Earthquake Epicenter Determination Using δt Data

by

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and

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e. $\delta t$ chart for Tucson, Arizona - Honolulu, Hawaii

f. " " " Honolulu, Hawaii - Hong Kong

g. " " " College, Alaska - Honolulu, Hawaii

h. " " " Sitka, Alaska - Honolulu, Hawaii

i. " " " Tucson, Arizona - College, Alaska

j. " " " Tucson, Arizona - Sitka, Alaska

k. " " " Sitka, Alaska - College, Alaska
The disadvantage of the (P-O) method lies in the possibility that the circles may not intersect at all or that if they do, they may intersect at more than one point. In either case, the epicenter location will not be a point on the globe but will lie somewhere in a roughly triangular-shaped area, bounded by the non-intersecting circles, or by the points of intersection, in the event the circles do intersect. Adjustments, therefore, have to be made in the origin time in order to obtain intersection at a point.

Another defect of the (P-O) method is that the arrival of the S-wave is often difficult to distinguish in the seismological record because of the residual radiation of P-waves; hence, the actual distance cannot always be calculated with accuracy.

Similarly, seismographs of greater sensitivity, or seismographs located at nearby stations, may record arrival of foreshocks which often precede the main shock and give an underestimate of the epicentral distance. In addition, if an earthquake is deep, other errors may be introduced in the estimation of origin time.

A method that utilizes the difference in the arrival times of P-waves (Δt) observed at any two seismic stations has been proposed for testing against the current (P-O) techniques. This method is not new but has been used extensively by the Japanese in locating the epicenters of earthquakes generating tsunamis locally, by the SOFAR Triangulation Network (Woollard, 1947), and by the LORAN Navigational System.
location. This is explained further in the section on the use of the charts.

The advantage of the 6t chart method lies in the fact that it greatly reduces the possibility of errors by reducing to a minimum the number of computations made at the time the epicenter of an earthquake is determined. There is also no need to assume an origin time.

A set of P-wave travel charts covering the Pacific Ocean area were developed for the Seismic Sea-Wave Warning System. These charts were based on data compiled by hand and by digital computer.

The following stations were used for the development of these charts:

Honolulu, Hawaii
Tucson, Arizona
Hong Kong
College, Alaska
Sitka, Alaska

A flow chart of the seismic spherical hyperbola program used in the compilation appears as Appendix 1. Appendix 2 gives the computer program used. Appendices 3 through 9 give the 6t charts computed and plotted to date.

Use of Charts

As soon as an earthquake is recorded at three different stations and the three different arrival times of P-waves are known, reference is made to the charts which include the three stations. For example,
for the Alaska earthquake of March 28, 1964, if the arrival times of P-waves are known for College, Alaska; Tucson, Arizona; and Honolulu, Hawaii; any two of the three possible sets of charts or all three sets can be used.

For the example cited, reference is made to the $\delta t$ chart for Honolulu-Tucson. Arrival time of P-waves at Honolulu was 03 43 53.8 z, and at Tucson 03 43 26.5 z. The difference in the arrival times is 27.3 seconds. A piece of transparent plastic is then superimposed on the chart for Honolulu-Tucson and the $\delta t$ curve for 27 seconds time difference is traced on the plastic, as well as the geographical coordinates of the area. The arrival time of P-waves at College was 03 37 15.6. The difference in the arrival times at Tucson and College was 370.9 seconds. The same piece of plastic is then superimposed on the chart of Tucson-College and another $\delta t$ curve, corresponding to the difference in the arrival times of these two stations, is traced. The intersection point of the two curves gives the earthquake epicenter (Fig. 1). As an additional check, the $\delta t$ chart of Honolulu-College
could also be used in a similar manner. The determination of the Alaska earthquake epicenter by this method was found to be 61.0N, 147.5W. The epicenter location given in the March 1964 Seismological Bulletin for this particular earthquake is 61.0N, 147.8W. The difference in the two determinations is only .3° of longitude, which proves that the method is quite accurate.

Spherical Hyperbola Program

The original spherical hyperbola program was written by the T-phase division of the Hawaii Institute of Geophysics, to be used in studies of underwater sound generated from earthquakes. This program works quite well under the assumption of nearly constant velocity for underwater sound in the ocean. A number of problems arise however, in modifying the constant velocity program and applying it to seismic wave velocities as obtained from empirically derived travel-time differences, δt, between seismic stations.

Variations in seismic wave velocities are due to density and crustal structure anomalies, and are characteristic of specific regions of the earth. As more data therefore become available, directional velocity anomalies will be determined and corrections will be necessary for the travel-time curves included as appendices of this report.

To date not all of the problems of the spherical hyperbola program have been resolved; however, the program is working effectively in 75% of the particular cases tried.
The travel time difference, $\delta t$, between any two stations from a source $x$ is:

$$\delta t = t_1 - t_2 = \frac{d_1}{c_1} - \frac{d_2}{c_2} \quad (1)$$

where $t_1$, $t_2$, $d_1$, $d_2$, $c_1$, $c_2$ are the seismic wave travel times, the distance from source $x$ to each station and velocities between source and stations, respectively. If we are working with sources on the same travel-time difference curve, $\delta t$ is constant or

$$\delta t = t_1 - t_2 = k \quad (2)$$

Equation (2) is the equation for one of the two branches of a hyperbola. Since in seismic studies we have distances on a spherical earth, the travel times obtained are for spherical distances and equation (2) is thus that for one of the branches of a spherical hyperbola.

If we construct a spherical triangle with the North Pole and two seismic stations as vertices, we have:

![Spherical Triangle Diagram](image)

where $S_1$ and $S_2$ are the seismic stations, $N$ is the North Pole, $P$ is the great circle distance between $S_1$ and $S_2$ on the spherical earth, defined by:
\[ P = \cos^{-1}[\cos(\text{COLAT}(s_2)) \cdot \cos(\text{COLAT}(s_1)) + \sin(\text{COLAT}(s_2)) \cdot \sin(\text{COLAT}(s_1)) \cdot \cos(\Delta \lambda)] \] (3)

Here, \(\text{COLAT}(s_1)\) is the colatitude of \(s_1\), \(\text{COLAT}(s_2)\) is the colatitude of \(s_2\), and \(\Delta \lambda\) is the difference in longitudes between the two stations.

If we add a source \(X\) at angles \(\alpha_1\) with \(P\) at \(s_1\) and \(\alpha_2\) with \(P\) at \(s_2\) and at distances \(D_1\) from \(s_1\) and \(D_2\) from \(s_2\), we have the following:

\[ D_1 = \cos^{-1}[\cos(\text{COLAT}(X)) \cdot \cos(\text{COLAT}(s_1)) + \sin(\text{COLAT}(X)) \cdot \sin(\text{COLAT}(s_1)) \cdot \cos(\lambda_X - \lambda_{s_1})] \] (4)

When \(X\) is considered as a source at each increment along a rectangular geographical boundary, the locus of all positions of \(X\) defines a travel-time curve with constant \(\delta t\). Since such curves are continuous, each contour must cross the limits of the rectangular boundary an even number of times.

Given incremental latitudes and longitudes along the boundary, and the distances and travel-time differences from each source point,
\(X\), to the station, we can interpolate along the boundary to obtain the entrance and exit points from the boundary, for each particular \(\delta t\). Once the latitude and longitude of the entrance point is known, the distance to each station can be obtained by using the travel-time curve and equations (1) through (4).

Using a pre-set distance increment, we can calculate the intermediate distances between the entrance and exit points, assuming \(\delta t\) remains constant. These distances are the same regardless of the orientation of the spherical triangle. In order to determine the latitudes and longitudes of these points, however, the orientation of the spherical triangle with respect to the great circle between the stations must be determined. This determination becomes necessary because both latitude and longitude can be obtained correctly only from a North Pole-oriented triangle. If, for example, \(X\) is south of \(S_2\), the angle \(\alpha_2\) is greater than \(\pi\). The computer, however, is unable to differentiate quadrants in its arcosine routine, being limited to values between 0 and \(\pi\). Orientation, therefore, must be specified by some other means, or the geographical coordinates will be computed to be that for \(X\), north rather than south of \(S_2\).

The solution to this problem comes from a theorem of spherical trigonometry which states that the distance from the pole of any great circle to that great circle is \(\pi/2\). Using the great circle between the two stations, therefore, as an "equator", we calculate the latitude
and longitude of the "pole". Then, given the coordinates of $\chi$, we can solve for the distance from $\chi$ to the "pole". If this distance is less than $\pi/2$, $\alpha_2$ is less than $\pi$, since $\alpha_2$ equals $\pi$ when $\chi$ is on the "equator". If this distance is greater than $\pi/2$, $\alpha_2$ is greater than $\pi$, or, since the arcsine routine is limited, $-\alpha_2$ replaces $\alpha_2$, i.e., since we are interested in the cos of $\alpha$,

\[
\cos(\pi + \theta) = -\cos(-\theta) = -\cos\theta.
\]

The four basic cases which can occur from geometrical considerations are:

1. Two crossings of the boundary, both crossings above the great circle;

2. Two crossings, both crossings below the great circle;

3. Two crossings, one above and one below the great circle;

4. Four crossings, two above and two below the great circle.

The first two cases are easy to handle; the last case can be broken into two parts, and the methods for cases (1) and (2) applied to solve it.

The main problem still existing occurs for case (3). In this case the great circle passes through the boundary, and the boundary is near and may often include one or both stations. The solution to this situation has not been found as yet. Use of the constant velocity program from the T-phase studies, which does work for the T-phase, has failed here. The cause may lie in the gradual change of the hyperbolas to ellipses as the station is neared, the situation being analogous to the equipotential lines lying between two point charges of opposite sign.
apart, at distance, $P$, which are hyperbolas at distances far from the charges, but become ellipses very near the charges. It is more probable, however, that the conversion from constant to variable velocities from travel-time curves has created the problem.

The data points were obtained through use of an IBM 7040 computer. Enough information was obtained by computer to allow many of the incomplete parts to be completed by hand. In these cases the plots were drawn with knowledge from the computer-plotted data that the curves were smooth, continuous, and symmetric.

Conclusions

P-wave travel time curves, as the ones shown in appendices 3 through 9, allow the quick determination of earthquake epicenters and could permit the Seismic Sea-Wave Warning System to issue earlier alerts, more accurate earthquake origin times, and precise tsunami arrival times. This method eliminates the need for repetition of calculations and adjustments in the estimation of origin times. In addition, it gives a precise epicenter location and good estimates of origin times.

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Bibliography


Earthquake Epicenter Determination Using $\delta t$ Data

Theoretical time-differences in the arrival of P-waves at different seismic stations around the Pacific are compiled by digital computer. Time-difference curves ($\delta t$) are plotted for a number of seismic stations on a number of charts. These charts allow the quick determination of earthquake epicenters. A modified version of the spherical hyperbola program that is used in the compilation is included, as well as compiled travel-time difference charts.
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