AD-750 769

APPLICATIONS OF THE JOINT EPICENTER DETERMINATION METHOD

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Teledyne Geotech
Alexandria, Virginia

25 June 1971

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JUNE 25, 1971

Prepared For
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D. C.

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Under
Project VELA UNIFORM

Sponsored By
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Order No. 624

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
TELEDYNE GEOTECH
ALEXANDRIA, VIRGINIA

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
APPLICATIONS OF THE JOINT EPICENTER DETERMINATION METHOD

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Scientific

5. AUTHOR(S) *(Last name, first name, initial)*
Ahner, R.O.; Blandford, R.R.; Shumway, R.H.

6. REPORT DATE
25 June 1971

7a. TOTAL NO. OF PAGES
56

7b. NO. OF REFS
10

8a. CONTRACT OR GRANT NO.
F33657-70-C-0941

b. PROJECT NO.
VELA T/0706

c. ARPA Order No. 624

d. ARPA Program Code No. 9F10

9a. ORIGINATOR'S REPORT NUMBER(S)
275

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES
~~This document~~ ... ~~s and each trans-~~
~~mittal to for~~ ... ~~may be made only~~
~~with prior ap~~

Approved for Public Release
Distribution Unlimited

11. SUPPLEMENTARY NOT

TY
Advanced Research Projects Agency
Nuclear Monitoring Research Office
Washington, D. C.

13. ABSTRACT

Joint Epicenter Determination (JED), a least squares method of estimating earthquake epicenters and station corrections, is shown to be unstable for some teleseismic nets in that estimated locations and station corrections change substantially when a few readings from a large set are omitted. Locations are also shown to change if different travel-time tables are used. The result is established both for a North American and a world-wide net, using an epicentral region ranging 30° along the Aleutian Islands. If the suite of epicenters were to be spread over the earth, a case not discussed in this study, JED may be stable. However, in that case it would appear to be impossible, using JED, to discover the corrections to the average earth travel time tables caused by geology at the source or in the mantle. Thus JED could not be used to determine station corrections which would result in teleseismic locations accurate to 2-4 kilometers.

JED does seem to be a suitable method for simultaneously determining improved locations and an improved travel time table in a region where the travel-time table is poorly known. An example of such an application for a local Alaskan network is given in this study.

14. KEY WORDS

Joint Epicenter Determination (JED)
Seismic Location
Least Squares

Unclassified
Security Classification

APPLICATIONS OF THE JOINT EPICENTER DETERMINATION METHOD

SEISMIC DATA LABORATORY REPORT No. 275

AFTAC Project No.:	VELA T/0706
Project Title:	Seismic Data Laboratory
ARPA Order No.:	624
ARPA Program Code No.:	9F10
Name of Contractor:	TELEDYNE GEOTECH
Contract No.:	F33657-70-C-0941
Date of Contract:	01 April 1970
Amount of Contract:	$ 1,828,736
Contract Expiration Date:	30 June 1971
Project Manager:	Royal A. Hartenberger (703) 836-7647

P. O. Box 334, Alexandria, Virginia

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

This research was supported by the Advanced Research Projects Agency, Nuclear Monitoring Research Office, under Project VELA-UNIFORM and accomplished under technical direction of the Air Force Technical Applications Center under Contract F33657-70-C-0941.

Neither the Advanced Research Projects Agency nor the Air Force Technical Applications Center will be responsible for information contained herein which may have been supplied by other organizations or contractors, and this document is subject to later revision as may be necessary.

ABSTRACT

Joint Epicenter Determination (JED), a least squares method of estimating earthquake epicenters and station corrections, is shown to be unstable for some teleseismic nets in that estimated locations and station corrections change substantially when a few readings from a large set are omitted. Locations are also shown to change if different travel-time tables are used. The result is established both for a North American and a world-wide net, using an epicentral region ranging 30° along the Aleutian Islands. If the suite of epicenters were to be spread over the earth, a case not discussed in this study, JED may be stable. However, in that case it would appear to be impossible, using JED, to discover the corrections to the average earth travel time tables caused by geology at the source or in the mantle. Thus JED could not be used to determine station corrections which would result in teleseismic locations accurate to 2-4 kilometers.

JED does seem to be a suitable method for simultaneously determining improved locations and an improved travel time table in a region where the travel-time table is poorly known. An example of such an application for a local Alaskan network is given in this study.

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INTRODUCTION

Douglas (1967) has presented a method of calculating travel time corrections to be applied to obtain a more accurate location whenever a particular station records an earthquake. We shall call these corrections "station corrections", but it must not be assumed that by this nomenclature we intend to imply that the correction is mostly due to the geology in the "vicinity" of the station. For example, if a high-velocity material lay to the south of an epicenter, then all stations to the south would receive signals early; if only epicenters from this restricted region were considered, then the "station effect" would be due to geology near the epicenter. However, if epicenters were uniformly distributed over the earth, it seems plausible that any "station correction" which on the average improved all locations would be due to the geology in the vicinity of the station.

These are at least two reasons for interest in these corrections: first, one can locate epicenters more precisely with them. This is important for the underground test detection program in order to narrow the area of search in on-site inspection. It is also important to determine if an event is on one side or the other of a political boundary, or within a tectonic region which is a source of earthquakes having known characteristics. For geophysical purposes, more accurate locations serve to define more precisely these tectonic zones. Also, if it can be determined how much of the station correction is due to station geology, the remainder may be traced to geophysical effects of interest at the source and in the mantle.

Douglas has called his method Joint Epicenter Determination (JED). In each equation expressing the difference between the observed and predicted station arrival time he includes an unknown station correction. Equations for several events and stations are written down at once, and, using least-squares, the station corrections are adjusted along with the origin times and epicenter locations to produce a minimum in the sum of the squared travel-time error terms.

In his first paper (1967) Douglas selected seven events distributed along the Aleutian chain from the Komandorskys to south of Alaska. One of these events was the underground test LONG SHOT which has been mislocated 20 km to the north by a 329 station world-wide net with good distribution.

Lambert, Ahner, and von Seggern (1970) have shown that with station corrections derived using the known location of either LONG SHOT or MILROW, one can locate the other event to within 1 km. LONG SHOT and MILROW were only 2.4 km apart, so that one would expect the station corrections determined from one event to be the same as for the other, within reading error. The accurate locations indicate that this is true. One should note that even poorly distributed sub-networks give good locations when these corrections are applied.

On the other hand, Chiburis and Ahner (1970a) have shown that the LONG SHOT corrections, when applied to the FLEXBAG explosion (70 km south of LONG SHOT), give locations with errors between 5 and 10 km for different networks (we might note that the true location of FLEXBAG is uncertain within ± 3.7 km). This is, however, a substantial improvement over the 10-20 km error typical of locations without the corrections. Still, it suggests that station corrections cannot be substantially constant over the entire Aleutian chain.

Douglas (1967) used 30 stations, well distributed in distance and azimuth, to estimate the station corrections for the seven events mentioned above. For this example he determined station corrections, implicitly valid for the entire Aleutian chain, which locate LONG SHOT with only a 1 km error.

Douglas and Lilwall (1968) apparently have averaged station corrections from LONG SHOT, a volcanic earthquake in

Hawaii, and tests at Eniwetok and Bikini. These corrections were deduced by knowing the correct origin time and location; no use was made of JED. When the average corrections were applied to each of the individual events, the average error of location changed from 17 to 6 km. Presumably, using corrections from a shot close to each of the individual events would reduce the error to the 1-2 km achieved by Lambert et al. (1970). The fact that in Douglas and Lilwall's paper all source areas are surrounded by the stations of the net helps all of them to have approximately a common ray-path to each seismometer. If this were not true the averaged corrections might not give such good locations.

Blamey and Gibbs (1968) used JED to perform relative locations in a small area, a procedure which can also be carried out by using one event to calculate travel time corrections for each station.

Lilwall and Douglas (1970) used JED on 81 events, 15 of them shots with known epicenters. The average location error was reduced from 10 km to 7 km. This result, not as good as in their 1968 paper, could be due either to JED or to the fact that the events are intermixed geographically with the 146 recording stations, thus making the corrections determined representative only of the average of the vicinity of each station.

The JED studies discussed above suggest that if an epicentral region is recorded at teleseismic distances which are large compared to its typical dimension, JED can determine corrections which will locate the events in this epicentral region to within 1 or 2 km. It is principally this hypothesis which we investigate in this study.

Douglas and Lilwall (personal communication, 1971) have applied JED to simulated data and have shown that for certain plausible epicenter-station distributions JED will not give an accurate answer. It is our conclusion that this is true also for real data.

J. W. Dewey (personal communication, 1971) has used WWSS data to show that JED gives better relative locations at NTS than does the master event technique.

In the first section following we discuss the JED method in some detail. In the following sections we then make four applications of the technique: (1) A suite of Aleutian events as seen by a North American net. (2) An attempt to reproduce Douglas's 1967 results for a similar suite of Aleutian events as seen by a world-wide network. (3) A world-wide network as applied to NTS and other North American explosions. (4) A local Alaskan network as applied to local Alaskan events. In this case a modification to JED which estimates a new travel-time table is also studied.

METHOD

In the standard method of earthquake location, see e.g. Flinn (196), the travel times for a particular event and a particular station are assumed to be nonlinear functions of the epicenter co-ordinates. For the i'th event and j'th station with longitude and latitude co-ordinates (x_i, y_i) the arrival time at the j'th station is written as A_{ij} (we assume in this study that the events are restrained to a best estimate of the depth. To allow the depth to vary involves only a minor theoretical elaboration, but Douglas (1967) has stated that convergence of JED is unreliable in that case). Then it is conventional to expand the nonlinear function in a first order Taylors series about some fixed initial location, $(x_i^{(0)}, y_i^{(0)})$ so that, for i=1,2,...n and j=1,...k

$$A_{ij} = A_{ij}^{(0)} + \left.\frac{\partial A_{ij}}{\partial x_i}\right]_{x_i^{(0)}} \left(x_i - x_j^{(0)}\right) + \left.\frac{\partial A_{ij}}{\partial y_i}\right]_{y_i^{(0)}} \left(y_i - y_i^{(0)}\right) + \left(t_i - t_i^{(0)}\right) \quad (1)$$

Now $\partial A_{ij}/\partial x_i = \partial T_{ij}/\partial x_i$ where T_{ij} is the travel time from i to j.

Also $T_{ij}^{(0)} = A_{ij}^{(0)} - t_i^{(0)}$, so that the linearized model may be written

$$A_{ij} - t_i^{(0)} - T_{ij}^{(0)} = \frac{\delta T_{ij}}{\partial x_i^{(0)}} \delta x_i + \frac{\partial T_{ij}}{\partial y_i^{(0)}} \delta y_i + \delta t_i + \varepsilon_{ij} \tag{2}$$

where ε_{ij} is a normal error independent of ε_{mn} $m \neq i$, $n \neq j$. In the usual method we determine for a fixed i the solutions which minimize $\Sigma_j \varepsilon_{ij}^2$, say $\hat{\delta}_{xi}, \hat{\delta}_{yi}$ and $\hat{\delta}_{ti}$; then since

$$\begin{aligned} x_i - x_i^{(0)} &= \delta x_i \\ &\vdots \end{aligned} \tag{3}$$

we have

$$\begin{aligned} \hat{x}_i &= x_i^{(0)} + \hat{\delta} x_i \\ &\vdots \end{aligned} \tag{4}$$

In particular it is convenient to define the k x 3 matrix

$$H_i = \begin{bmatrix} \left[\frac{\partial T_{i1}}{\partial x_i}\right]_{x_i^{(0)}} & \left[\frac{\partial T_{i1}}{\partial y_i}\right]_{y_i^{(0)}} & 1 \\ \vdots & \vdots & \vdots \\ \left[\frac{\partial T_{ik}}{\partial x_i}\right]_{x_i^{(0)}} & \left[\frac{\partial T_{ik}}{\partial y_i}\right]_{y_i^{(0)}} & 1 \end{bmatrix} \tag{5}$$

and the 3 x 1 vectors

$$\underline{\delta}_i = \begin{bmatrix} \delta x_i \\ \delta y_i \\ \delta t_i \end{bmatrix} \qquad \underline{Z}_i = \begin{bmatrix} x_i \\ y_i \\ t_i \end{bmatrix} \tag{6}$$

and the k x 1 vectors

$$\underline{R}_i = \begin{bmatrix} R_{i1} \\ \cdot \\ \cdot \\ \cdot \\ R_{ik} \end{bmatrix} , \qquad \underline{\varepsilon}_i = \begin{bmatrix} \varepsilon_{i1} \\ \\ \\ \varepsilon_{ik} \end{bmatrix} \tag{7}$$

where $R_{ij} = A_{ij} - t_i^{(0)} - T_{ij}^{(0)}$

Then the least squares solution for the i'th event would come from the regression model

$$\underline{R}_i = H_i \underline{\delta}_i + \underline{\varepsilon}_i \tag{8}$$

with

$$\underline{Z}_i = \underline{Z}_i^{(0)} + \hat{\underline{\delta}}_i \tag{9}$$

As a practical matter the iteration continues using each time the previous solution as $\underline{Z}_i^{(0)}$.

The solution is seen to be

$$\hat{\underline{\delta}}_i = (H_i' H_i)^{-1} \; H_i' \; \underline{R}_i \tag{10}$$

The error variance of the fitted model is

$$\hat{\sigma}_i^2 = \frac{1}{N-3}(\underline{R}_i - H_i\hat{\underline{\delta}}_i)'(\underline{R}_i - H_i\hat{\underline{\delta}}_i) \qquad (11)$$

at each stage and since $E(\hat{\underline{\delta}}_i) = \underline{\delta}_i$ the variance-covariance matrix of the estimated location is approximated by

$$\begin{aligned} &E(\underline{Z}_i - E\ Z_i)(\underline{Z}_i - E\ Z_i) = \\ &E(\hat{\delta}_i - \delta_i)(\hat{\delta}_i - \delta_i)' = \sigma^2(H_i'H_i)^{-1} \end{aligned} \qquad (12)$$

where we have set $\sigma_i = \sigma$, anticipating the hypothesis of equal expected variance for each event. Now suppose that it is proposed with the classical model that the epicenters be located jointly, say for all events so that the overall model corresponding to (8) gets written as

$$\begin{bmatrix} \underline{R}_1 \\ \underline{R}_2 \\ \vdots \\ \underline{R}_n \end{bmatrix} = \begin{bmatrix} H_1 & 0 \cdots & 0 \cdots & 0 \\ 0 & H_2 \cdots & 0 & \vdots \\ \vdots & \vdots & \vdots & \\ 0 & 0 & & H_n \end{bmatrix} \begin{bmatrix} \underline{\delta}_1 \\ \underline{\delta}_2 \\ \vdots \\ \delta_n \end{bmatrix} + \begin{bmatrix} \underline{\varepsilon}_1 \\ \underline{\varepsilon}_2 \\ \vdots \\ \underline{\varepsilon}_n \end{bmatrix} \qquad (13)$$

or

$$\underline{R} = H\underline{\delta} + \underline{\varepsilon} \qquad (14)$$

where $\underline{R}$ and ε are nk x 1 matrices with H an nk x 3n matrix and

$\underline{\delta}$ is a 3n x 1 vector. The new solution would be

$$\hat{\underline{\delta}} = (H'H)^{-1}H'\underline{R} \tag{15}$$

or

$$\begin{bmatrix} \underline{\delta}_1 \\ \vdots \\ \\ \underline{\delta}_n \end{bmatrix} = \begin{pmatrix} H_1'H_1^{-1} & 0 \cdots & 0 \\ & & \\ 0 & H_2'H_2^{-1} \cdots & 0 \\ \vdots & & \\ 0 & & H_n'H_n^{-1} \end{pmatrix} \begin{pmatrix} H_1'\underline{R}_1 \\ \vdots \\ \\ H_n'\underline{R}_n \end{pmatrix} \tag{16}$$

or

$$\begin{bmatrix} \underline{\delta}_1 \\ \vdots \\ \vdots \\ \underline{\delta}_n \end{bmatrix} = \begin{pmatrix} (H_1'H_1)^{-1} \; H_1'\underline{R}_1 \\ \vdots \\ \vdots \\ (H_n'H_n)^{-1} \; H_n'R_n \end{pmatrix} \tag{17}$$

or exactly the same solution as in the separate case (see equation (10)).

Now suppose we attempt a generalization based on incorporating station corrections into the model. Then we might rewrite the observed arrival time as

$$G_{ij}(\mu,S_j, x_i,y_i) = \mu + S_j + A_{ij}(x_i,y_i) \tag{18}$$

where μ is a constant network correction for the origin times, and S_j a station correction. Since we are estimating the mean of the correction to the origin times we may restrain $\Sigma\delta t_i = o$. The true t_i may be recovered by adding μ to the final estimate for $t_i^{(0)}$. Then the expansion corresponding to (1) yields, replacing the letter G by A,

$$A_{ij} = A_{ij}^{(o)} + \frac{\partial A_{ij}}{\partial x_i}\Big]_{x_i^{(o)}} (x_i - x_i^{(o)}) + \frac{\partial A_{ij}}{\partial y_i}\Big]_{y_i^{(o)}} (y_i - y_i^{(o)}) \tag{19}$$

or

$$A_{ij} - t_i^{(o)} - T_{ij}^{(o)} = \frac{\partial T_{ij}}{\partial x_i^{(o)}} \delta x_i + \frac{\partial T_{ij}}{\partial y_i^{(o)}} \delta y_i + \delta t_i + \varepsilon_{ij} \tag{20}$$

Now in order to reduce the dimensionality to the full-rank situation we restrict the station corrections by requiring that

$$\sum_{j=1} \delta S_j = 0 \tag{21}$$

The condition $\Sigma\delta S_j = 0$ is not physically significant, since if each S_j is increased by some constant amount, the only effect is to change the origin time of all events, which would be absorbed in μ.

Then under the reparameterized model the matrix representation becomes

$$\underline{R} = (\underline{1}\ , x_1, x_2, H) \begin{bmatrix} \delta_\mu \\ \underline{\delta}_t \\ \underline{\delta}_s \\ \underline{\delta} \end{bmatrix} + \underline{\varepsilon} \tag{22}$$

where $\underline{R}$ and $\underline{\delta}$ are as before with

$$\delta_\mu = \delta\mu \quad , \underline{\delta}_t = \begin{bmatrix} \delta t_1 \\ \vdots \\ \delta t_{n-1} \end{bmatrix} \quad , \quad \underline{\delta}_s = \begin{bmatrix} \delta S_1 \\ \vdots \\ \delta S_{k-1} \end{bmatrix} \tag{23}$$

$$\underset{nk\times(n-1)}{x_1} = \underset{t_j}{\overset{\longleftarrow\, n-1\, \longrightarrow}{\begin{array}{c}\uparrow\\ k\\ \downarrow\\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \end{array}\left[\begin{array}{ccccc} 1&0&0&\cdots&0\\ \vdots&&&&\\ 1&0&0&\cdots&0\\ \hline 0&1&0&\cdots&0\\ \vdots&&&&\\ 0&1&0&&0\\ \hline \vdots&&&&\\ \hline 0&0&0&\cdots&1\\ \vdots&&&&\\ 0&0&0&\cdots&1\\ \hline -1&-1&-1&\cdots&-1\\ \vdots&&&&\\ -1&-1&-1&\cdots&-1 \end{array}\right]}} \qquad \underset{nk\times(k-1)}{x_2} = \underset{s_j}{\overset{\longleftarrow\, k-1\, \longrightarrow}{\begin{array}{c}\uparrow\\ \\ k\\ \\ \downarrow\\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \end{array}\left[\begin{array}{cccc} 1&0&\cdots&0\\ 0&1&\cdots&0\\ \vdots&&&\\ 0&0&\cdots&1\\ -1&-1&\cdots&-1\\ \hline 1&0&\cdots&0\\ 0&1&\cdots&0\\ \vdots&&&\\ 0&0&\cdots&1\\ -1&-1&\cdots&-1\\ \hline \vdots&&&\\ \hline 1&0&\cdots&0\\ 0&1&\cdots&0\\ \vdots&&&\\ 0&0&&1\\ -1&-1&\cdots&-1 \end{array}\right]}} \tag{24}$$

Then the overall solution could be written from (22) as

$$\begin{array}{r} 1\text{x}1 \\ (n-1)\text{x}1 \\ (k-1)\text{x}1 \\ 2n\text{x}1 \end{array}\begin{pmatrix}\hat{\delta}_\mu \\ \underline{\hat{\delta}}_t \\ \underline{\hat{\delta}}_s \\ \underline{\hat{\delta}}\end{pmatrix} = \begin{pmatrix} nk & \underline{1}'x_1 & \underline{1}'x_2 & \underline{1}'H \\ x_1'\underline{1} & x_1'x_1 & x_1'x_2 & x_1'H \\ x_2'\underline{1} & x_2'x_1 & x_2'x_2 & x_2'H \\ H'\underline{1} & H'x_1 & H'x_2 & H'H \end{pmatrix}^{-1} \begin{pmatrix} \underline{1}'\underline{R} \\ x_1'\underline{R} \\ x_2'\underline{R} \\ H'\underline{R} \end{pmatrix} \tag{25}$$

Hence under the full model the total number of parameters to be estimated is $1+n-1+k-1+2n=3n+k-1$. The program is set up to handle a different number of stations (say k_i) for each event, but for convenience we have chosen $k_i=k$, $i=1, \ldots, n$ in illustrating the x_1 and x_2 matrices. The program will run with or without station corrections.

Station elevation corrections are used, assuming a velocity of 5.8 km/sec. Ellipticity corrections are calculated using the standard Clarke 1866 ellipsoid.

RESULTS

Aleutian Teleseismic Results

The first test of the method used a set of nine earthquakes plus LONG SHOT strung out along the Aleutian Chain from the Near Islands to the Fox Islands, as shown in Table I together with the north latitude and east longitude determined at SDL using primarily NOS arrival times and observed depth phases. LONG SHOT has its true latitude and longitude.

Table II gives the nine stations used in the test. Arrival times were read for every event at every station, and are given in Table III. The Jeffrey-Bullen travel-time tables were used in the JED calculations.

Figure 1 is a map showing the event locations, and Figure 2 is a map showing the station locations. The azimuth aperture of the array around the relatively small source area is roughly 100 degrees. The variation in distance is between 20 and 70 degrees.

This set of data was chosen for our first test of JED because the times had been read at SDL and we could be confident that they were correct. Furthermore these data had been used extensively in studies of single event location procedures and we had some knowledge of the location errors which should result from their use. For example, the slightly different network used in Case II (mentioned below) is interesting in that it happens to be one which locates LONG SHOT to within 1 km without station corrections.

The networks in Cases I and II have the defect that they are not as well distributed as is required for satisfactory use of JED, (Douglas, personal communication). However, it would seem plausible that if JED worked well with a good distribution, it would work fairly well for a moderately good distribution. In any event these results are the first in the literature, showing that results from JED are indeed very poor with a moderately good network of stations.

After the following discussion of Cases I and II we shall take up the case of a well-distributed network, in particular we shall use the same network and suite of events used by Douglas (1967).

As a check of the method, we applied the JED program without station corrections to the data from Case I and found to the number of decimal places printed out, exactly the same locations and mean square errors for each event as were found by running each event through our standard single-event location program.

When JED is applied using station corrections, all the locations move, more or less in parallel, 200 km to the northwest. (The average single-event location shift was 10 km).

The result was repeated using double-precision arithmetic and resulted in no change in the computed locations.

Exactly the same results were obtained using two different sets of initial conditions. First, we determined locations with zero initial estimates for the station corrections. We did this accepting both the full estimated correction, and accepting 0.1 of the estimated correction on each successive iteration. Secondly, we located the events using as initial guesses for the station corrections the values determined from LONG SHOT.

As another test of JED we took the station corrections as determined by JED and entered them into the standard single-event location program. The event locations moved off to exactly the same locations as were determined in the JED runs, and had, naturally, exactly the same mean-square time errors. Table IV gives the net shifts in degrees of each event from the input locations.

There is no question that JED is achieving its goal of reducing the sum of the squares of the error terms. Without station effects the squared error is 38.70 $\sec^2$ (an average error per equation of 0.65 sec). With station effects this error is reduced to 9.14 $\sec^2$. There are respectively 60 and 52 degrees of freedom for the two cases. This results in an

F statistic at 8 and 52 degrees of freedom of 21.0, which is significant far above the 99.9% confidence interval.

Table V shows the breakdown of the squared time error among events, with and without station corrections. Only event number 9 shows an increase with station corrections.

Table VI shows the station corrections together with their standard errors. The station corrections can be seen to be much larger than are normally seen, reflecting the 200 km error in location.

One clue within the statistics indicating that the new locations are incorrect is given by the estimated average standard deviations of locations. In the runs without station corrections the standard deviations are about 12 km in latitude and longitude, while with station corrections the standard deviations go up to 60 km in longitude and 30 km in latitude. Thus we see that minimizing the residual time terms has not minimized the estimated squared location errors. It is not surprising that this should occur, since the matrix in (25), which also connects the location variances to the squared residual time terms, could well have been substantially changed from the single-event location matrix by the addition of the terms corresponding to station corrections.

Another measure of the unreliability of this solution may be found in the fact that the estimated mean correction to the initial guesses of the origin times is 0.99 sec with a standard deviation of 2.36 seconds.

A second test, Case II, was run in which LAO, WMO, and KN-UT were replaced by PRU, EDM, and SHL, at (49.99N, 14.54E), (53.22N-113.35W), and (25.57N, 91.88E) respectively. The station at SHL is opposite North America from the Aleutians, thus substantially improving the azimuthal coverage of the net. Perhaps as a result, the locations shifted only 50 km to the northwest. However, the statistics are generally similar. The variance of the locations is closely similar, the station corrections are smaller by about a factor of 2.0 but the variances of the station corrections are larger by a factor of about 2.0. The decrease in the squared time residuals is as significant as before. The mean origin time correction and its variance is much the same as before.

As the next step in our study we decided to study the stability of JED, when used with a well-distributed net, to perturbations in the data. We thought to use as our starting point the network and events used by Douglas (1967).

To do this it was necessary to use the Herrin-61 travel-time table, since it was that table and not the Jeffrey-Bullen table that Douglas used, (Douglas, personal communication).

In addition Dr. Douglas kindly made available to us three arrival times for LONG SHOT which were not available from the USC&GS Earthquake Data Reports and which were used in his calculations; they were as follows:

MAT 21:06:32.2
CPO 21:10:45.6
BMO 21:07:48.7.

The remaining data were taken directly from the Earthquake Data Reports.

Following the prescription given in Douglas' paper, we discarded all readings from stations closer than 15° to the epicenter. We also discarded the following readings from the set:

BRS-19 July, Andreanof Islands
BRS-19 July, Komandorsky Islands
UBO-06 February
COL-06 February
BRS-22 January
KOU-22 January
WES-19 July, Komandorsky Islands.

These readings were the ones discarded by Douglas (personal communication) in his 1967 paper because they had residuals greater than 3 sec after convergence of the first run.

The calculation yielded a location for LONG SHOT 14 km to the southwest of the true location. This is not in agreement with Douglas' result, which placed the estimated location 1 km north of the true location. The standard deviation of the LONG SHOT location estimated by our program was 20 km in latitude and 15 km in longitude.

The typical station correction was on the order of 2.0 sec, and the typical standard deviation of the station corrections was about 1.3 sec.

To investigate the stability of the procedure when a different travel-time curve was used, we repeated the above calculation using the J-B tables. In this case the estimated location was 20 km almost due west of the true location. The standard deviations of the estimated location of LONG SHOT were again 20 km in latitude and 15 km in longitude. The station corrections were, naturally, different; the typical correction was still on the order of 2.0 sec and the typical standard deviation on the order of 1.3 sec.

We then decided to investigate other methods of discarding poor readings. Using the NOS locations, we first discarded all readings which resulted in residuals greater than 5.8 sec. Ten readings were discarded by this procedure, and application of JED to the remainder gave a location for LONG SHOT 25 km to the northwest of the true location. The standard deviation of the location was 18 km in latitude and 13 km in longitude.

Four readings gave residuals greater than 2.0 sec on the final iteration of the above calculation, so these were discarded and the run repeated. The result was a location 35 km almost due north of LONG SHOT with a standard deviation of 14 km in latitude and 10 km in longitude. Both the station corrections and their standard deviations were close to 1.0 sec. The largest two residuals were 2.15 and -1.86 sec.

In all of the cases discussed above, the residual time sum of squares using JED was reduced by a highly significant amount.

It seems apparent that on the scale of about 10 km, JED is unstable for a geometry like that used in Douglas' original paper. It seems unstable both to travel-time table changes and to discarding a few out of many readings. This instability probably explains our failure to duplicate Douglas' results. Only a few misreadings from the Earthquake Data Reports by either of us might cause this result.

NTS and other North American Teleseismic Results

We thought then to apply JED to a suite of NTS explosions, using a well-distributed world-wide array. We shall not report this result in detail, because as anticipated the calculations were extremely unstable, the iterations would not converge, and all the events shifted around at distances of several hundred kilometers from NTS. Had one of the event locations been restrained, this would not occur; but simpler relative location techniques which work well are already available (Chiburis, 1968).

Table VII gives a list of North American explosions with their true latitude and longitude, the latitude and longitude determined by the single event location program, and also the latitude and longitude determined by the JED calculation. Table VIII gives the arrival times read for the network of stations used. Every station recorded at least two events and a total of 94 readings were used. All times were read at SDL. FLEXBAG, SALMON, GNOME, and SHOAL were recorded at the least number of stations: 5, 7, 7, 7 respectively. In this calculation the events do not have even approximately a common ray-path to the stations, so we can only expect to estimate a station correction characteristic of the immediate vicinity of the station and constant for all azimuths.

We may note that for only three of the nine explosions does JED locate better than the single-station location program.

A noteworthy feature of this calculation is that the standard deviations of location using JED are only about 10 percent larger than when using the single-event location program. This is presumably due to the wide range in space over which the explosions are spread since this is the principal difference between this calculation and all previous ones where the standard deviations of locations calculated using JED were two or more times larger than from the single-event determination method.

Alaskan Regional Results

The events and stations in Figure 3 were used to study applications of JED in a small seismic region. The event locations shown were those determined by the NOS.

If events can be accurately located with a regional network and also detected teleseismically, then they may be used to determine teleseismic travel-time corrections. We may ask if it is possible to use JED to obtain more accurate locations with a regional net than is possible with a single-event program. Certainly one might imagine that in a small area of the crust there exist station corrections (or possibly corrections for small distances to the world-wide average travel time table) which would improve locations.

As an initial calculation we used the observations available from all the events and stations seen in Figure 3 and listed in Table IX.

We applied the standard single event location program using the Herrin (1968) tables. The resulting locations were 10-20 km from the NOS locations. The locations, both depth-unrestrained and with depth restrained to pP depths, were within 0.4 km of one another. The depths estimated in the depth-free runs were in good agreement with the pP depths except for the 31 March and 28 December events; as can be seen by inspection of Table X. All the solution depths are less than the pP depths.

The same calculations were repeated using the J-B travel time tables with substantially the same results. The depth-free and depth-restrained locations were within 1.0 km of one another. All of the depth estimates were slightly too great.

The depth-restrained locations using the J-B and Herrin tables were such that the Herrin location is typically 2.5 km northwest of the J-B location. For the depth-free locations the difference is only 0.4 km to the northwest. The locations are thus apparently insensitive to the travel-time table used, and the location results are apparently quite good.

We then applied JED, using the Herrin 1968 travel-time table and constraining depth to the pP depths, to all of the events in Table IX except for the 31 March event. This event was omitted because of the poor depth estimate determined by the single event program. We might hope that the station corrections determined by JED would improve the depth estimate.

The results were similar to those found earlier in this paper; the travel-time residuals were significantly reduced, but the location standard deviations estimated by the JED program increased by a factor of 2.0. The average difference between the apparently reliable single station locations and the JED locations was 8.5 km. On the other hand, when the station corrections were inserted in depth-free runs of the single event location program the depth estimates were found to be far more accurate, even for the 31 March event which was not used to determine the corrections.

Similar results were obtained using the J-B tables; the only notable difference being that the average difference between the single event and the JED locations was only 2 km.

The clearest indication that JED is unsatisfactory is that the JED location for the J-B and Herrin travel time curves are on the average 8 km apart.

We turn now to a modification of JED which seems to have merit when applied to a region where the basic travel-time table is not well known. In this modification we discard the notion of station corrections and replace it by a correction to the travel-time table dependent only on the distance between the station and the event. Thus, in equation (20) S_j is replaced by S_K where K is the index for the distance interval which includes the distance between event i and station j. We assume that $\Sigma S_k = 0$. With this constraint, the total change in the travel time is $\mu + S_K$. The upper bounds of the six distance intervals selected were 160, 220, 265, 400, 700, and 1000 km.

With the program modified to operate in this mode, we re-analyzed the events in Table IX, using the Herrin tables and again excepting the 31 March 67 event. Again, the travel time standard deviation is significantly reduced; in this case, however, the location standard deviations are substantially the same as for the single event location program. The average difference between the JED and single event locations is a 3.0 km shift of the JED locations to the West. Also, as can be seen from Table X, when the travel time corrections are entered in the single event location program, the depth estimates improve to within observational error, even for the 31 March event which was not used to determine the travel-time corrections.

An identical calculation was performed using the J-B tables. Again the travel-time standard deviations were reduced significantly. In this case the location standard deviation was reduced by 30% on the average, and the average location determined using travel-time table corrections was 5.5 km west-northwest of the single event locations. Again the depth estimates are improved to within observational error.

The clearest indication that the changed locations are valid is that the locations with travel table corrections using either the J-B or Herrin tables lie on the average within 1.0 km of one another.

Given these results, one would expect that the corrections to the two travel-time tables would lead to a common travel-time curve. In Figure 4 we have plotted the difference between the J-B and the Herrin curves. Also plotted are the new travel-time curves determined when running with the Herrin or the J-B curves. We see that the curves are identical within the error estimates determined by the JED program itself.

To investigate the stability of this solution we first repeated the J-B calculation with the 04 November 67 event excluded. The resulting locations were within 0.1 km of the previous solutions, and the corrections to the travel time table differed from the previous values by an average of 0.04 sec, with a maximum difference of 0.1 sec.

As a second test of stability we inserted a new travel-time-table interval, 265 to 330 km. The average resulting shift in location was 0.4 km with a maximum of 1.0 km. The new travel-time table is plotted in Figure 4, and we see that it also is identical with the previous ones within the estimated error.

Thus on the basis of depth determination and location consistency we may tentatively conclude that the locations determined using the modified JED are superior to those determined by the conventional JED or by the single event location program.

We may note at this point, that as previously seen in this study, the standard deviation of travel-time residuals seems to be a misleading indicator of location quality. Using the J-B tables, the estimated standard deviation of travel-time residuals for all events except 31 March 67 for the single event location program was 0.66 sec; for the conventional JED, 0.24 sec; and for the modified JED, 0.36 sec. For the Herrin curve the corresponding numbers are 0.47, 0.28, and 0.36 sec.

CONCLUSIONS

All of our trials of JED using teleseismic data have yielded locations less accurate than those determined from the single event location technique. It follows that station corrections derived from these locations would not be correct. It appears that JED can best be used teleseismically to estimate station corrections for a world-wide array of stations looking at a world-wide suite of events, or, to estimate improvements on a spherically symmetric model as done by Lilwall and Douglas (1970). Such corrections could not, of course, be used to locate with an expected error of 2-4 km.

Douglas and Lilwall (personal communication, 1971) have performed simulations of JED which support the results in this paper by illustrating that a large location variance is to be expected from the application of JED to teleseismic data from small source areas such as the Aleutians. They find that when the JED model does not correspond to the simulated data, then JED yields poor results. We have found the same to be true for real data.

We have seen some preliminary indications that JED can be used with a regional net to yield improved depth and location estimates, while simultaneously estimating an improved travel time table. Whether JED gives better results in these applications than the classical method of successive approximations is, however, not shown.

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TABLE I

Events Used in Test I,
North and East are positive.

Event Number	Event	Latitude	Longitude
1	19 June 1967	52.712	-166.977
2	27 November 1968	52.502	-170.623
3	05 December 1967	51.561	-173.523
4	25 February 1968	51.312	-176.076
5	15 May 1966	51.461	-178.442
6	22 November 1965	51.299	-179.754
7	29 October 1965	51.438	179.183 (LONGSHOT)
8	07 April 1968	51.516	176.537
9	28 May 1967	52.070	175.033
10	26 February 1966	52.455	173.544

TABLE II

Stations Used in Test I, North & East are Positive

Station	Latitude	Longitude
NUR	60.51	24.65
COL	64.90	-147.79
NP-NT	76.25	-119.37
HN-ME	46.16	- 67.99
RKON	50.84	- 93.67
WMO-06	34.72	- 98.59
LAO-10	46.69	-106.22
KNUT	37.02	-112.83
UBO-10	40.32	-109.57

TABLE III

Arrival-Time Data for Case I

Stations	19 Jun 67 Fox Is.	27 Nov 68 Fox Is.	05 Dec 67 Andreanof	25 Feb 68 Andreanof	15 May 66 Andreanof	22 Nov 65 Andreanof	29 Oct 65 LONG SHOT	07 Apr 68 Rat Is.	28 May 67 Rat Is.	26 Feb 66 NEAR Is.
COL	171121.0	122448.0	090929.0	181247.0	145047.0	203015.4	210450.3	044520.0	013657.0	003853.0
HN-ME	171746.6	123106.9	091540.4	181854.6	145649.6	203616.7	211050.6	045115.4	014253.2	004447.8
KN-UT	171522.7	122848.3	091323.0	181641.5	145441.7	203411.0	210848.6	044918.0	014059.3	004258.4
LASA	171508.2	122833.7	091309.8	181628.1	145426.9	203356.2	210831.6	044900.9	014042.1	004239.9
NP-NT	171348.7	122706.7	091139.2	181452.1	145244.9	203212.0	210644.2	044707.1	013841.2	004033.5
NUR	171833.5	123140.5	091604.4	181909.1	145657.3	203619.4	211048.3	045104.0	014235.0	004423.2
RK-ON	171546.6	122910.4	091346.1	181703.0	145459.6	203428.6	210903.7	044931.3	014111.2	004307.1
UBSO	171522.1	122847.6	091322.7	181641.2	145441.2	203410.6	210847.1	044916.8	014057.7	004256.4
WMSO	171641.8	123005.4	091440.0	181757.6	145556.2	203525.0	211001.2	045029.6	014210.1	004407.8

TABLE IV

Change in latitude and longitude from input locations for the earthquakes and from the correct location for LONG SHOT (Event 7), Case I.

Event Number	Delta Latitude	Delta Longitude
1	1.088	-1.675
2	1.066	-1.627
3	1.210	-1.632
4	1.346	-1.685
5	1.268	-1.471
6	1.523	-1.319
7	1.512	-1.648
8	1.553	-1.479
9	1.732	-1.322
10	1.878	-1.382

TABLE V

Squared residual time errors per event with and without station corrections.

	Squared Error	
Event Number	No Station Correction	Station Corrections
1	2.75	0.61
2	5.26	0.55
3	2.33	0.50
4	4.07	0.85
5	5.07	1.75
6	4.51	0.37
7	7.13	1.67
8	4.96	0.83
9	0.99	1.34
10	1.63	0.68
	38.70	9.14

TABLE VI

Station corrections and their standard error.

Units of seconds.

Station	Station Corrections	Standard Error of Station Corrections
NUR	8.82	3.62
COL	3.68	1.05
NPNT	7.81	1.71
HNME	0.13	0.44
RKON	-1.73	0.43
WMO-06	-4.63	1.08
LAO-10	-3.25	1.08
KNUT	-5.99	1.64
UBO-10	-4.84	Not Computed

TABLE VII

Location Results for Nine-Explosion Test

Event	True Location	Distance to JED Location	Distance to Single-Event Location
Flexbag	51.125N, 178.367E	0.351N, 0.678E	0.270S, 0.441E
Milrow	51.418N, 179.187E	0.306N, 0.105E	0.209N, 0.050W
Jorum	37.314N, 116.460W	0.266N, 0.108W	0.168N, 0.014W
Salmon	31.140N, 89.570W	0.159 , 0.047W	0.123N, 0.186E
Faultless	38.634N, 116.215W	0.217N, 0.004E	0.078N, 0.109E
Shoal	39.200N, 118.380W	0.209N, 0.043E	0.103N, 0.310E
Gasbuggy	36.678N, 107.208W	0.165N, 0.121W	0.062N, 0.021W
Gnome	32.260N, 103.870W	0.140S, 0.231W	0.836S, 0.117W
Rulison	39.406N, 107.948W	0.168N, 0.124W	0.059N, 0.018W

TABLE V111

Arrival Time Data for Nine-Explosion Test

	06 Sep 68 Flexbag	02 Oct 69 Milrow	16 Sep 69 Jorum	22 Oct 64 Salmon	19 Jan 68 Faultless	26 Oct 63 Shoal	10 Dec 67 Gasbuggy	10 Dec 61 Gnome	10 Sep 69 Rulison	No. Event/ Station
AAM		221620.9			182024.6		193424.7		210420.5	4
ARE			144104.5		182609.0	171119.2	194028.1		211044.0	5
COL	021208.4	221049.8		160847.4	182130.0	170620.0	193713.1	190755.8	210648.8	8
CPSO	021802.1	221645.7	143524.7							3
DH-NY				160345.3		170635.0		190526.1		3
FLN			144155.8		182649.4		194132.6		211122.1	4
KEV			144111.3	161109.0			194104.8		211049.1	4
KIP		221253.6	143731.0		182236.0					3
KIR		221604.5	144113.6			171106.6		191125.0		4
MAT			144207.0		182703.1		194239.0		211225.5	4
MRG		221646.5	143558.7		182653.2		193453.8			4
NP-NT	021400.8	221244.2	143729.2	160835.0	182218.3	170713.8	193738.1		210713.4	8
NUR		221648.0	144156.3	161137.0			194145.5	191202.8	211131.8	6
RK-ON	021620.5	221503.6	143445.9	160431.5	181934.6	170443.0	193358.6		210332.3	8
SCP			143610.5		182104.8		193509.7	190501.4	210505.0	5
SHK			144231.9		182728.6					2
SJG		221901.0	143840.5		182340.5		193741.1		210751.5	5
SOD		221603.0	144123.8	161117.0				191136.0	211101.5	5
SV3QB	021726.9				182207.7		193636.1			3
UPP		221657.3	144148.1			171141.6	194134.5	191151.0	211123.4	6
#Station/ Event	5	12	16	7	13	7	14	7	13	94

TABLE IX

Arrival times picked at the SDL for the indicated NOS epicenters.

04 Dec 67

Latitude - 62.4N
Longitude - 151.8W
Depth - 108 Km

Station	Distance (Km)	Distance (Deg)	Azimuth (Deg)	Arrival Time (GMT)
SCM	228.6	2.06	102	8 19 43.00
BLR	320.3	2.88	63	8 19 55.00
TNN	329.2	2.96	357	8 19 54.75
COL	344.5	3.10	31	8 19 57.10
PGD	364.5	3.28	32	8 19 59.20
BIG	381.6	3.43	212	8 20 1.65
WH2YK	901.2	8.10	94	8 21 4.10

10 Nov 67

Latitude - 62.3N
Longitude - 151.4W
Depth - 93 Km

Station	Distance (KM)	Distance (Deg)	Azimuth (Deg)	Arrival Time (GMT)
SCM	208.1	1.87	101	18 30 28.50
SVW	264.6	2.38	244	18 30 35.15
BLR	308.6	2.78	60	18 30 41.90
TNN	340.8	3.06	354	18 30 44.30
COL	344.1	3.09	28	18 30 44.90
PJD	363.9	3.27	29	18 30 47.25
BIG	383.9	3.45	216	18 30 50.05
WH2YK	881.6	7.93	94	18 31 50.10

11 Oct 67

Latitude - 63.0N
Longitude - 151.1W
Depth - 113 Km

Station	Distance (Km)	Distance (Deg)	Azimuth (Deg)	Arrival Time (GMT)
SCM	224.5	2.02	121	7 57 10.30
TNN	266.1	2.39	350	7 57 14.80
BLR	267.5	2.41	73	7 57 16.05
COL	272.3	2.45	33	7 57 15.50
PJD	292.4	2.63	34	7 57 18.00
SVW	315.0	2.83	232	7 57 20.90
BIG	453.8	4.08	212	7 57 37.85
WH2YK	879.0	7.90	99	7 58 28.70

TABLE IX (Cont'd.)

28 Dec 68

Latitude - 63.0N
Longitude - 148.2W
Depth - 85 Km

Station	Distance (Km)	Distance (Deg)	Azimuth (Deg)	Arrival Time (GMT)
SCM	125.6	1.13	58	4 16 16.30
BLR	125.7	1.13	165	4 16 16.60
MCBAL	204.7	1.84	10	4 16 25.30
GEOAL	216.9	1.95	2	4 16 26.70
COL	221.6	1.99	2	4 16 27.10
PJD	237.5	2.14	5	4 16 29.20
TNN	324.2	2.92	325	4 16 40.10
SVW	448.4	4.03	246	4 16 55.35
BIG	553.8	4.98	227	4 17 8.95
WH2YK	729.0	6.56	104	4 17 29.80

05 May 67

Latitude - 63.7N
Longitude - 148.5W
Depth - 100 Km

Station	Distance (Km)	Distance (Deg)	Azimuth (Deg)	Arrival Time (GMT)
COL	146.0	1.31	158	17 6 39.30
PJD	163.0	1.47	12	17 6 40.90
SCM	202.1	1.82	166	17 6 46.07
TNN	258.4	2.32	317	17 6 51.75
BIG	601.5	5.41	221	17 7 34.10
WH2YK	759.9	6.83	109	17 7 53.30

31 Mar 67

Latitude - 63.1N
Longitude - -148.5W
Depth - 82 Km

Station	Distance (Km)	Distance (Deg)	Azimuth (Deg)	Arrival Time (GMT)
SCM	145.5	1.31	159	4 18 55.00
PJD	222.8	2.00	10	4 19 4.25
TNN	302.8	2.72	326	4 19 13.65
BIG	555.1	4.99	225	4 19 45.20
WH2YK	746.4	6.71	105	4 20 8.70

TABLE X

Locations and Depths Determined with Single Event Location Program

Event	Depth Restrained J-B Latitude		Depth Restrained Herrin(68) Latitude		Depth Restrained J-B Longitude	
	No Corrections	SΔ Corrections	No Corrections	SΔ Corrections	No Corrections	S(Δ) Corrections
24 Dec 67	62 312	62 342	62 319	62 340	-151 573	-151 679
10 Nov 67	62 220	62 254	62 224	62 252	-151 211	-151 289
1 Oct 67	62 908	62 930	62 930	62 928	-150 989	-151 062
28 Dec 68	62 917	62 936	62 948	62 936	-147 978	-148 081
25 May 68	63 603	63 607	63 638	63 609	-148 164	-148 303
1 Mar 67	63 065	63 074	63 084	63 083	-148 249	-148 397

Event	Depth Restrained Herrin(68) Longitude		pP Depth	Depth Free J-B		Depth Free Herrin	
	No Corrections	S(Δ) Corrections		No Corrections	S(Δ) Corrections	No Corrections	S(Δ) Corrections
24 Dec 67	-151 586	-151 651	108	132	102	102	101
10 Nov 67	-151 240	-151 273	95	123	99	90	96
1 Oct 67	-151 007	-151 044	113	138	110	111	110
28 Dec 68	-147 951	-148 064	85	97	82	64	82
25 May 68	-148 195	-148 274	100	121	106	96	107
1 Mar 67	-148 274	-148 379	82	96	81	51	77

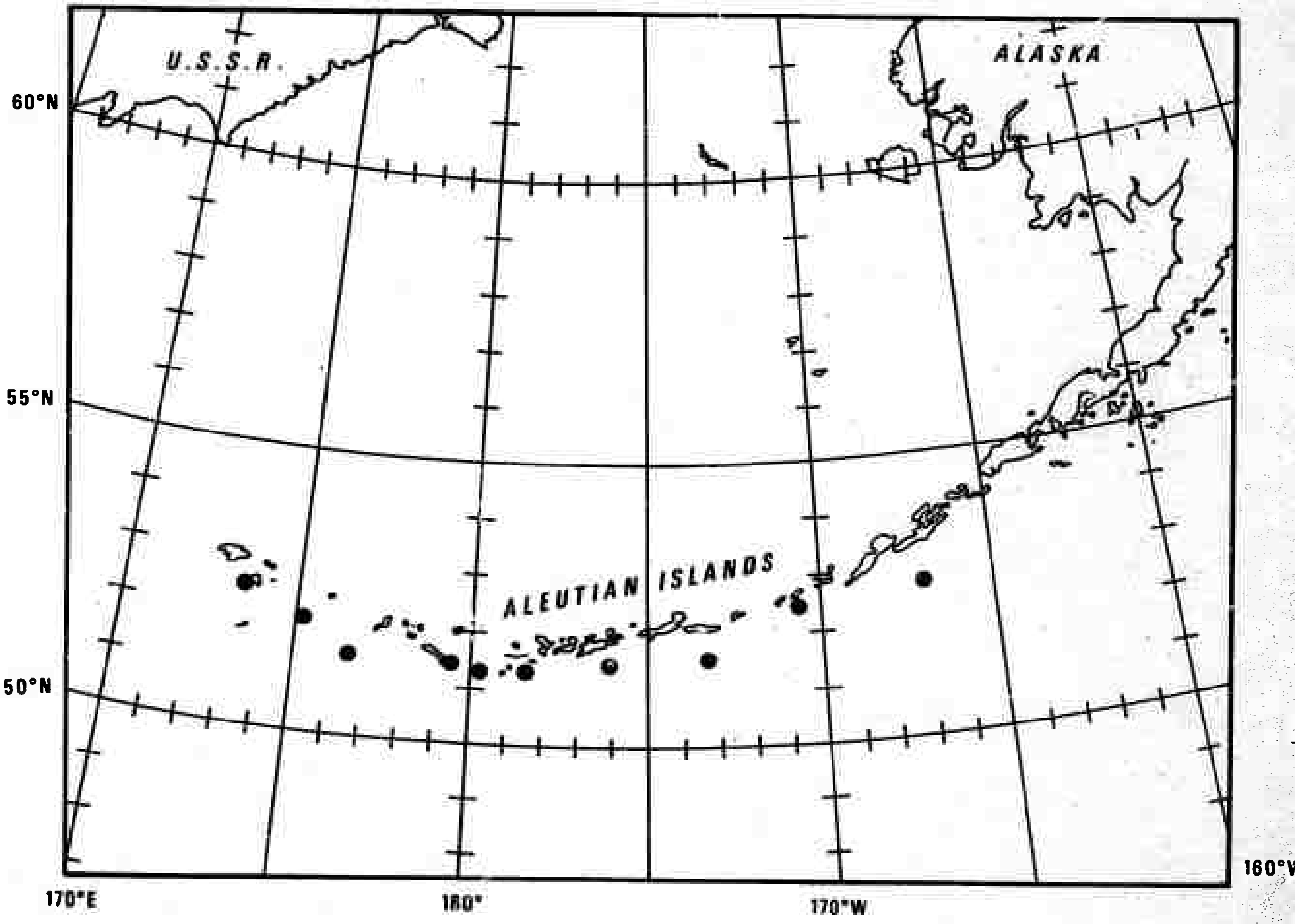

Figure 1. Epicenters for Case I.

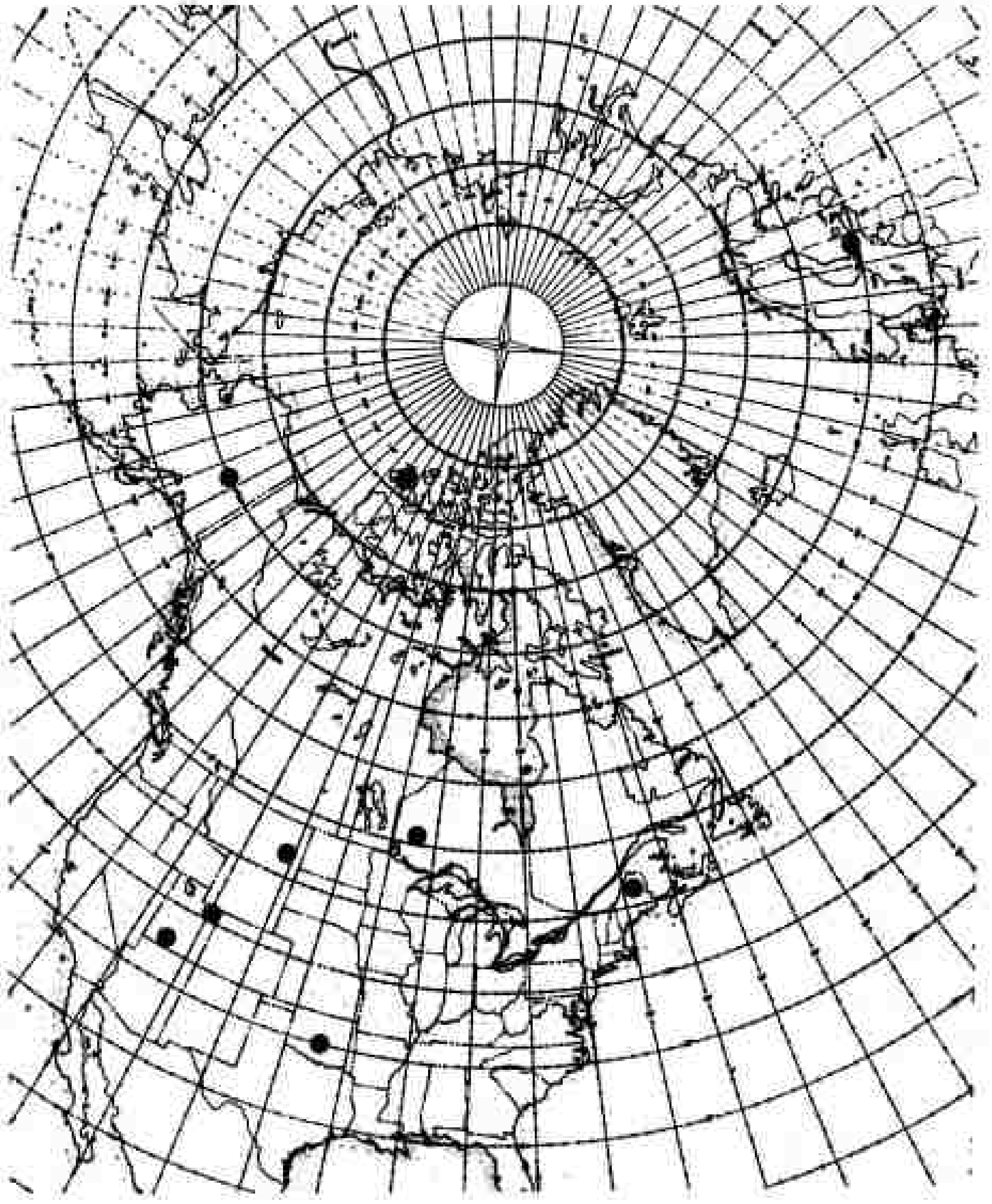

Figure 2. Recording stations for Case I.

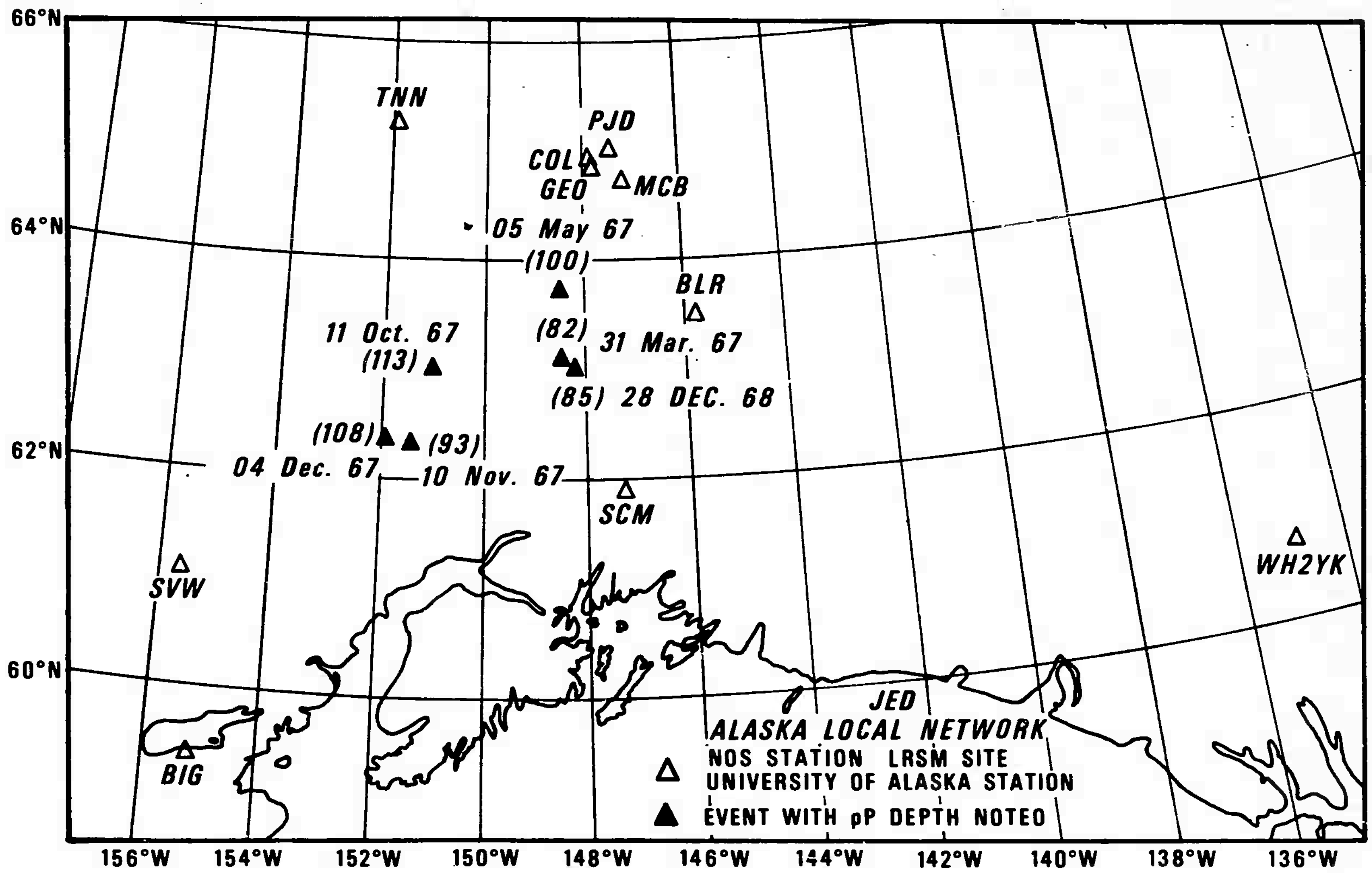

Figure 3. Epicenters and recording stations for Alaskan events. Depths in parentheses are determined by pP.

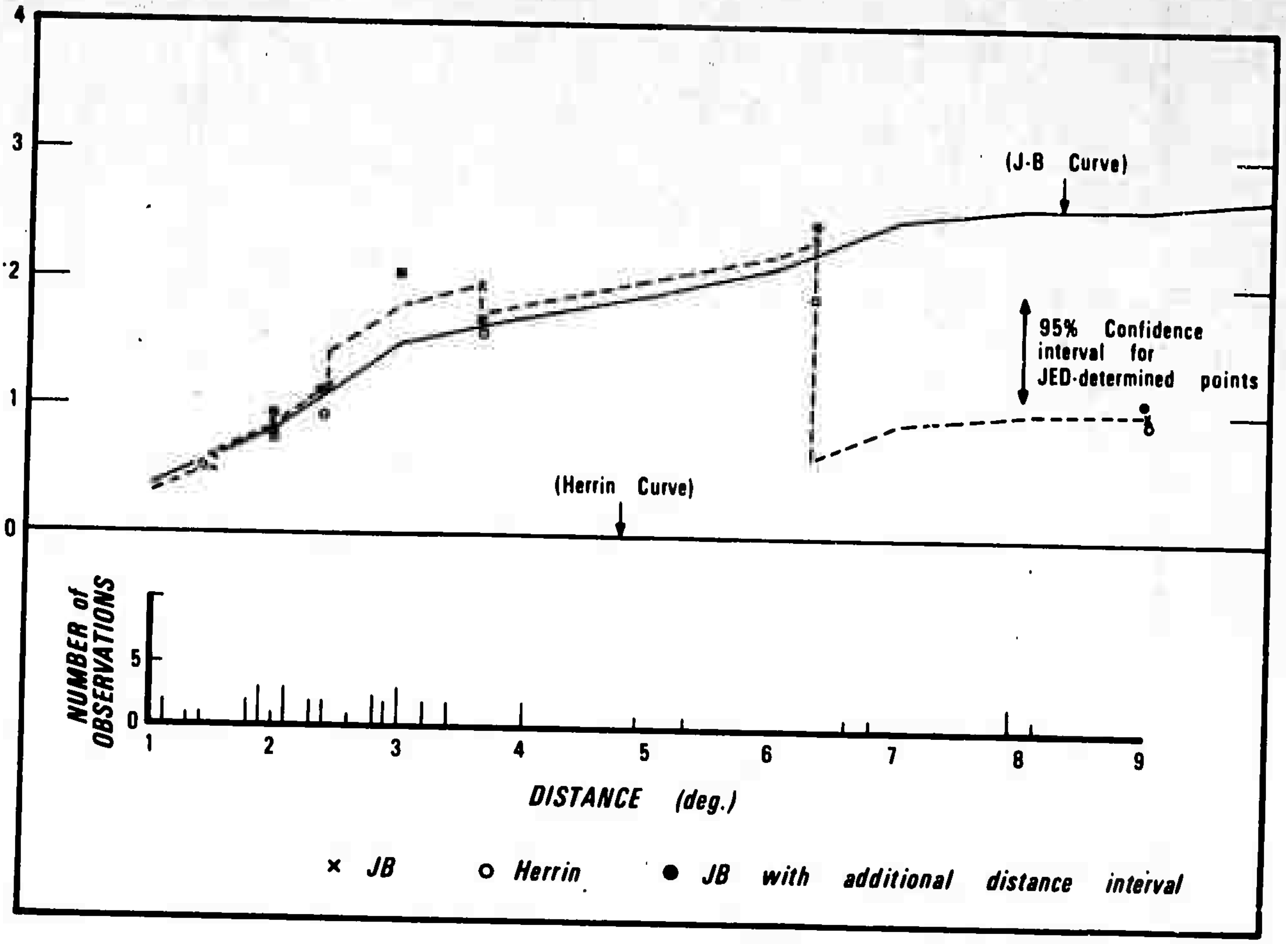

Figure 4. Travel time tables determined by different runs of the modified JED program, plotted as a function of distance. The solid line is the difference between the J-B and Herrin tables. The abscissa is therefore the Herrin curve itself. The dashed line represents the JED estimate for the travel time curve when the initial travel time estimate was the J-B table: The open circles determine the corresponding curve when using the Herrin tables as an initial estimate. The solid circles are derived from the J-B tables using a different division of the station-epicenter distances into clusters, as discussed in the text. Below the travel time curves is a histogram of the number of observations available to determine the travel-time curve as a function of distance.