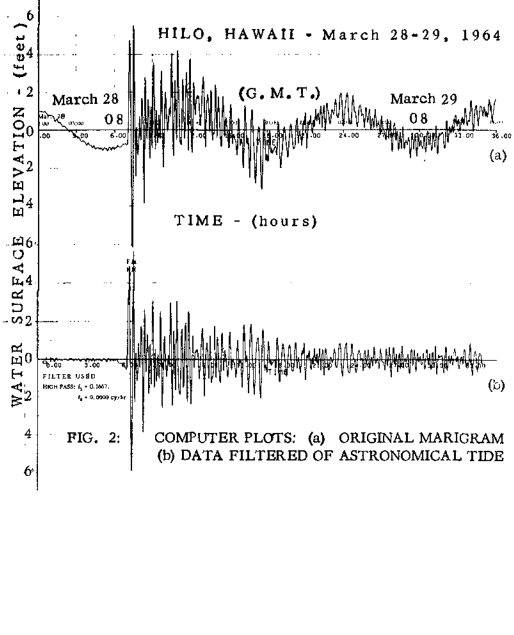

FIG. 2: COMPUTER PLOTS: (a) ORIGINAL MARIGRAM (b) DATA FILTERED OF ASTRONOMICAL TIDE

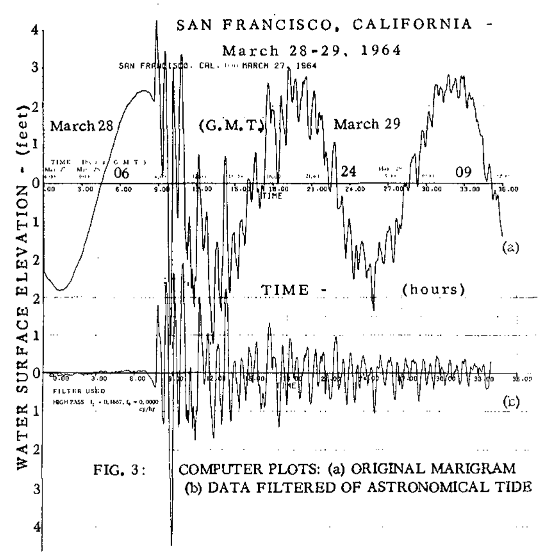

FIG. 3: COMPUTER PLOTS: (a) ORIGINAL MARIGRAM (b) DATA FILTERED OF ASTRONOMICAL TIDE

for Hilo, Hawaii, obtained in this fashion. Fig. 3(a) is the corresponding marigram for San Francisco, California. The digitized data were pre-filtered through a high-pass (2P + 1 =) 51-point filter for elimination of tides and other long wave effects in the frequency range 0 to 0.167 cy/hr (T > 6 hrs) with the results shown in Figs. 2(b) and 3(b). The filtered data were then analyzed to yield the energy spectra, substantially in accord with the principles detailed in references [5,11], and utilizing the spectrum parameter sets B to F given in Table I.

Loomis' spectra of 1966 [14], using the set A_1 in Table I, failed ro show any indication of an energy density peak at or near the frequency $f = 0.555$ cy/hr, (period 1.8 hrs). The resolution of A_1 is seen to be rather poor and the confidence only moderately good. In his later work of 1972 [13], Loomis' parameters A_2 yield somewhat better resolution at high confidence. Examination of his spectrum in this case does suggest the presence of somewhat low energy long waves at about 0.54 cy/hr (period $T \approx 1.85$ hrs). This was apparently overlooked, or otherwise dismissed as noise, by Van Dorn and Cox [12].

The important effects of resolution, found by use of the parameter-sets C, D, E and F of Table I on the marigram for Hilo, Hawaii, are shown in the spectra of Figs. 4(a) to (d). Fig. 4(a), with low resolution and good confidence, fails to show any evidence of an energy peak at 0.55 cy/hr frequency ($T \approx 1.8$ hr). Fig. 4 (b) reveals the emergence of several minor peaks as resolution improves and confidence recedes. The use of 51-point filters with parameters C and D led to difficulties in the plot-out of wave forms. Parameter set E was made

TABLE 1: SETS OF SPECTRUM PARAMETERS USED OR TESTED

Parameter Set	Investigator & Reference	SPECTRUM PARAMETERS ADOPTED							
		Record Length T_r (hrs)	No. of Points N	Time Interval Δt (hr)	Nyquist Frequency f_n (cy/hr)	No. of Lags M	Degrees of Freedom (Confidence) ν	Frequency Increment (Resolution) Δf (cy/hr)	No. of Filter Points $2P+1$
A_1	Loomis (14)	8	249	0.03	15	41	12	0.372	?
A_2	Loomis (13)	34	1024	0.03	15	60	34	0.250	?
B	Wilson (5)	30	300	0.10	5	160	4	0.031	51
C	" (5)	36	1800	0.02	25	200	18	0.125	51
D	" (5)	36	1800	0.02	25	300	12	0.083	51
E	" (5)	36	1800	0.02	25	300	12	0.083	255
F	" (5)	36	1800	0.02	25	400	9	0.063	153

identical to D in all respects save for the adoption of 255-point filters. The more finely tuned filters had the influence of reducing energy losses in the high-pass filtering process, and as Fig. 4(c) shows, allowed emergence of more prominent spectrum peaks, compared to Fig. 4(b), including a small one at 0.56 cy/hr frequency ($T \approx 1.79$ hrs). In the case of Fig. 4(d) the number of lags was increased further ($M = 400$) and filter points reduced to 153 ($P = 75$). Resolution was hereby increased still further and confidence somewhat reduced ($\nu = 9$). The smaller value of P was a concession to reduction of computing time and reduction of terminal losses of output record-lengths resulting from application of filters. Fig. 4(d) further enhances the spectral energy peaks, including some residual tidal energy (unshaded) not completely removed by the initial high-pass filter.

In the case of the marigram for San Francisco (Fig. 3), application was made of the spectrum parameters B, E and F, with results shown in the spectra of Figs. 5(a), (b) and (c). It is very evident from Fig. 5 that the tsunami at San Francisco was composed primarily of two almost discrete wave systems with periods approximating 1.8 hrs and 40 mins. The high resolution of parameter-set B elicits some minor peaks in the equivalent spectrum Fig. 5(a). These are virtually smoothed away by the use of the parameter-set F [Fig.5(c)], and are non-existent in Fig. 5(b), obtained from use of parameter-set E.

4. COMPARISON OF THE WAVE-FORMS FROM SPECTRUM AND RESIDUATION ANALYSIS

In Fig. 6 the primary (P) and secondary (S) wave systems of periods, respectively, $T_1 \approx 1.8$ hrs and $T_2 \approx 40$ mins, have been separated out from the San Francisco marigram by use of appropriate filters, for comparison with the results of the Residuation analysis, P(d) and (S). The computer results from

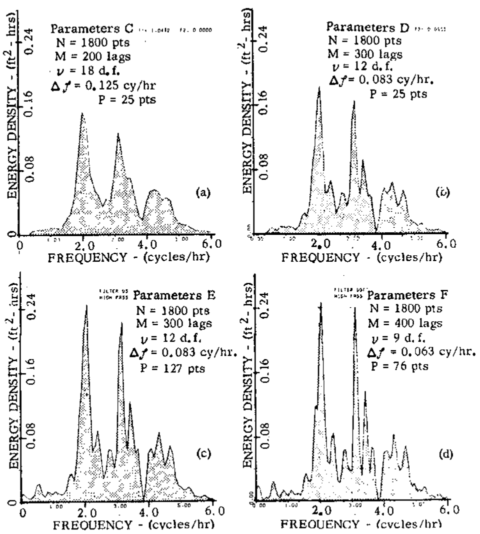

FIG. 4 - COMPARATIVE WAVE-ENERGY SPECTRA FROM HILO, HAWAII, MARIGRAM OF MAR. 28-29, 1964. T_r = 36 hrs; Δt = 0.02 hr.

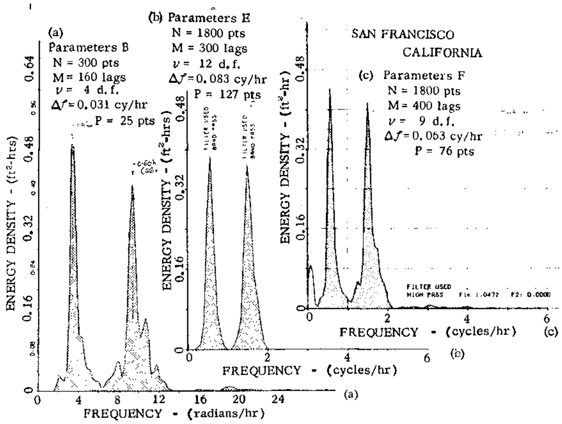

FIG. 5 - COMPARATIVE WAVE-ENERGY SPECTRA FROM SAN FRANCISCO MARIGRAM OF MAR. 28-29, 1964. T_r = 36 hrs; Δt = 0.02 hr.

use of the spectrum parameters E appear to accord most closely with the Residuation wave forms in period, amplitude and beat-shapes.

In the case of the Hilo, Hawaii, record, the wave form of the small peak of low frequency energy, centered at 0.56 cy/hr in Fig. 4(d), was obtained by passing the digitized wave data through a numerical band-pass filter having cut-off frequencies at $f_1 = 0.30$, $f_2 = 0.80$ cy/hr. The plot-out is shown as P(a) in Fig. 7, and it is to be compared with P(b), obtained by the Residuation method [2]. The long-wave system P(a) in Fig. 7, obtained by use of a band-pass

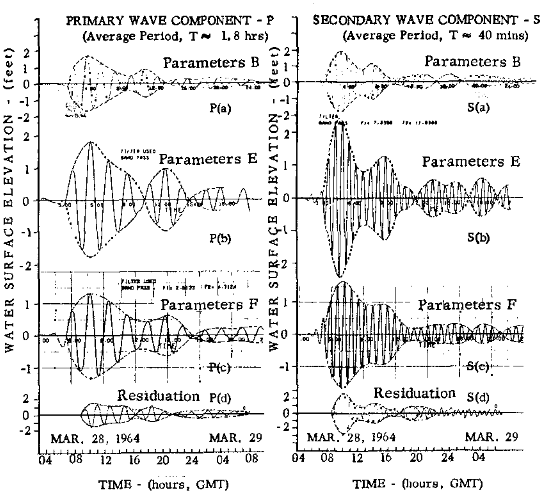

FIG. 6 - WAVE FORMS OF PRIMARY (P) AND SECONDARY (S) COMPONENTS OF MARIGRAM OF MAR. 28, 1964, SAN FRANCISCO, CALIFORNIA. Spectrum analyses a, b and c are derived from parameters B, E, F respectively (Table I); Residuation analyses d are graphical.

filter with cut-off frequencies $f_1 = 0.30$, $f_2 = 0.80$ cy/hr, retains some high-frequency contamination, but its envelope shape and maximum amplitude are generally similar to P(b). The remaining residual wave forms, after elimination of P(a) and P(b) are shown in Fig. 7 as S(a) and S(b). There is again general similarity of shape and amplitude.

On the basis of this experimental probing, it was decided to adopt the spectrum parameter-set F as capable of yielding reliable results for spectrum analysis of the sampling of 24 marigrams. The parameter-set F was adopted in preference to E, the more desirable set, in the interests of economy, research funds being limited.

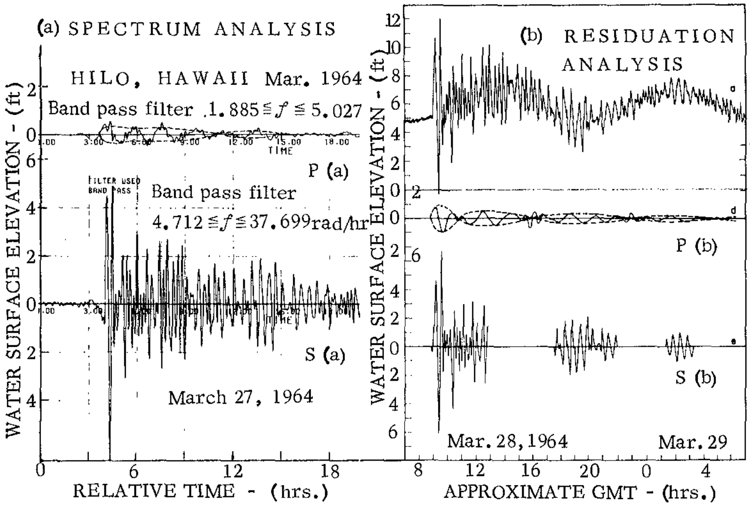

FIG. 7 - WAVE FORMS OF LOW-FREQUENCY COMPONENTS (P) AND SECONDARY COMPONENTS (S) IN MARIGRAM OF MAR. 28, 1964, FOR HILO, HAWAII. Spectrum analyses (a) used parameters F (Table I); Residuation analyses (b) are graphical.

5. SPECTRUM ANALYSIS RESULTS

As an example of the procedure followed in the spectrum analyses of the 24 marigrams, we give here briefly, the main elements of the analysis of the record for Hilo, Hawaii, being a case already cited, and one of the more complicated of all those analysed.

Use of the parameters F of Table I was shown to yield the spectrum given already in Fig. 4(d). The next step, typically followed, was to inspect the power spectrum for any peak in the frequency range 0.30 to 0.80 cy/hr. Within this band Residuation analysis had shown, in all cases, that a definitive wave component was to be expected [2]. In the case of Hilo, Hawaii, as already discussed, use of a band-pass filter with these frequency limits isolated the minor peak of energy shown in Fig. 8(a). The residual spectrum from S(a) in Fig. 7 is shown in Fig. 8(f). By using successive band-pass filters applied to the data, (in all cases, pre-filtered of tides), the important peaks of wave energy were isolated in succession, as in (b), (c), (d) and (e) in Fig. 8. The wave-form associated with each such peak or group of peaks was next computer-plotted to yield the wave components reproduced in Fig. 9. Fig. 9(a) and (b) are the same, respectively, as P and S in Fig. 7. Fig. 9(c) is the waveform corresponding to the energy group of Fig. 8(b); 9(d), that of 8(c); 9(e),

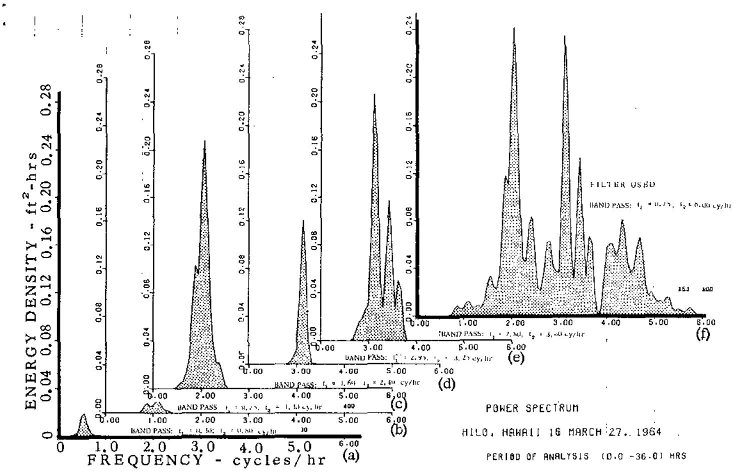

FIG. 8 - WAVE-ENERGY SPECTRA FROM DATA S(a) IN FIG. 7, AS FILTERED THROUGH BAND-PASS FILTERS (a) TO (f), HILO, HAWAII.

that of 8(e), and 9(f), that of 8(d).

Fig. 9 thus shows that the most dominant low-frequency components of the Hilo marigram were oscillations of periods 1.82 hrs, 1.0 hr, 29.1 mins and 19.2 mins. The latter, as revealed by Fig. 9(f), is a remarkably steady oscillation of long duration, (about 9 ins amplitude over 9 hours), before dying away. It is modulated, however, as apparent in Fig. 9(e), by the two wave components of periods 17.5 and 16.5 mins.

6. "PRIMARY" WAVES OF THE SPECTRUM ANALYSES

It is not possible in this short paper to reproduce results of all the spectrum analyses, as conducted in the form of Figs. 8 and 9. They are given, however, in full detail in Reference [5]. We limit ourselves here to presenting results for the lower frequency components of the tsunami at the different stations. Fig. 10 thus gives comparative evidence for the presence in all 24 marigrams studied, of a long wave component at a frequency between 0.50 and 0.65 cy/hr (average period 1.75 hrs). In all cases a definable peak of energy exists at or near this period, being very pronounced at stations close to the tsunami source, and at a few stations far afield. The relative heights of the energy peaks in the spectra are given along the top of the composite diagram as percentages in relation to 100% for Yakutat, Alaska. The spectrum peaks in Fig. 10, of necessity, have different ordinate scales. It will be seen that response at Port Alberni, Canada, was 10 times that of Yakutat. At Talcahuano, Chile, and at Lyttelton, New Zealand, about two thirds the distance across the Pacific Ocean from the source, in a north-south direction, the responses were 43% and 63%, .

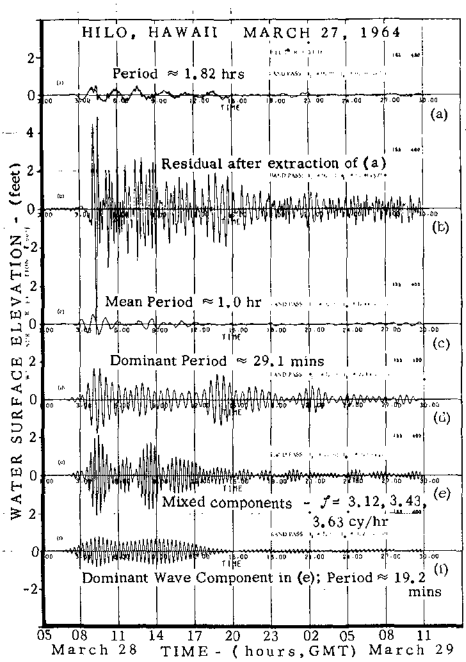

FIG. 9 - NUMERICALLY FILTERED AND PLOTTED WAVE-FORMS OF COMPONENTS OF THE ALASKAN TSUNAMI AT HILO, HAWAII, MARCH, 1964

respectively, virtual proof that this long-wave component was exciting some degree of resonance in the embayments at these locations.

The wave-forms corresponding to the spectrum peaks of Fig. 10 are computer plotted in Figs. 11 and 12; the vertical scales, be it noted, are not uniform. Considerable interest attaches to the beat-shapes of the envelopes of the waveforms, which are often quite similar, as between stations fairly close together; even over great distances they still retain a general similarity. It appears that the number of waves in the first beat increases with distance in the north-south direction along the eastern boundary of the Pacific, from 5 near the source, to 6 at Prince Rupert, Canada, 7 at San Francisco, 8 at Talcahuano, Chile, and to semi-uniform wave-train formation near Antarctica. In the east-west and central north-south directions across the Pacific, the beat-shapes of the long waves , shown in Fig. 12, are quite markedly different from those of Fig. 11. Except in the cases of Hilo and Mokuoloe Is., Hawaii, the beats are all extremely long and phase changes apparently did not occur.

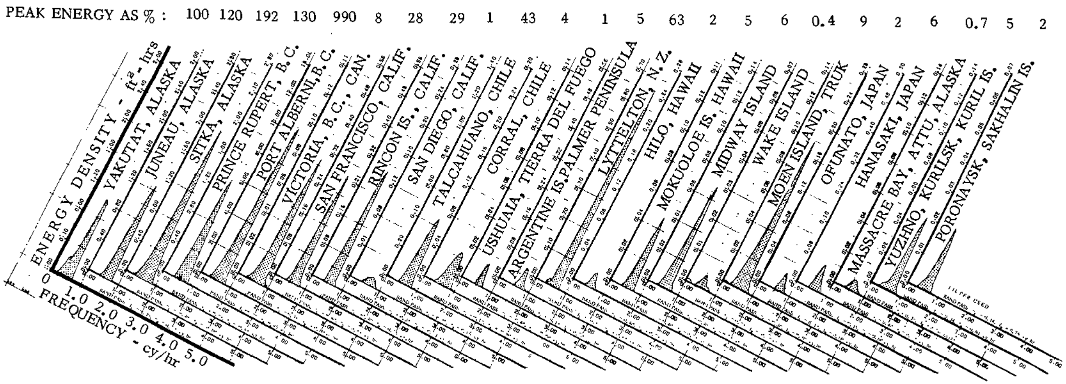

FIG. 10 - COMPARATIVE POWER-SPECTRA FROM BAND-PASS FILTERED DATA, ESTABLISHING THE PRESENCE IN ALL 24 MARIGRAMS OF PACIFIC OCEAN TIDE-STATIONS OF A DISTINCTIVE TSUNAMI COMPONENT-WAVE-FREQUENCY BETWEEN 0.50 AND 0.65 CY/HR (AVERAGE PERIOD 1.75 HRS). Note that ordinate scales are not all uniform.

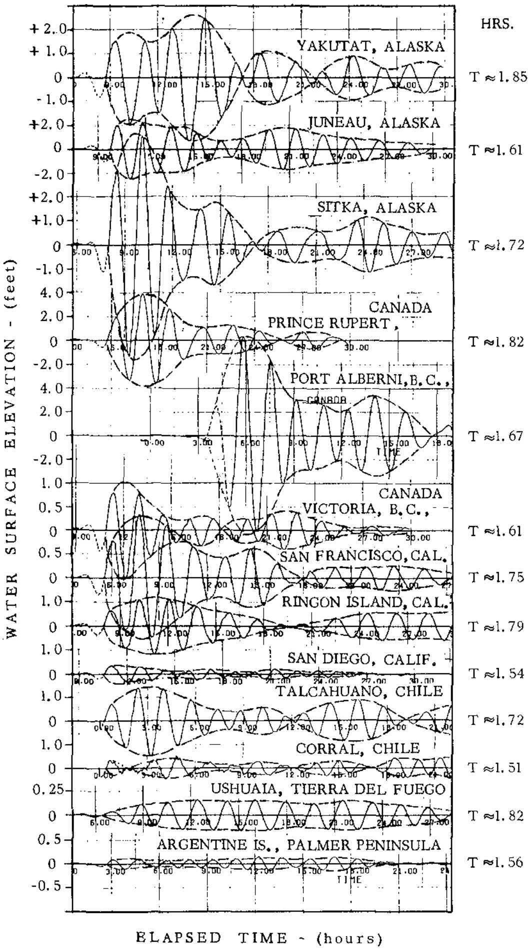

FIG. 11 - COMPUTER-PLOTTED WAVE-FORMS OF LONG-PERIOD COMPONENT (AVERAGE PERIOD 1.73 HRS) OF THE MARCH, 1964, ALASKAN TSUNAMI, NUMERICALLY DETERMINED FROM MARIGRAMS OF PACIFIC OCEAN TIDE-STATIONS.
Note: ordinate scales are not all uniform; dash-line envelopes are hand-drawn.
The plot for Port Alberni is intentionally set back to avoid confusion with adjacent plots.

It is of interest at this point to compare some samples of the Residuation analyses [2, 5], (as discussed earlier in Sections 2 and 4), with those obtain-in Figs. 11 and 12. Thus, Fig. 13 gives a selection of "primary" wave-trains *residuated* graphically from the marigrams of seven tide-stations. It is evident at once that the Residuation method succeeded in isolating the correct forms of the primary waves, both as to beat-shapes and number of waves in

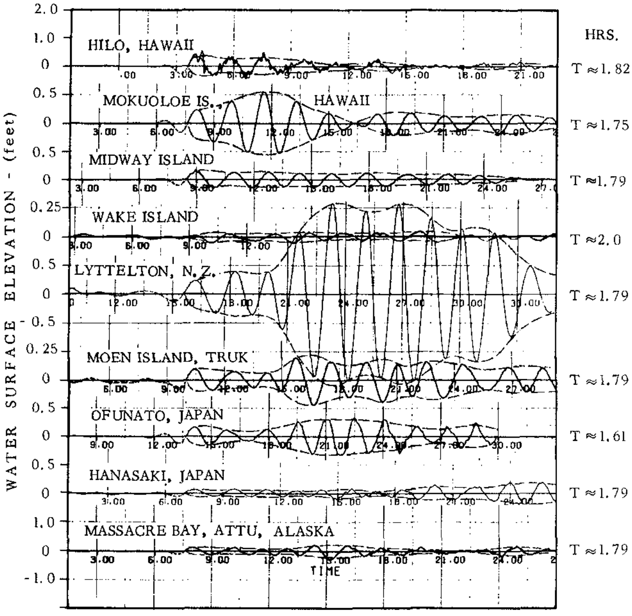

FIG. 12 - COMPUTER-PLOTTED WAVE-FORMS OF LONG-PERIOD COMPONENT (AVERAGE PERIOD 1.77 HRS) OF THE MARCH, 1964, ALASKAN TSUNAMI, NUMERICALLY DETERMINED FROM MARIGRAMS OF PACIFIC OCEAN TIDE-STATIONS: (ordinate scales not uniform; envelopes hand-drawn).

beats. Agreement on amplitudes is somewhat less satisfactory, but values are well within "ball-park" range of each other. The degree of concurrence of results from the two analysis methods is sufficient to validate the general reliability of the Residuation process used in Reference [2].

When the average period of the first three waves occurring in each wave-train of Figs. 11 and 12 are plotted as histograms of their relative frequency of occurrence, as in Fig. 14(a) and (b), the inference seems to be that along the west coast of the Americas, the predominant wave period of what we have called the *primary* waves was about 1.73 hrs, within a range from 1.55 to 1.95 hrs. In the west Pacific Ocean the dominant wave period was about 1.77 hrs within a tighter range of about 1.70 to 1.90 hrs.

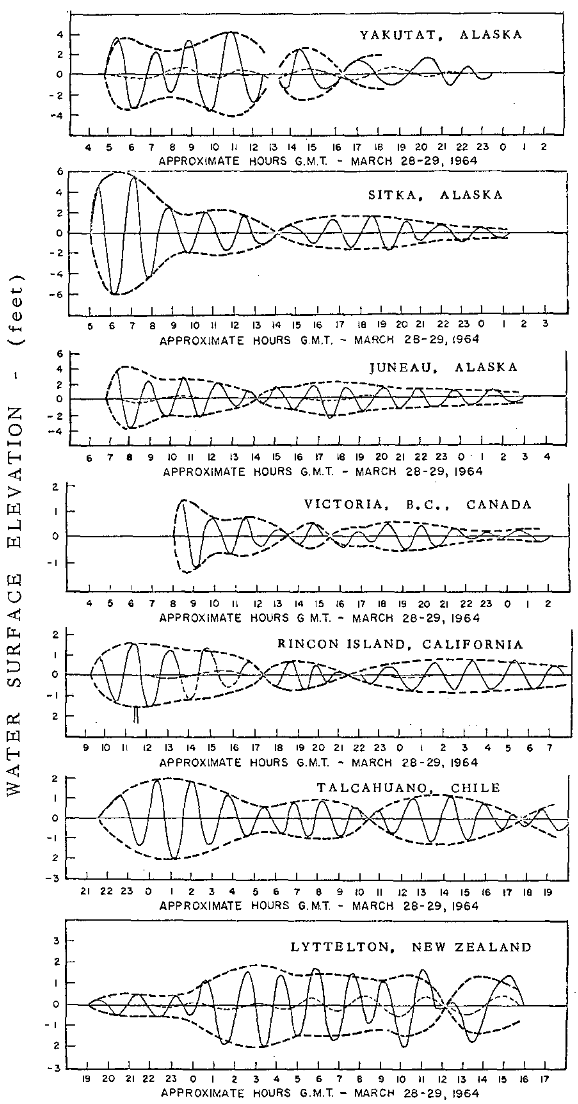

FIG. 13 - SAMPLES OF 'PRIMARY' WAVE TRAINS AS DETERMINED BY GRAPHICAL RESIDUATION OF THE MARIGRAMS FOR THE SEVEN TIDE-STATIONS; AVERAGE PERIOD 1.75 HRS: (Compare with computer-plots of 'Primary' waves obtained from Numerical Energy Spectrum Analyses in Figs. 11 and 12).

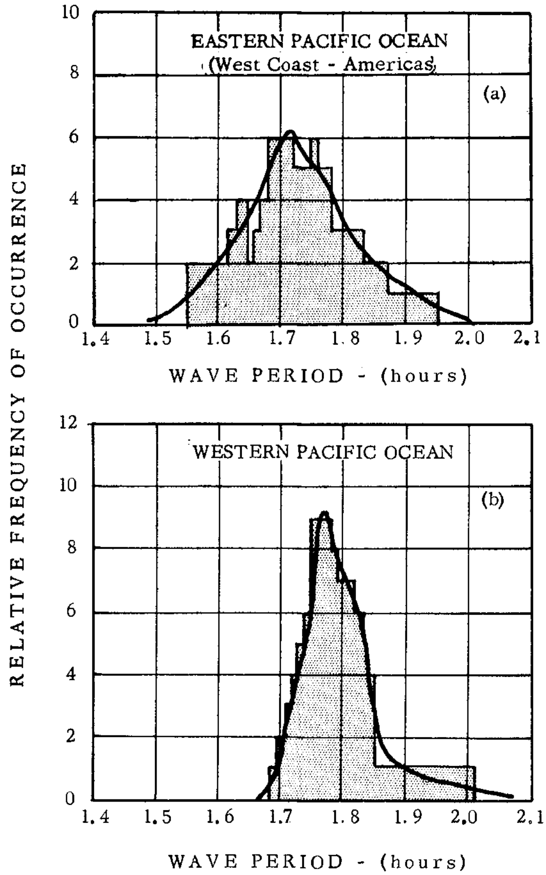

FIG. 14 - HISTOGRAMS OF WAVE PERIODS FOR "PRIMARY" LONG WAVE COMPONENT OF MARCH, 1964, ALASKAN TSUNAMI: (a) EASTERN PACIFIC OCEAN; (b) WESTERN PACIFIC OCEAN; (based on first three waves in Figs. 11 and 12)

On the supposition that the beats of long waves resulted from the interference of just two trains of periods T_1 and T_2 (frequencies f_1 and f_2), thereby yielding beat frequencies f_b and apparent wave frequencies f_a , it is readily shown that:

$$
\left.\begin{aligned}
&(i) && T_1 = 1/f_1 = [f_a + f_b]^{-1} = [1/T_a + 1/T_b]^{-1} \\
&(ii) && T_2 = 1/f_2 = [f_a - f_b]^{-1} = [1/T_a - 1/T_b]^{-1} \\
&(iii) && T_b = 2(n-1)\,T_a
\end{aligned}\right\} \quad (4)
$$

where T_a and T_b, respectively, are the periods of the waves apparent in the beat and of the beat itself, n being the number of waves occurring in the beat. Adopting $T_a = 1.72$ hrs for the Eastern Pacific, the values of T_1 and T_2 for particular values of T_b and n are found in Table II. For the Western Pacific Ocean they are given in Table III, for the apparent wave period $T_a = 1.77$ hrs.

Table II shows that the periods T_1 and T_2 in the last columns, are contained quite easily in the period-spread of the histogram, Fig. 14(a). Table III, likewise, shows similar containment in the histogram spead of Fig. 14(b). The idea gains support, therefore, that the envelope shapes of the long wave systems are the result of interfering frequency components with periods of the

TABLE II - RANGE OF INTERFERING FREQUENCIES TO ACCOUNT FOR BEATS OF LONG WAVES (NOMINAL PERIOD 1.72 HRS)

(Eastern Pacific Ocean; west coast - Americas)

No. of Waves in beat	Beat Period [Eq. (7)]	Beat Frequency	Wave Frequency	Component Wave Frequencies		Component Wave Periods	
n	T_b (hrs)	f_b (cy/hr.)	f_w (cy/hr.)	f_1 (cy/hr.)	f_2 (cy/hr.)	T_1 (hrs)	T_2 (hrs)
5	13.76	0.0727	0.5814	0.6541	0.5087	1.53	1.96
6	17.20	0.0581	0.5814	0.6395	0.5233	1.56	1.91
7	20.64	0.0484	0.5814	0.6298	0.5330	1.59	1.88
8	24.08	0.0415	0.5814	0.6229	0.5399	1.61	1.85
10	30.96	0.0323	0.5814	0.6137	0.5491	1.63	1.82

TABLE III - RANGE OF INTERFERING FREQUENCIES TO ACCOUNT FOR BEATS OF LONG WAVES (NOMINAL PERIOD 1.77 HRS)

(Western Pacific Ocean)

No. of Waves in beat	Beat Period [Eq. (7)]	Beat Frequency	Wave Frequency	Component Wave Frequencies		Component Wave Periods	
n	T_b (hrs)	f_b (cy/hr.)	f_w (cy/hr.)	f_1 (cy/hr.)	f_2 (cy/hr.)	T_1 (hrs)	T_2 (hrs)
7	21.24	0.0471	0.5650	0.6121	0.5189	1.63	1.93
8	24.78	0.0404	0.5650	0.6054	0.5246	1.65	1.90
10	28.32	0.0353	0.5650	0.6003	0.5297	1.67	1.89
12	31.86	0.0314	0.5650	0.5964	0.5336	1.68	1.87

order given by T_1 and T_2 in Tables II and III. The seemingly consistent trends of change with distance, suggested by the increasing number of waves in a beat, and the varying periods given in Tables II and III are interesting, but as yet unexplained. It may be that this simplified an interpretation of the beat phenomena cannot be justified, because the declining component period T_2 with distance runs counter to an expected increase of period over distance and time for expanding waves. Despite this difficulty, the overall consistencies of change with distance from the origin suggest that the wave formations of Figs. 11 and 12 must have originated at the source and not as mere local excitations.

7. EXISTENCE OF ULTRA-LONG PERIOD WAVE-TRAINS

Both the Residuation and the Numerical Spectrum analyses have revealed that, for about half of the marigrams studied, there is evidence of still longer period wave-trains in the composition of the tsunami than those already discussed. They are found to lie within a frequency range of about 0.30 to 0.35 cy/hr, (average period 3.2 hrs). The strongest such wave-train of period 3.0 hrs occurred at Yakutat, Alaska, close to the tsunami source (Fig. 1). Its height (Fig. 15) was comparable to the height of the 1.85 hr period waves shown in Fig. 11 for Yakutat. For the marigrams in which these extremely long waves were detectable, as in Fig. 15, the largest effects besides those of Yakutat, occurred at Victoria, Canada, at the Palmer Peninsula, Argentine Island, Antarctica, and at Lyttelton, New Zealand. Some of the wave-trains in Fig. 15 overlie residual astronomical tide-waves, not completely eliminated in the numerical filtering for the 3.2 hr period waves.

At Yakutat, near the mouth of triangular-shaped Yakutat Bay (natural period of oscillation about 41 mins), the marine topography is not favorable to any resonance of incident waves with periods as large as 3.0 or 1.8 hrs. The much smaller triangular Monti Bay, at the head of which Yakutat harbor actually lies, is an offshoot of Yakutat Bay at its mouth, and therefore in a nodal position with respect to any oscillations of Yakutat Bay. Because of this and the fact that Monti Bay has a fundamental period of free oscillation of about 17 mins only, there could have been no possibility of resonant amplification of 1.8 and 3.0 hr tsunami wave components. The waves of these periods, shown in Figs. 11 and 15, would therefore have been incident waves enhanced only by the shoaling and funnelling effect of the small Monti Bay, to the extent perhaps of 6 times their deep-water height (in accord with Green's Law). The inference from this is that the nominal 1.8 and 3.2 hr component long waves of the tsunami originated from the source and propagated across the Pacific Ocean.

At Victoria, Canada, the natural periods of oscillation of the Juan de Fuca Strait (fundamental, about 4.3 hrs; second mode, about 1.8 hrs), would have been conducive to some enhancement of the long wave-trains, as Figs. 11 and 15 suggest. A pseudo-resonance effect would also have occurred at Lyttelton, N.Z., where the period of free oscillation for Port Lyttelton Channel and Pegasus Bay is about 2,6 hrs. The marigram for Lyttelton harbor, in fact, recorded 2.6 hr oscillations prior to the arrival of the tsunami waves; they were probably locally generated by barometric fluctuations or other causes. The

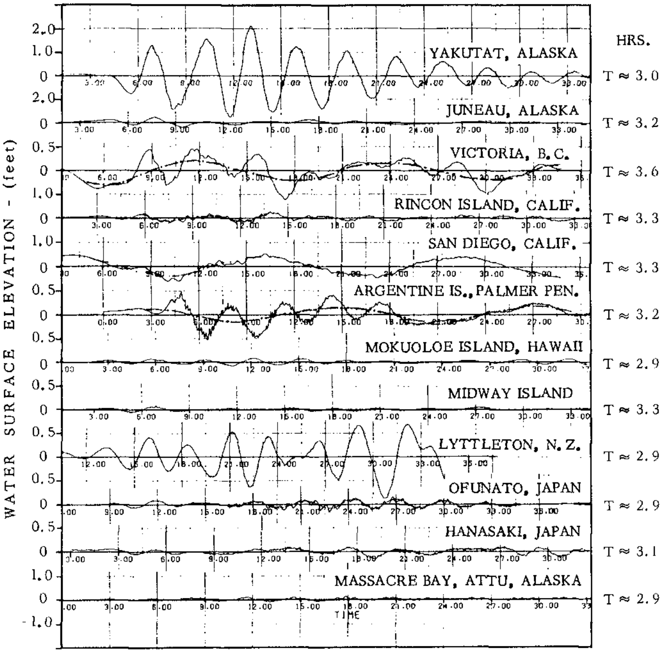

FIG. 15 - COMPUTER-PLOTTED WAVE-FORMS OF ULTRA-LONG PERIOD (AV. 3.2 HRS) OF THE MARCH, 1964, ALASKAN TSUNAMI.

enhancement of the 3.2 hr waves at Palmer Peninsula, Antarctica, probably relates to the shoaling and restrictive effect of the Antarctic Sound. As to why these ultra-long period waves drew no strong responses at other stations where the 1.8 hr period waves recorded well, as in Figs. 11 and 12, cannot be known without a detailed wave-refraction study and examination of the oscillating characteristics of the areas.

8. CONCLUSIONS

Numerical power-spectrum and graphical Residuation analyses have been shown to be mutually supportive of the existence in the records of the Alaskan tsunami of March, 1964, of very long wave-trains with periods approximating 1.75 and 3,2 hrs, originating at the source and propagating across the Pacific Ocean. In the north-south direction encompassing the eastern half of the Pacific Ocean, the 1.75 hr (nominal) period waves occurred in beats, their numbers per beat increasing with time and distance.

REFERENCES

1 Spaeth, M.C. and Berkman, S.C.: "The Tsunami of March 28, 1964, as Recorded at Tide Stations"; U.S. Coast and Ceodetic Survey, Dept. of Commerce, Rockville, Maryland, April 1965, 59 pp.

2 Wilson, B.W. and Tørum, A.: "The Tsunami of the Alaskan Earthquake, 1964; Engineering Evaluation"; Tech. Memo. No.25, Coastal Engineering Research Center, U.S.Army Corps of Engineers, Washington, D.C. May, 1968.

3 Chrystal, G.: "Investigation of the Seiches of Loch Earn by the Scottish Loch Survey"; (Parts I and II); Trans. Royal Soc. Edinb., v.45(2), 1906, pp. 361-396.

4 Cox, D.C.: "Status of Tsunami Knowledge"; Proc. of Tsunami Meetings, 10th. Pacific Science Congr., Monograph No. 24, Internatl. Union of Ceodesy and Ceophysics, Paris, July 1963, pp. 1-6.

5 Wilson, B.W.: "Tsunami Characteristics at Representative Tide Stations along the Pacific Seaboard"; Contract Report to Coastal Engineering Research Center, U.S.Army Corps of Engineers, Washington, D.C., May, 1971, 184 pp.

6 Pierson, W.J. and Marks, W.: "The Power Spectrum Analysis of Ocean Wave Records"; Trans. Amer. Geophys. Union, v.33(6), Dec. 1952, pp. 834-844.

7 Blackman, R.B. and Tukey, J.W.: "The Measurement of Power Spectra"; Dover Publications, New York, 1958, 190 pp.

8 Munk, W.H., Snodgrass, F.E. and Tucker, M.J.: "Spectra of Low Frequency Ocean Waves"; Bulln. Scripps Inst. Oceany., La Jolla, Calif., v. 7(4), 1959, Univ. Calif. Press, pp. 283-362.

9 Eagle, A.: "A Practical Treatise on Fourier's Theorem and Harmonic Analysis"; Longmans, Creen & Co., London, 1925, 178pp.

10 Wilson, B.W.: "Research and Model Studies on Range Action in Table Bay Harbour, Cape Town"; Trans. So. Afr. Inst. C.E., v.1(6), 1959, pp. 131-148; v.1(7), pp. 153-177

11 Wilson, B.W., Chakrabarti, S.K. and Snider, R.H.: "Spectrum Analysis of Ocean Wave Records"; Internatl. Sympos. on Ocean Wave Measurement and Analysis, New Orleans, LA, USA, Sept. 1974, ASCE, v.1, pp. 87-106.

12 Van Dorn, W.C. and Cox, D.C.: "Oceanic Character, Propagation and Coastal Modification of the 1964 Alaskan Tsunami"; The Great Alaska Earthquake of 1964; Oceanography and Coastal Engineering, Natl.Acad. Sci., Washington, D.C., 1972, pp. 147-157.

13 Loomis, H.C.: "The Major Tsunami in the Hawaiian Islands"; The Creat Alaska Earthquake of 1964; Oceanography and Coastal Engineering, Natl. Acad. Sci., Washington, D.C., 1972, pp. 181-190.

14 Loomis, H.C.: "Spectral Analysis of Tsunami Records from Stations in the Hawaiian Islands"; Bulln. Seis. Soc.Am., v.56(3), 1966, pp. 697-713.