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A PROGRAM FOR ROUTINE LOCATION OF
T-PHASE SOURCES IN THE PACIFIC

By

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MARCH 1965

HAWAII INSTITUTE OF GEOPHYSICS
UNIVERSITY OF HAWAII

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Contents

ABSTRACT

A program for the routine location of T-phase sources in the Pacific has been initiated. Data for this program is supplied principally by the Pacific Missile Range hydrophone network. Hydrophone records are forwarded weekly for reading at Honolulu. In correlating arrivals records from all stations are viewed together. Correlation is established by similarity in shape and level and by locations determined roughly from arrival time differences. Arrival times and power levels are read for processing by an IBM 7040 computer.

The solution for location and origin time is the least-squares fit to all hydrophone arrivals which are weighted according to their distribution in azimuth and their distance from the T-phase source. The iterative solution proceeds on the assumption of zero parallax and flat earth in the vicinity of the source.

Velocity is derived from shot calibrations and from averaging across a contour map of local velocity. For the computer program this is expressed as a power series in latitude and longitude for each station and for each quadrant of the Pacific.

A T-phase strength is computed from readings of peak power level. This strength is computed for a distance of thirty degrees from the source. The lower half and the upper quarter of all hydrophone readings are arbitrarily rejected from computation of strength as being influenced by topographic shadowing or containing mistakes.

Events which can be correlated at four or more hydrophones occur at an average rate of about one per hour. Tabulated solutions will be published at regular intervals.

Introduction

Studies of T phases in the Pacific during recent years have shown that many naturally occurring seismic events were detected by SOFAR hydrophone that were not located by the existing seismograph network. Johnson et al. (1963) reported that about one-fifth of the T-phase arrivals at a single hydrophone station could be correlated with earthquake epicenters determined from seismograph data available to the Coast and Geodetic Survey. This observation implies that the use of the T phase in seismic source location might significantly reduce the threshold for seismicity studies of the Pacific and its borders.

In addition, studies of the T-phase mechanism require a determination of the T-phase source, as distinct from the earthquake focus. In order to satisfy the requirements of T-phase research, and in hope of providing a supplementary source of data for seismicity studies, a program for routine location of T-phase sources in the Pacific was developed.

Background

A statistical method for earthquake location was first described by Geiger (1910). With the advent of the high-speed computer, application of the basic least-squares technique is no longer laborious and a number of computer programs have been written (Bolt, 1960; Flinn, 1960; Gunst and Engdahl, 1962; Steinhart, 1964).

Workers in underwater sound have tended to favor geometric solutions, perhaps because the number of recording stations is usually small and also possibly because a lower order of effort is required to develope the computer program. Also, these programs have generally dealt with underwater explosions for which the arrival times are much more precisely defined than those of T phases.

The reduced precision of arrival time determination in the present application, together with the high incidence of events, requires that as many arrivals as possible be read and that all weighting procedures be incorporated in the computer program. These requirements are satisfied by the method of least squares which is employed in the present program.

Data Collection

Hydrophones are currently being recorded at five locations in the Pacific; Eniwetok, Wake, Midway, Oahu, and California. A sixth recording station in the Aleutians is planned. At each of the Pacific Missile Range stations at Eniwetok, Wake, and Midway, data are recorded from four widely-spaced hydrophones (~ 100 km). The California record is from two well-spaced hydrophones. Data from two hydrophones are recorded at Oahu, but only one is used in computations.

Records from which arrival times and T-phase pow r levels are read are roll-chart displays of sound power level versus time (Fig. 1). The charts are multi-channel, from those stations having multiple hydrophone sites.

As the T phase is strong in low frequencies, the signal is passed through a 15-cps low-pass filter. This filtering improves the signal-to-noise ratio by 10-20 decibels. Most ship noise and explosion signals are also eliminated. Because of the low frequencies, a low stylus response speed is used in order to give a smoother trace and a more meaningful reading of power level.

To reduce the bulk of records as well as paper costs, the slowest available chart speed is used (0.25 mm/sec). This practice does not compromise reading accuracy as the T-phase peak is typically broad and its position cannot usually be defined more precisely than about $\pm$ 3 seconds.

The arrival time of a signal is defined as the time of peak power. Each trace is kept near the bottom of its paper channel so that a large amplitude T phase will not lose its peak against the stylus stop. Seasonal variations of sea-noise background may make it necessary to adjust the attenuators so that the traces remain near the bottom of the paper channel but not off it.

The system is calibrated daily for power level by injecting a 10-cps signal in place of the sea noise at the input to the hydrophone amplifier. This calibration signal is varied by 10-db steps throughout the full dynamic range of the system. It appears on the record as shown in Figure 1. This calibration signal is used to measure the power level of T phases.

On each chart, one margin stylus records 15-second marks from a tuning fork chronometer while a second margin stylus is actuated by the 440-and 600-cps tones of radio time signals (WWV, WWVH, and JJY). The radio time is essential to detect errors of the local chronometer.

Chart rolls are changed nearly simultaneously at all stations according to a twice-a-week schedule. They are mailed to Honolulu at least weekly.

Data Processing

The first task of analysis is to decide which T-phase arrivals at the various stations are from the same earthquake. This is made difficult by the fact that there are usually several T waves crossing the ocean in different directions at the same time. To correlate the arrivals, all records from a particular set are put onto a large chart table (Fig. 2). The records are synchronized and cranked across the table one hour at a time.
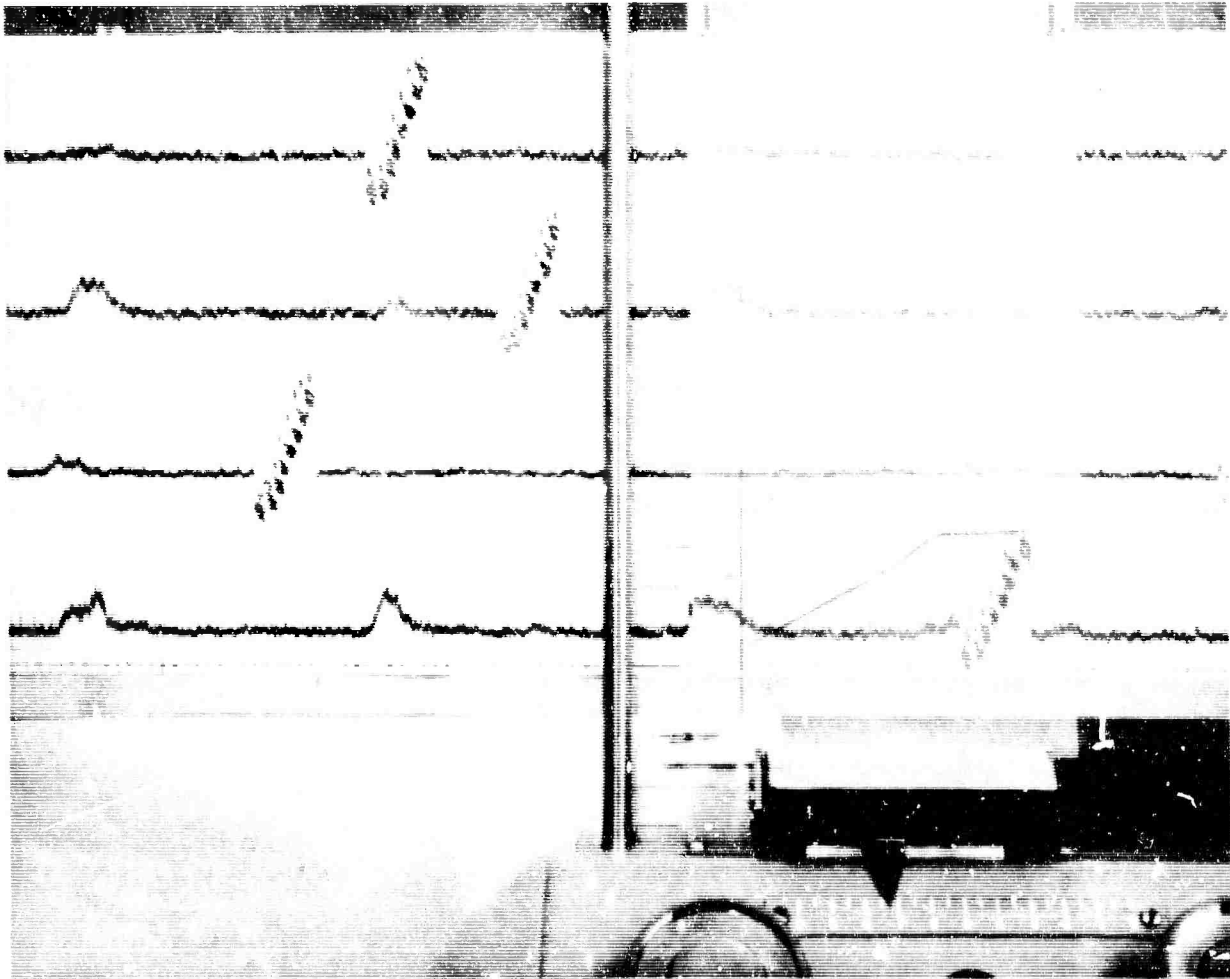
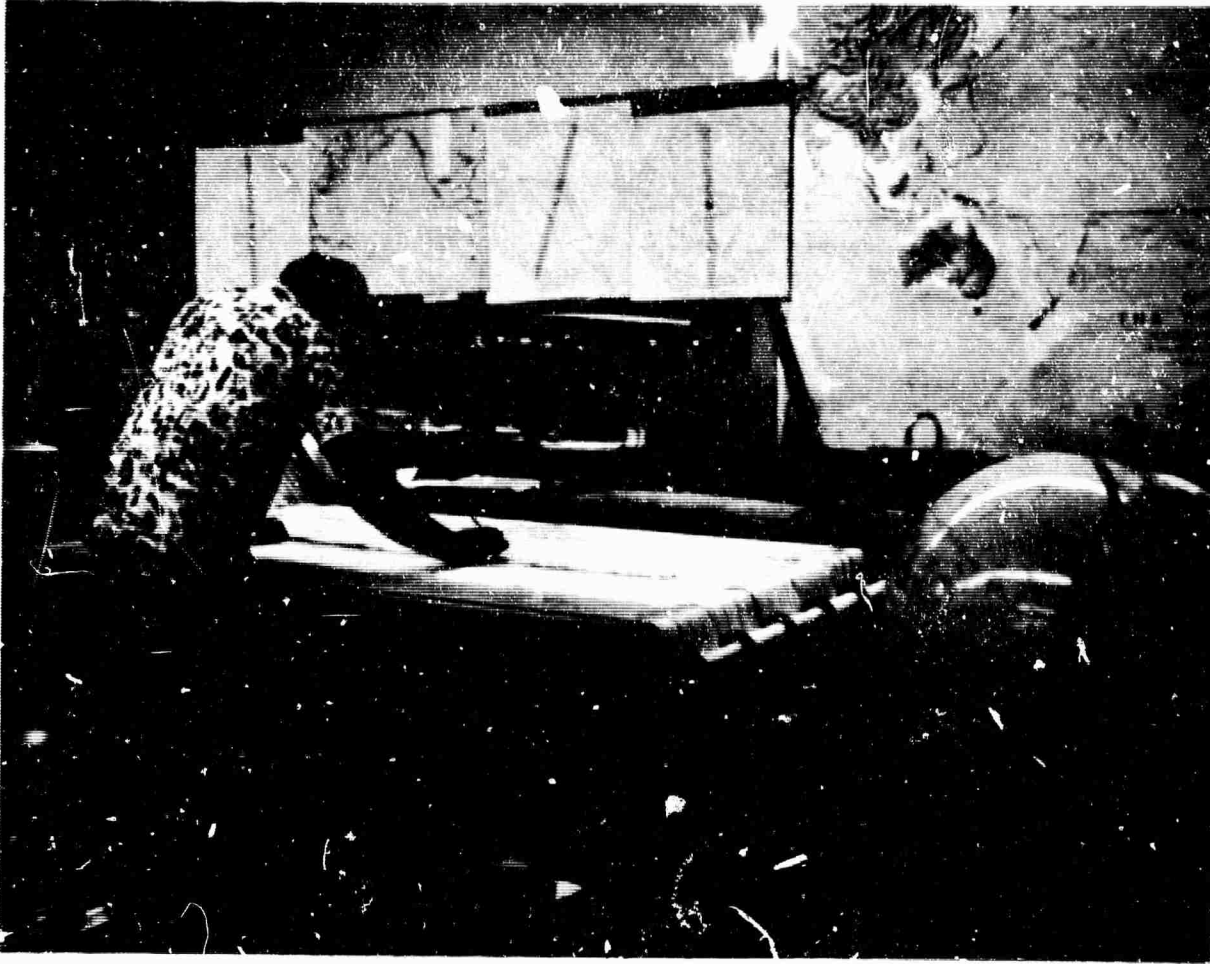Fig. 1. Roll chart display of sound power level versus time.

Fig. 2. View of correlating table.

Correlation is done by: (1) scanning the synchronous chart display for T phases of similar size and shape within a possible time range; (2) comparing the bearings at each station as given by the phone-to-phone differences in arrival time; and (3) comparing the station-to-station differences of arrival time with the Pacific Ocean chart above the table which shows position lines for given time difference. Distances from suspected source areas are checked on a 81.28 cm globe with a tape calibrated in SOFAR travel time.

When a signal is found which correlates at four or more hydrophones and at two or more stations, it is assigned a two-digit serial number. This number is written on the record over each hydrophone trace which shows the signal clearly. The serial numbers and approximate source areas are logged for future reference.

After the correlations have been completed, the records are ready for digitizing on an automatic chart reader. This chart reader is connected to a card-punching machine, which translates the data to IBM cards. The automatic chart reader handles one roll at a time and feeds the following information to the card-punching machine: serial number, power level, date, arrival time, and hydrophone number. It is only necessary for the operator to align cross hairs, turn switches, and press a button. One card is punched for each T phase at each hydrophone.

One of the "cross hairs" which the operator aligns when measuring power level is actually a pencilled curve on a plastic sheet which he constructs from the power-level calibration. Each time he encounters a calibration in the chart roll, he checks his curve to see whether it agrees with the new calibration. If it does not, this indicates that the system characteristics have changed, perhaps due to recorder sensitivity or centering adjustments, or to attenuator changes. As this is precisely the purpose of the calibration, the operator reconstructs the curve to agree with the new characteristics.

After the data from a complete set of chart rolls have been punched on cards, the cards are machine sorted by serial number and by arrival time within serial number. They are then ready for the electronic digital computer which solves for source coordinates and origin times.

Computational Method

The machine program first checks arrival time differences and the number of readings in each set to detect gross errors in chart reading. It then proceeds to select four hydrophones for use in a geometric fix. This geometric fix serves as the starting point for an iterative least-squares estimate of the source which uses all arrival times.

It is commonly thought that three detectors are sufficient to obtain a fix where velocity is assumed. However, three hydrophones give two solutions (a hyperbola on the surface of a sphere is a closed curve) and a fourth hydrophone is still required to resolve the ambiguity.

The first hydrophone selected for the four-hydrophone fix is the one with the earliest arrival time. The second is the earliest hydrophone among the remaining recording stations. If the signal was recorded at more than two stations, the process continues; if not, the third hydrophone is the second earliest at the station recording the earliest signal. If only one hydrophone was recorded at that station, the choice passes to the succeeding station, etc. The objective is to select four hydrophones as wide-spread as possible but as near the source is possible where alternatives exist.

Although it is possible to obtain latitude, longitude, origin time, and average velocity from four hydrophone arrivals (Frosch et al., 1961), the purpose of the solution requires only that an approximate latitude and longitude be obtained. Therefore, for this preliminary solution, an average SOFAR velocity of 2.32×10^{-4} geocentric radians per second is assumed to apply throughout the Pacific.

Four-Station Fix

Consider hydrophones designated 0, 1, 2, and 3, and increasing distances Δ, Δ_1, Δ_2, and Δ_3, respectively, from the source at k. Distances from hydrophone 0 to the other hydrophones are B_1, B_2, and B_3, respectively, and angles $\emptyset$, α, and β, are as shown in Figure 3.

The basic equations are the set

$$ H = T_i - \frac{\Delta_i}{c} $$

for origin time H, arrival time T_i, average velocity c, and i corresponding to hydrophones 0 through 3.

Fig. 3

Eliminating H between equations 0 and i and multiplying by c,

$$ c(T_1 - T) + \Delta = \Delta_1 = \cos^{-1}(\cos B_1 \cos \Delta + \sin B_1 \sin \Delta \cos \emptyset) $$

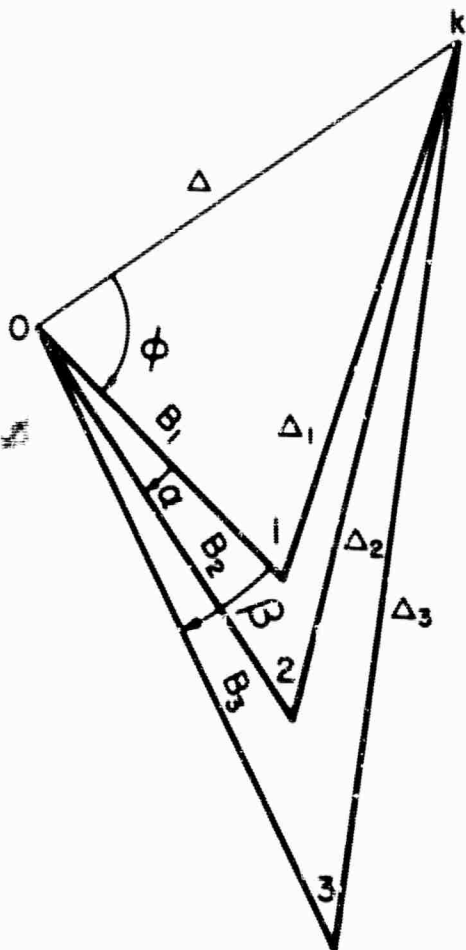Taking the cosine, expanding the left-hand side, dividing by $\sin \Delta$, and

solving for cot Δ, gives

$$\cot \Delta = \frac{\sin D_1 + \sin B_1 \cos \emptyset}{\cos D_1 - \cos B_1} \qquad (1)$$

where

$$D_1 = c(T_1 - T).$$

By parallel construction,

$$\cot \Delta = \frac{\sin D_2 + \sin B_2 \cos (\emptyset + \alpha)}{\cos D_2 - \cos B_2} .$$

Eliminating Δ ,

$$E_2 \sin D_1 + E_2 \sin B_1 \cos \emptyset = E_1 \sin D_2 + E_1 \sin B_2 \cos (\emptyset + \alpha)$$

where

$$E_1 = \cos D_1 - \cos B_1 .$$

Expanding $\cos (\emptyset + \alpha)$ and collecting terms,

$$\cos \emptyset \ (E_2 \sin B_1 - E_1 \sin B_2 \cos \alpha) + \sin \emptyset (E_1 \sin B_2 \sin \alpha) =$$
$$E_1 \sin D_2 - E_2 \sin D_1$$

By parallel construction,

$$\cos \emptyset \ (E_3 \sin B_1 - E_1 \sin B_3 \cos \beta) + \sin \emptyset (E_1 \sin B_3 \sin \beta) =$$
$$E_1 \sin D_3 - E_3 \sin D_1$$

These equations may be solved for $\cos \emptyset$ and $\sin \emptyset$ which may in turn be combined to yield a single equation in velocity. As the purpose is to achieve a starting point for the iterative least-squares estimate, the solution for velocity does not seem profitable. Rather, an approximate

value of 2.32×10^{-4} radians per second is substituted for c in the solutions for $\sin \emptyset$ and $\cos \emptyset$. Although both of these functions give poor resolution when the value of the function is near unity, $\tan \emptyset$, formed from the quotient of $\sin \emptyset$ and $\cos \emptyset$, yields good resolution throughout the circle. The quadrant of $\emptyset$ is determined from the algebraic signs of the numerator and denominator.

Distance, Δ, may be obtained from (1) or its two parallel equations, each of which involves a different pair of hydrophones. In cases where two hydrophones are close together in azimuth from the source, the small velocity error may cause a large distance error. To avoid the selection of such a pair of hydrophones, distance is computed from each of the three equations and the median value is chosen.

Velocity

For the final solution, velocity is determined from a function of hydrophone i and point k. This function is the least-squares fit to average velocities determined from such spot calibrations as are available and from velocities, averaged across a contour chart of local velocity, Figure 4, (Johnson and Norris, 1964), to selected points in seismically active areas of the Pacific. The function is a power series of degree 2 in latitude L and longitude λ of the form

$$c = \sum_{j=0}^{2} \sum_{\ell=0}^{2} a_{j\ell} \ L^{j} \ \lambda^{\ell}$$

The normal equations for obtaining the coefficients $a_{j\ell}$ are

$$\sum_{r=1}^{h} c_r \ L_r^{p} \ \lambda_r^{q} = \sum_{j=0}^{2} \sum_{\ell=0}^{2} a_{j\ell} \sum_{r=1}^{h} L_r^{j+p} \ \lambda_r^{\ell+q}$$

for h points to which velocity has been measured. $p = 0, 1, 2$ and $q = 0, 1, 2$.

A separate set of coefficients was obtained for each quadrant of the Pacific and a separate set of functions was derived for each recording station.

Calculation of velocity in geocentric radians for specific recording stations obviates the consideration of ellipticity corrections.

Weight Function

The least-squares estimate of the T-phase source is that latitude L_0 and longitude λ_0 which yields the minimum estimate of the variance of origin times to the set of equations
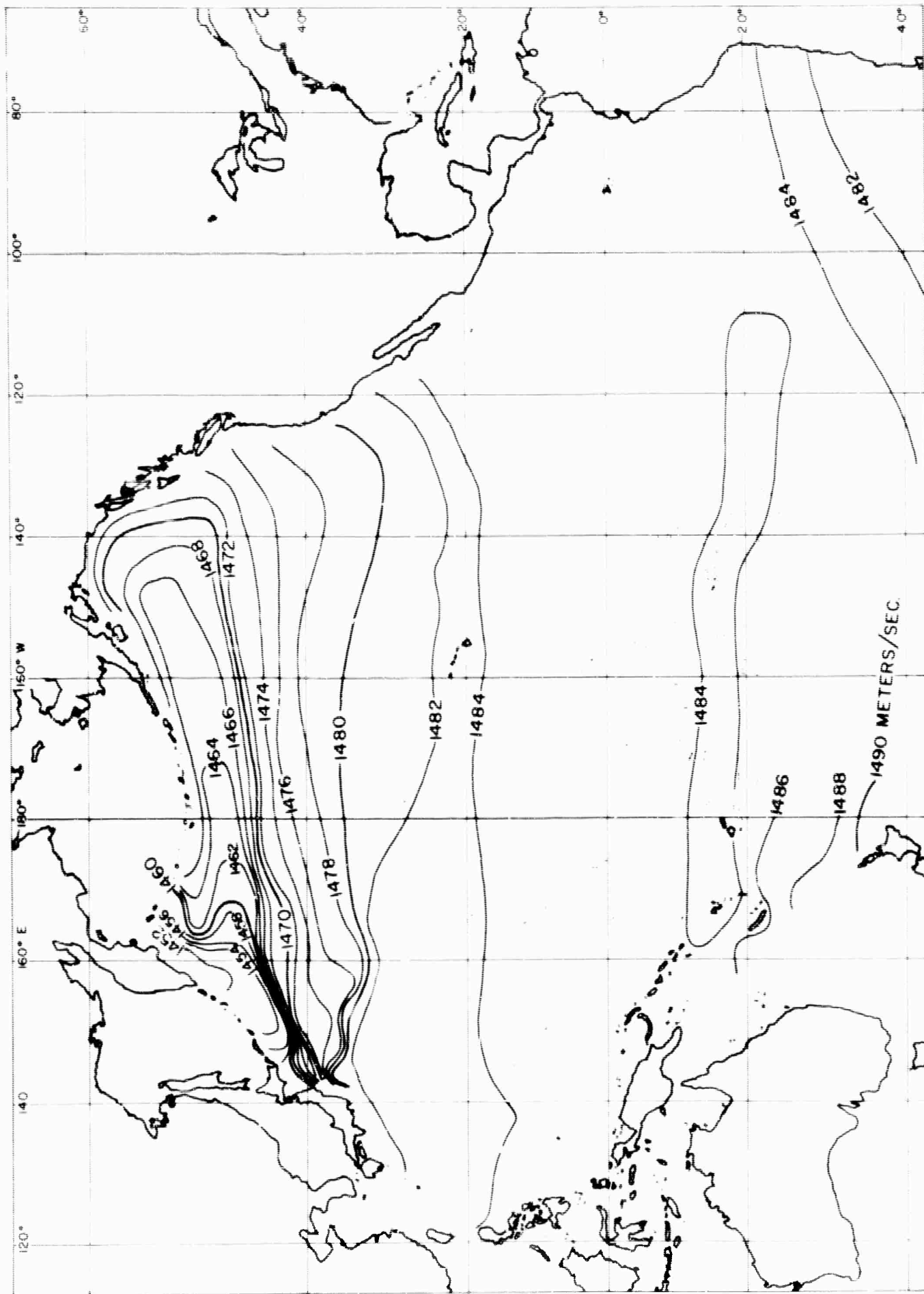
Fig. 4. SOFAR velocity chart of the Pacific Ocean.

$$H_i = T_i - \frac{\Delta_i}{c_{ki}} \qquad\qquad (2)$$

This definition is completely equivalent to that customarily used in determining earthquake epicenters--that the epicenter is given by that origin time, latitude, and longitude for which the sum of the squares of the station residuals (observed minus computed arrival time) is minimum. The present definition has the advantage, however, that it is not necessary to initially assume a trial origin time as this quantity is supplied by the weighted mean of the computed origin times.

Weighting would be best achieved from an analysis of the computed deviations in origin time were the number of recording hydrophones statistically significant and uniformly spread in azimuth. However, in the present hydrophone network, a $\underline{T}$ phase for which a source is computed is well recorded at an average of six hydrophones. The number of independent recording stations is even less. Also, it is the nature of T-phase observation that hydrophones are confined to a small sector of azimuth with respect to the T-phase source. Therefore, it seems appropriate for the present problem to weight according to considerations of geometry.

The distance, Δ, is subject to uncertainties $c\,\delta T$ and $\Delta\,\delta c/c$ where δT and δc are uncertainties in arrival time and velocity, respectively. Combining these according to the rule for addition of errors, the uncertainty in Δ is

$$\delta\Delta = \sqrt{(c\,\delta T)^2 + (\Delta\,\frac{\delta c}{c})^2}$$

The uncertainty of arrival time varies considerably from event to event according to the sharpness of the peak of power level. To assess this quantity objectively for each arrival does not appear practical considering the high incidence of events and the available labor force. A value of three seconds is considered representative and is applied to all arrivals.

Similarly, the uncertainty in velocity varies with the path as certain areas are better calibrated than others and the functions from which velocities are computed give varying fits to the calibrations. Here, a value of 0.0005 is considered representative of $\delta c/c$ and is applied to all paths.

If a pair of hydrophones is considered, the uncertainty in the hyperbola of position of the source depends both on the uncertainty of distances to the two hydrophones and on their difference in azimuth. In Figure 5, with hydrophones i and m, the hyperbola of position is shown passing through the trial source location k. Y_{mi} is the

difference in azimuth from k of the hydrophone pair. The uncertainties in distance form a parallelogram with side $\delta\Delta_{ki}/\sin \gamma_{mi}$ and $\delta\Delta_{km}/\sin \delta_{mi}$. The projection of this parallelogram upon the normal to the hyperbola is a measure of the uncertainty U_{mi} in the position of the hyperbola.
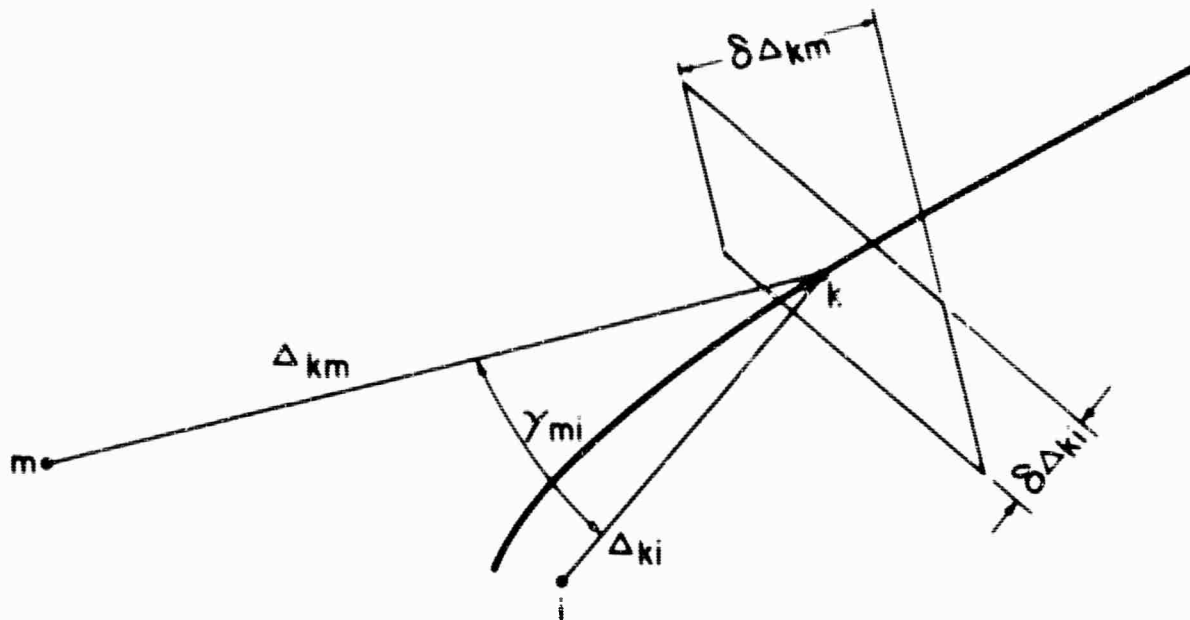
Fig. 5

If the hyperbola is approximated by the bisector of γ_{mi}

$$U_{mi} = \frac{\delta\Delta_{ki}}{\sin \gamma_{mi}} \cos \frac{\gamma_{mi}}{2} + \frac{\delta\Delta_{km}}{\sin \gamma_{mi}} \cos \frac{\gamma_{mi}}{2}$$

$$2U_{mi} = \frac{\delta\Delta_{ki} + \delta\Delta_{km}}{\sin \dfrac{\gamma_{mi}}{2}}$$

The weighting function is taken as

$$w_i = \sum_{m=1}^{n} 2U_{mi}^{-2} = \sum_{m=1}^{n} \frac{\sin^2 \dfrac{\gamma_{mi}}{2}}{(\delta\Delta_{ki} + \delta\Delta_{km})^2}$$

for arrival times read at n hydrophones.

Least-Squares Estimate

In obtaining the least-squares estimate of source location, the formula for distance is linearized by assuming zero parallax and flat earth in the vicinity of trial source point k. As shown in Figure 6,
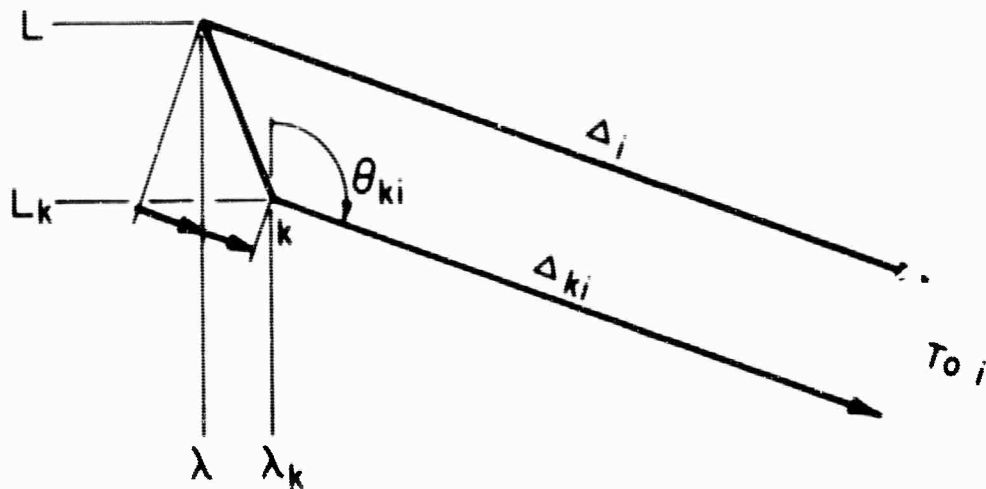
Fig. 6

$$\Delta_i = \Delta_{ki} + (\lambda - \lambda_k) \cos L_k \sin \theta_{ki} - (L - L_k) \cos \theta_{ki} \quad (3)$$

for azimuth θ_{ki}. Steinhart (1964), in solving a related problem, arrived at an equivalent linearization through a Taylor expansion of the exact formula. The coefficients of the latitude and longitude differences can also be obtained by differentiating the exact formula (Hodgson, 1937).

Substitution of (3) into (2) leads to the least-squares estimates of λ_0 and L_0

$$\lambda_0 = \frac{\sum w_i \sigma^2 \sum w_i FI - \sum w_i FG \sum w_i GI}{\cos L_k \left[(\sum w_i FG)^2 - \sum w_i \sigma^2 \sum w_i F^2 \right]}$$

$$L_o = \frac{\sum w_i \, FG \sum w_i \, FI - \sum w_i \, F^2 \sum w_i \, GI}{\left(\sum w_i \, FG \right)^2 - \sum w_i \, G^2 \sum w_i \, F^2}$$

where

$$G = \frac{\cos \theta_{ki}}{c_{ki}} - \frac{\sum w_i \, \dfrac{\cos \theta_{ki}}{c_{ki}}}{\sum w_i} \tag{4}$$

$$F = \frac{\sin \theta_{ki}}{c_{ki}} - \frac{\sum w_i \, \dfrac{\sin \theta_{ki}}{c_{ki}}}{\sum w_i} \tag{5}$$

$$I = (T_i - J) - \frac{\sum w_i (T_i - J)}{\sum w_i}$$

and

$$J = \frac{1}{c_{ki}} \left(\Delta_{ki} - \lambda_k \cos L_k \sin \theta_{ki} + L_k \cos \theta_{ki} \right) .$$

The new coordinates of the source, L_o and λ_o, are compared with the previous estimate, L_k and λ_k. If either differs by 0.1 degrees or more, then L_k and λ_k are replaced by L_o and λ_o and the iteration continues. If both differ by less than 0.1 degrees, the position is accepted, distances Δ_i are computed and an estimate of origin time is obtained as

$$\overline{H} = \frac{\sum w_i \left(T_i - \dfrac{\Delta_i}{c_{ki}} \right)}{\sum w_i}$$

L_o is converted to geodetic latitude before print-out.

Satisfactory estimates are usually obtained in three iterations and the machine time per event is about five seconds. However in cases where the recording stations are confined to a small sector of azimuth, the convergence is not adequate for the flat-earth approximation and the iterative estimates may oscillate. If the oscillations are of decreasing amplitude the program is allowed to continue. If the machine program detects increasing amplitudes, then the last two estimates are averaged and iteration proceeds from the midpoint. If oscillation of increasing amplitude again takes place, then the average of the last two estimates is printed with lower precision indicated by one less significant figure in latitude and longitude. The averaging process is also used to accellerate convergence if oscillations with decreasing amplitude require more than six iterations.

Measurement of Precision

If we consider the variance of origin times, V, as a quantity which varies continuously with L and λ, then L_0, λ_0 is that point at which V is a minimum ($\nabla V = 0$). It can be shown that any vertical section through the variance surface is parabolic in the vicinity of L_0, λ_0. The shape of such a section, then is defined in the vicinity of L_0, λ_0, by two quantities, V, and its second derivative. The variance surface at L_0, λ_0, is characterized by V and the Laplacian of V

$$\nabla^2 V = \frac{d^2 V}{dL^2} + \sec^2 L \frac{d^2 V}{d\lambda^2}$$

$$= \frac{2n}{(n-1) \sum w_i} \left(\sum w_i G^2 + \sum w_i F^2 \right)$$

where G and F are as defined in (4) and (5).

It will be noticed that $\nabla^2 V$ is independent of arrival times. It serves as a measure of the accuracy of the geometry of the fix, the position being more sharply determined for larger values of $\nabla^2 V$. Bolt (1960) recognized the usefulness of such a measure. Examples of calculations giving high and low values of $\nabla^2 V$ are: (a) An earthquake T-phase source in the Marcus-Necker Seamount Chain at 18.7 N, 176.8 E, 01h 44m 36s GMT on 27 January 1965 was recorded on four hydrophones at Eniwetok, three at Wake, and three at Midway. $\nabla^2 V$ was calculated as 34.3 seconds^2/milliradian^2. Independent calculations using P waves gave an epicenter with the same coordinates and one second earlier in origin time. (b) A T-phase source was computed for a Solomon Island earthquake at 11.2 S, 159.1 E, 20h 04m 41s GMT on 22 August 1964. It was recorded on one hydrophone at Eniwetok, two at Wake, and one at Midway. $\nabla^2 V$ was 1.0. The C & GS epicenter was at 10.1 S, 161.7 E, 0h 7m 51.7s. Figure 7 shows the geometry of both fixes.

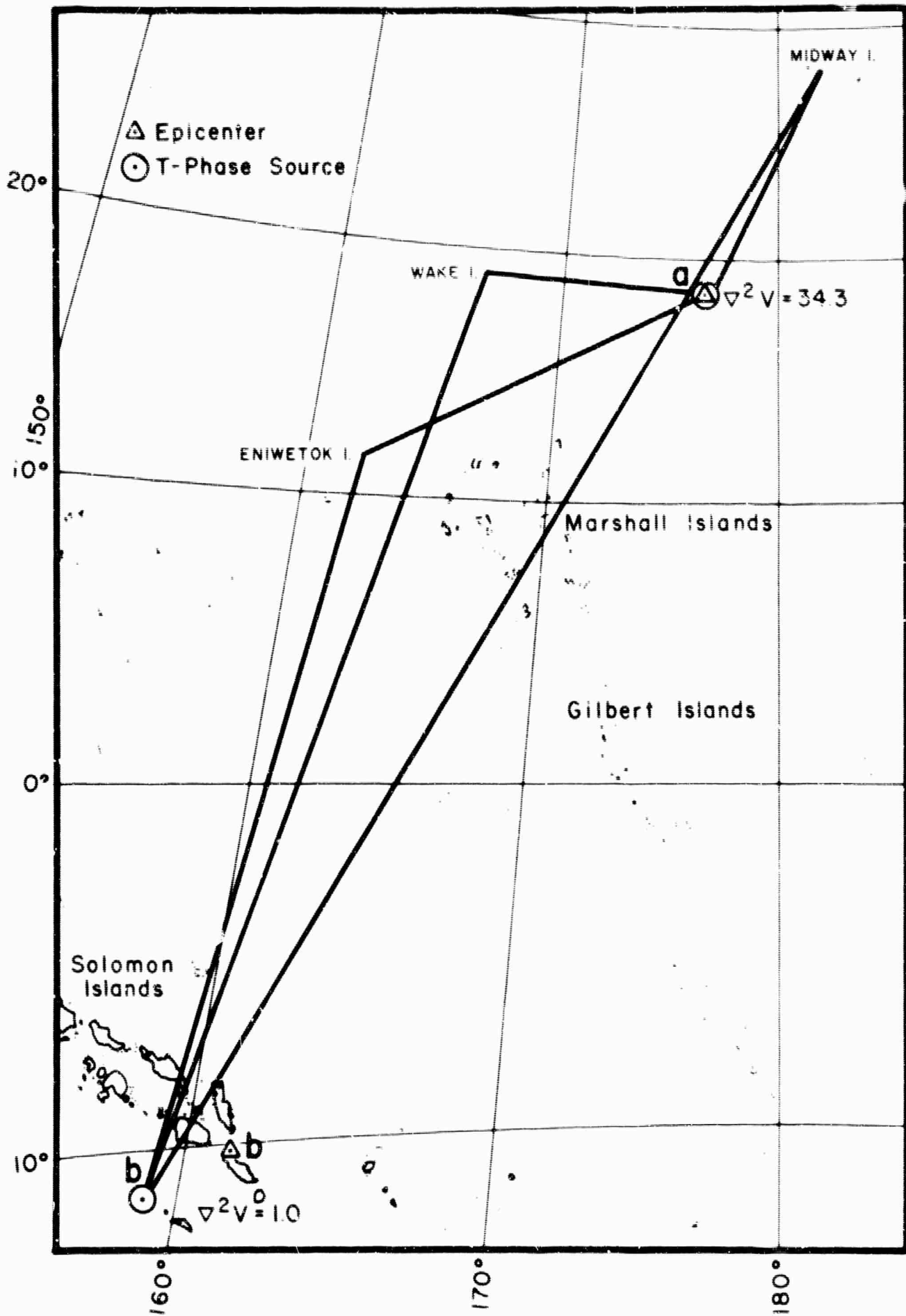Oscillation is . e to occur when $\nabla^2 V$ is less than 2.

Fig. 7. Chart of fixes illustrating $\nabla^2 V$.

T-Phase Strength

Measurements of power level of the T-phase peak at the various hydrophones are used to compute a T-phase strength--a concept similar to earthquake magnitude. The T-phase strength is intended to represent the peak power level, in decibels relative to 0.1 microbar, of the T phase at a distance of 30° from the source on an unobstructed path, and as seen through a system with a frequency response equivalent to that of the Pacific Missile Range stations. The effect of the PMR system response is to shift the peak of the T-phase power spectrum to about 10 cps. The 0.1 microbar reference was chosen so that all power level measurements would be positive. The 30° distance was chosen as the length of a typical T-phase path from source to hydrophone. Such adjustments, then, as are necessary to compute the power level at the standard 30° distance are minimized.

Reduction of each reading to the standard distance is accomplished by the formula

$$S_i = P_i + 10 \log 2 \sin \Delta_i + 11.1 \left(\Delta_i - \frac{\pi}{6} \right)$$

for standard power level S, and measured power level P. The second term on the right hand side of the equation accounts for spatial spreading over the earth's surface while the third term accounts for losses at a rate of 1.6 db per megayard as reported by Urick (1964) for a frequency of 10 cps. For the computer solution, Δ_i is in radians and the loss coefficient is shown in appropriate units (db/radian). A point source, such as an underwater explosion, would require an additional term to account for spreading of the signal in time (Urick, ibid). The earthquake T-phase source, however, is spread in both time and space, and the T-phase peak is typically broader than the rise time of the explosion SOFAR signal. Time spreading, then, does not affect the measurement of peak power of the T phase.

Depending on the location of a particular source, arrivals at certain hydrophones, although readable, are along paths partially obstructed by topographical features. The power levels at these hydrophones are consequently low. Also, the incidence of mistakes leading to inordinately high readings of power level is not negligible. As the volume of data makes the subjective investigation of each case prohibitive, and as the minimum number of hydrophones used in determining a T-phase source is four, it seems appropriate, in the case of the four-station fix, to arbitrarily eliminate the lowest two and the highest standard power levels and to accept the next highest value as the T-phase strength.

To extend this evaluation to fixes from n hydrophones the following formula has been devised

$$\bar{S} = \frac{4}{n} \sum_{i = \frac{n}{2} + 1}^{3n/4} S_i$$

where

$$S_{\frac{n}{2} + 1} = \frac{e}{2} S_{\frac{n + e}{2}}$$

and

$$S_{\frac{3n}{4}} = \frac{f}{4} S_{\frac{3n + 4 - f}{4}}$$

where

$$\frac{e}{2} = \left[\frac{n}{2} \right] + 1 - \frac{n}{2}$$

and

$$\frac{f}{4} = \left[\frac{3n}{4} \right] + 1 - \frac{3n}{4}$$

where brackets signify that the next smaller integer value is to be used if the value within the brackets is not an integer. S_i is ordered in ascending values. $\bar{S}$ is the T-phase strength.

It is noted that the evaluation of T-phase strength does not consider the degree of coupling of body waves to T waves at the source, azimuthal radiation patterns at the source, nor the relative efficiencies of the wave guides to the various hydrophones.

Simplified Flow Diagram

Read constants

Read arrival times

Select four arrival times for geometric fix

Calculate four-station fix

Calculate velocities from velocity function

Calculate weights

differences
>0.1°

Estimate least-squares latitude and longitude

Compute $L_k - L_o$ and $\lambda_k - \lambda_o$

differences <0.1°

print out L_o, λ_o

Calculate origin times, mean origin time,
deviations, standard deviation, and Laplacian
of variance.

print out

Calculate Standard power levels and T-phase
strength

print out

Halt or proceed to next event

Data Dissemination

The computer output is obtained on punched cards, printed pages and on a plotted map. The printer output contains details of the solution process as aids in reviewing and screening the results. The cards for events whose solutions appear inadequate are pulled from the deck. If it appears that the results can be improved sufficiently by deleting inconsistent input data, the solution is recomputed.

The data from remaining output cards is then listed on multilith masters. A sample listing is shown in Figure 8. The explanation of the columns is:

Columns 1-5	M D H M S	Greenwich Mean Time of T-phase source
Columns 6-7	LAT LONG	Geodetic coordinates of T-phase source
Column 8	AREA	Name descriptive of 10° square containing T-phase source
Column 9	SD	Standard deviation of origin times
Column 10	CONV	Convergence of the gradient (Laplacian) of variance of origin times in seconds squared per milliradian squared
Column 11	NO	Number of hydrophones read
Column 12	DB	T-phase strength in decibels relative to 0.1 microbar

Lists will be mailed at regular intervals to interested addressees.

PACIFIC T-PHASE SOURCES FOR SEPTEMBER 1964

HAWAII INSTITUTE OF GEOPHYSICS   MARCH 16, 1965
HONOLULU, HAWAII 96822

M	D	H	M	S	LAT	LONG	AREA	SD	CONV	NO	DY
SEP	21	19	45	14	47.6 N	153.5 E	KURILS	0.3	5.6	4	24
SEP	21	19	52	48	47.6 N	153.6 E	KURILS	1.7	8.0	9	42
SEP	21	20	10	50	47.5 N	153.7 E	KURILS	0.7	4.0	4	24
SEP	21	20	47	53	48.2 N	152.9 E	KURILS	1.0	6.9	9	45
SEP	21	22	2	19	48.0 N	153.1 E	KURILS	1.4	6.6	10	56
SEP	21	22	4	11	47.9 N	153.2 E	KURILS	0.9	6.6	10	42
SEP	21	22	9	33	48.1 N	152.9 E	KURILS	2.1	6.6	10	47
SEP	21	22	39	50	47.7 N	153.4 E	KURILS	1.0	6.7	10	23
SEP	21	22	41	28	56.4 N	163.9 E	KAMCHATKA	1.3	3.4	9	10
SEP	21	23	19	11	17.7 S	128.9 W	CORDILLERA	2.3	1.0	5	26
SEP	21	23	47	51	51.9 N	123.7 W	CANADA	0.8	2.7	4	20
SEP	22	0	30	28	48.2 N	152.7 E	KURILS	0.5	6.8	8	25
SEP	22	0	41	18	47.9 N	153.2 E	KURILS	1.4	6.5	9	20
SEP	22	0	47	18	48.0 N	153.0 E	KURILS	1.1	5.3	7	18
SEP	22	0	47	41	48.1 N	152.9 E	KURILS	1.2	6.5	9	21
SEP	22	0	51	24	13.9 S	176.1 W	SAMOA	0.8	2.6	4	23
SEP	22	1	1	57	53.0 N	167.6 W	FOX IS	1.0	7.9	6	19
SEP	22	1	5	55	58.0 N	148.0 W	ALASKA	0.8	24.2	5	43
SEP	22	1	6	31	57.6 N	148.5 W	ALASKA	0.6	25.3	5	43
SEP	22	1	51	6	54.9 N	160.6 E	KAMCHATKA	2.4	5.9	6	20
SEP	22	2	24	28	47.8 N	153.3 E	KURILS	1.2	5.6	8	26
SEP	22	2	26	21	54.4 N	161.0 E	KAMCHATKA	5.9	6.3	7	23
SEP	22	2	47	11	51.6 N	180.0 E	NEAR IS	5.4	8.7	6	22
SEP	22	3	1	33	53.9 N	163.1 W	FOX IS	1.0	27.6	9	31
SEP	22	3	1	49	53.7 N	163.2 W	FOX IS	1.0	28.2	9	31
SEP	22	3	25	44	57.3 N	150.1 W	ALASKA	1.2	4.7	4	24
SEP	22	4	3	55	10.6 S	165.8 E	NEW HEBRIDES	0.7	2.9	5	21
SEP	22	4	49	44	52.2 N	155.6 W	ALASKA	0.5	5.7	4	18
SEP	22	5	12	18	54.0 N	153.1 W	ALASKA	2.3	5.0	4	19
SEP	22	5	49	37	48.0 N	153.1 E	KURILS	1.3	6.4	9	26
SEP	22	6	20	53	53.3 N	167.6 W	FOX IS	0.3	5.3	4	19
SEP	22	6	41	48	51.4 N	179.2 E	NEAR IS	2.2	8.6	9	33
SEP	22	7	32	37	12.4 S	175.6 W	SAMOA	8.5	4.3	6	36
SEP	22	9	6	13	44.3 N	146.9 E	HOKKAIDO	0.6	8.5	5	33
SEP	22	9	6	45	23.1 S	71.9 W	CHILE	2.3	1.6	10	69
SEP	22	9	7	12	44.0 N	147.3 E	HOKKAIDO	0.3	0.6	4	39
SEP	22	9	26	58	50.9 N	154.6 E	KAMCHATKA	4.7	6.8	9	24
SEP	22	10	5	13	15.7 S	176.5 E	FIJI	0.2	4.2	5	26
SEP	22	11	15	6	53.1 N	173.7 W	ANDREANOF IS	0.7	4.7	4	19
SEP	22	11	21	34	41	126 W	OREGON-WASH	1.4	2.1	9	31
SEP	22	12	8	34	40.8 N	127.3 W	OREGON-WASH	6.6	46.3	5	27
SEP	22	12	48	13	56.7 N	163.0 E	KAMCHATKA	1.3	3.4	9	26
SEP	22	12	58	2	52.3 N	167.5 E	KAMCHATKA	3.6	4.1	9	25
SEP	22	14	25	33	51.4 N	158.9 E	KAMCHATKA	3.1	6.6	10	27
SEP	22	15	17	52	51.7 N	152.6 E	KAMCHATKA	4.3	3.4	5	19
SEP	22	15	57	3	53.2 N	167.2 W	FOX IS	0.4	7.8	6	25

Fig. 8. Output list.

Acknowledgments

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13 ABSTRACT

A program for the routine location of T-phase sources in the Pacific has been initiated. Data for this program is supplied principally by the Pacific Missile Range hydrophone network. Hydrophone records are forwarded weekly for reading at Honolulu. In correlating arrivals records from all stations are viewed together. Correlation is established by similarity in shape and level and by locations determined roughly from arrival time differences. Arrival times and power levels are read for processing by an IBM 7040 computer.

The solution for location and origin time is the least-squares fit to all hydrophone arrivals which are weighted according to their distribution in azimuth and their distance from the T-phase source. The iterative solution proceeds on the assumption of zero parallax and flat earth in the vicinity of the source.

Velocity is derived from shot calibrations and from averaging across a contour map of local velocity. For the computer program this is expressed as a power series in latitude and longitude for each station and for each quadrant of the Pacific.

A T-phase strength is computed from readings of peak power level. This strength is computed for a distance of thirty degrees from the source. The lower half and the upper quarter of all hydrophone readings are arbitrarily rejected from computation of strength as being influenced by topographic shadowing or containing mistakes.

Events which can be correlated at four or more hydrophones occur at an average rate of about one per hour. Tabulated solutions will be published at regular intervals.

DD FORM 1473

14	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	T Phase						
	SOFAR						
	Hydrophone						
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