HYPOLAYR, a Computer Program for Determining Hypocenters of Local Earthquakes in an Earth Consisting of Uniform Flat Layers over a Half Space

by

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69-85

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INTRODUCTION

HYPOLAYR was designed to determine hypocenters of local earthquakes recorded at close range on a dense cluster of seismographs, primarily on the basis of first P-wave arrivals. A first estimate of the hypocenter (from subroutine PREHY) is adjusted by Geiger's method so as to minimize the sum of the squares of the residuals of observed arrival times with respect to those computed from an earth model consisting of flat-lying constant velocity layers (from subroutine TRVDRV). Adjustment (by subroutine HYCOR) is continued until a set of adequacy criteria are met, or until an iteration limit is exceeded. Individual arrivals are weighted in this adjustment according to two factors: quality or clarity of the P-wave arrival, and epicentral distance of the station (for later adjustments). If amplitude, period, and calibration data are available, the program computes two magnitudes for the earthquake, one from the P-phase and the other from the maximum, X, phase (by subroutine MAGNTD).

The program is set up for batch processing of earthquakes. Station parameters (location, elevation, delay, model), model parameters (depths to boundaries and layer velocities), and control parameters are first read in, and some preliminary calculationsaare carried out. Data for the first earthquake (arrival times, amplitudes, periods, calibrations) are then read in, and its hypocenter and magnitude are computed and the results printed out. Additional earthquakes are located one at a time until the batch is completed. A variety (or combination) of solution modes (free solution, depth restricted, origin time restricted) can be called by an instruction card that is required to initiate execution of each hypocenter determination.

An optional statistical summary of arrival time and magnitude residuals at individual stations can be called by a control parameter.

HYPOLAYR contains a number of special features that should be noted:

1. The traveltime and derivatives of the direct refracted wave are computed without recourse to interpolation between tabulated precalculated reference curves; so the earth model can be changed without difficulty. Thus, any earth model consisting of not more than 24 flat-lying constant velocity layers, velocity increasing from layer to layer downward, can be used--it simply is read in along with the station locations, etc., at the time of execution.

2. For the specific circumstance in which a group of earthquakes occurs along a known boundary between differing crustal structure provinces (e.g., aftershocks along the San Andreas fault), two earth models can be read in and individual stations can be assigned to the

model appropriate for the side of the fault on which they lie. Lateral refraction induced by the juxtaposition of the two structures is neglected. This option should be used with caution.

3. The program is designed to permit locations to be calculated for events recorded on any number of stations from 3 to 98. If only three stations record the event, the depth or origin time must be specified (depth assigned or origin time computed from S-P data) so that the number of variables does not exceed the number of equations.

4. Several solution modes (free, depth restricted, origin time fixed by S-P) can be called by the variable INST on the "execution" card at the end of an event "phase" deck.

5. The usual condition under which solutions cannot be obtained (other than due to gross errors) is that in which the epicenter lies far outside of the cluster of seismographs. In this case, the next best estimate of the earthquake's point or origin is calculated: the azimuth to the source and the apparent velocity of the P-wave across the cluster.

HYPOLAYR makes only limited use of S-phase data. Under the "origin-time-restrained" option, the origin time is set equal to that computed from available S-P data. S-wave arrival times are not used along with P-wave data in adjusting the hypocenter.

In this write-up of HYPOLAYR, the mathematical bases of the principal sections of the program will be outlined. Also included are several appendices that will be helpful to anyone wishing to use the program:

1. annotated listing of HYPOLAYR and subroutines.

2. block diagrams (simplified flow charts) of HYPOLAYR and subroutines.

3. list and definition of variables used in HYPOLAYR and subroutines.

4. annotated list and explanation of input parameters and the role they play in the control and use of the program.

5. description of the output options, together with a listing of the output "blocks" and an explanation of the variables printed.

Least-Squares Adjustment of an Initial Approximate Hypocenter by Geiger's Method

Definitions:

x_o, y_o, z_o are the cartesian grid coordinates of the hypocenter,

t_o is the origin time of the event

x_i, y_i, z_i are grid coordinates of station i

τ_i is the observed first P-wave arrival time at station i

T_i is the computed traveltime of the first P-wave arrival to station i

t_i is the computed P-wave arrival time at station i

$$t_i = t_o + T_i \qquad (1)$$

$F_i = \tau_i - t_i$ is the arrival time anomaly at station i. (2)

---

t_i is a function of the hypocentral parameters $x_o, y_o, z_o, + t_o$ and we can express the change in t_i due to small changes in these parameters by a Taylor's expansion

$$dt_i = \frac{\partial t_i}{\partial x_o} dx_o + \frac{\partial t_i}{\partial y_o} dy_o + \frac{\partial t_i}{\partial z_o} dz_o + \frac{\partial t_i}{\partial t_o} dt_o \qquad (3)$$

If we had only four stations, we could set $F_i + dF_i = 0$ (or $F_i - dt_i = 0$) at each station and calculate dx_o, dy_o, dz_o, and dt_o which would result in zero anomalies at all stations. With more than four stations such a solution cannot, in general, be found. Rather any adjustment of x_o, y_o, z_o, and t_o designed to reduce the arrival-time anomalies results in "residuals" at at least some stations.

Thus, we can write for station i, $F_i + dF_i = E_i$, or

$$F_i - dt_i = E_i \qquad (4)$$

where F_i is the arrival time anomaly we wish to eliminate, dt_i is the change in calculated arrival time resulting from adjustment dx_o , dy_o , dz_o , and dt_o , and E_i is the residual arrival-time anomaly after the adjustment. From (3) and (4), we have

$$\frac{\partial t_i}{\partial x_o} dx_o + \frac{\partial t_i}{\partial y_o} dy_o + \frac{\partial t_i}{\partial z_o} dz_o + \frac{\partial t_i}{\partial t_o} dt_o - F_i = -E_i \qquad (5)$$

Since $t_i = T_i(x_o, y_o, z_o) + t_o$,

$$\frac{\partial t_i}{\partial x_o} = \frac{\partial T_i}{\partial x_o}, \quad \frac{\partial t_i}{\partial y_o} = \frac{\partial T_i}{\partial y_o}, \quad \frac{\partial t_i}{\partial z_o} = \frac{\partial T_i}{\partial z_o}, \quad \frac{\partial t_i}{\partial t_o} = 1$$

Thus

$$\frac{\partial T_i}{\partial x_o} dx_o + \frac{\partial T_i}{\partial y_o} dy_o + \frac{\partial T_i}{\partial z_o} dz_o + dt_o - F_i = -E_i \qquad (6)$$

For convenience in writing, let

$$\frac{\partial T_i}{\partial x_o} = \alpha_i, \quad \frac{\partial T_i}{\partial y_o} = \beta_i, \quad \frac{\partial T_i}{\partial z_o} = \gamma_i, \quad \text{and}$$

$$dx_o = Y_1, \quad dy_o = Y_2, \quad dz_o = Y_3, \quad dt_o = Y_4 .$$

Then equation (6) becomes

$$\alpha_i Y_1 + \beta_i Y_2 + \gamma_i Y_3 + Y_4 - F_i = -E_i \qquad (7)$$

Following Geiger, let us calculate the adjustments Y_j in our over-determined system so that $\sum E_i^2$ is a minimum.

To have $\sum E_i^2$ a minimum, we must have

$$\frac{\partial}{\partial Y_j}\left[\sum_{i=1}^{N} E_i^2\right] = 0$$

or

$$\sum_{i=1}^{N} E_i \frac{\partial E_i}{\partial Y_j} = 0 \quad , j = 1, 4 \tag{8}$$

From (7)

$$\frac{\partial E_i}{\partial Y_1} = -\alpha_i \, , \; \frac{\partial E_i}{\partial Y_2} = -\beta_i \, , \; \frac{\partial E_i}{\partial Y_3} = -\gamma_i \, , \; \frac{\partial E_i}{\partial Y_4} = -1 \tag{9}$$

From equations (8) and (9),

$$\alpha_1 E_1 + \alpha_2 E_2 + \alpha_3 E_3 + \cdots + \alpha_n E_n = 0 \quad \text{for } j = 1 \text{, etc.} \tag{10}$$

To assign weights w_i to the individual stations we can modify equation (10) to

$$w_1 \alpha_1 E_1 + w_2 \alpha_2 E_2 + w_3 \alpha_3 E_3 + \cdots + w_n \alpha_n E_n = 0 \tag{11}$$

for $j = 1$, etc.

Expanding equation (11), we have (for j = 1)

$$\begin{aligned}
& w_1 \alpha_1 \alpha_1 Y_1 + w_1 \alpha_1 \beta_1 Y_2 + w_1 \alpha_1 \gamma_1 Y_3 + w_1 \alpha_1 Y_4 - w_1 \alpha_1 F_1 \\
+ \; & w_2 \alpha_2 \alpha_2 Y_1 + w_2 \alpha_2 \beta_2 Y_2 + w_2 \alpha_2 \gamma_2 Y_3 + w_2 \alpha_2 Y_4 - w_2 \alpha_2 F_2 \\
+ \; & \vdots \\
+ \; & w_n \alpha_n \alpha_n Y_1 + w_n \alpha_n \beta_n Y_2 + w_n \alpha_n \gamma_n Y_3 + w_n \alpha_n Y_4 - w_n \alpha_n F_n \\
= \; & 0
\end{aligned}$$

Summing columns and employing the summing convention for repeated indices, we can write the foregoing equation for j = 1 (and analogous equations for j = 2, 3, and 4) as follows:

$$
\begin{aligned}
j=1 \quad & [w_i\alpha_i\alpha_i]\,Y_1 + [w_i\alpha_i\beta_i]\,Y_2 + [w_i\alpha_i\gamma_i]\,Y_3 + [w_i\alpha_i]\,Y_4 - [w_i\alpha_i F_i] = 0 \\
j=2 \quad & [w_i\beta_i\alpha_i]\,Y_1 + [w_i\beta_i\beta_i]\,Y_2 + [w_i\beta_i\gamma_i]\,Y_3 + [w_i\beta_i]\,Y_4 - [w_i\beta_i F_i] = 0 \\
j=3 \quad & [w_i\gamma_i\alpha_i]\,Y_1 + [w_i\gamma_i\beta_i]\,Y_2 + [w_i\gamma_i\gamma_i]\,Y_3 + [w_i\gamma_i]\,Y_4 - [w_i\beta_i F_i] = 0 \\
j=4 \quad & [w_i\alpha_i]\,Y_1 + [w_i\beta_i]\,Y_2 + [w_i\gamma_i]\,Y_3 + [w_i]\,Y_4 - [w_i F_i] = 0
\end{aligned}
\qquad (12)
$$

$i = 1, N$

Further, let us write

$$
\begin{aligned}
& A_{11} = [w_i\alpha_i\alpha_i],\ A_{12} = [w_i\alpha_i\beta_i],\ A_{13} = [w_i\alpha_i\gamma_i],\ A_{14} = [w_i\alpha_i] \\
& A_{21} = [w_i\beta_i\alpha_i],\ A_{22} = [w_i\beta_i\beta_i],\ A_{23} = [w_i\beta_i\gamma_i],\ A_{24} = [w_i\beta_i] \\
& A_{31} = [w_i\gamma_i\alpha_i],\ A_{32} = [w_i\gamma_i\beta_i],\ A_{33} = [w_i\gamma_i\gamma_i],\ A_{34} = [w_i\gamma_i] \\
& A_{41} = [w_i\alpha_i],\ A_{42} = [w_i\beta_i],\ A_{43} = [w_i\gamma_i],\ A_{44} = [w_i]
\end{aligned}
\qquad (12^{+})
$$

and

$$B_1 = [w_i\alpha_i F_i],\ B_2 = [w_i\beta_i F_i],\ B_3 = [w_i\gamma_i F_i],\ B_4 = [w_i F_i]$$

$i = 1, N$

Then equations (12) can be written as:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix}; \text{ or } \bar{A}\,\bar{Y} = \bar{B} \tag{13}$$

Finally

$$\bar{Y} = \overline{A^{-1}}\,\bar{B} \tag{14}$$

yielding the components of the solution vector $\bar{Y}$ $(Y_1, Y_2, Y_3, Y_4$ or $dx_0, dy_0, dz_0, dt_0)$ that should result in $\sum E_i^2$ being minimized.

The procedure outlined above is strictly valid only if the corrections are small and if all of the derivatives $(\alpha_i, \beta_i, + \gamma_i)$ are continuous in the region containing the original and corrected hypocenters. In fact, we shall apply the method to a layered medium (hence, one with discontinuities), and we shall initiate the search for a hypocenter from a very approximate first estimate. We shall assume that a single application of the method will yield an improved (if not accurate) hypocenter, and we shall except repeated adjustments to converge on the actual hypocenter. Readjustment will be continued until the average residual, mean deviation of the residuals, and change (from one adjustment to the next) in mean deviation of the residuals all become smaller than prescribed test values, or until the number of iterations exceeds a prescribed limit.

Under certain conditions, the normal equations (13) from which we seek to determine hypocentral adjustments, Y_i , fail to be linearly independent. One such condition occurs when $\partial T/\partial z_0$ becomes the same (or very nearly the same) at all stations: Y_4 (dt_0) and Y_3 (dz_0) are then linearly dependent. Adjustment can proceed only if t_0 or z_0 is held constant during the adjustment, causing one variable and one equation in (13) to disappear. Another indeterminate case occurs when the focus is outside of the cluster and the ratio of $\partial T/\partial x_0$ to $\partial T/\partial y_0$ approaches the same value at all stations. In this case restriction of z_0 usually has already been required as per the condition described above, and an adjustment can be computed only if t_0 is also specified or its adjustment blocked--leading to further degeneracy of the normal equations.

Normally, z_0 is less strongly determined by the data than the other parameters, and its adjustment requires special consideration and control. Therefore, a strategy restricting adjustment of z_0 until the epicenter has been fairly well established has been included in the program. Furthermore, the range in values of $\partial T/\partial z_0$ calculated prior to each adjustment is tested, and adjustment of z_0 is blocked if this range is smaller than a prescribed value (i.e., if effective depth control has been lost). Finally, negative focal depths are inadmissable physically; so each computed adjustment to z_0 is tested prior to application of the hypocentral adjustments. If the computed adjustment in z_0 would result in the focus emerging above the surface, the z_0 adjustment is scaled down so that the focus moves only a fraction (6/10) of the distance to the surface, and the other adjustments are scaled down somewhat less severely (to not less than 4/10 of the computed values).

If the epicenter recedes from the cluster so that the nearest station is farther than a prescribed distance or if the normal equations (even with the automatic restrictions) become indeterminate, the search for a hypocenter is terminated; and the apparent velocity and azimuth of approach of a plane wave that would explain the observed arrival-time differences across the cluster are calculated as an alternate solution (subroutine VELAZ).

Further restrictions on the adjustment of hypocentral parameters can be called into play by the control variable INST (z_o fixed, t_o fixed); and even if a free solution is specified (by INST = 0), z_o is automatically restricted to reduce the number of normal equations if only three stations are available.

Solution of the Normal Equations for the Hypocentral Corrections

I. Free solution for $Y(1), Y(2), Y(3), Y(4)$: dx_o, dy_o, dz_o, dt_o

1. Calculate the matrix of cofactors, $[C(M,N)]$, of the matrix of the coefficients of the unknowns in the normal equations, $[A(I,J)]$

2. Calculate $DETA$, the determinant of $[A(I,J)]$:

$$DETA = A(1,1)*C(1,1)+A(2,1)*C(2,1)+A(3,1)*C(3,1)+A(4,1)*C(4,1)$$

3. Solve for $Y(1), Y(2), Y(3)$, and $Y(4)$ by Cramer's rule:

$$Y(I) = \left(B(1)*C(1,I)+B(2)*C(2,I)+B(3)*C(3,I)+B(4)*C(4,I)\right)/DETA \qquad I=1,4$$

4. Calculate the elements of the principal diagonal of the inverse matrix of coefficients of the normal equation unknowns, $[A(I,J)]^{-1}$:

$$A(I,I)^{-1} = C(I,I)/DETA \qquad I=1,4$$

These elements are needed in the evaluation of the errors in the computed corrections, $Y(I)$.

II. Restricted solution: $Y(3)=0$ $(dz_o = 0)$. This restriction eliminatesone of the normal equations and amounts to striking out all quantities in equation (13) that have "3" in the subscript.

For convenience, define auxiliary variables to simplify the expressions for the solution of the 3x3 normal equations:

A11 = A(2,2)*A(4,4) − A(4,2)*A(2,4)

A12 = A(4,1)*A(2,4) − A(2,1)*A(4,4)

A14 = A(2,1)*A(4,2) − A(4,1)*A(2,2)

A21 = A(4,2)*A(4,1) − A(1,2)*A(4,4)

A22 = A(1,1)*A(4,4) − A(4,1)*A(1,4)

A24 = A(4,1)*A(1,2) − A(1,1)*A(4,2)

A41 = A(1,2)*A(2,4) − A(2,2)*A(4,1)

A42 = A(2,1)*A(1,4) − A(1,1)*A(2,4)

A44 = A(1,1)*A(2,2) − A(2,1)*A(1,2)

DETA = A(1,1)*A11 + A(2,1)*A21 + A(4,1)*A41

Then, solving the 3x3 normal equations for the corrections Y(I),

Y(1) = (B(1)*A11 + B(2)*A21 + B(4)*A41) / DETA

Y(2) = (B(1)*A12 + B(2)*A22 + B(4)*A42) / DETA

Y(3) = 0

Y(4) = (B(1)*A14 + B(2)*A24 + B(4)*A44) / DETA

The moduli of the elements of the principal diagonal of the inverse matrix of coefficients of normal equation unknowns can be written:

ASDX = |A11 / DETA|

ASDY = |A22 / DETA|

ASDZ = 1 , by arbitrary definition

ASDT = |A44 / DETA|

III. Restricted solution: $Y(4) = 0$ ($dt_0 = 0$). This restriction eliminates one of the normal equations and amounts to striking out all quantities in equation (13) that have "4" in the subscript.

For convenience, define auxiliary variables to simplify the expressions for the solution of the 3x3 normal equations:

```
A11 = A(2,2)*A(3,3) - A(3,2)*A(2,3)
A12 = A(3,1)*A(2,3) - A(2,1)*A(3,3)
A13 = A(2,1)*A(3,2) - A(3,1)*A(2,2)
A21 = A(3,2)*A(1,3) - A(1,2)*A(3,3)
A22 = A(1,1)*A(3,3) - A(3,1)*A(1,3)
A23 = A(3,1)*A(1,2) - A(1,1)*A(3,2)
A31 = A(1,2)*A(2,3) - A(2,2)*A(1,3)
A32 = A(2,1)*A(1,3) - A(1,1)*A(2,3)
A33 = A(1,1)*A(2,2) - A(2,1)*A(1,2)
DETA = A(1,1)*A11 + A(2,1)*A21 + A(3,1)*A31
```

Then, solving the 3x3 normal equations for the corrections $Y(I)$;

$$Y(1) = (B(1)*A11 + B(2)*A21 + B(3)*A31)\ /DETA$$
$$Y(2) = (B(1)*A12 + B(2)*A22 + B(3)*A32)\ /DETA$$
$$Y(3) = (B(1)*A13 + B(2)*A23 + B(3)*A33)\ /DETA$$
$$Y(4) = 0$$

The moduli of the elements of the principal diagonal of the inverse matrix of coefficients of the normal equation unknowns can be written:

$$ASDX = |A11/DETA|$$
$$ASDY = |A22/DETA|$$
$$ASDZ = |A33/DETA|$$
$$ASDT = 1\text{, by arbitrary definition}$$

IV. Restricted solution: $Y(3)=0$, $Y(4)=0$. These restrictions eliminate two of the normal equations and strike out all quantities in equation (13) that have "3" or "4" in the subscript.

Solving the 2x2 normal equations for the corrections $Y(I)$,

$$Y(1) = (B(1)*A(2,2) - B(2)*A(1,2))\ /\ DETA$$
$$Y(2) = (A(1,1)*B(2) - A(2,1)*B(1))\ /\ DETA$$

$Y(3) = 0$ and $Y(4) = 0$ where

$$DETA = A(1,1)*A(2,2) - A(2,1)*A(1,2)$$

The moduli of the principal diagonals of the inverse matrix of the matrix of coefficients of normal equation unknowns can be written:

$$ASDX = |A(2,2)/DETA|$$
$$ASDY = |-A(1,1)/DETA|$$
$$ASDZ = 1.0$$, for convenience.
$$ASDT = 1.0$$, for convenience.

Miscellaneous Computational Routines

Calculation of Epicentral Distances

Richter's method for calculating short distances is used to determine epicentral distances (in km). Let ϕ_o, λ_o and ϕ_i, λ_i be latitude (N) and longitude (W) of the epicenter and station i, respectively. Let QQ be the number of kilometers per minute of latitude and PP be the number of kilometers per minute of longitude at latitude $(\phi_o + \phi_i)/2$. Then the distance of station i from the epicenter is approximately:

$$\Delta_i = \sqrt{\left[60.0 * PP * (\lambda_i - \lambda_o)\right]^2 + \left[60.0 * QQ * (\phi_i - \phi_o)\right]^2}$$

where $\lambda_i, \lambda_o, \phi_i, + \phi_o$ are in degrees and Δ_i is in kilometers. QQ and $PPP \left(= \frac{PP}{\cos \bar{\phi}}, \text{ where } \bar{\phi} = \frac{\phi_i + \phi_o}{2}\right)$ vary only slowly with latitude; so appropriate values of QQ and PPP (obtained from Richter's "Elementary Seismology") for the location of the seismograph network are read in as parameters.

The azimuth of station i from the epicenter can be obtained from the equation:

$$\tan AZ_i = \frac{PP * (\lambda_i - \lambda_o)}{QQ * (\phi_i - \phi_o)}$$

The proper range of the argument AZ_i (between 0 and 360°) can be ascertained by considering the signs of the numerator and denominator in the foregoing equation.

Calculation of Km-Grid Coordinates

In subroutines PREHY and VELAZ it is convenient to express the locations of stations (and preliminary hypocenter in PREHY) in cartesian coordinates. For this purpose portions of the Richter short-distance calculations are used. The km-grid coordinates of station i are:

$$XH_i = 60.0 * PH * (\lambda_i - \lambda_r) \qquad \text{km west of } \varphi_r, \lambda_r$$

$$YH_i = 60.0 * QQ * (\varphi_i - \varphi_0) \qquad \text{km north of } \varphi_r, \lambda_r$$

where φ_r, λ_r are coordinates of an arbitrary point in the region of the network chosen as a "reducing" latitude and longitude and $PH = PPP * \cos\varphi_{near}$

φ_{near} is the latitude of the earliest station.

The azimuth of station i from the earliest station (station "near") can be obtained from

$$\tan \theta_i = \frac{XH_i - XH_{near}}{YH_i - YH_{near}}$$

where the appropriate interval for θ_i (between) and 360°) can be deduced from the signs of the numerator and denominator.

Selection of Special Stations for Initial Estimate of Hypocenter or "Plane-Wave" Solution

Both the main program and the VELAZ subroutine require an initial approximate solution from which to proceed by successive adjustments to a final solution. If the initial estimate is very poor, the adjustment routines are prone to fail; so it is desirable to obtain reliable first estimates. Because the methods used to calculate these estimates involve exact solutions for only three or four stations (with an oversimplified model in PREHY), success depends on a good choice of this limited set of stations.

Some of the elements affecting the selection of stations are:

1. Early stations tend to have clearer, more certain, arrivals than late (more distant) ones.

2. Computations based on stations clustered too closely together or lying along or near a straight line tend to be strongly affected by small errors in arrival time.

The procedure actually employed is as follows:

1. The stations with P-wave arrival weights greater than 0.3 are ordered in terms of increasing arrival time from the first to the KOLT'th. KOLT is a parameter on the input list.

2. The stations lying farthest toward the right and farthest toward the left of the line joining the first and the KOLT'th station are identified.

3a. In PREHY the first, KOLT'th, and the two stations identified under 2 above are the stations selected for the determination of the preliminary hypocenter. If only three stations are available, they are the ones that are used.

3b. In VELAZ the first, KOLT'th, and the station farthest from the line (under 2 above) are selected as the three stations for the calculation of the initial plane-wave solution.

Calculation of the Preliminary Hypocenter

(Subroutine PREHY)

Our earth model will consist of a uniform half space with constant P-wave velocity V. A km-grid-cartesian coordinate system will be used to specify position. Hypocentral parameters are x_o, y_o, z_o, the location, and t_o, the origin time. Station parameters are x_i, y_i, z_i, the location; and P_i, S_i, and $(S-P)_i$, the P- and S-wave arrival times and the S-P interval; $T_i\ (=P_i - t_o)$, the P traveltime; and D_i, the hypocentral distance.

Our fundamental equation (Pythagoras) is $T_i * V = D_i$

We shall consider three cases as follows:

a. Four stations available.

Eliminate z_o by differencing station equations pair by pair and noting that $z_i - z_j \approx 0$. Solve the resulting three equations for x_o, y_o, and t_o. Substitute x_o, y_o, and t_o in the "near" station equation and solve for z_o. If z_o is less than 1/2 the epicentral distance of the near station, set $z_o = ZTR$.

b. Three stations, with at least one measured S-P interval available.

Eliminate z_o by differencing the three equations pair by pair and solve the resulting two equations for x_o and y_o in terms of T_1, the P-wave traveltime to station 1 (the nearest station). Compute the origin time from available S-P data:

$$t_o = \frac{1}{N} \sum_{i=1}^{N} \left[P_i - 1.37\,(S-P)_i \right] \quad , \text{ whence } \quad T_1 = P_1 - t_o \ .$$

Substitute T_1 into the equations for x_o and y_o (in terms of T_1) to evaluate x_o and y_o. Set $z_o = ZTR$.

c. Three stations, without S-P data to establish t_o.

Proceed as under b to evaluate X_o and y_o in terms of T_1. Substitute $X_o(T_1)$ and $y_o(T_1)$ and $Z_o = ZTR$ into the original station I equation and solve the resulting quadratic for T_1. Substitute the two roots, successively, into the quadratic and select the one that satisfies it. If the "residual" $(AT_1^2 + BT_1 + C)$ is less than 0.001, use that root for T_1. If not, transfer to the routine that places the hypocenter at the earliest station.

a. Four stations.

The fundamental equations for station I through 4 are

1 $$(x_1 - x_o)^2 + (y_1 - y_o)^2 + (z_1 - z_o)^2 = V^2 (P_1 - t_o)^2$$

2 $$(x_2 - x_o)^2 + (y_2 - y_o)^2 + (z_2 - z_o)^2 = V^2 (P_2 - t_o)^2$$

3 $$(x_3 - x_o)^2 + (y_3 - y_o)^2 + (z_3 - z_o)^2 = V^2 (P_3 - t_o)^2$$

4 $$(x_4 - x_o)^2 + (y_4 - y_o)^2 + (z_4 - z_o)^2 = V^2 (P_4 - t_o)^2$$

By definition $t_o = P_1 - T_1$. It is easy to show that

$$(P_2 - t_o)^2 - (P_1 - t_o)^2 = 2T_1(P_2 - P_1) + (P_2 - P_1)^2$$
$$(P_3 - t_o)^2 - (P_1 - t_o)^2 = 2T_1(P_3 - P_1) + (P_3 - P_1)^2$$
$$(P_4 - t_o)^2 - (P_1 - t_o)^2 = 2T_1(P_4 - P_1) + (P_4 - P_1)^2$$

For simplicity, let

$$r_i^2 = x_i^2 + y_i^2 + z_i^2$$

Subtracting equation (1) from equations (2), (3), and (4), we have

$$2(X_2-X_1)X_0+2(y_2-y_1)y_0+2(z_2-z_1)z_0=r_2^2-r_1^2-V^2\left[2T_1(P_2-P_1)+(P_2-P_1)^2\right]$$

$$2(X_3-X_1)X_0+2(y_3-y_1)y_0+2(z_3-z_1)z_0=r_3^2-r_1^2-V^2\left[2T_1(P_3-P_1)+(P_3-P_1)^2\right]$$

$$2(X_4-X_1)X_0+2(y_4-y_1)y_0+2(z_4-z_1)z_0=r_4^2-r_1^2-V^2\left[2T_1(P_4-P_1)+(P_4-P_1)^2\right]$$

Since $z_2-z_1 \approx 0$, $z_3-z_1 \approx 0$, + $z_4-z_1 \approx 0$, the terms in z_0 can be neglected.

Thus,

$$(X_2-X_1)X_0+(y_2-y_1)y_0+(P_2-P_1)V^2T_1=\frac{1}{2}\left[r_2^2-r_1^2-V^2(P_2-P_1)^2\right]$$

$$(X_3-X_1)X_0+(y_3-y_1)y_0+(P_3-P_1)V^2T_1=\frac{1}{2}\left[r_3^2-r_1^2-V^2(P_3-P_1)^2\right]$$

$$(X_4-X_1)X_0+(y_4-y_1)y_0+(P_4-P_1)V^2T_1=\frac{1}{2}\left[r_4^2-r_1^2-V^2(P_4-P_1)^2\right]$$

Set

$$a_{11}=(X_2-X_1),\ a_{12}=(y_2-y_1),\ a_{13}=(P_2-P_1)V^2,\ b_1=\frac{1}{2}\left[r_2^2-r_1^2-V^2(P_2-P_1)^2\right]$$

$$a_{21}=(X_3-X_1),\ a_{22}=(y_3-y_1),\ a_{23}=(P_3-P_1)V^2,\ b_2=\frac{1}{2}\left[r_3^2-r_1^2-V^2(P_3-P_1)^2\right]$$

$$a_{31}=(X_4-X_1),\ a_{32}=(y_4-y_1),\ a_{33}=(P_4-P_1)V^2,\ b_3=\frac{1}{2}\left[r_4^2-r_1^2-V^2(P_4-P_1)^2\right]$$

Finally,

$$a_{11}X_0+a_{12}y_0+a_{13}T_1=b_1$$

$$a_{21}X_0+a_{22}y_0+a_{23}T_1=b_2$$

$$a_{31}X_0+a_{32}y_0+a_{33}T_1=b_3$$

Solve for X_0, y_0, T_1 by Cramer's rule. Then $t_0 = P_1 - T_1$

Substitute X_0, y_0, T_1 into the station 1 equation

$$Z_0 \approx \sqrt{V^2 T_1^2 - (X_1 - X_0)^2 - (y_1 - y_0)^2}$$

If Z_0 so computed is imaginary or if it is less than half the epicentral distance of the nearest station, set $Z_0 = ZTR$.

b. Three stations.

$$(X_2 - X_1)X_0 + (y_2 - y_1)y_0 + (P_2 - P_1)V^2 T_1 = \frac{1}{2}\left[r_2^2 - r_1^2 - V^2(P_2 - P_1)^2\right]$$

$$(X_3 - X_1)X_0 + (y_3 - y_1)y_0 + (P_3 - P_1)V^2 T_1 = \frac{1}{2}\left[r_3^2 - r_1^2 - V^2(P_3 - P_1)^2\right]$$

Solve these equations for X_0 and y_0 in terms of T_1, and set

$$RP2 = \frac{1}{2}\left[r_2^2 - r_1^2 - V^2(P_2 - P_1)^2\right]$$

$$RP3 = \frac{1}{2}\left[r_3^2 - r_1^2 - V^2(P_3 - P_1)^2\right]$$

$$DET3 = (y_3 - y_1)(X_2 - X_1) - (y_2 - y_1)(X_3 - X_1)$$

$$X_0 = \frac{(y_3 - y_1)RP2 - (y_2 - y_1)RP3}{DET3} - \frac{\left[(y_3 - y_1)(P_2 - P_1) - (y_2 - y_1)(P_3 - P_1)\right]V^2 T_1}{DET3}$$

$$y_0 = \frac{(X_2 - X_1)RP3 - (X_3 - X_1)RP2}{DET3} - \frac{\left[(X_2 - X_1)(P_3 - P_1) - (X_3 - X_1)(P_2 - P_1)\right]V^2 T_1}{DET3}$$

Then we can write

$$X_0 = G_1 T_1 + G_2$$

$$y_0 = G_3 T_1 + G_4$$

where

$$G_1 = \frac{[(y_2-y_1)(P_3-P_1)-(y_3-y_1)(P_2-P_1)]\ V^2}{DET3}$$

$$G_2 = \frac{(y_3-y_1)\,RP2 - (y_2-y_1)\,RP3}{DET3}$$

$$G_3 = \frac{[(X_3-X_1)(P_2-P_1)-(X_2-X_1)(P_3-P_1)]\ V^2}{DET3}$$

$$G_4 = \frac{(X_2-X_1)\,RP3 - (X_3-X_1)\,RP2}{DET3}$$

If t_o is available from S-P data; i.e., if $t_o = ORGS$, calculate X_o and y_o and set $Z_o = ZTR$.

If t_o is not available, set $Z_o = ZTR$ and substitute X_o and y_o (in terms of T_1) into the station 1 equation.

$$G_5 T_1^2 + G_6 T_1 + G_7 = 0$$

where

$$G_5 = (G_1^2 + G_3^2 - V^2)$$

$$G_6 = -2[G_1(X_1-G_2) + G_3(y_1-G_4)]$$

$$G_7 = (X_1-G_2)^2 + (y_1-G_4)^2 + ZTR^2$$

Set

$$G_8 = G_6^2 - 4G_5G_7$$

$$G_9 = \sqrt{G_8}$$

The two roots of the quadratic are

$$TIM = \frac{-G_6 - G_9}{2G_5}$$

$$TIP = \frac{-G_6 + G_9}{2G_5}$$

Substitute $T1M$ and $T1P$, successively, into the quadratic. Select the root that leaves the smallest "residual" and test whether that residual < 0.001. If so, set T_1 equal to that root. If not, go to the routine that places the hypocenter at the nearest station.

Calculation of Traveltimes, Derivatives, and Angles of Incidence

(Subroutines TPAR and TRVDRV)

Program TRVDRV, on which these subroutines are based, was designed to calculate traveltimes and derivatives of traveltimes with respect to epicentral distance and focal depth for events in an "earth" consisting of N-1 flat layers above a homogeneous half space. The earth model is described by the depth to the top of layer L and the P-velocity in layer L; i.e., by D(L), V(L), L = 1, N, where the index N refers to the half space.

The course of the program can be outlined as follows:

1. Determine the layer, J, that contains the focus at depth, H.

2. Determine which of the several possible waves (direct, and refractions from successively lower horizons) is the first arrival at distance DELTA.

3. Calculate the traveltime and derivatives by an appropriate method: for refracted waves these calculations are straightforward, but for the direct waves a numerical solution must be employed.

Because the traveltime, derivative, and angle of incidence calculations are a critical central part of the hypocenter determination, these subroutines are treated more thoroughly than other subroutines in the program. This writeup describes a somewhat more elaborate version of the subroutine that constitutes a self-contained program as well as a test of the program on an actual earth model (the 3-layer "Hawaii B" structure). It is supplemented by an independent flow chart and a FORTRAN listing of the TRVDRV program. The variables used in the program and flow chart are identified in the accompanying list. The same notation will be used, generally, in the following section of the writeup, which outlines the mathematical formulation of the program and discusses some of the principal problems that must be solved. The notation used in this section is nearly identical (but not exactly) to that used in HYPOLAYR and its subroutines.

Traveltime of Refracted Waves

(See Sketch A)

The traveltime, to distance DELTA, of seismic waves from a focus in layer J that are refracted along the top of layer M can be written:

$$T = TINJ(M) + DELTA/V(M)$$

The intercept, $TINJ(M)$, can be written:

$$TINJ(M) = TID(J,M) - \frac{TKJ * \cos\theta_M^J}{V(J)}$$

where $TID(J,M)$ is the intercept of a wave with its focus at the top of layer J (at depth D(J)) that is refracted along the top of layer M (at depth D(M)).

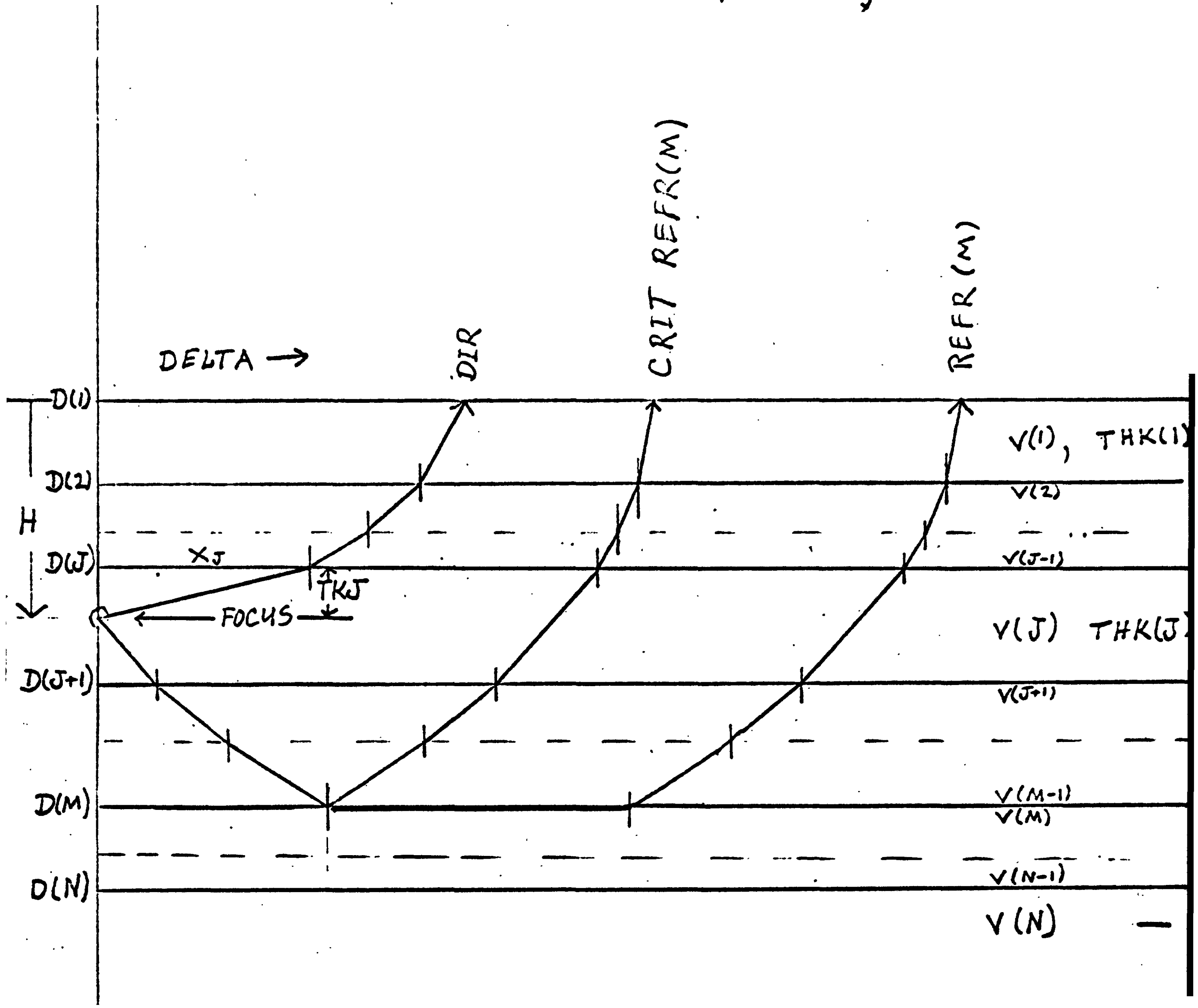
Finally,

$$TID(J,M) = \sum_{L=J}^{M-1} \frac{THK(L) * \cos\theta_M^L}{V(L)} + \sum_{L=1}^{M-1} \frac{THK(L) * \cos\theta_M^L}{V(L)}$$

In these equations, θ_M^L is the angle of incidence in layer L of a wave that is refracted horizontally in layer M.

Sketch A

Notation used to specify model



Critical Distance (Initial Point) of Refracted Waves

Analogous equations can be written for the distance to the initial point (distance of critical reflection) of the wave from a focus at depth H (in layer J) that is refracted along the top of layer M.

$$DIDJ(M) = DID(J,M) - TKJ * \tan\theta_M^J \quad , \text{ and}$$

$$DID(J,M) = \sum_{L=J}^{M-1} THK(L) * \tan\theta_M^J + \sum_{L=1}^{M-1} THK(L) * \tan\theta_M^J$$

where $DID(J,M)$ is the critical distance for a wave with a focus at the top of layer J (depth D(J)) that is reflected from the top of layer M (depth D(M)).

For waves that are refracted along or critically reflected from the top of layer M, the angle of incidence in layer M is $\pi/2$.

Critical Distance and Intercept Formulas in Terms of Layer Velocities and Thicknesses

From Snell's law $\quad \sin\theta_M^L = \dfrac{V(L)}{V(M)}$. Hence,

$$\cos\theta_M^L = \left(1 - V(L)^2/V(M)^2\right)^{1/2} = \frac{\sqrt{V(M)^2 - V(L)^2}}{V(M)} \quad , \text{ and}$$

$$\tan\theta_M^L = V(L)\Big/\sqrt{V(M)^2 - V(L)^2} \; .$$

The expressions for TID(J,M), DID(J,M) TINJ(M), and DIDJ(M) can be written:

$$TID(J,M) = \sum_{L=J}^{M-1} \frac{THK(L) * \sqrt{V(M)^2 - V(L)^2}}{V(M) * V(L)} + \sum_{L=1}^{M-1} \frac{THK(L) * \sqrt{V(M)^2 - V(L)^2}}{V(M) * V(L)}$$

$$DID(J,M) = \sum_{L=J}^{M-1} \frac{THK(L)*V(L)}{\sqrt{V(M)^2 - V(L)^2}} + \sum_{L=1}^{M-1} \frac{THK(L)*V(L)}{\sqrt{V(M)^2 - V(L)^2}}$$

$$TINJ(M) = TID(J,M) - TKJ * \frac{\sqrt{V(M)^2 - V(J)^2}}{V(M)*V(J)}$$

$$DIDJ(M) = DID(J,M) - TKJ * \frac{TKJ*V(J)}{\sqrt{V(M)^2 - V(J)^2}}$$

In these equations, TKJ is the depth of the focus below the top of layer J, ie., TKJ = H - D(J).

<u>Traveltime of the Direct Wave</u>

The traveltime of the direct wave to distance DELTA from a focus in the first layer is simply:

$$T = \sqrt{H^2 + DELTA^2} / V(1)$$

For a focus in a deeper layer (J = 2, N) the expression for T as a function of DELTA is too complex to be useful, if it can be obtained at all. However, both T and DELTA are relatively simple functions of $\sin\theta_J$, where θ_J is the angle of incidence of the ray at the focus in layer J. In the program "DIRECT", a simple method for determining $\sin\theta_J$ and then calculating T for any specified DELTA was developed. This routine is employed in the present program to compute the traveltime of the direct ray to distance DELTA for $J > 1$.

Maximum Distance at Which the Direct Wave Can Be a First Arrival.

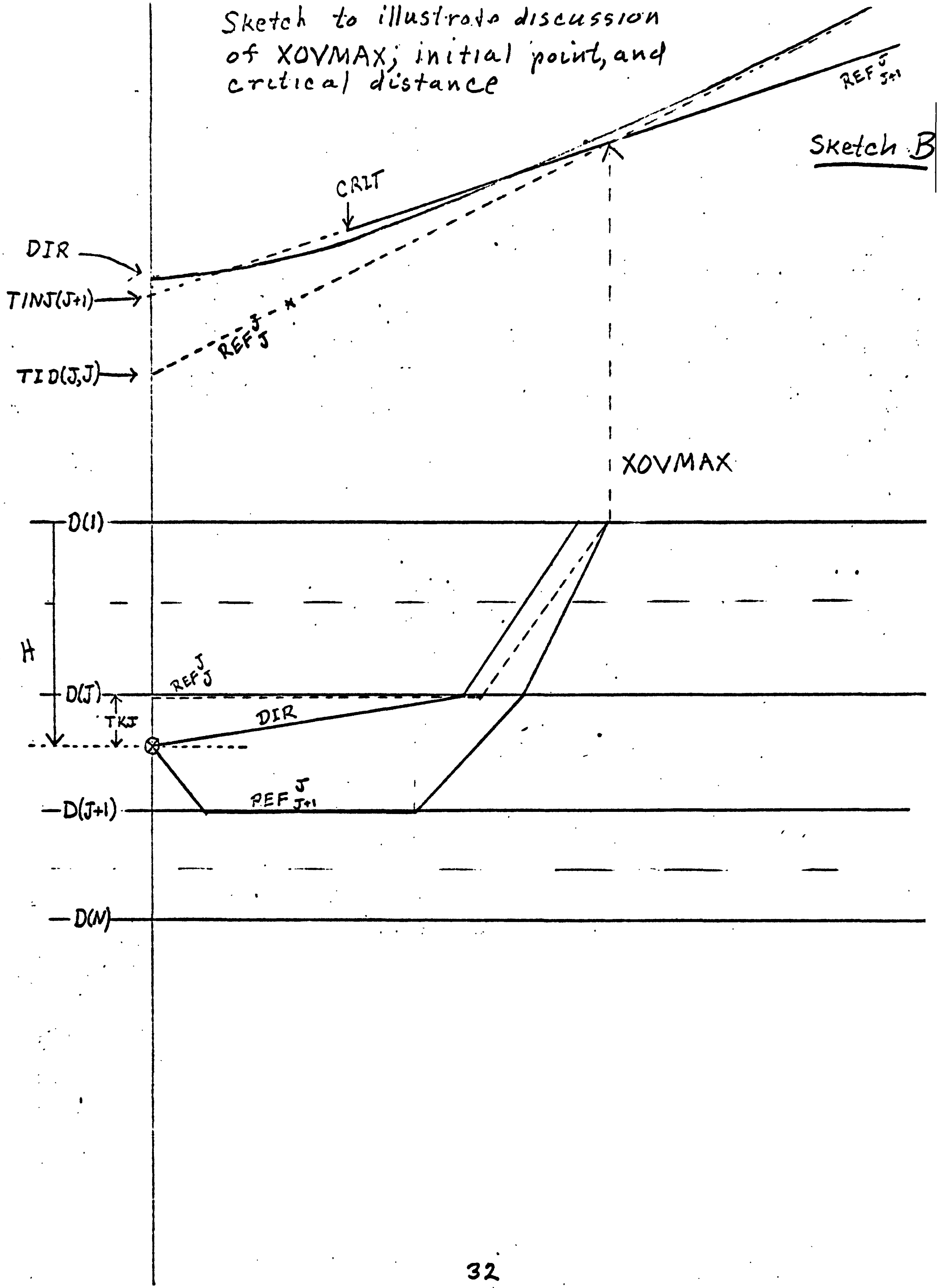
(See Sketch B)

Because the traveltime of the direct wave is more time-consuming to calculate than the traveltimes of refracted waves, a preliminary test is made to determine whether DELTA is beyond the range of possible direct-wave first arrivals. Consider a focus at depth H in layer J. At large DELTA the direct wave is asymptotic to the refraction line for a focus at the very top of layer J; but the direct wave is always later than the asymptote. Let the crossover distance between the wave refracted along the top of J from a focus at the top of J and the wave refracted along the top of J + I from a focus at depth H be XOVMAX. Then the crossover between the direct wave and the refracted wave from J + I will be smaller than XOVMAX, and the first arrival at DELTA larger than XOVMAX must be a refracted wave, if $J < N$.

Because the initial point of the refraction from layer K + 1 is coincident with the critical reflection from the top of K + 1 (or the bottom of K) and because the reflection from the base of K must be later than the direct wave (if K = J) or a refracted wave from the top of K, the initial point of the K + 1 refraction curve must lie above the K-refraction curve (or the direct-wave curve if K = J). Hence, for DELTA greater than XOVMAX and $J < N$ the first arrival must be a refracted wave recorded beyond its initial point.

Determination of Which Wave Is the First Arrival at DELTA < XOVMAX

For DELTA less than XOVMAX the first arrival may be the direct wave: so the traveltime of the direct wave must be computed and


Sketch to illustrate discussion of XOVMAX; initial point, and critical distance
Sketch B
CRIT
DIR
TINJ(J+1)
TID(J,J)
XOVMAX
D(1)
H
D(J)
TKJ
DIR
D(J+1)
D(N)

compared with the traveltimes of possible refracted phases to establish which arrival is earliest. In this range of DELTA, however, it must be established that any prospective refracted first arrival actually exists at the specific value of DELTA considered; i.e., is DELTA beyond the initial point of the refracted wave?

<u>Derivatives of Traveltime with Respect to Epicentral Distance and Focal Depth.</u>--When the nature of the first arrival at distance DELTA has been established, the traveltime of that arrival is set equal to T and derivatives of the traveltime with respect to DELTA and H are computed by methods that are appropriate for the first-arrival wave type.

<u>Derivatives of refracted-wave traveltimes with respect to DELTA and H.</u>--For refracted waves, by differentiation of the equation for T as a function of DELTA and H:

$$\partial T/\partial DELTA = \frac{1}{V(M)}$$

$$\partial T/\partial H = \frac{-\sqrt{V(M)^2 - V(J)^2}}{V(M) * V(J)}$$

<u>Derivatives of first-layer direct arrivals.</u>--For the direct wave through layer 1:

$$\frac{\partial T}{\partial DELTA} = \frac{DELTA}{V(1) * \sqrt{H^2 + DELTA^2}}$$

$$\frac{\partial T}{\partial H} = \frac{H}{V(1) * \sqrt{H^2 + DELTA^2}}$$

Derivatives of direct-wave traveltimes: $J > 1$.--(See sketch C.)

Because both T and DELTA for the direct wave from layers below the first can be expressed in terms of the parameter $\sin \Theta_J$

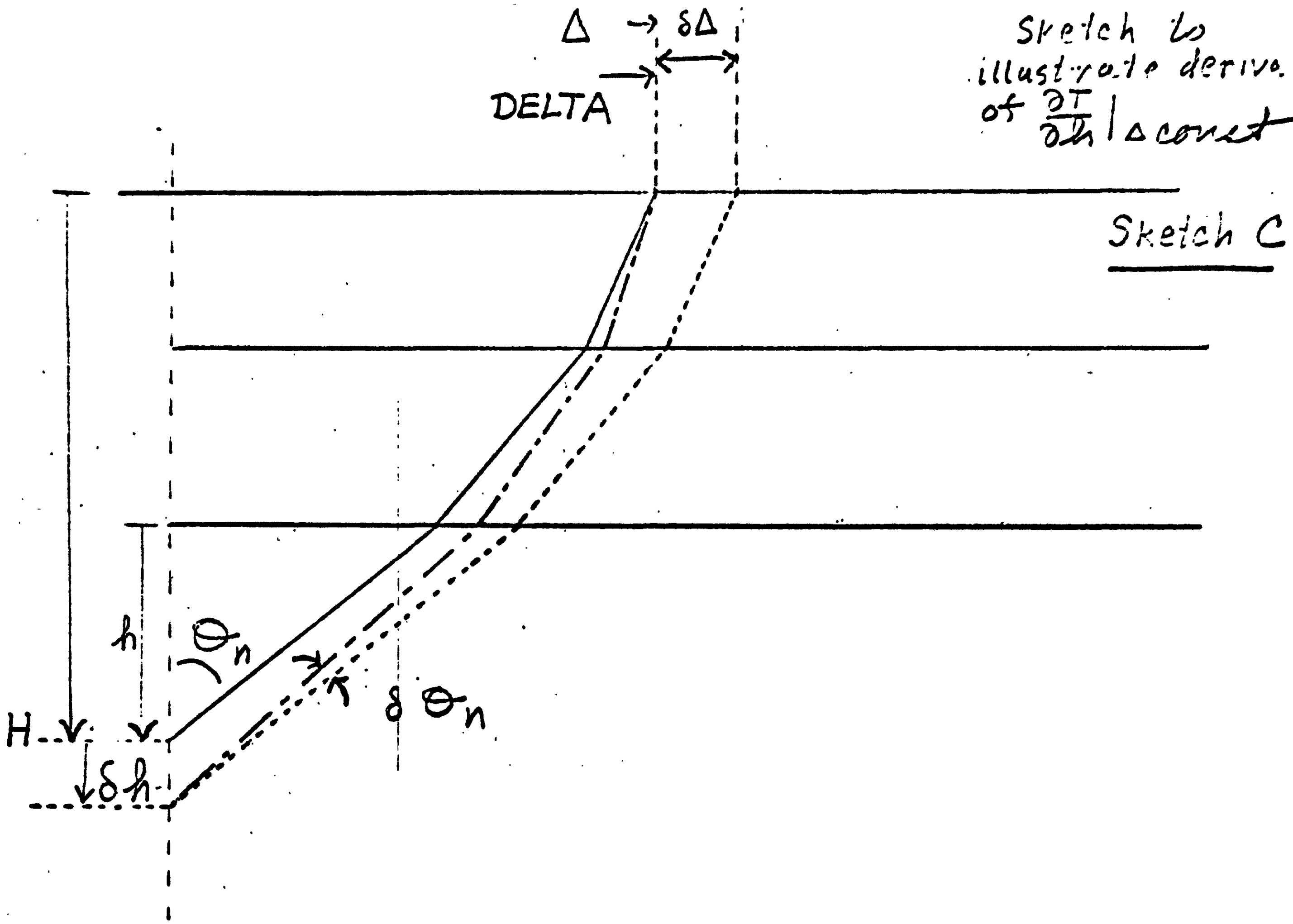
$$\frac{\partial T}{\partial DELTA} \quad \text{can be computed as} \quad \frac{\dfrac{\partial T}{\partial \sin \Theta_J}}{\dfrac{\partial DELTA}{\partial \sin \Theta_J}}$$

$$\frac{\partial T}{\partial DELTA} =$$

$$\frac{TKJ*U/\left(V(J)*(1.0-U^2)^{3/2}\right) + \sum_{L=1}^{J-1} THK(L)*V(J)*U/\left(V(L)^2*\left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{3/2}\right)}{TKJ/(1.0-U^2)^{3/2} + \sum_{L=1}^{J-1} THK(L)*V(J)^2/\left(V(L)^2*\left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{3/2}\right)}$$

where

$$U = \sin \Theta_J$$


Sketch to illustrate derivat of $\frac{\partial T}{\partial h}|_{\Delta\ const}$
Sketch C
Δ
δΔ
DELTA
h
θ_n
$\delta\theta_n$
H
δh

Next, we must calculate $\left.\frac{\partial T}{\partial H}\right|_{DELTA}$ for the direct arrival from layer J.

Letting U = $\sin\theta_J$, and h = TKJ = H - D(J), and DELTA = Δ,

$$T = \frac{h}{V(J)*\sqrt{1.0-U^2}} + \sum_{L=1}^{J-1} \frac{THK(L)*V(J)}{V(L)^2 \times \left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{1/2}}$$

$$\Delta = \frac{h*U}{\sqrt{1.0-U^2}} + \sum_{L=1}^{J-1} \frac{THK(L)*U}{\left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{1/2}}.$$

Holding U = $\sin\theta_J$ = const, increase h by an amount δh. The corresponding changes in T and Δ are

$$\delta T_1 = \left.\frac{\partial T}{\partial h}\right|_U * \delta h$$

$$\delta \Delta_1 = \left.\frac{\partial \Delta}{\partial h}\right|_U * \delta h$$

Next, change U by an amount δU, holding h constant so that the change in Δ, $\delta\Delta_2$, is equal and opposite to that caused by the previous change in h.

$$\delta\Delta_2 = \left.\frac{\partial \Delta}{\partial U}\right|_h * \delta U \doteq -\left.\frac{\partial \Delta}{\partial U}\right|_U * \delta h = -\delta\Delta_1$$

Thus, the required δu is:

$$\delta u = -\frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h} * \delta h$$

The corresponding change in T is

$$\delta T_2 = \left.\frac{\partial T}{\partial u}\right|_h \delta u$$

Substituting the previous expression for δu

$$\delta T_2 = -\left.\frac{\partial T}{\partial u}\right|_h * \frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h} * \delta h$$

The total change in Δ, i.e., $\delta\Delta_1 + \delta\Delta_2 = 0$, and the total change in T is

$$\delta T = \delta T_1 + \delta T_2 = \left.\frac{\partial T}{\partial h}\right|_u * \delta h - \left.\frac{\partial T}{\partial u}\right|_h * \frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h} * \delta h$$

$$\left.\frac{\delta T}{\delta h}\right|_\Delta = \left.\frac{\partial T}{\partial h}\right|_u - \left.\frac{\partial T}{\partial u}\right|_h * \frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h}$$

We have previously calculated

$$\frac{\left.\frac{\partial T}{\partial u}\right|_h}{\left.\frac{\partial \Delta}{\partial u}\right|_h} = \left.\frac{\partial T}{\partial \Delta}\right|_h$$

Passing to the limit

$$\left.\frac{\partial T}{\partial h}\right|_\Delta = \left.\frac{\partial T}{\partial h}\right|_u - \left.\frac{\partial T}{\partial \Delta}\right|_h * \left.\frac{\partial \Delta}{\partial h}\right|_u \quad .$$

But $\left.\frac{\partial T}{\partial h}\right|_u = \frac{1}{V(J)\sqrt{1.0 - u^2}}$; $\left.\frac{\partial \Delta}{\partial h}\right|_u = \frac{u}{\sqrt{1.0 - u^2}}$

and

$$\left.\frac{\partial T}{\partial h}\right|_{\Delta} = \frac{1.0}{V(J)*\sqrt{1.0-u^2}} - \frac{u}{\sqrt{1.0-u^2}} * \left.\frac{\partial T}{\partial \Delta}\right|_{h}$$

Thus

$$\left.\frac{\partial T}{\partial h}\right|_{\Delta} = \frac{1.0 - V(J)*u*\left.\frac{\partial T}{\partial \Delta}\right|_{h}}{V(J)*\sqrt{1.0-u^2}}$$

In the notation used in the FORTRAN program

$$DTDH = \frac{1.0 - V(J)*u * DTDD}{V(J)*\sqrt{1.0-u^2}}$$

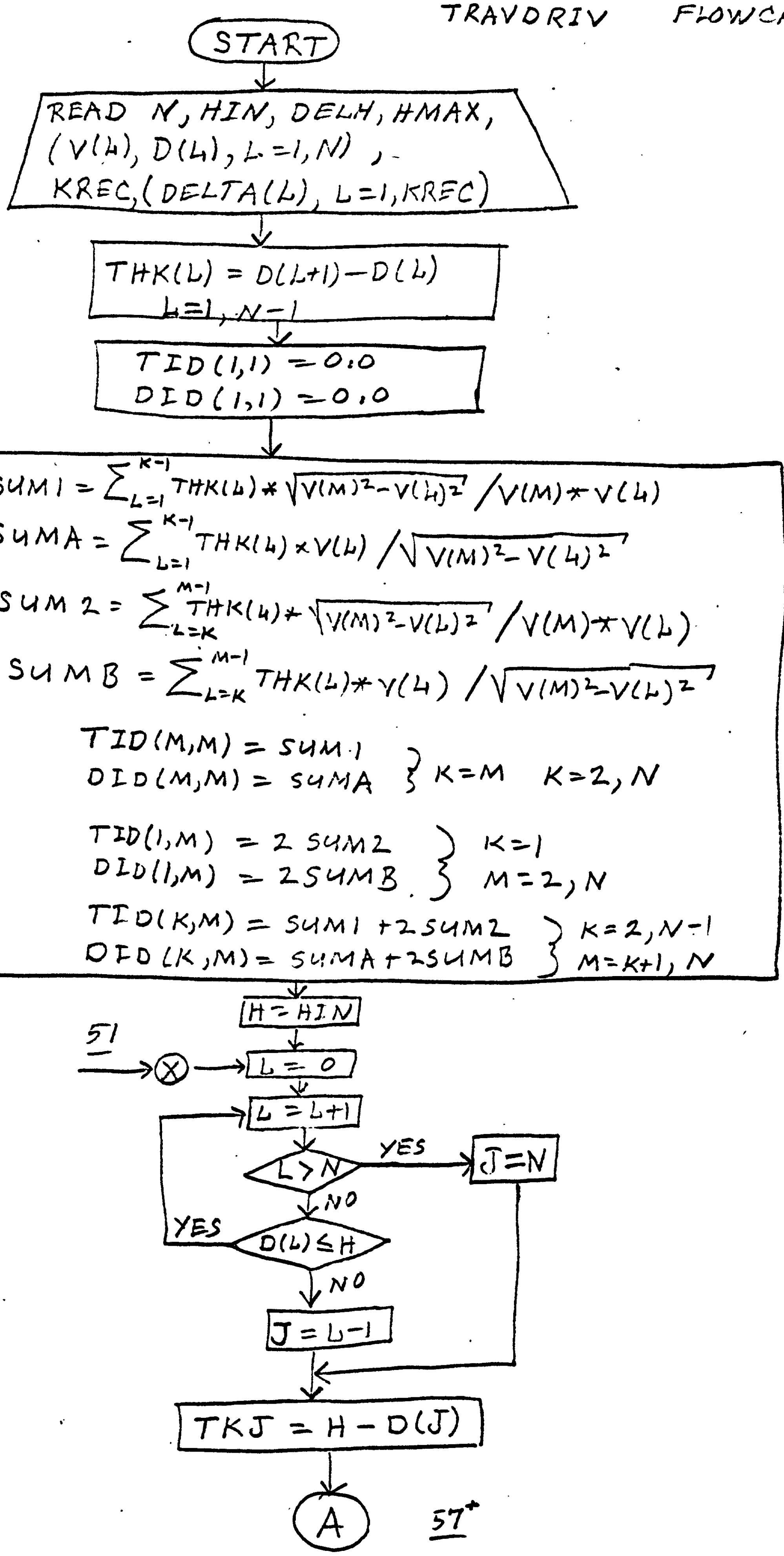
Notation Used In the TRVDRV Program

HIN	initial focal depth	) Used in test of program
DELH	increment in focal depth	)
MAXH	maximum focal depth	)
KREC	total number of stations considered	)
N	number of layers plus one	
V(L)	P-velocity in layer L	
D(L)	depth to top of layer L	
DELTA(I)	epicentral distance to station I	
THK(L)	thickness of layer L	
TID(K,M)	intercept of refracted wave from a focus at boundary D(K) and refracted along boundary D(M); M $\geq$ K.	
DID(K,M)	critical distance of refracted wave described above; i.e., epicentral distance of the initial point of the refraction curve.	
H	focal depth	
J	layer containing focus	
TKJ	distance of focus from top of layer J	
TINJ(L)	intercept of wave from depth H (in layer J) and refracted along boundary D(L); L $\geq$ J.	
DIDJ(L)	critical distance of wave from depth H (in layer J) and refracted along D(L).	
TR(M)	traveltime of refracted wave from focus at depth H to distance DELTA(I)	

TMIN= 999.99	arbitrarily large traveltime for use in scheme to identify first arrival at distance DELTA(I)
XOVMAX	"safe" estimate of maximum distance at which the first arrival might be the direct wave
T(I)	traveltime of wave from focus at depth H to epicentral distance DELTA(I)
DTDD(I)	∂T(I) / ∂DELTA
DTDH(I)	∂T(I) / ∂H
MODE(I) = 1	identifies "refracted" arrivals.
TDJ1	traveltime of direct wave from a focus in layer 1.
MODE(I) = 2	identifies a direct arrival from a focus in layer 1.
XBIG	upper limit of interval containing the point at which the direct wave from a focus in J leaves layer J
XLIT	lower limit of interval containing the point at which the direct wave from a focus in J leaves layer J.
UL	value of sin θ_J computed from XLIT
UB	value of sin θ_J computed from XBIG
DELBIG	value of DELTA corresponding to XBIG
DELLIT	value of DELTA corresponding to XLIT
XTR	trial value of X_J, the epicentral distance at which the direct ray leaves layer J
U	value of sin θ_J computed from XTR (θ_J = angle of incidence in layer J).

DELXTR	the value of DELTA that corresponds to XTR
TEST = DELTA(I) - DELXTR	
LL	iteration counter in loop to find X_J, $\sin\theta_J$, etc.
TDC	asymptote approached by TDIR when DELTA(I) >> TKJ
MODE(I) = 3	indicates direct traveltime and derivatives calculated on the basis of TDC for DELTA(I) >> TKJ
ALFA) BETA)	Sums required in the calculation of DTDD(I) for the direct wave
MODE(I) = 4	indicates direct arrival
TDIR	traveltime of direct wave

TRAVDRIV FLOWCHART



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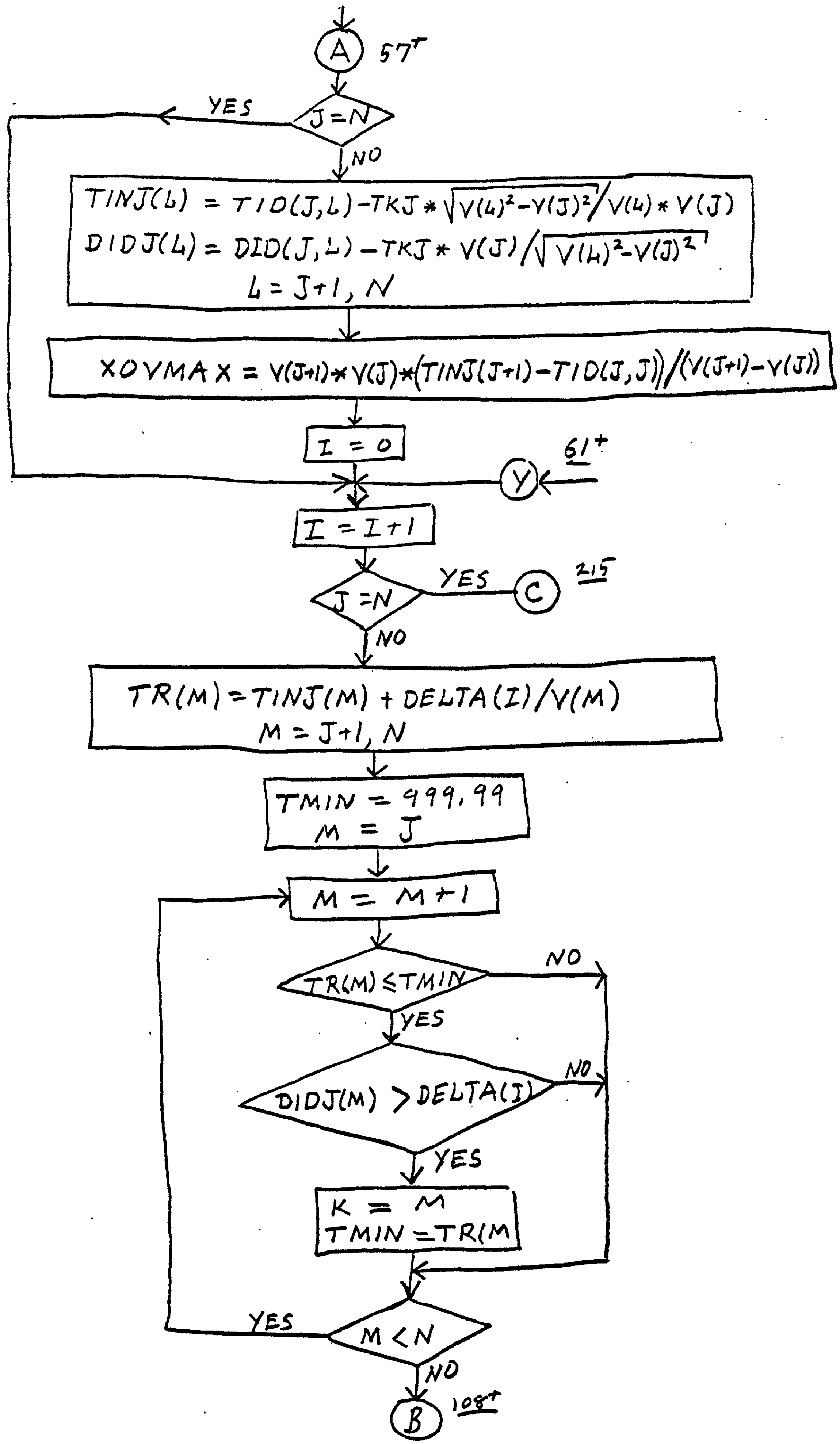
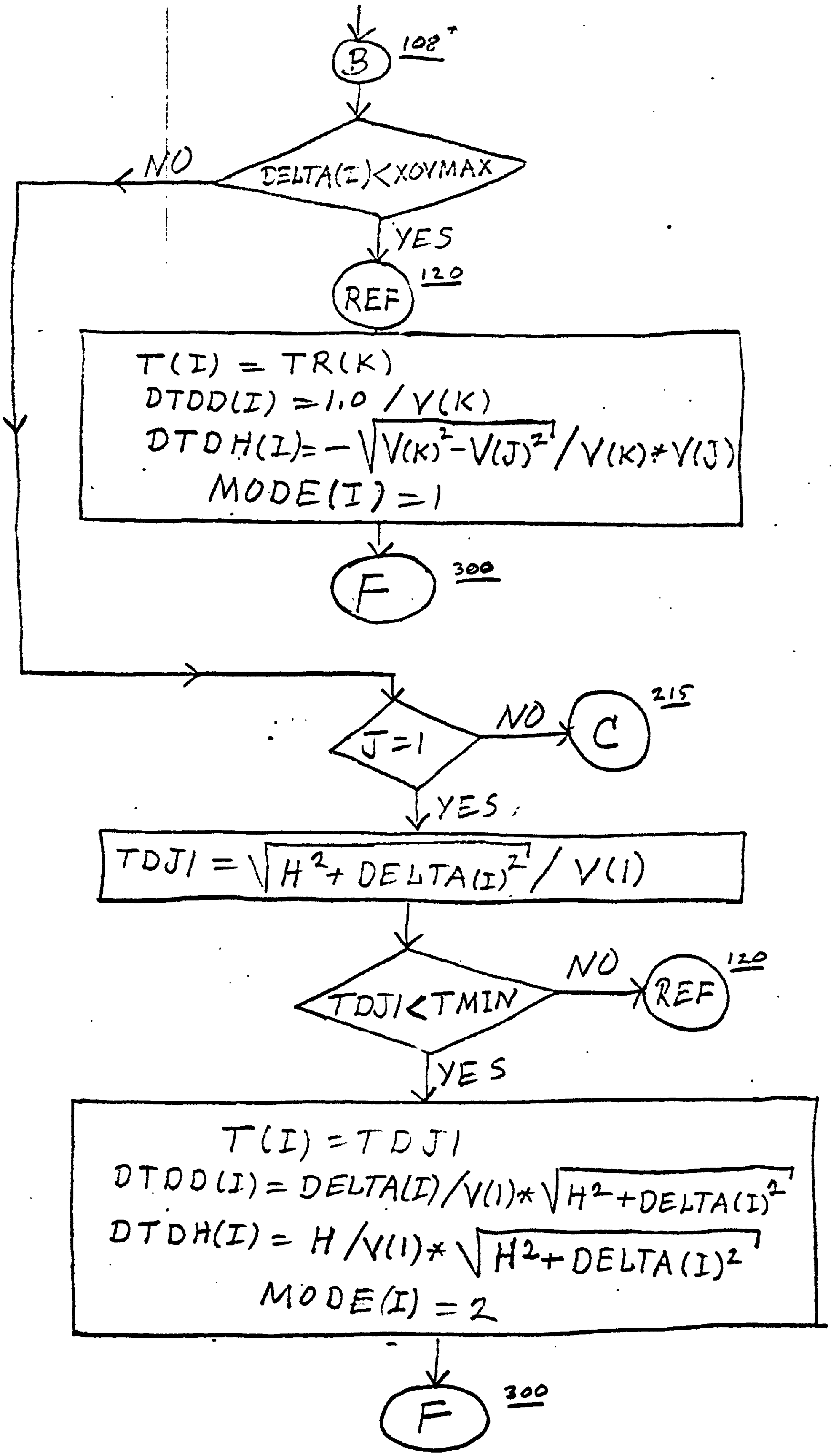
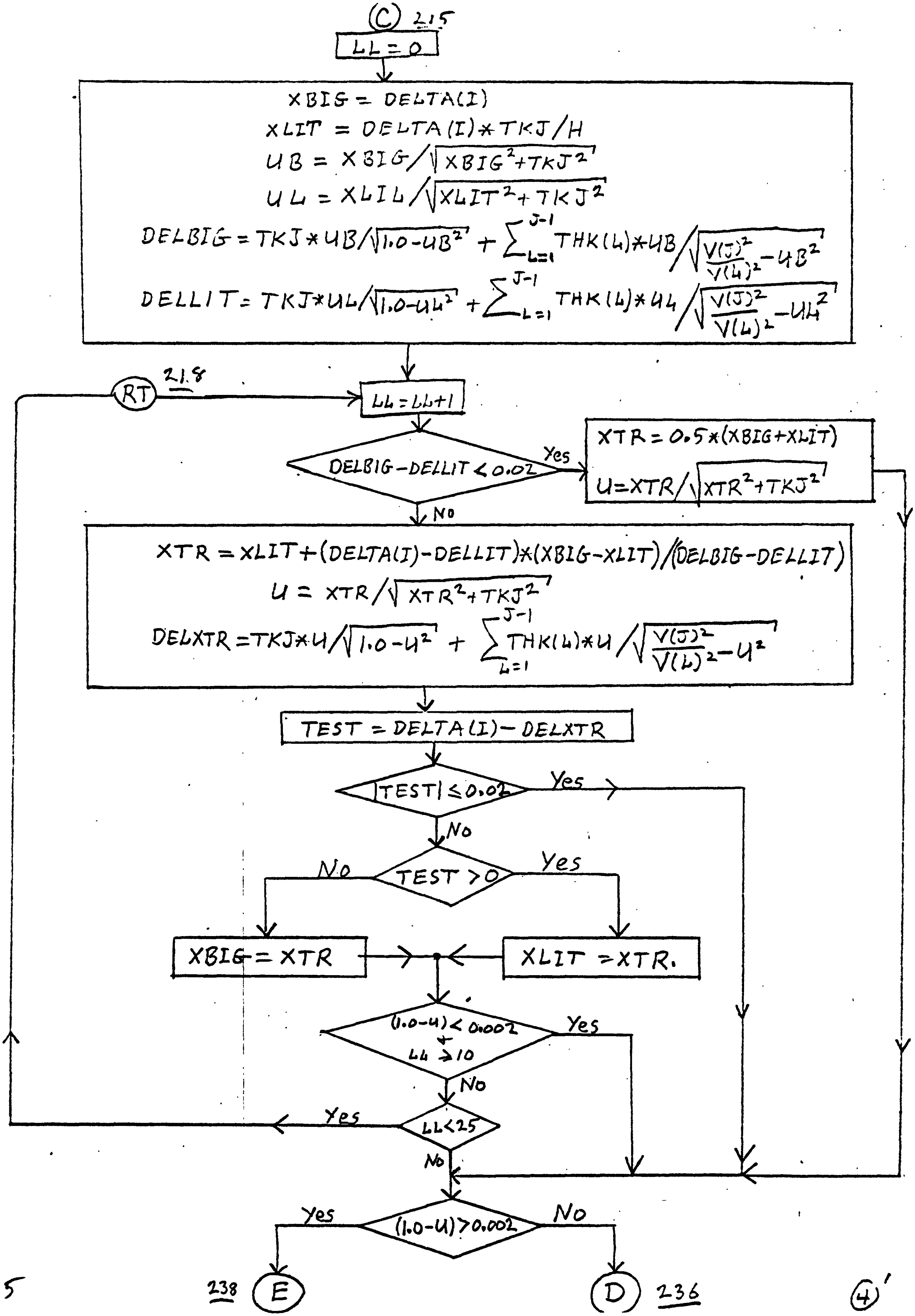
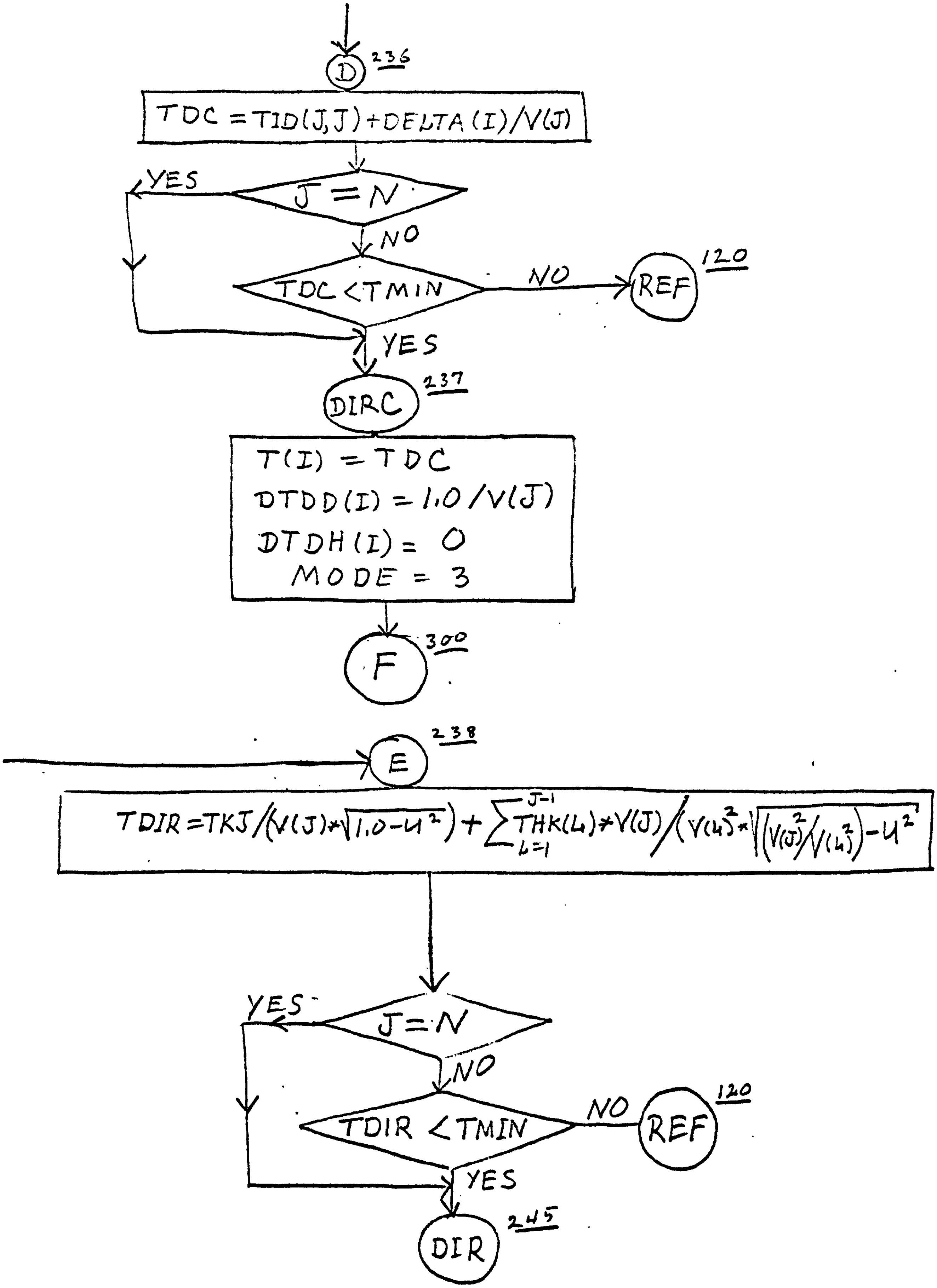

A
57+
J=N
YES
NO
TINJ(L) = TID(J,L)-TKJ * √(V(L)²-V(J)²)/V(L) * V(J)
DIDJ(L) = DID(J,L) - TKJ * V(J)/√(V(L)²-V(J)²)
L = J+1, N
XOVMAX = V(J+1)*V(J)*(TINJ(J+1)-TID(J,J))/(V(J+1)-V(J))
I = 0
61+
Y
I = I+1
J=N
YES
C
215
NO
TR(M) = TINJ(M) + DELTA(I)/V(M)
M = J+1, N
TMIN = 999.99
M = J
M = M+1
TR(M) ≤ TMIN
NO
YES
DIDJ(M) > DELTA(I)
NO
YES
K = M
TMIN = TR(M)
M < N
YES
NO
B
108+

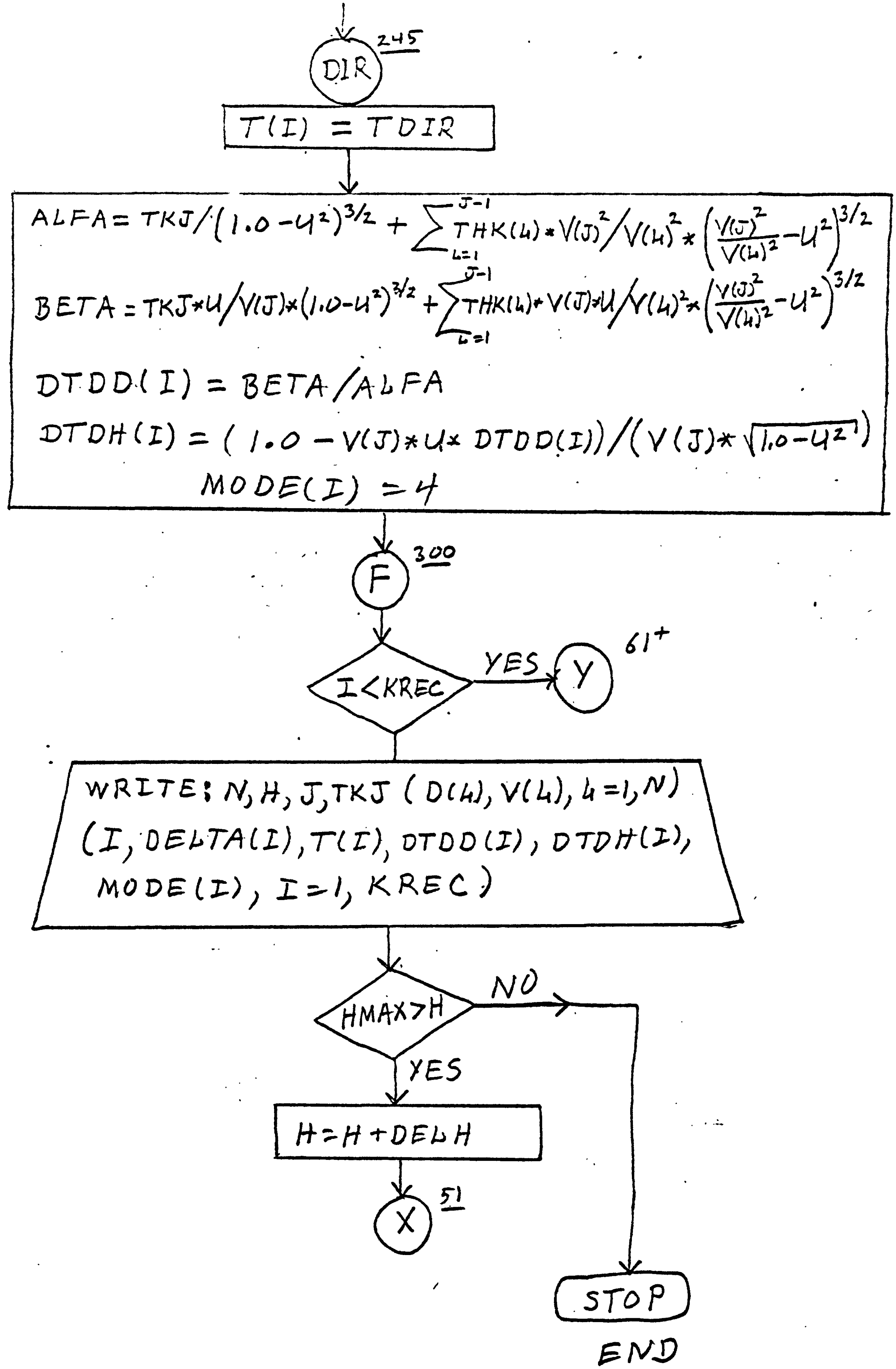


B
108
DELTA(I)<XOYMAX
NO
YES
REF
120
T(I) = TR(K)
DTOD(I) = 1.0 / V(K)
DTDH(I) = − SQRT(V(K)² − V(J)²) / V(K)*V(J)
MODE(I) = 1
F
300
J=1
NO
C
215
YES
TDJ1 = SQRT(H² + DELTA(I)²) / V(1)
TDJ1<TMIN
NO
REF
120
YES
T(I) = TDJ1
DTOD(I) = DELTA(I)/V(1)*SQRT(H² + DELTA(I)²)
DTDH(I) = H/V(1)*SQRT(H² + DELTA(I)²)
MODE(I) = 2
F
300



(C) 215
LL = 0
XBIG = DELTA(I)
XLIT = DELTA(I)*TKJ/H
UB = XBIG/√(XBIG²+TKJ²)
UL = XLIL/√(XLIT²+TKJ²)
DELBIG = TKJ*UB/√(1.0-UB²) + Σ(L=1 to J-1) THK(L)*UB/√(V(J)²/V(L)² - UB²)
DELLIT = TKJ*UL/√(1.0-UL²) + Σ(L=1 to J-1) THK(L)*UL/√(V(J)²/V(L)² - UL²)
21.8
RT
LL = LL+1
DELBIG-DELLIT < 0.02
Yes
XTR = 0.5*(XBIG+XLIT)
U=XTR/√(XTR²+TKJ²)
No
XTR = XLIT+(DELTA(I)-DELLIT)*(XBIG-XLIT)/(DELBIG-DELLIT)
U = XTR/√(XTR²+TKJ²)
DELXTR = TKJ*U/√(1.0-U²) + Σ(L=1 to J-1) THK(L)*U/√(V(J)²/V(L)² - U²)
TEST = DELTA(I)-DELXTR
|TEST| ≤ 0.02
Yes
No
TEST > 0
No
Yes
XBIG = XTR
XLIT = XTR.
(1.0-U) < 0.002 + LL > 10
Yes
No
LL<25
Yes
No
(1.0-U) > 0.002
Yes
No
238 (E)
(D) 236
(4)'


D 236
TDC = TID(J,J) + DELTA(I)/V(J)
J = N
YES
NO
TDC < TMIN
NO
REF 120
YES
DIRC 237
T(I) = TDC
DTDD(I) = 1.0/V(J)
DTDH(I) = 0
MODE = 3
F 300
E 238
TDIR = TKJ/(V(J)*√(1.0−U²)) + Σ[L=1 to J−1] THK(L)*V(J)/(V(L)²*√((V(J)²/V(L)²)−U²))
J = N
YES
NO
TDIR < TMIN
NO
REF 120
YES
DIR 245


245
DIR
T(I) = TDIR
ALFA = TKJ/(1.0-U²)^3/2 + Σ(L=1 to J-1) THK(L)*V(J)²/V(L)²*(V(J)²/V(L)² - U²)^3/2
BETA = TKJ*U/V(J)*(1.0-U²)^3/2 + Σ(L=1 to J-1) THK(L)*V(J)*U/V(L)²*(V(J)²/V(L)² - U²)^3/2
DTDD(I) = BETA/ALFA
DTDH(I) = (1.0 - V(J)*U* DTDD(I))/(V(J)* √(1.0-U²))
MODE(I) = 4
300
F
I<KREC
YES
Y
61+
WRITE: N, H, J, TKJ (D(L), V(L), L=1, N)
(I, DELTA(I), T(I), DTDD(I), DTDH(I),
MODE(I), I=1, KREC)
HMAX>H
NO
YES
H=H+DELH
X
51
STOP
END

TRAVDRIV Listing (BCD interpreter

```
//TRAVDRIV JOB [C488,437,3,3],:948 EATON:,MSGLEVEL×1
// EXEC FORTHCLG,PARM.FORT×:MAP,NODECK,BCD:
//FORT.SYSIN DD *
C TRAVELTIME AND DERIVATIVES   N-1 LAYERS
      DIMENSION V(10),D(10),THK(10),TID(10,10),TINJ(10),TR(10),
     1DID(10,10),DIDJ(10),DELTA(20),T(20),DTDD(20),DTDH(20),MODE(20)
      SRTBK(X,Y,Z)=SQRT((X*X)/(Y*Y)-(Z*Z))
      READ(5,500)N,HIN,DELH,HMAX
  500 FORMAT(I5,3F10.3)
      READ(5,505) (V(L),D(L),L=1,N)
  505 FORMAT(2F10.3)
C READ LIST OF DELTAS FOR TRIAL CALCULATIONS
      READ(5,510)KREC,(DELTA(L),L=1,KREC)
  510 FORMAT(I5,(5F10.3))
C COMPUTE THK(L)
      THK(N)=0.0
      DO 10 K=2,N
      L=K-1
      THK(L)=D(K)-D(L)
   10 CONTINUE
C COMPUTE INTERCEPTS AND CRITICAL DISTANCES FOR  BOUNDARY FOCI
      TID(1,1)=0.0
      DID(1,1)=0.0
      N1=N-1
      DO 15 M=2,N
      M1=M-1
      SUM1=0.0
      SUMA=0.0
      DO 12 L=1,M1
      SUM1=SUM1+THK(L)*SQRT(V(M)*V(M)-V(L)*V(L))/(V(M)*V(L))
      SUMA=SUMA + THK(L)*V(L)/SQRT(V(M)*V(M)-V(L)*V(L))
   12 CONTINUE
      TID(M,M)=SUM1
      DID(M,M)=SUMA
   15 CONTINUE
      DO 20 M=2,N
      M1=M-1
      SUM2=0.0
      SUMB=0.0
      DO 18 L=1,M1
      SUM2=SUM2+THK(L)*SQRT(V(M)*V(M)-V(L)*V(L))/(V(M)*V(L))
      SUMB=SUMB + THK(L)*V(L)/SQRT(V(M)*V(M)-V(L)*V(L))
   18 CONTINUE
      TID(1,M)=2.0*SUM2
      DID(1,M)=2.0*SUMB
   20 CONTINUE
      DO 50 K=2,N1
      KK=K+1
      K1=K-1
      DO 50 M=KK,N
      M1=M-1
      SUM1=0.0
      SUM2=0.0
      SUMA=0.0
      SUMB=0.0
```

```
      DO 30 L=1,K1
      SUM1=SUM1+THK(L)*SQRT(V(M)*V(M)-V(L)*V(L))/(V(M)*V(L))
      SUMA=SUMA + THK(L)*V(L)/SQRT(V(M)*V(M)-V(L)*V(L))
   30 CONTINUE
      DO 40 L=K,M1
      SUM2=SUM2+THK(L)*SQRT(V(M)*V(M)-V(L)*V(L))/(V(M)*V(L))
      SUMB=SUMB + THK(L)*V(L)/SQRT(V(M)*V(M)-V(L)*V(L))
   40 CONTINUE
      TID(K,M)=SUM1+2.0*SUM2
      DID(K,M)=SUMA+2.0*SUMB
   50 CONTINUE
C COMPUTE LAYER J CONTAINING FOCUS AT DEPTH H AND DEPTH TKJ OF FOCUS
C BELOW TOP OF LAYER J
      H=HIN
   51 L=0
   53 L=L+1
      IF(L .GT. N)GO TO 56
      IF(D(L)-H)53,53,55
   55 J=L-1
      GO TO 57
   56 J=N
   57 TKJ=H-D(J)
      IF(J .EQ. N)GO TO 61
CCOMPUTE THE INTERCEPT OF WAVE FROM FOCUS IN LAYER J AND REFRACTED
C ALONG THE TOP OF LAYER L
      DO 58 L=1,N
      TINJ(L)=0.0
      DIDJ(L)=0.0
   58 CONTINUE
      JJ=J+1
      DO 60 L=JJ,N
      TINJ(L)=TID(J,L)-TKJ*SQRT(V(L)*V(L)-V(J)*V(J))/(V(L)*V(J))
      DIDJ(L)=DID(J,L)-TKJ*V(J)/SQRT(V(L)*V(L)-V(J)*V(J))
   60 CONTINUE
C COMPUTE DELTA BEYOND WHICH ALL IST ARRIVALS ARE REFRACTIONS
      XOVMAX=V(JJ)*V(J)*(TINJ(JJ)-TID(J,J))/(V(JJ)-V(J))
   61 CONTINUE
C BEGIN CALCULATIONS FOR DEPTH H AND DELTA(I) I=1,KREC
      DO 300 I=1,KREC
C DETERMINE WHICH BRANCH OF THE TT CURVE CORRESPONDS TO DELTA(I)
      DO 90 L=1,N
      TR(L)=0.0
   90 CONTINUE
      IF(J .EQ. N)GO TO 215
  100 DO 102 M=JJ,N
      TR(M)=TINJ(M)+DELTA(I)/V(M)
  102 CONTINUE
      TMIN=999.99
      M=J
  104 M=M+1
      IF(TR(M)-TMIN)106,106,108
  106 IF(DIDJ(M) .GT. DELTA(I)) GO TO 108
      K=M
      TMIN=TR(M)
  108 IF(M .LT. N) GO TO 104
```

```
      IF(DELTA(I)-XOVMAX)202,120,120
C CALCULATE TT AND DERIVS FOR WAVES RECORDED BEYOND XOVMAX
  120 T(I)=TR(K)
      DTDD(I)=1.0/V(K)
      DTDH(I)=-SQRT(V(K)*V(K)-V(J)*V(J))/(V(K)*V(J))
      MODE(I)=1
      GO TO 300
C COMPUTE TT OF DIRECT WAVE THROUGH LAYER J
  202 IF(J .NE. 1)GO TO 215
      TDJ1=SQRT(H*H+DELTA(I)*DELTA(I))/V(1)
  203 IF(TDJ1-TMIN)205,120,120
  205 T(I)=TDJ1
      DTDD(I)=DELTA(I)/(V(1)*SQRT(H*H+DELTA(I)*DELTA(I)))
      DTDH(I)=H/(V(1)*SQRT(H*H+DELTA(I)*DELTA(I)))
      MODE(I)=2
      GO TO 300
  215 LL=0
C BEGIN ROUTINE TO FIND ROOT OF REFRACTION EQUATION
      XBIG=DELTA(I)
      XLIT=DELTA(I)*TKJ/H
      UB=XBIG/SQRT(XBIG*XBIG+TKJ*TKJ)
      UL=XLIT/SQRT(XLIT*XLIT+TKJ*TKJ)
      DELBIG=TKJ*UB/SQRT(1.0-UB*UB)
      DELLIT=TKJ*UL/SQRT(1.0-UL*UL)
      J1=J-1
      DO 216 L=1,J1
      DELBIG=DELBIG+(THK(L)*UB)/SRTBK(V(J),V(L),UB)
      DELLIT=DELLIT+(THK(L)*UL)/SRTBK(V(J),V(L),UL)
  216 CONTINUE
  218 LL=LL+1
      IF(DELBIG-DELLIT .LT. 0.02) GO TO 231
      XTR=XLIT+(DELTA(I)-DELLIT)*(XBIG-XLIT)/(DELBIG-DELLIT)
      U=XTR/SQRT((XTR*XTR)+(TKJ*TKJ))
      DELXTR=TKJ*U/SQRT(1.0-U*U)
      DO 220 L=1,J1
      DELXTR=DELXTR+(THK(L)*U)/SRTBK(V(J),V(L),U)
  220 CONTINUE
      TEST=DELTA(I)-DELXTR
      IF(ABS(TEST)-0.02)235,235,221
  221 IF(TEST)222,235,226
  222 XBIG=XTR
      DELBIG=DELXTR
      GO TO 230
  226 XLIT=XTR
      DELLIT=DELXTR
      IF(1.0-U .LT. 0.0002 .AND. LL .GE. 10) GO TO 235
  230 IF(LL .LT. 25) GO TO 218
      GO TO 235
  231 XTR=0.5*(XBIG+XLIT)
      U=XTR/SQRT((XTR*XTR)+(TKJ*TKJ))
  235 CONTINUE
      IF(1.0-U .GT. 0.0002) GO TO 238
C IF U IS TOO NEAR 1.0 COMPUTE TDIR AS WAVE ALONG TOP OF LAYER J
  236 TDC=TID(J,J)+DELTA(I)/V(J)
      IF(J .EQ. N)GO TO 237
```

```
      IF(TDC-TMIN)237,120,120
  237 T(I)=TDC
      DTDD(I)=1.0/V(J)
      DTDH(I)=0.0
      MODE(I)=3
      GO TO 300
C COMPUTE TDIR FROM ROOT OF DELTA(U) EQUATION
  238 TDIR=TKJ/(V(J)*SQRT(1.0-U*U))
  239 DO 240 L=1,J1
      TDIR=TDIR+(THK(L)*V(J))/(V(L)*V(L)*SRTBK(V(J),V(L),U))
  240 CONTINUE
      IF(J .EQ. N)GO TO 245
  243 IF(TDIR-TMIN)245,120,120
  245 T(I)=TDIR
C COMPUTE DTDD(I) AND DTDH(I)
      ALFA=TKJ/SQRT(1.0-U*U)**3
      BETA=TKJ*U/(V(J)*SQRT(1.0-U*U)**3)
      DO 247 L=1,J1
      ALFA=ALFA+THK(L)*V(J)*V(J)/(V(L)*V(L)*SRTBK(V(J),V(L),U)**3)
      BETA=BETA+THK(L)*V(J)*U/(V(L)*V(L)*SRTBK(V(J),V(L),U)**3)
  247 CONTINUE
      DTDD(I)=BETA/ALFA
      DTDH(I)=(1.0-V(J)*U*DTDD(I))/(V(J)*SQRT(1.0-U*U))
      MODE(I)=4
  300 CONTINUE
  310 WRITE(6,530)N,H,J,TKJ,(D(L),V(L),L=1,N)
  530 FORMAT(1H-,7X,2HN=,I3,5X,2HH=,F7.2,3X,2HJ=,I3,2X,4HTKJ=,F7.2,//
     110X,5HDEPTH,10X,8HVELOCITY,/,(8X,F7.3,10X,F7.3))
  315 WRITE(6,535)(I,DELTA(I),T(I),DTDD(I),DTDH(I),MODE(I),I=1,KREC)
  535 FORMAT(1H0,4X,1HI,5X,8HDELTA(I),10X,4HT(I),7X,7HDTDD(I),
     17X,7HDTDH(I),7X,7HMODE(I),/(3X,I3,5X,F8.3,6X,F8.3,6X,F8.3,
     26X,F8.3,7X,I3))
C TEST FOR COMPLETION OF RUNS WITH DIFFERENT DEPTHS
  320 IF(HMAX-H)325,325,321
  321 H=H+DELH
  322 GO TO 51
  325 STOP
      END
/*
//GO.SYSIN DD *
   4     1.000      2.500      25.000
     3.900      0.000
     5.000      3.100
     6.800     11.200
     8.250     14.800
  10     1.000      5.000      10.000      15.000      20.000
    30.000     50.000     80.000     100.000     150.000
/*
//
```

```
IEF285I   LOADSET.TRAVDRIV                                     DELETED
IEF285I   VOL SER NOS= SYS03 .
IEF285I   SYS1.FORTLIB                                         KEPT
IEF285I   VOL SER NOS= CAMP09.
IEF285I   SYS2.XTRINSIC                                        KEPT
IEF285I   VOL SER NOS= SYS01 .
IEF285I   SYS1.UT1                                             KEPT
IEF285I   VOL SER NOS= CAMP08.
IEF285I   GOSET.TRAVDRIV                                       PASSED
IEF285I   VOL SER NOS= SYS03 .
IEF285I   SYSOUT                                               SYSOUT
IEF285I   VOL SER NOS=        .
//GO      EXEC  PGM=*.LKED.SYSLMOD,COND=((5,LT,FORT),(5,LT,LKED))        0000
//FT01F001 DD DSNAME=SYS1.UT1,DISP=OLD,DCB=(RECFM=V)                     0000
//FT02F001 DD DSNAME=SYS1.UT2,DISP=OLD,DCB=(RECFM=V)                     0000
//FT03F001 DD DSNAME=SYS1.UT3,DISP=OLD,DCB=(RECFM=V)                     0000
//FT04F001 DD DSNAME=SYS1.UT4,DISP=OLD,DCB=(RECFM=V)                     0000
//FT05F001 DD  DDNAME=SYSIN                                              0000
//FT06F001 DD  SYSOUT=A                                                  0000
//FT07F001 DD  UNIT=SYSCP                                                0000
//FT13F001 DD DSNAME=SYS1.UT5,DISP=OLD,DCB=(RECFM=V)                     0000
//GO.SYSIN DD *
IEF236I ALLOC. FOR TRAVDRIV GO
IEF237I PGM=*.DD ON 330
IEF237I FT01F001 ON 1C0
IEF237I FT02F001 ON 330
IEF237I FT03F001 ON 330
IEF237I FT04F001 ON 330
IEF237I FT05F001 ON 00C
IEF237I FT07F001 ON 00D
IEF237I FT13F001 ON 330
```

N# 4   H# 1.00   J# 1   TKJ# 1.00

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<	DTDD%I<	DTDH%I<	MODE%I<
1	1.000	0.363	0.181	0.181	2
2	5.000	1.307	0.251	0.050	2
3	10.000	2.577	0.255	0.026	2
4	15.000	3.834	0.200	-0.160	1
5	20.000	4.834	0.200	-0.160	1
6	30.000	6.834	0.200	-0.160	1
7	50.000	10.412	0.121	-0.226	1
8	80.000	14.049	0.121	-0.226	1
9	100.000	16.473	0.121	-0.226	1
10	150.000	22.533	0.121	-0.226	1

N# 4   H# 3.50   J# 2   TKJ# 0.40

DEPTH	VELOCITY
0.0	3.900
3.100	5.000

11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<	DTDD%I<	DTDH%I<	MODE%I<
1	1.000	0.910	0.068	0.188	4
2	5.000	1.511	0.193	0.053	4
3	10.000	2.503	0.200	0.013	4
4	15.000	3.499	0.200	0.007	4
5	20.000	4.502	0.200	0.005	4
6	30.000	6.497	0.200	0.0	3
7	50.000	9.874	0.121	-0.159	1
8	80.000	13.510	0.121	-0.159	1
9	100.000	15.935	0.121	-0.159	1
10	150.000	21.995	0.121	-0.159	1

N# 4 H# 6.00 J# 2 TKJ# 2.90

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<	DTDD%I<	DTDH%I<	MODE%I<
1	1.000	1.394	0.037	0.197	4
2	5.000	1.781	0.142	0.141	4
3	10.000	2.622	0.184	0.078	4
4	15.000	3.571	0.194	0.049	4
5	20.000	4.549	0.197	0.035	4
6	30.000	6.533	0.199	0.022	4
7	50.000	9.476	0.121	-0.159	1
8	80.000	13.113	0.121	-0.159	1
9	100.000	15.537	0.121	-0.159	1
10	150.000	21.598	0.121	-0.159	1

N# 4 H# 8.50 J# 2 TKJ# 5.40

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<	DTDD%I<	DTDH%I<	MODE%I<
1	1.000	1.888	0.025	0.198	4
2	5.000	2.171	0.110	0.167	4
3	10.000	2.870	0.162	0.117	4
4	15.000	3.738	0.182	0.083	4
5	20.000	4.671	0.190	0.062	4
6	30.000	6.527	0.147	-0.136	1
7	50.000	9.079	0.121	-0.159	1
8	80.000	12.715	0.121	-0.159	1
9	100.000	15.139	0.121	-0.159	1
10	150.000	21.200	0.121	-0.159	1

N# 4 H# 11.00 J# 2 TKJ# 7.90

DEPTH VELOCITY

0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<		DTDD%I<	DTDH%I<	MODE%I<
1	1.000	2.385	✓	0.019	0.199	4
2	5.000	2.606	605	0.088	0.180	4
3	10.000	3.197	194	0.142	0.141	4
4	15.000	3.978	979	0.168	0.108	4
5	20.000	4.717	✓	0.147	-0.136	1
6	30.000	6.188	✓	0.147	-0.136	1
7	50.000	8.681	✓	0.121	-0.159	1
8	80.000	12.317	✓	0.121	-0.159	1
9	100.000	14.742	✓	0.121	-0.159	1
10	150.000	20.802	✓ ±3	0.121	-0.159	1

N# 4 H# 13.50 J# 3 TKJ# 2.30

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<		DTDD%I<	DTDH%I<	MODE%I<
1	1.000	2.761	760	0.015	0.146	4
2	5.000	2.930	✓	0.068	0.130	4
3	10.000	3.397	✓	0.114	0.093	4
4	15.000	4.031	030	0.136	0.056	4
5	20.000	4.733	731	0.143	0.034	4
6	30.000	6.033	✓	0.121	-0.083	1
7	50.000	8.458	✓	0.121	-0.083	1
8	80.000	12.094	✓	0.121	-0.083	1
9	100.000	14.518	✓	0.121	-0.083	1
10	150.000	20.579	✓ ±2	0.121	-0.083	1

N# 4 H# 16.00 J# 4 TKJ# 1.20

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<		DTDD%I<		DTDH%I<		MODE%I<
1	1.000	3.095	096	0.011	012	0.121		4
2	5.000	3.230	✓	0.054		0.108		4
3	10.000	3.610	608	0.094		0.076	077	4
4	15.000	4.139	137	0.114		0.040	041	4
5	20.000	4.727	724	0.120		0.020		4
6	30.000	5.931	930	0.121		0.009		4
7	50.000	8.354	353	0.121		0.004		4
8	80.000	11.986	✓	0.121		0.0	002	3 4
9	100.000	14.410	✓	0.121		0.0		3
10	150.000	20.471	✓ ±3	0.121		0.0		3

5|4 N# 4 H# 18.50 J# 4 TKJ# 3.70

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<	DTDD%I<	DTDH%I<	MODE%I<
1	1.000	3.397	0.009	0.121	4
2	5.000	3.507	0.045	0.113	4
3	10.000	3.822	0.079	0.092	4
4	15.000	4.278	0.101	0.067	4
5	20.000	4.813	0.112	0.047	4
6	30.000	5.973	0.119	0.025	4
7	50.000	8.374	0.121	0.012	4
8	80.000	11.999	0.121	0.007	4
9	100.000	14.419	0.121	0.005	4
10	150.000	20.478	0.121	0.003	4

N# 4 H# 21.00 J# 4 TKJ# 6.20

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<	DTDD%I<	DTDH%I<	MODE%I<
1	1.000	3.700	0.008	0.121	4
2	5.000	3.792	0.038	0.115	4
3	10.000	4.062	0.069	0.100	4
4	15.000	4.464	0.090	0.081	4
5	20.000	4.952	0.104	0.063	4
6	30.000	6.055	0.115	0.039	4
7	50.000	8.414	0.120	0.020	4
8	80.000	12.021	0.121	0.011	4
9	100.000	14.437	0.121	0.009	4
10	150.000	20.488	0.121	0.005	4

N# 4 H# 23.50 J# 4 TKJ# 8.70

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<	DTDD%I<	DTDH%I<	MODE%I<
1	1.000	4.002	0.007	0.121	4
2	5.000	4.082	0.033	0.117	4
3	10.000	4.318	0.061	0.105	4
4	15.000	4.677	0.082	0.090	4
5	20.000	5.123	0.096	0.074	4
6	30.000	6.166	0.110	0.050	4
7	50.000	8.473	0.118	0.027	4
8	80.000	12.054	0.120	0.016	4
9	100.000	14.463	0.121	0.012	4
10	150.000	20.504	0.121	0.008	4

N# 4 H# 26.00 J# 4 TKJ# 11.20

DEPTH	VELOCITY
0.0	3.900
3.100	5.000
11.200	6.800
14.800	8.250

I	DELTA%I<	T%I<		DTDD%I<	DTDH%I<	MODE%I<
1	1.000	4.305	✓	0.006	0.121	4
2	5.000	4.375	✓	0.029	0.118	4
3	10.000	4.585	584	0.054	0.108	4
4	15.000	4.910	909	0.074	0.096	4
5	20.000	5.319	✓	0.089	0.082	4
6	30.000	6.303	304	0.106	0.060	4
7	50.000	8.550	549	0.116	0.034	4
8	80.000	12.099	✓	0.120	0.020	4
9	100.000	14.497	498	0.120	0.015	4
10	150.000	20.526	525	0.121	0.010	4

±1

Calculation of the plane-wave substitute solution

(VELAZ)

Let a plane wave, from a distant source at an azimuth ψ from the cluster and with a speed of V across the cluster strike station 1 at t_1 (nearest), station 2 at t_2 (farthest) and station 3 at t_3 (intermediate). Let the azimuths and distances of stations 2 and 3 (from station 1) be θ_2, l_2 + θ_3, l_3, respectively. Let $\phi \left(= \psi - \frac{3}{2}\pi\right)$ be the azimuth parallel the advancing wave front.

$$t_2 - t_1 = l_2 \sin(\theta_2 - \phi) / V$$

$$t_3 - t_1 = l_3 \sin(\theta_3 - \phi) / V$$

whence, eliminating V and setting $\gamma = \frac{t_3 - t_1}{t_2 - t_1} * \frac{l_2}{l_3}$

$$\sin(\theta_3 - \phi) = \gamma \sin(\theta_2 - \phi)$$

(See sketch D)

$$\tan \phi = \frac{\sin\theta_3 - \gamma \sin\theta_2}{\cos\theta_3 - \gamma\cos\theta_2}$$

Thus,

$$\phi = \tan^{-1}\left(\frac{\sin\theta_3 - \gamma\sin\theta_2}{\cos\theta_3 - \gamma\cos\theta_2}\right)$$

$$V = \frac{l_2 \sin(\theta_2 - \phi)}{t_2 - t_1}$$

VELAZ SKETCH D

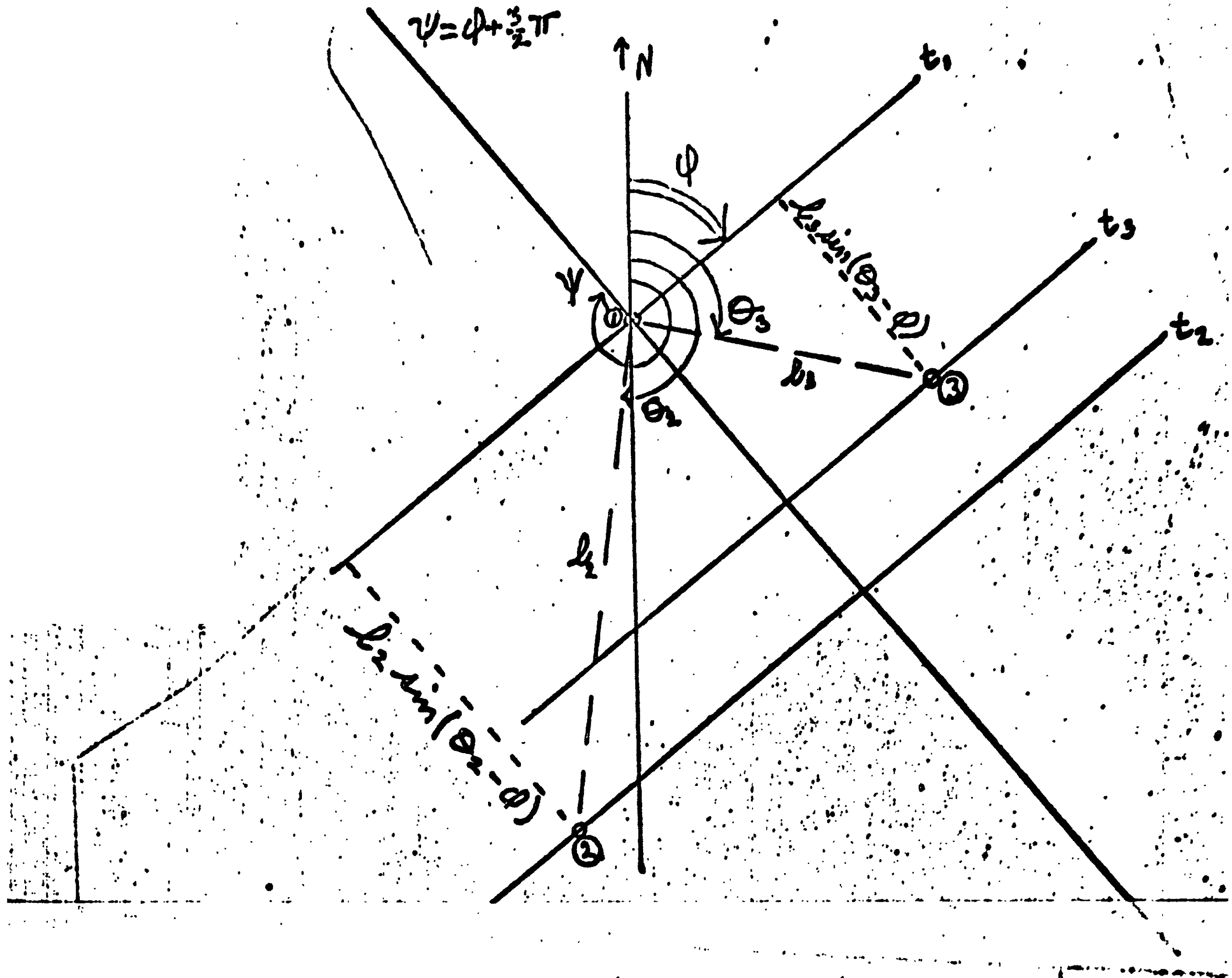


Diagram illustrating notation used in the VELAZ subroutine

Let $T_i = l_i \sin(\theta_i - \phi) / V = (t_i - t_1)_c$
be the calculated traveltime between stations 1 and i.

Let $\tau_i = (t_i - t_1)$ be the corresponding observed traveltime.

Let $F_i = \tau_i - T_i$, the station 1 to station i traveltime anomaly.

T_i is a function of V and ϕ (and hence F_i is also). In any adjustment of V and ϕ, $dF_i = -dT_i$.

Let E_i be the residual that remains after an adjustment of T_i $(E_i = F_i + dF_i)$. Then

$$E_i = F_i - dT_i.$$

$$dT_i = \frac{\partial T_i}{\partial V} dV + \frac{\partial T_i}{\partial \phi} d\phi$$

$$\frac{\partial T_i}{\partial V} = -\frac{l_i \sin(\theta_i - \phi)}{V^2}, \quad \frac{\partial T_i}{\partial \phi} = -\frac{l_i \cos(\theta_i - \phi)}{V}$$

$$E_i = F_i + \frac{l_i \sin(\theta_i - \phi)}{V^2} dV + \frac{l_i \cos(\theta_i - \phi)}{V} d\phi.$$

Let $\alpha_i = \dfrac{l_i \sin(\theta_i - \phi)}{V^2}$, $\beta_i = \dfrac{l_i \cos(\theta_i - \phi)}{V}$,
$Y_1 = dV$, and $Y_2 = d\phi$.

Then $E_i = F_i + \alpha_i Y_1 + \beta_i Y_2$

To minimize $\sum E_i^2$ we must have

$$\frac{\partial}{\partial Y_1} \sum E_i^2 = 0 \quad \text{and} \quad \frac{\partial}{\partial Y_2} \sum E_i^2 = 0.$$

Thus

$$\sum \frac{\partial E_i}{\partial Y_1} * E_i = 0 \quad \text{and} \quad \sum \frac{\partial E_i}{\partial Y_2} * E_i = 0.$$

$$\frac{\partial E_i}{\partial Y_1} = \alpha_i \ , \quad \frac{\partial E_i}{\partial Y_2} = \beta_i$$

$$\sum \alpha_i E_i = [\alpha_i \alpha_i] Y_1 + [\alpha_i \beta_i] Y_2 + [\alpha_i F_i] = 0$$

$$\sum \beta_i E_i = [\beta_i \alpha_i] Y_1 + [\beta_i \beta_i] Y_2 + [\beta_i F_i] = 0$$

Let

$$A_{11} = [\alpha_i \alpha_i] \ , \quad A_{12} = [\alpha_i \beta_i] \ , \quad B_1 = -[\alpha_i F_i] \ ,$$

$$A_{21} = [\beta_i \alpha_i] \ , \quad A_{22} = [\beta_i \beta_i] \ , \quad B_1 = -[\beta_i F_i] \ .$$

Then

$$A_{11} Y_1 + A_{12} Y_2 = B_1$$
$$A_{21} Y_1 + A_{22} Y_2 = B_2$$

Let

$$DET = A_{11} A_{22} - A_{21} A_{12} \ .$$

Finally

$$Y_1 = \frac{B_1 * A_{22} - B_2 * A_{12}}{DET} = dV$$

$$Y_2 = \frac{A_{11} B_2 - A_{21} B_1}{DET} = d\phi$$

Apply these corrections to V and ϕ, and then recalculate the residuals F_i and proceed with another round of correction. When the adjustment in ϕ, $d\phi$, falls below 0.0001 rad, discontinue the adjustment.

Calculate $AAF = \sum_{i=1}^{N} |F_i| \Big/ N$ as a measure of "fit".

Determination of Magnitudes of Microearthquakes Recorded at Small Epicentral Distances

(MAGNTD)

In his pioneering studies of southern California earthquakes during the early 1930's, C. F. Richter observed that the manner in which the maximum trace amplitude, recorded by a standard short-period Wood-Anderson seismograph, diminished with increasing epicentral distance was independent of the size of the earthquake. Thus, $\log \mathcal{B}$ vs Δ plots ($\mathcal{B}$ = maximum trace amplitude recorded on the Wood-Anderson and Δ = epicentral distance) for earthquakes of various sizes were of a single shape but were displaced, without rotation, relative to each other parallel to the $\log \mathcal{B}$ axis: the vertical separation of the curves for two earthquakes being equal to the logarithm of the ratio of their amplitudes. The separation of the curves for two earthquakes is a convenient measure of their difference in size, or (as it was defined by Richter) their difference in magnitude.

Richter (1935) defined magnitude as follows: "The magnitude of any shock is taken as the logarithm of the maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer (To = 0.8 sec, V = 2800, h = 0.8) would register that shock at an epicentral distance of 100 kilometers." He plotted $\log \mathcal{B}$ vs Δ curves for earthquakes recorded on the southern California network during January 1932 (about 50 earthquakes with magnitudes between 0.5 and 4.5). He then fitted a curve to the $\log \mathcal{B}$ vs Δ diagram which, at every distance, was parallel the data curves and crossed the $\log \mathcal{B}$ axis at Δ = 100 km. This curve (call it the $\log \mathcal{B}_0$ vs Δ curve) corresponds to that for an earthquake with magnitude zero. The "kit" for computation of earthquake magnitudes was then complete. For an earthquake recorded with maximum amplitude B_1 at distance Δ_1, $M_1 = \log B_1 - \log B_0$, where $\log B_0$ is read from the curve at distance Δ_1.

To check the validity of the $\log B$ vs Δ curve, Richter applied the method outlined above to calculate magnitudes for 21 previously studied southern California earthquakes, with magnitudes from 3.2 to 5.2, recorded at distances between 44 and 520 km. He found that data from these earthquakes did not suggest any need to revise the $\log B$ vs Δ curve but did show the need for individual station corrections that ranged from + .25 unit (Pasadena N-S) to - .40 unit (Tinemeha E-W). Richter cautioned that the $\log B$ vs Δ curve was only poorly established for distances less than 50 km; and below 25 km it was not established at all.

An attempt to establish the curve for smaller epicentral distances was described by Gutenberg and Richter (1942) in conjunction with further manipulation of the magnitude concept. They showed that $\log B' - M + 2\log D \approx const$ for Δ between 22 and 525 km (assuming a focal depth, h, of 18 km, with $D = \sqrt{\Delta^2 + 18^2}$, where M is the earthquake magnitude and where B' is the maximum trace amplitude of short-period waves on the strong-motion torsion seismometers at Pasadena). Thus, $B'D^2 \approx const$, and this relationship can be used to calculate $\log B_0$ for Δ less than 50 km if we assume a standard focal depth (18 km was chosen). For an earthquake with a focal depth significantly different from 18 km recorded at a small epicentral distance, the magnitude computed on the basis of the extended $\log B_0$ curve could be grossly in error. We might also protest that the method used to establish the relationship $B'D^2 \approx const$ involved the use of only one instrument and a whole series of earthquakes of increasing magnitude and distance. Thus, variations in the relative excitation of long- vs short-period waves, variations in the rate of attenuation with distance of long- vs short-period waves, etc., are inextricably involved in the relationship obtained, which in turn is used to extend the $\log B_0$ vs Δ curve to short distances for use with very small earthquakes.

Several extremely thorny problems arise when one attempts to compute magnitudes for microearthquakes recorded on modern seismographic equipment at short distances. These problems include:

1. focal depth cannot properly be ignored at short distances so we need a relationship between amplitude and hypocentral (not epicentral) distance for the zero magnitude earthquake.

2. the response of the Wood-Anderson seismograph is implicitly included in Richter's definition of magnitude. These instruments are quite inadequate for the study of microearthquakes. Moreover, their sensitivity is so much lower than most instruments used in microearthquake studies that it is difficult to "calibrate" the new systems for magnitude calculations by simple overlap of observations.

3. the Wood-Anderson records horizontal ground motion, whereas the most widely deployed microearthquake seismographs are vertical component instruments.

4. unlike teleseisms, for which quite specific wave types can be identified (P, PP, S, etc.) and used for assignment of magnitudes, local

earthquakes generally cannot be reliably resolved into their component waves. The waves which are largest in any given range of distance (indeed those which can be identified at all) vary from region to region depending on the details of crustal structure. In very general terms, the direct S-wave (through the upper crust) is usually largest from 0 to 100-200 km. Between 100 and 200 km (varying with crustal structure and focal depth) the S-wave reflection from the base of the crust emerges with much larger (up to 10 times) the amplitude of the direct S-wave. Beyond the point of emergence of S_MS, this phase diminishes rapidly; and within the next 100 km it has dropped into the background and waves with more complex paths become the largest on the seismogram.

5. attenuation of seismic waves within the crust varies widely from region to region, and assignment of magnitudes on the basis of waves with paths predominantly within the crust will be strongly affected by such variations: the $\log B_0$ vs Δ curve, in short, should vary from region to region.

Subroutine MAGNTD was written to assign magnitudes compatible with the Richter "local" magnitude to microearthquakes recorded on the USGS portable seismograph cluster. The method employed to achieve this goal can be outlined as follows:

1. the exponent, k, of hypocentral distance in a law $A D^k = const$ (A = ground amplitude corresponding to the maximum vertical component trace amplitude, D = hypocentral distance) was evaluated on the basis of about 100 earthquakes recorded on the portable cluster in central California at distances of 0 to 150 km and for focal depths of $\approx$ 0 to

14 km. It was found that $k = 1.7$ fit the data (earthquake by earthquake) quite closely and that k does not appear to depend on focal depth nor on magnitude.

2. the $\log B_0$ vs Δ curve of Richter was converted to a $\log B_0$ vs $\log D$ plot (where $D = \sqrt{\Delta^2+18^2}$) and lines with slopes of 1.5, 1.7, and 2.0 were drawn through the plotted points to test the adequacy of a relationship of the form $B_0 D^k = const$ to express the zero magnitude earthquake amplitude vs distance relationship. Beyond 200 km k is greater than 2. Between 50 and 150 km, a value $k = 1.5$ fits the data quite well. For $K = 1.7$, the overall fit from 30 km to nearly 300 km is adequate: no point lies more than 0.10 unit (of $\log B_0$) off the curve. The plotted points lie above the curve for D less than 40 km and D between 80 and 250 km. Between 40 and 80 km and beyond 250 km, they lie below the $K = 1.7$ curve. At distances smaller than 30 or 40 km, the B_0 values are too poorly established to be considered seriously.

If we divide B_0 by 2800 (i.e., by the static magnification of the Wood-Anderson) to obtain $A_{0\mu}$, the equation representing the ground amplitude (in microns) of the zero magnitude earthquake can be written $A_{0\mu} \cdot D^{1.7} = 0.71$. This relationship is not independent of the WA response curve because for earth periods greater than 0.8 sec, the magnification of this instrument falls rapidly from its static magnification of 2800.

The difference in response of the USGS portable systems from that of the WA results from several factors: (a) gross difference in sensitivity, (b) restricted passband of the portable system electronics--

ca 17 cps to 0.5 cps, (c) displacement "velocity" response of the EV17 seismometers in the portable system vs displacement response of the WA. As in the derivation of the equation in A_{o_μ} above, it is convenient to ignore the portion of the period-dependency in the EV17 response that results from the tendency of the suspended mass to "follow" the ground motion at earth periods that are longer than the free period of the seismometer (1.0 sec). Such a simplification in the reduction of recorded amplitude to ground amplitude in the case of the portable system introduces an error that is very nearly the same as that introduced in the derivation of A_{o_μ}, above. Consequently, the logarithm of the maximum recorded ground motion, as calculated from the portable system seismogram, minus the logarithm of A_{o_μ} for the corresponding value of D, should yield the same magnitude as would have been obtained from a super-sensitive Wood-Anderson.

4. Since the WA measures the horizontal component of ground motion and the EV17 measures the vertical component, we must correct the computed magnitudes for a systemmatic difference in maximum horizontal and vertical recorded amplitudes. A number of the portable systems employed to establish the value of k included horizontal (EV17-H) seismographs as well as verticals. At those stations the ratios X_H/P_z and X_H/X_z were measured for annumber of events. The first ratio varied from less than 0.5 to about 8, with a median value of 2.5 (the distribution was bimodal, with peaks at 1.2 and 3.3). The second ratio varied from 0.2 to 8, with a median value of 1.75 (mode = 1.25). As only about 90 observations were used in this study, further work is required. Tentative corrections are + .40 to magnitudes based on P_z and + .25 to magnitudes based on X_z.

An analysis of the portable system response shows that record amplitude can be converted to ground-motion amplitude by the relationship

$$A'_{\mu} = 1.03 \times (T \times S / C_{10}) \times 10^{-2}$$

for earth periods shorter than about 1.0 sec, where

A'_{μ} = ground amplitude in microns

S = maximum trace amplitude in mm (peak to trough).

C_{10} = trace amplitude in mm (peak to trough) resulting from a $10\mu V(rms)$ signal introduced into the seismic amplifier in lieu of the seismometer output.

T = period (in seconds) of the wave with amplitude S.

The logarithm of $A'_{\mu} / A_{o_{\mu}}$ is the magnitude of the earthquake. Thus,

$$Mag = \log A'_{\mu} - \log A_{o_{\mu}} = \log\left(1.03 \times \frac{S \cdot T}{C_{10}} \times D^{1.7}\right) - 1.85$$

This relationship would apply to the calculation of magnitude using the maximum amplitude on the horizontal EV17-H trace. To shift to the EV17 vertical trace the constant should be changed from -1.85 to -1.60 if the maximum vertical amplitude is used or to -1.45 if the P-wave amplitude is used.

In subroutine MAGNTD provision is made for the use of both P and the maximum ("X") on the vertical component for the computation of magnitude. The magnitude equation is written in the form:

$$MAGP = \log\left(CNST * \frac{S*T}{C_{10}}\right) + PWRP * \log D^2 - ZPMAG$$

for P, and

$$MAGX = \log\left(CNST * \frac{S*T}{C_{10}}\right) + PWRX * \log D^2 - ZXMAG$$

for X.

The parameters CNST, PWRP, ZPMAG, PWRX, and ZXMAG are read into the program at execution time. Thus, the exponent of D and the constants (composed of many factors, including instruments sensitivity, etc.) can be adjusted as required by variations in instrumentation and region.

The constant (0.71) in the equation $A_{o\mu} * D^{1.7} = 0.71$ is sensitive to the distance range over which we choose to fit the power law most closely to the zero magnitude reference data. Because magnitude is "defined" at $\Delta = 100\ km$, it is tempting to draw the power-law curve through the $\log B_o$ point at $\Delta = 100\ km$. For the microearthquakes recorded by the portable system, most observations are at distances smaller than 100 km--averaging 30 km or so. Thus, the curve resulting in the constant 0.71 was drawn to match the B_o vs D data in the range of 30 to 100 km.

In view of the difference in attenuation from region to region, it seems that 100 km is unfortunately large for a magnitude-reference distance if we truly wish an earthquake's magnitude to be simply related to the energy radiated from the focus. Use of a smaller reference distance would require a higher precision in depth determination that is generally attainable at present, however.

Statistical Calculations

Statistical Calculations for Individual Earthquakes

To characterize the quality and reliability of individual hypocentral solutions, a variety of residuals and statistical parameters are calculated. These include:

$F_i = \tau_i - t_i$ = the arrival time residual at station i

$AAF = \sum_{i=1}^{N} |F_i| / N$ = the mean deviation

$AVR = \sum_{i=1}^{N} F_i / N$ = the average residual

$SDP = \left(\frac{\sum_{i=1}^{N} F_i^2}{N-MM-1} \right)^{1/2}$ = the standard deviation of the arrival-time residuals

$SDX = SDP \times (A_{11}^{-1})^{1/2}$ = standard error in longitude (km)

$SDY = SDP \times (A_{22}^{-1})^{1/2}$ = standard error in latitude (km)

$SDZ = SDP \times (A_{33}^{-1})^{1/2}$ = standard error in depth (km)

$SDT = SDP \times (A_{44}^{-1})^{1/2}$ = standard error in origin time (sec)

N = number of observations (with combined weights greater than 0.1).

MM = number of hypocentral parameters adjusted.

A_{11}^{-1}, etc. = appropriate elements on the principal diagonal of the inverse matrix of coefficients of the unknowns.

$(RSPMG)_i$ = station i P-mag—average P-mag.

$(RSXMG)_i$ = station i X-mag—average X-mag.

Statistical Summary Calculations for a Batch of Earthquakes

A number of counters and sum registers and a variety of tests have been included in the main program to permit the calculation of average residual, standard deviation of the residual, and standard error of the mean residual for the residuals of arrival time, P-magnitude, and X-magnitude at each station for which an adequate number of observations are available in a batch of earthquakes.

For station i (arrival-time-residual statistics):

$$AVRES_i = \sum_{j=1}^{L} (F_i)_j \Big/ L$$

$$SDRES_i = \left[\frac{\left(L \times \sum_{j=1}^{L} (F_i)_j^2 \right) - \left(\sum_{j=1}^{L} (F_i)_j \right)^2}{L(L-1)} \right]^{1/2}$$

$$SEM_i = SDRES_i \Big/ L^{1/2}$$

The equations for P-magnitude and X-magnitude are analogous.

For inclusion in the statistical summary, an earthquake must be recorded by at least KTTA stations, have an AAF less than TAAF, and have been located with fewer than IIT iterations. For an individual observation to be included in the summary it must not be larger than TFR (for an arrival-time residual) or AMTST (for a magnitude residual) and must have a combined weight (of the P-phase) of at least TWT (for an arrival-time residual).

KTTA, TAAF, IIT, TFR, AMTST, and TWT are parameters read in at execution time.

These data can be used to correct for obvious persistent station anomalies. For the arrival-time residual this correction can be made by adding the average residual for a station to the "station delay" on the station parameter list.

Provision has also been made to include a station and its data in a batch of earthquakes in such a manner that it is not used in the adjustment of the hypocenter but is treated normally in other respects, including the calculation of summary statistical parameters. Stations listed in the "KOMIT" list on the parameter card extension DX2 are treated in this manner.

<u>Restrictions and Termination Conditions Applied in the Adjustment of Hypocentral Parameters in HYPOLAYR</u>

1. Depth is not adjusted:

   a. on the first iteration.

   b. if the range in $\partial T/\partial z$, RAH, is less than 0.02.

   c. if the previous adjustment in epicenter is greater than 10 km.

2. Depth is not permitted to become negative (focus in air). Any calculated correction that would place the hypocenter above ground is scaled down so that the hypocenter is raised 6/10 of the distance to the surface. Horizontal and time adjustments are also scaled down, but no farther than 4/10 of the values originally computed.

3. Adjustment is not terminated prior to the 5th iteration.

4. If depth control has been lost by the 4th iteration, the depth is returned to ZTR before the 5th.

5. If $|AVR| \leq$ AVLT (e.g., $\leq$ 0.002),

a. adjustment is terminated after 5 iterations if AAF < AFLT (e.g., < 0.10) and DAAF < ADLT (e.g., < 0.005).

b. adjustment is terminated after 8 iterations if AAF < AFLP (e.g., < 0.30) and DAAF < ADLP (e.g., < 0.003).

6. If |AVR| ≥ AVLT

a. adjustment is terminated if DAAF < AVLT, i.e., for a stationary solution. II is set equal to "14", AVR is added to the origin time, and the arrival-time residuals and solution statistics are recalculated.

b. II = 12

II is set equal to "13", AVR is added to the origin time, and the arrival-time residuals and solution statistics are recalculated.

HYPOLAYR

List of variables

NSTA (2,99)	A4	Station name (on station list)
LAT (2,99)	F2.0	Station latitude, degrees
YAT (2,99)	F5.2	Station latitude, minutes
LON (2,99)	F3.0	station longitude, degrees
XON (2,99)	F5,2	station longitude, minutes
EL (2,99)	F4.0	station elevation, meters
DLY (2,99)	F5.2	station delay, seconds
MDL (2,99)	I1	Crustal model used with station
KSITE		Number of stations in station list
V1(25)	F7.3	Layer velocity, model 1
DP1(25)	F7.3	Depth to top of layer, model 1
NL1		Number of layers, model 1
V2(25)	F7.3	Layer velocity, model 2
DP2(25)	F7.3	Depth to top of layer, model 2
NL2		Number of layers, model 2
LATR	F2.0	Trial latitude, degrees
YATTR	F5.2	Trial latitude, minutes
LOTR	F3.0	Trial longitude, degrees
XONTR	F5.2	Trial longitude, minutes
ZTR	F5.2	Trial focal depth, km
LARED	F2.0	Latitude reduction, degrees
LORED	F3.0	Longitude reduction, degrees
DELAZ	F6.1	Test distance for calling VELAZ

VB	F5.2	Half-space velocity for PREHY
MODE	I1	Key to "MODE" computation options
LPC	I1	Punch card option selector
INPRIN	I1	Intermediate printout option selector
IFMT	I1	Phase-card format selector
QQ	F7.5	Factor for latitude to km conversion
PPP	F7.5	Factor for longitude to km conversion
ISTS	I1	Statistical section option selector
KOLT	I2	Number of stations in ordered P-arrival list
SMP	F5.2	Factor to convert "S-P" interval to "P-O" interval
XNEAR	F5.0	Lower limit in "distance weighting" equation
XFAR	F5.0	Upper limit in "distance weighting" equation
HILO	F5.2	Multiplier to convert low-gain-trace amplitudes
CNST	F5.2	System sensitivity factor
PWRP	F5.2	Distance exponent in "P" amplitude-distance law
ZPMAG	F5.2	Constant depending on "0" magnitude earthquake P-amplitude
PWRX	F5.2	Distance exponent in "X" amplitude-distance law
ZXMAG	F5.2	Constant depending on "0" magnitude earthquake P-amplitude

AVLT	F5.2	Test value for average residual (AVR)
AFLT	F5.2	First test value for mean deviation (AAF)
AFLP	F5.2	Second test value for mean deviation (AAP)
ADLT	F5.3	First test value for change in mean deviation (DAAP)
ADLP	F5.3	Second test value for change in mean deviation (DAAF)
TAAF	F10.3	Test value for mean deviation in station section
TFR	F10.3	Test value for station residual in station section
TWT	F10.3	Test value for combined weight in station section
AMTST	F10.3	Test value for magnitude residual in station section
IIT	I5	Test value for number of iterations in station section
KTTA	I5	Test value for number of observations in station section
KOMIT	I5	Number of stations on "neglect" list
NOMIT(99)	A4	Name of station on "neglect" list

NL		Number of layers	TPAR working variables
V(25)		Velocity of P in layer	
DP(25)		Depth to top of layer	
THK(25)		Thickness of layer	
TID(25,25)		"Boundary" source intercept	
DID(25,25)		"Boundary" source critical distance distance	
THK1(25)		Layer thickness, model 1	
TID1(25,25)		"Boundary" source intercept, model 1	
DID1(25,25)		"Boundary" source critical distance, model 1	
THK2(25)		Layer thickness, model 2	
TID2(25,25)		"Boundary" source intercept, model 2	
DID2(25,25)		"Boundary" source critical distance model 2	
KSW, SUM1, SUM2, SUMA, SUMB, SQT		TPAR internal utility variables	
MSTA(99)	A4	Station name on phase list	
QSABE(99)	A3	Alphameric tag, e.g., "IPU"	
W(99)	F2.1	Weight (quality of P-arrival)	
KDATE(99)	I6	Date (year, month, day)	
JHR(99)	I2	Hour	

JMIN(99)	I2	Minute
P(99)	F5.2	P arrival time (seconds)
AMP(99)	F4.0	P amplitude (peak-trough, mm)
PRP(99)	F3.2	P period (seconds)
S(99)	F5.2	S arrival time (seconds
AMS(99)	F4.0	S amplitude (peak-trough, mm)
PRS(99)	F3.2	S period (seconds)
AMX(99)	F4.0	"X" amplitude (peak-trough, mm)
PRX(99)	F3.2	"X" period (seconds)
CALP(99)	F4.1	Calibration for P-phase amplitude
CALS(99)	F4.1	Calibration for S phase amplitude
CALX(99)	F4.1	Calibration for "X" phase amplitude
RK(99)	A3	Remarks
DT(99)	F5.2	Chronometer correction (sec)
INST	I2	Key to "INST" operation options
ZRES	F5.2	Depth restriction for specific event (km)
KREC		Number of phase cards read for earthquake
IHR		"Hour" of earliest arrival
G(99)		Distance-dependent weighting factor for P
GW(99)		Aux. variable in routine for omitting specified stations
TP(99)		Reduced P-arrival time (seconds)
PT(99)		Array used in ordering of P-arrival times
ORGS		"S-P" derived origin time

LOSW	Flag indicating existence of ORGS
KOLT	Number of stations in ordered P-time array
KO(99)	Array of indices of stations in ordered P-time array
NEAR	Index of earliest station
PMIN	P-arrival time at earliest station
MFAR	Index of latest station in ordered P-array
PFAR	P-arrival time at latest station in ordered P-array
KALX	Index of ordered array station farthest from line joining station NEAR and station MFAR
LHY	Flag indicating PREHY option used
ORG	Origin time in seconds (reduced)
LONEP	Epicenter longitude (degrees)
XONEP	Epicenter longitude (minutes)
LATEP	Epicenter latitude (degrees)
YATEP	Epicenter latitude (minutes)
Z	Focal depth (km)
ZHLAT	Reduced latitude (minutes) of station NEAR
PH	Km per minute of longitude at ZHLAT
DIST1(99)	Distance of station from station NEAR
TH1(99)	Azimuth of given station from station NEAR

ALT	Distance from line between station NEAR and station KOLT
KALMX	Index of station farthest to "right" of line between station NEAR and station KOLT
KALMN	Index of station farthest to "left" of line between station NEAR and station KOLT
ALTMX	Distance of station KALMX from line between station NEAR and station KOLT
ALTMN	Distance of station KALMN from line between station NEAR and station KOLT
XH(99)	Distance of station (in km) west of station NEAR
YH(99)	Distance of station (in km) north of station NEAR
AP(3,3)	Coefficients of unknowns in Inglada's equation
BP(3)	Known's in Inglada's equation
DETAP	Determinant of AP's
XNOT	Epicenter X-coord (km)
YNOT	Epicenter Y-coord (km)
T1	Traveltime of P to station NEAR
ZSQ	Utility variable in PREHX
DST1	Utility variable in PREHY
DST2	Utility variable in PREHY

DET3	Determinant of unknowns in "reduced problem
RP2	Combination of knowns in "reduced" problem
RP3	combination of knowns in "reduced" problem
G1	Combination of knowns in "reduced" problem
G2	Combination of knowns in "reduced" problem
G3	Combination of knowns in "reduced" problem
G4	Combination of knowns in "reduced" problem
G5	Combination of variables in "reduced" problem
G6	Combination of variables in "reduced" problem
G7	Combination of variables in "reduced" problem
G8	Combination of variables in "reduced" problem
G9	Combination of variables in "reduced" problem
T1P	T1, using $-\sqrt{\ }$
T1M	T1, using $+\sqrt{\ }$
AG5	Utility variable in PREHY
QSM	Utility variable in PREHY
AQSM	Utility variable in PREHY
QSP	Utility variable in PREHY
AQSP	Utility variable in PREHY
DEDN	Coefficient for calculating "distance" weighting factor

KAZ	Flag indicating routine used in VELAZ
KZSW	Switch to inhibit focal depth adjustment
II	Iteration counter in hypocenter adjustment loop
XEP	Epicenter "N-S" grid coordinate (+ = N)
YEP	Epicenter "E-W" grid coordinate (+ = W)
DELMN	Smallest epicenter-to-station distance
ZLAT	Mean of epicenter and station latitudes
PP	Longitude scale factor--minutes to km
DX(99)	Difference in station and epicenter X-grid coord
DY(99)	Difference in station and epicenter Y-grid coord
DELTA(99)	Epicentral distance (km)
KEY	Utility variable for selecting model in TRVDRV
TKJ	Depth of focus below top of layer
TINJ(25)	Intercept of wave refracted along top of layer from a focus in layer JL
DIDJ(25)	Critical distance of wave reflected from top of layer L from a focus in layer JL
XOVMAX	Distance beyond which first arrival must be a head wave
TR(99)	Calculated refraction time (tentative)
T(99)	First arrival traveltime

DTDD	$\partial T/\partial \Delta$
DTDH	$\partial T/\partial z$
ANIN(99)	Angle of incidence at the focus
TDJ1	Calculated traveltime of direct wave in layer J
LL	Iteration counter in loop to find root of refraction equation
XBIG	Utility variable in TRVDRV
XLIT	Utility variable in TRVDRV
UB	Utility variable in TRVDRV
UL	Utility variable in TRVDRV
ARGB	Utility variable in TRVDRV
ARGL	Utility variable in TRVDRV
DELBIG	Utility variable in TRVDRV
DELLIT	Utility variable in TRVDRV
XTR	Utility variable in TRVDRV
U	Root of refraction equation
ARGJ	Utility variable in TRVDRV
DELXTR	Utility variable in TRVDRV
TEST	Utility variable in TRVDRV
TDC	Traveltime of wave from focus very near top of layer
TDIR	Traveltime of wave from focus inside layer
ALFA	Utility variable in TRVDRV
BETA	Utility variable in TRVDRV

AX(99)	$\partial T / \partial x$
AY(99)	$\partial T / \partial y$
AH(99)	$\partial T / \partial z$
F(99)	Arrival-time residual
AAF	Mean deviation of arrival times
AAF1	Previous value of AAF
DAAF	Change in AAF
AWF	"Weighted" mean deviation
KSTA	Number of stations used in a solution
WSTA	Sum of weights of stations used in a solution
AVR	Average residual
ABVR	Absolute value of average residual
WT	Combined weight (W(I) * G(I))
AVR1	"Saved" value of AVR
[A(4,4)]	Coefficient of unknowns in normal equation
[B(4)]	Coefficient of knowns in normal equation
AHMX	Maximum AH
AHMN	Minimum AH
RAH	Range of AH
[D(3,3)]	Cofactor of A(I,J)
[C(4,4)]	Cofactor matrix of [A(4,4)]
DETA	Determinant of cofactor matrix

[Y(4)]	Hypocenter correction vector
MM	Rank of matrix of coefficient of adjustment equations
KOUT	Flag indicating HYCOR routine used in adjustment of hypocenter (which components adjusted)
ASDX ASDY ASDZ ASDT	Absolute values of the elements of the principal diagonal of the inverse matrix of the matrix of normal equation coefficients
A11 . . . A44	Utility variables in "reduced" HYCOR routines
GAM	Utility variable in VELAZ
DENOM	Utility variable in VELAZ
TH1(99)	Azimuth of station from earliest station
PFI	Angle (cw) between north and wave front
VA	Average velocity of wave front across net
KAZ	Flag indicating which VELAZ routine was used
KT	Iteration counter in adjustment loop
Y1	Adjustment in VA
Y2	Adjustment in PFI
FT1(99)	Residual in traveltime from earliest station to another
AT(99)	$\partial T/\partial V$
BT(99)	$\partial T/\partial \varphi$
AT11	Coefficient in normal equations

AT12	Coefficient in normal equations
AT22	Coefficient in normal equations
BT1	Coefficient in normal equations
BT2	Coefficient in normal equations
DEAT	Determinant of coefficient of unknowns in normal equations
PSY	Azimuth toward source of plane wave
R	Depth adjustment restriction factor
VH	Horizontal shift in epicenter
LREC	Number of stations summed in error estimate
SDP	Standard error in individual P-arrival time
SDX	Standard error in X-coord (km)
SDY	Standard error in Y-coord (km)
SDZ	Standard error in depth (km)
SDT	Standard error in origin time (sec)
OSO	Utility variable in M/Prog
KHR	Origin hour (reduced)
FHR	Origin hour (reduced)
KMIN	Origin minute
FMIN	Origin minute
SEC	Origin second
TS(99)	Traveltime of S-wave
AZ(99)	Azimuth of station from epicenter

EPMG(99)	P-magnitude residuals
EXMG(99)	X-magnitude residuals
MC	Utility variable in MAGNTD
MP	Utility variable in MAGNTD
SXMAG	Utility variable in MAGNTD
SPMAG	Utility variable in MAGNTD
RAD2	Square of hypocentral distance
ARGP	Utility variable in MAGNTD
ARGX	Utility variable in MAGNTD
PMAG(99)	Magnitude computed from P-phase at station
XXMG(99)	Magnitude computed from X-phase at station
PPMG	Average PMAG
XMAG	Average XXMG
WGJ	Combined "saved" weight
ABFJ	Absolute value of arrival-time residual at station
MPC(99)	Utility variable in summary statistical calculation
SCOF(99)	Utility variable in summary statistical calculation
SCOF2(99)	Utility variable in summary statistical calculation
ABEPM	Utility variable in summary statistical calculation

MPCP(99)	Utility variable in summary statistical calculation
SCOP(99)	Utility variable in summary statistical calculation
SCOP2(99)	Utility variable in summary statistical calculation
ABEXM	Utility variable in summary statistical calculation
MPCX(99)	Utility variable in summary statistical calculation
SCOX(99)	Utility variable in summary statistical calculation
SCOX2(99)	Utility variable in summary statistical calculation
KPLUS	Switch for extra summary card
AVRES(99)	Average arrival-time residual at station
SDRES(99)	Standard deviation of arrival-time residual at station
SEM(99)	Standard error of mean of average arrival-time residual at station
AVREP(99)	Average residual in P-magnitude at station
SDREP(99)	Standard deviation of P-magnitude residual at station
SEMP(99)	Standard error of mean of P-magnitude residual at station

AVREX(99)	Average residual of X-magnitude at station
SDREX(99)	Standard deviation of X-magnitude residual at station
SEMX(99)	Standard error of mean of X-magnitude residual at station

HYPOLAYR OUTPUT

Printout (blocks)

INPRIN =	0	1	2	3	4	5
	[11	1	1	1	1	1
	12	[11	(3	(3	(3	2
	13]	12	[11	5	5	(3
		13]	12	{7	(6)	4
			13]	8	{7	5
				9	8	(6)
				10	9	{7
				[11	10	8
				12	[11	9
				13]	12	10
					13]	[11
						12
						13]

No bracket = printed once per batch

(bracket = printed once per earthquake

[bracket = printed once per solution

( ) bracket = printed first 3 iterations

{ bracket = printed once each iteration

The normal INPRIN is 2, which provides a listing of station data, model parameters, and control parameters as well as a listing of the input data for each earthquake and the output results for each solution.

Card punch output

LPC =	0	1	2	3
	none	P1	P1	P1
Output blocks punched as		P2	P3	P1
indicated, once per solution		P3		P2
				P3

Term by Term Identification of HYPOLAYR Output

BLOCK	WRITE STATEMENT NUMBER	CONTENT
1	58	KSITE
	59	NSTA(1,L) LAT(1,L) YAT(1,L) LON(1,L) EL(1,L) DLY(1,L) MDL(1,L) L = 1,KSITE
	61	NL1 NL2 LATR YATTR LOTR XONTR ZTR LARED LORED DELAZ MODE LPC INPRIN /
		IFMT KOLT QQ PPP ISTS
	62	SMP XNEAR XFAR HILO CNST PWRP ZPMAG PWRX ZXMAG AVLT AAFLT AFLP ADLT ADLP
	65	TAAF TFR TWT AMTST IIT KTTA KOMIT (If ISTS = 0)
	68	V1(L) DP1(L) L = 1,NL1
	70	V2(L) DP2(L) L = 1,NL2: Omitted if only 1 model used
2	76/81	THK1(J) TID1(L,J) DID1(L,J) L = 1, 10/6, J = 1, 10/6
	78/83	THK2(J) TID2(L,J) DID2(L,J) L = 1, 10/6, J = 1, 10/6
3a	96	KREC INST ZRES
	97	MSTA(L) KDATE(L) JHR(L) JMIN(L) QSABE(L) W(L) P(L)/
		AMP(L) PRP(L) S(L) AMS(L) PRS(L) AMX(L) PRX(L)/
		CALP(L) CALS(L) CALX(L) RK(L) DT(L) L = 1, KREC

BLOCK	WRITE STATEMENT NUMBER	
3b	119	KREC INST ZRES
	121	MSTA(L) QSABE(L) DATE(L) JHR(L) JMIN(L) P(L) AMP(L) PRP(L) S(L) AMS(L)/ PRS(L) AMX(L) PRX(L) CALP(L) RK(L) DT(L) L = 1, KREC
4	202	IHR MSTA(NEAR) LOSW PMIN ORGS
	204	MSTA(L) NSTA(2,L) LAT(2,L) YAT(2,L) LON(2,L) XON(2,L) DLY(2,L) EL(2,L) MDL(2,L) TP(L) W(L) L = 1, KREC
5	208	MODE LHY LATEP YATEP LONEP XONEP Z ORG MSTA(NEAR) MSTA(MFAR) MSTA(KALX)
6	283	MSTA(L) DELTA(L) T(L) AX(L) AY(L) AH(L) ANIN(L) F(L) L = 1, KREC
7	286	YEP XEP Z AAF DAAF KSTA AWF WSTA
8	341	A(1,1) A(1,2) A(1,3) A(1,4) A(2,2) A(2,3) A(2,4) A(3,3) A(3,4) A(4,4) B(1) B(2) B(3) B(4) RAH INST

BLOCK	WRITE STATEMENT NUMBER	
9	345	MM KOUT DETA ASDX ASDY ASDZ ASDT Y(1) Y(2) Y(3) Y(4)
10	382	YATEP XONEP Z ORG VH Y(1) Y(2) Y(3) Y(4)
11	485	MODE LPC INST LOSW LHY KOUT KAZ OGS AVR PPMG
	486	Headings
	487	KDATE(NEAR) KHR KMIN SEC LATEP YATEP LONEP XONEP Z AAF SDP SDX SDY/ SDZ SDT KSTA XMAG II KREC VH
12	495	Headings
	497	NSTA(2,I) DELTA(I) AZ(I) ANIN(I) QSABE(I) TP(I) TS(I) F(I) PMAG(I) / EPMG(I) XXMG(I) EXMG(I) RK(I) W(I) G(I) L = 1, KREC
13	501	Skip four spaces to separate events on printout
PI	491	KDATE(NEAR) KHR KMIN SEC LATEP YATEP LONEP XONEP Z AAF SDP SDX SDY SDZ SDT/ KSTA XMAG II KREC KOUT

BLOCK	WRITE STATEMENT NUMBER	
P2	499	NSTA(2,I) DELTA(I) AZ(I) ANIN(I) QSABE(I) TP(I) TS(I) F(I) PMAG(I) / RK(I) W(I) G(I)
P3	504	Punch $$$$ card to separate event decks
R1	149	KDATE(J) JHR(J) JMIN(J) MSTA(J) "Not ON STATION LIST, REJECT QUAKE"
	150	Skip 4 lines
R2	174	KDATE(1) JHR(1) JMIN(1) "INSUFFICIENT DATA FOR LOCATION"
	175	Skip 4 lines
S1	274	MODE LHY LATEP YATEP LONEP XONEP Z ORG MSTA(NEAR) MSTA(MFAR) MSTA(KALX)
	275	MSTA(L) DELTA(L) T(L) AX(L) AY(L) AH(L) ANIN(L) F(L) L = 1, KREC
	276	AAF AVR AWF XSTA WSTA
	278	Skip 4 lines

BLOCK	WRITE STATEMENT NUMBER	
S2	353	KDATE(NEAR) JHR(NEAR) JMIN(NEAR) P(NEAR) PSY VA AAF MSTA(NEAR MSTA(MFAR) /
		MSTA(KALX) KAZ II KT
	356	MSTA(I) FT1(I) TH1(I) I = 1, KREC (except I = NEAR)
	358	Skip 4 lines
X1	541	NSTA(1,K) AVRES(K) SDRES(K) SEM(K) MPC(K) AVREP(K) SDREP(K) SEMP(K) MPCP(K) /
		AVREX(K) SDREX(K) SEMX(K) MPCX(K) K = 1, KSITE (if ISTS ≠ 0)
X2	546	NOMIT(K) K = 1, KOMIT (if KOMIT ≠ 0)

Description of content of HYPOLAYR output

CONTENT

BLOCK	WRITE STATEMENT NUMBER	
1	58	KSITE = number of stations on station list
	59	Station list: See Variable List p. 1
	61	NL1, NL2 = Number of layers in models 1 and 2, respectively
		Card D4 parameters: See Variable List p. 2
	62	Card D5 parameters: See Variable List pp. 2-3
	65	Card DXI parameters: See Variable List p. 3
	68	Model 1, from card D2: See Variable List p. 1
	70	Model 2, from card D3; See Variable List p. 1
2	76/81	Model 1 arrays from TPAR: See Variable List p. 4
	78/83	Model 2 arrays from TPAR: See Variable List p. 4
3	96/119	Card D7 parameters and number of phase cards: See Variable List p. 5
	97	Format 2 phase card (D6-2) parameters: See Variable List pp. 4-5
	121	Format 1 phase card (D6-1) parameters: See Variable List pp. 4-5
4	202	See Variable List p. 5
	204	Match station--phase list: See Variable List pp. 1, 4, 5

BLOCK	WRITE STATEMENT NUMBER	
5	208	Results on preliminary hypocenter from PREHY: See Variable List pp. 5, 6.
6	283	Results from TRVDRV and arrival-time residuals: See Variable List pp. 8-10
7	286	Location of hypocenter, and statistical parameters: See Variable List pp. 8-10
8	341	Coefficients and constants in normal equations plus range in $\partial T/\partial z$, RAH, and INST value: See Variable List p. 10
9	345	Results of HYCOR subroutine: See Variable List pp. 10-11
10	382	Corrected hypocenter and adjustments applied: See Variable List pp. 6, 10, 12
11	485	Condition codes plus "S-P origin time," average residual, and mean P-magnitude: See Variable List
	487	Summary card printout: See Variable List, especially pp. 8, 10, 12, 13
12	497	Station data printout: See Variable List, especially pp. 8, 10, 12, 13

BLOCK	WRITE STATEMENT NUMBER	
P1	491	Card punch summary card: cf 11
P2	499	Card punch station data card: cf 12
R1	149	Printout indicating phase card--station card matching failure
R2	174	Printout indicating too little data for location--this condition can result from event receding from net until too many stations have G-weights = 0
S1	274, 275, 276	Printout for special "solution" in which program is used to compute traveltimes, derivatives, etc., for a specified focus and model
S2	353, 356	Printout for the VELAZ subroutine
X1	541	Printout of statistical data on arrival-time residuals and P- and X-magnitude residuals at individual stations
X2	546	Printout of list of stations that were not used in hypocentral adjustments

Condition Codes

MODE: chooses method of preliminary hypocenter assignment

= 0 : Put hypocenter at depth ZTR beneath the earliest station

= 1 : Put hypocenter at depth ZTR beneath the trial epicenter (LATR, YATTR, LOTR, XONTR)

= 2 : Calculate preliminary hypocenter from reduced data set using a half-space model

LHY: identifies the PREHY section used in assignment of the preliminary hypocenter.

= 1 MODE = 0; etc.

= 2 Mode = 1; etc.

= 3 MODE = 2; 4 station solution for x_o, y_o, z_o, t_o

= 4 MODE = 2; 3 station solution for x_o , y_o :
t_o computed from S-P data, z_o = ZTR.

= 5 MODE = 2; 3 station solution for x_o, y_o, t_o ; z_o = ZTR

LPC: Card punch instruction

= 1 : Punch 1 summary card, 1 station card per station, and 1 separator card

= 2 : Punch 1 summary card and 1 separator card

= 3 : Punch 2 summary cards, 1 station card per station, and 1 separator card

= 0 : No card punch output

INST: Controls type and number of solutions for a single earthquake

= 0 : FREE solution; adjust x_o, y_o, z_o, t_o

= 1 : ZFIX solution; adjust x_o, y_o, t_o

= 2 : TFIX solution; adjust x_o, y_o, z_o

= 4 : first a ZFIX solution, second a FREE solution

= 5 : first a TFIX solution, second a ZFIX solution

= 6 : first a TFIX solution, second a ZFIX solution, third a FREE solution

= 8 : go to subroutine VELAZ

= 9 : Printout first TRVDRV results and other data recording parameters of hypocenter and statistics of residuals

LOSW: indicates availability of S-P origin time

= 0 : ORGS not available

= 1 : ORGS available

KOUT: identifies the HYCOR routine used in the last adjustment of the hypocenter.

= 1 : Free adjustment of all variables

= 2 : ZFIX adjustment of x_0, y_0, t_0 only

= 3 : TFIX adjustment of x_0, y_0, z_0 only

= 4 : ZFIX— TFIX adjustment of x_0, y_0 only

KAZ: indicates which VELAZ routine was used

= 0 : VELAZ not used

= 1 : 3-station solution for velocity and azimuth only

= 2 : least-squares adjustment of velocity and azimuth

Appendix 3

Data card variables, and a short explanation of their use and significance.

DI. "NSTA" list--one per station

NSTA(1,L)	Station L name
LAT(1,L)	Station L latitude (degrees)
YAT(1,L)	Station L latitude (minutes)
LON(1,L)	Station L longitude (degrees
XON(1,L)	Station L longitude (minutes)
EL(1,L)	Station L elevation (meters)
DLY(1,L)	Station L delay (seconds)
MDL(1,L)	Crustal model to be used with station L

D2. Model 1 list

V1(L)	Velocity in layer L (km/sec)
DP1(L)	Depth to top of layer L (km)

D3. Model 2 list

V2(L)	Velocity in layer L (km/sec)
DP2(L)	Depth to top of layer L (km)

D4. Parameter card 1

LATR	Trial hypocenter latitude (degrees)
YATTR	Trial hypocenter latitude (minutes)
LOTR	Trial hypocenter longitude (degrees)
XONTR	Trial hypocenter longitude (minutes)
ZTR	Trial hypocenter depth (km)
LARED	Latitude reduction (degrees)
LORED	Longitude reduction (degrees)
DELAZ	Distance (in km) to nearest station beyond which VELAZ subroutine is called

VB — Half-space velocity used in MODE = 2 solution (below).

MODE — 0, 1, 2 Keys mode of PREHY hypocenter determination

0 - preliminary hypocenter placed at depth ZTR beneath nearest station

1 - "trial" hypocenter assigned

2 - preliminary hypocenter computed from 4 (or 3) selected stations on the basis of a uniform half-space model

LPC — 0, 1, 2, 3 Keys punch-card output

0 - no cards punched

1 - cards punched

2 - summary cards and $$$$ only

3 - duplicate summary cards, station cards, and $$$$

INPRIN — 0 (or blank), 1, 2, 3, 4, 5

Different output levels can be obtained by use of different INPRIN commands. The levels range from final results only (0) to step-by-step printout of the results of read and calculate operations (5).

0 Hypocenter summary and station summary list

1 + "NSTA" station list, parameters, and model lists

2 + "MSTA" phase list

3 + PREHY hypocenter, and adjustment data (1/iteration)

4 + Time and derivative lists (first 3 iterations)

5 + TPAR arrays and match-list

(Do not use "5" if NL1 or NL2 > 10; 888 FORMAT inadequate)

IFMT Indicates "MSTA" phase list format that will be used

1 "HYPOLO" format

2 "HYPOLAYR" format--provides for weighting of reading and for independent calibration for S and max (X).

DX1 Test values needed in the section providing a statistical summary of individual station time and magnitude residuals

TAAF If AAF $\geq$ TAAF earthquake is skipped

TFR If F(J) $\geq$ TFR } station is skipped in section
If W(J) * G(J) $\leq$ TWR } on traveltime residuals

AMTST If |EPMG(J)| > AMTST, station is skipped in section on P-mag residuals

AMTST If |EXMG(J)| > AMTST, station is skipped in section on X mag residuals

IIT If II > IIT, earthquake is skipped

KTTA If KSTA < KTTA, earthquake is skipped

KOMIT Number of stations (listed on card DX2) that are to be ignored in the determination of the hypocenter but treated normally otherwise.

DX2 List of stations to be ignored as specified under "KOMIT" above

D5 Parameter card 2

KOLT In order of increasing P-arrival times, stations 1 through KOLT are considered in the selection of stations for use in calculating the preliminary hypocenter, in PREHY, and in calculating the preliminary velocity and azimuth in VELAZ.

SMP To calculate P traveltimes from measured S-P intervals, the equation P - O = SMP * (S-P) is used. If Poisson's ratio is 0.25, SMP = 1.37.

XNEAR (km)	For DELTA(I) < XNEAR, the distance--dependent weighting factor, G(I), is 1.0.
XFAR (km)	For DELTA(I) > XFAR, G(I) = 0.0. For XNEAR < DELTA(I) < XFAR, G(I) = 1.0 - (DELTA(I) - XNEAR) / [(XFAR - XNEAR) / 0.9]
HILO	Sensitivity ratio between high and low channels on playback(if same calibration is used for both levels).
CNST	Proportionality constant used in reducing record amplitude to ground amplitude.
PWRP	Exponent of hypocentral distance used in the calculation of "P" magnitudes
ZPMAG	Reference constant used in calculation of "P" magnitudes.
PWRX	Analogous to PWRP, but for X phase.
ZXMAG	Analogous to ZPMAG, but for X phase
AVLT	Small value for AVR (average residual) used in solution convergence tests.
AFLT	Small value for AAF (average absolute residual) used in solution convergence tests
AFLP	Second small value for AAF (average absolute residual) used in solution convergence tests
ADLT	Small value for DAAF (change in AAF) used in solution convergence tests
ADLP	Second small value for DAAF (change in AAF) used in solution convergence tests.

D6. (D6-1 = HYPOLO format; D6-2 = HYPOLAYR format)

MSTA(L)	Station L name
QSABE(L)	Station L P-phase description (e.g., I P+)
KDATE(L)	Date (e.g., 68 02 24 - year, month, day)
JHR(L)	Time (hour, e.g., 13)
JMIN(L)	Time (minutes, e.g., 27)
P(L)	Arrival time of P at station L (seconds)
AMP(L)	Peak-to-trough max P record amplitude (mm)
PRP(L)	Period of max P-phase (seconds)
S(L)	S arrival time (seconds)
AMS(L)	S amplitude (peak-to-trough mm)
PRS(L)	S period (seconds)
AMX(L)	"Max" phase amplitude (peak-to-trough mm)
PRX(L)	"Max" phase period (seconds)
W(L)	P-wave phase weighting factor (seconds) 0 1.0, 1 0.75, 2 0.50, 3 0.25, 4 0.0
CALP(L)	Peak-to-trough record amplitude (in mm) resulting from a 10 V calibration signal--on Z channel
CALS(L)	Calibration, but on channel recording S
CALX(L)	Calibration, but on channel recording Max
RK(L)	Remarks (in 3 alphmeric symbols)
DT(L)	Chronometer correction (seconds)

D7. Final card in phase list group (one per earthquake)

INST	0 (or blank), 1, 2, 3, 4, 5, 6, and 9. Special instruction on constraints to be placed on hypocenter determination.

0 FREE solution

1 ZFIX (restrict depth to ZRES)

2 TFIX (restrict origin time to that computed from S-P data)

3 First TFIX, then FREE

4 First ZFIX, then FREE

5 First TFIX, then ZFIX

6 First TFIX, second ZFIX, third FREE

9 Requires program to compute only traveltimes, residuals, etc., for a specified focus (MODE = 1), with no subsequent adjustment of focus.

(km) Depth at which hypocenter is restricted under the INST equal 1, 4, and 6 commands.

Data Deck Set-Up

D1	(Station list)
Blank	
D2	(Model 1)
Blank	
D3	(Model 2) Omit for 1 - model case
Blank	
D4	Param 1
D5	Param 2
DX1	If required
DX2	If required
D6-2	(Phase cards)
D7	Instr card (can be blank)
D6-2	
D7	
D6-2	
D7	
⋮	
D6-2	
D7	

1 2....10 11 12 13 14 15 ....
1 1 1 1 0 0
} "Go to STOP" card

1*

END

Form 9-1506 (Mar.62) GENERAL PURPOSE [illegible]

8/10/68 gpe

HYPOLAYR INPUT CARD FORMATS

D1 — "Station" list

	xx	NSTA(1,L)	LAT(1,L)	YAT(1,L)	x	LON(1,L)	XON(1,L)	x	EL(1,L)	x	DLY(1,L)	x	MDL(1,L)
Format	xx	A4	F2.0	F5.2	x	F3.0	F5.2	x	F4.0	x	F5.2	x	I1

--- D1 list terminated by a blank card ---

D2 — Crustal model #1

	V1(L)	DP1(L)
Format	F7.3	F7.3

--- D2 list terminated by a blank card ---

D3 — Crustal model #2

	V2(L)	DP1(L)
Format	F7.3	F7.3

--- D3 list terminated by a blank card ---

D4

	xxx	LATR	x	YATTR	xx	LOTR	x	XONTR	xx	ZTR	xx	LARED	x	LORED	xx	DELAZ	xx	VB	xx	MODE	x	LPC	x	INPRIN	x	IFMT	x	QQ	x	PPP	x	ISTS
Format	xxx	F2.0	x	F5.2	xx	F3.0	x	F5.2	xx	F5.2	xx	F2.0	x	F3.0	xx	F6.1	xx	F5.2	xx	I1	x	I1	x	I1	x	I1	x	F7.5	x	F7.5	x	I1

D5

	KOLT	xxx	SMP	XNEAR	XFAR	HILO	CNST	PWRP	ZPMAG	PWRX	ZXMAG	AVLT	AFLT	AFLP	ADLT	ADLP
Format	I2	xxx	F5.2	F5.0	F5.0	F5.2	F5.2	F5.2	F5.2	F5.2	F5.2	F5.2	F5.2	F5.2	F5.3	F5.3

DX1 — Required if ISTS ≠ 0

	TAAF	TFR	TWR	AMTST	IIT	KTTA	KOMIT
Format	F10.3	F10.3	F10.3	F10.3	I5	I5	I5

DX2 — Required if KOMIT ≠ 0.

	x	NOMIT(1)	x	NOMIT(2)	x	NOMIT(3)	...	...	x	NOMIT(KOMIT)
Format	x	A4	x	A4	x	A4	...	...	x	A4

D6-1 — "Phase" list (Cholame only)

	W(L)	MSTA(L)	QSABE(L)	KDATE(L)	JHR(L)	JMIN(L)	P(L)	AMP(L)	PRP(L)	S(L)	AMS(L)	PRS(L)	xxxxx	AMX(L)	PRX(L)	xxxxx	CALP(L)	RK(L)	DT(L)
Format	F2.1	A4	A3	I6	I2	I2	F5.2	F3.0	F3.2	F5.2	F3.0	F3.2	xxxxx	F3.0	F3.2	xxxxx	F4.1	A3	F5.2

D6-2 — "Phase" list (Post-Cholame)

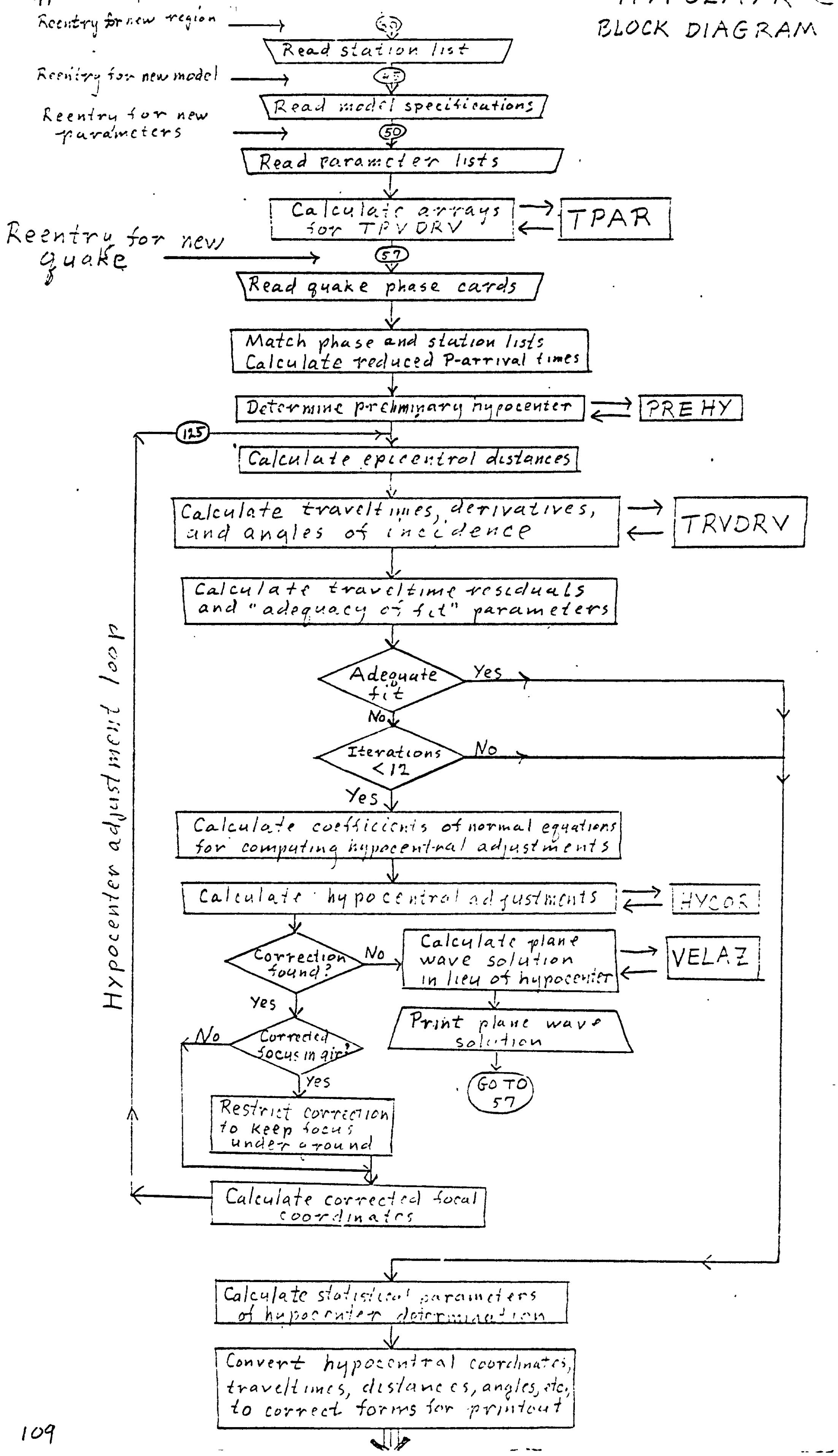
	MSTA(L)	QSABE(L)	W(L)	KDATE(L)	JHR(L)	JMIN(L)	P(L)	AMP(L)	PRP(L)	S(L)	AMS(L)	PRS(L)	AMX(L)	PRX(L)	CALP(L)	CALS(L)	CALX(L)	RK(L)	DT(L)
Format	A4	A3	F2.1	I6	I2	I2	F5.2	F4.0	F3.2	F5.2	F4.0	F3.2	F4.0	F3.2	F4.1	F4.1	F4.1	A3	F5.2

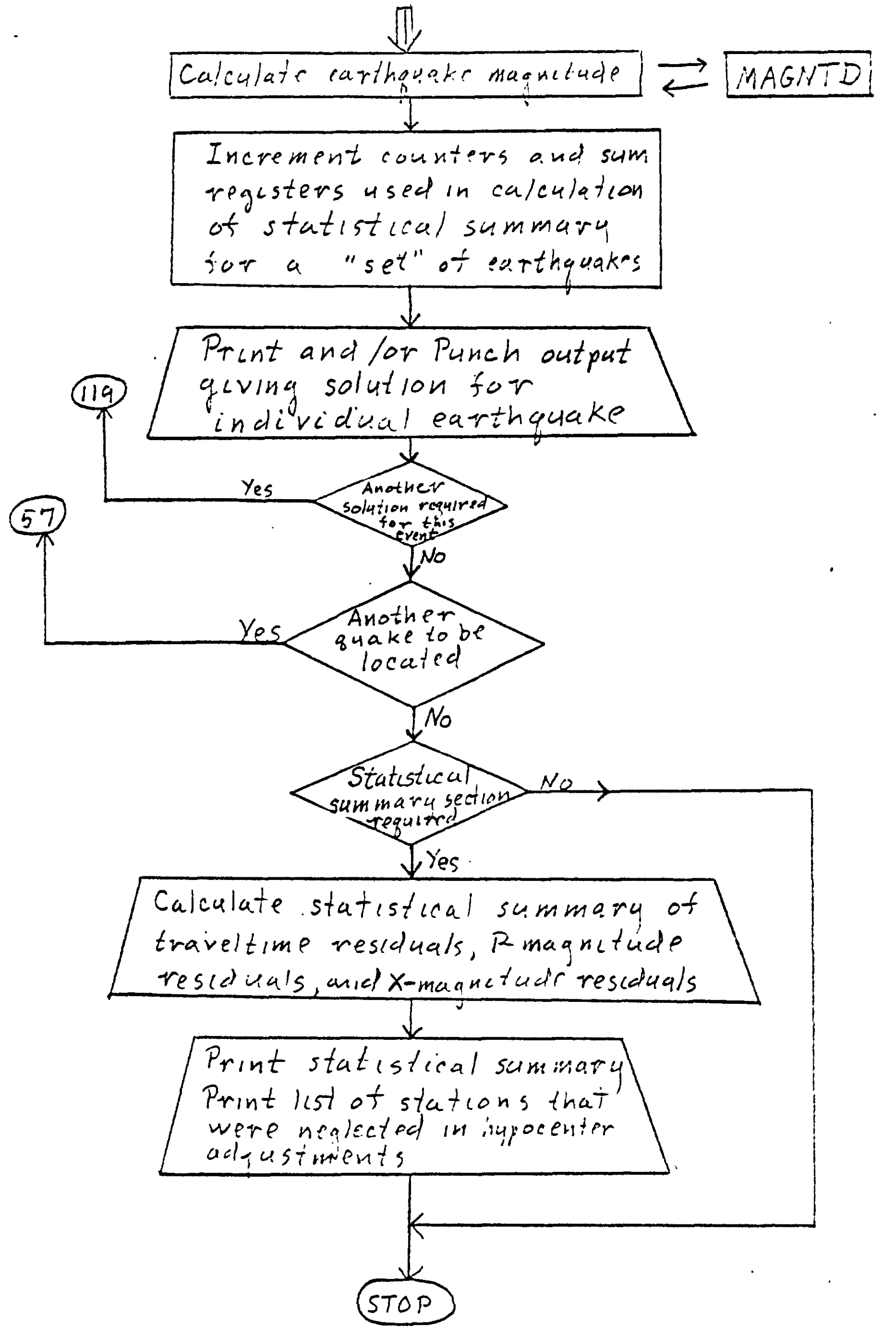
D7

	xx xxx	INST	ZRES
Format	xx xxx	I2	F5.2

Appendix 4

HYPOLAYR BLOCK DIAGRAM




Calculate earthquake magnitude
MAGNTD
Increment counters and sum registers used in calculation of statistical summary for a "set" of earthquakes
Print and/or Punch output giving solution for individual earthquake
119
Another solution required for this event
Yes
No
57
Another quake to be located
Yes
No
Statistical summary section required
No
Yes
Calculate statistical summary of traveltime residuals, P-magnitude residuals, and X-magnitude residuals
Print statistical summary
Print list of stations that were neglected in hypocenter adjustments
STOP

SUBROUTINE TPAR

Load subroutine with model #1 parameters: boundary depths and layer velocities DP1(K), V1(K)

↓

Calculate layer thicknesses, THK(K)

↓

Compute intercepts TID(K,L) and critical distances DID(K,L) for refracted waves from focus on boundary K and refracted along boundary L : K=1, NL ; L=K, NL

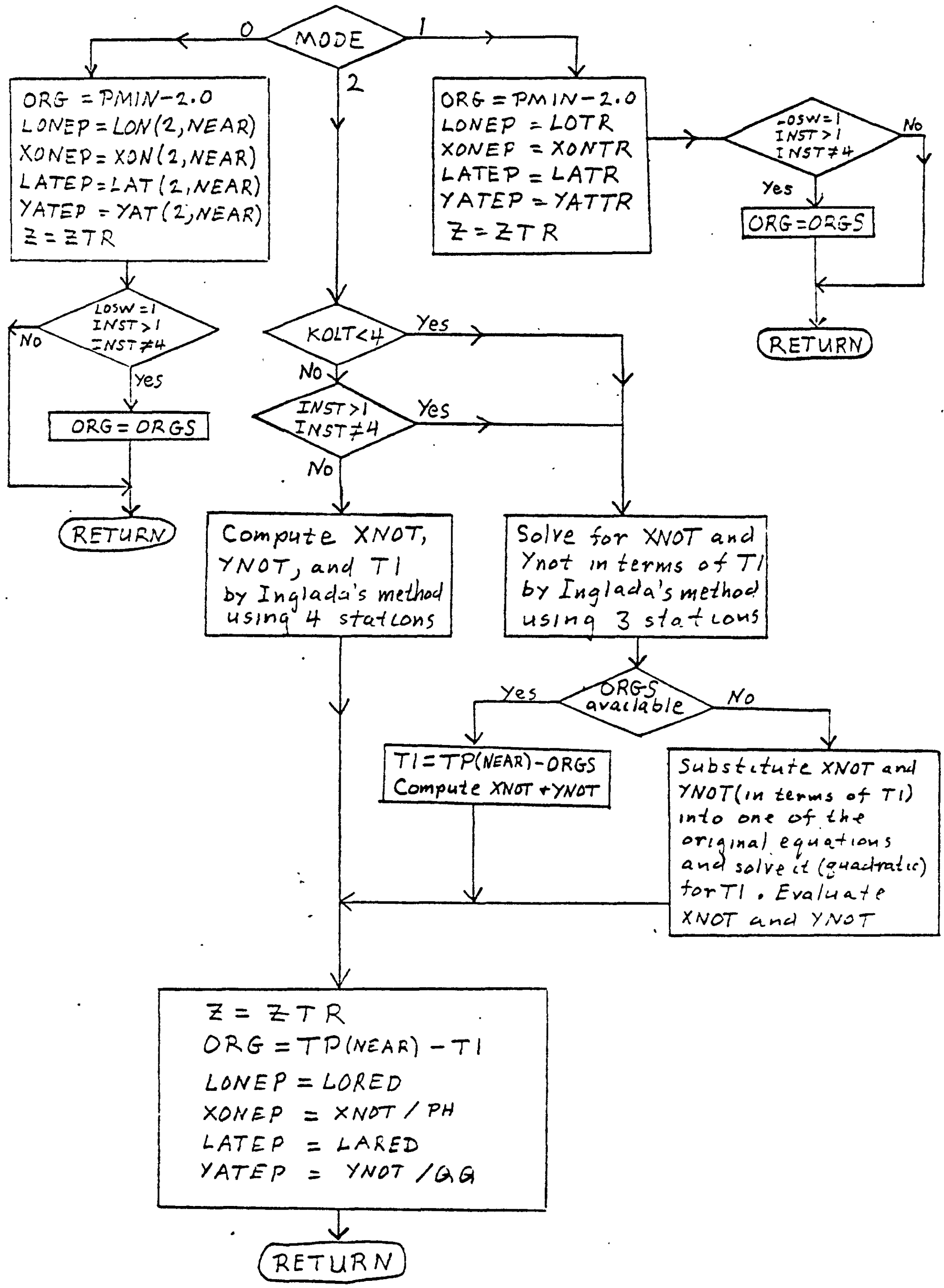
↓

Transfer results from subroutine working arrays to storage arrays: THK1(K), TID1(K,L), DID1(K,L) ; K=1, NL1 ; L=K, NL1

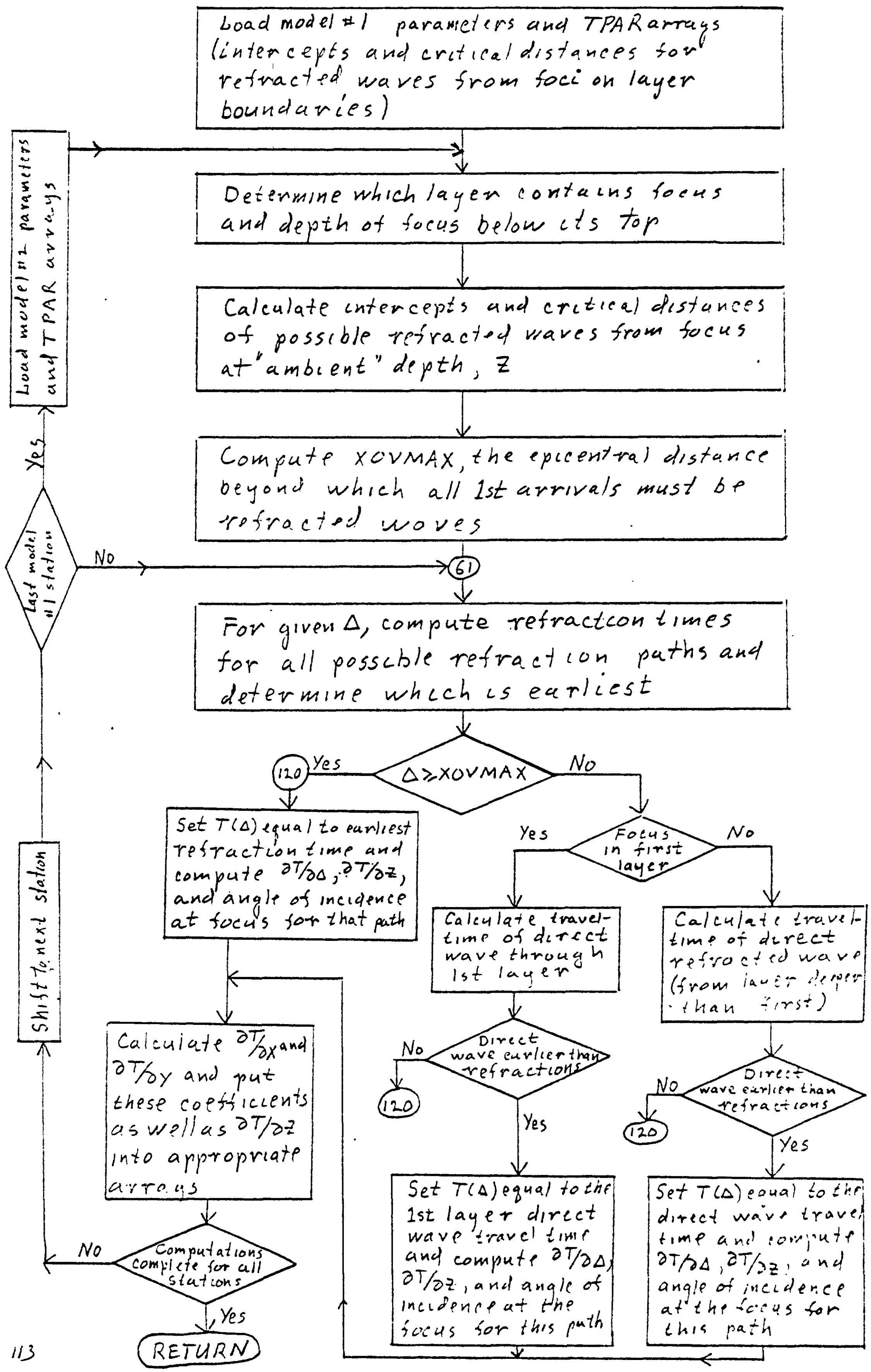
⇓

Return to beginning; load subroutine with model #2 parameters; repeat calculations to obtain model #2 arrays; transfer model #2 results to storage arrays: THK2(K), TID2(K,L), DID2(K,L) ; K=1, NL2 ; L=K, NL2

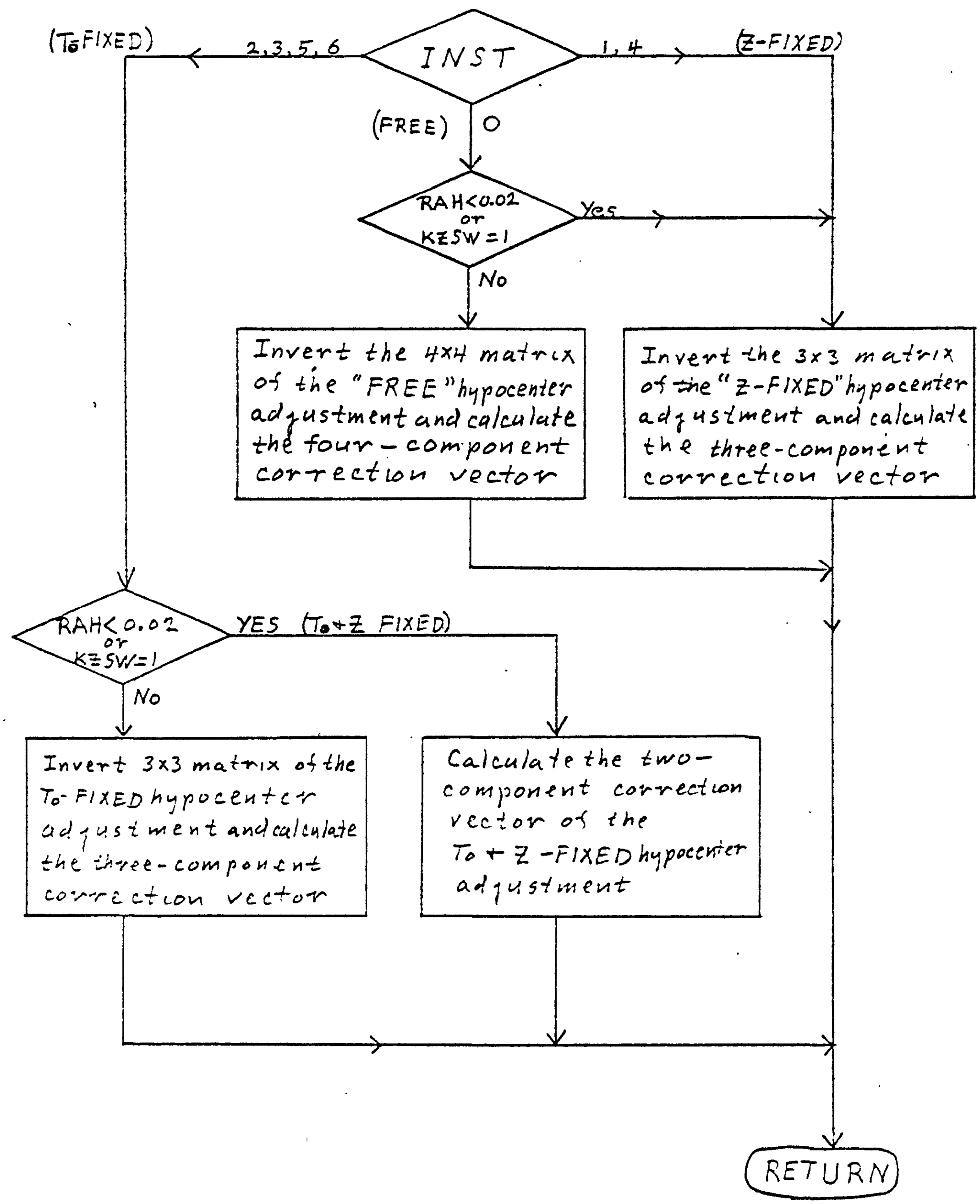
SUBROUTINE PREHY



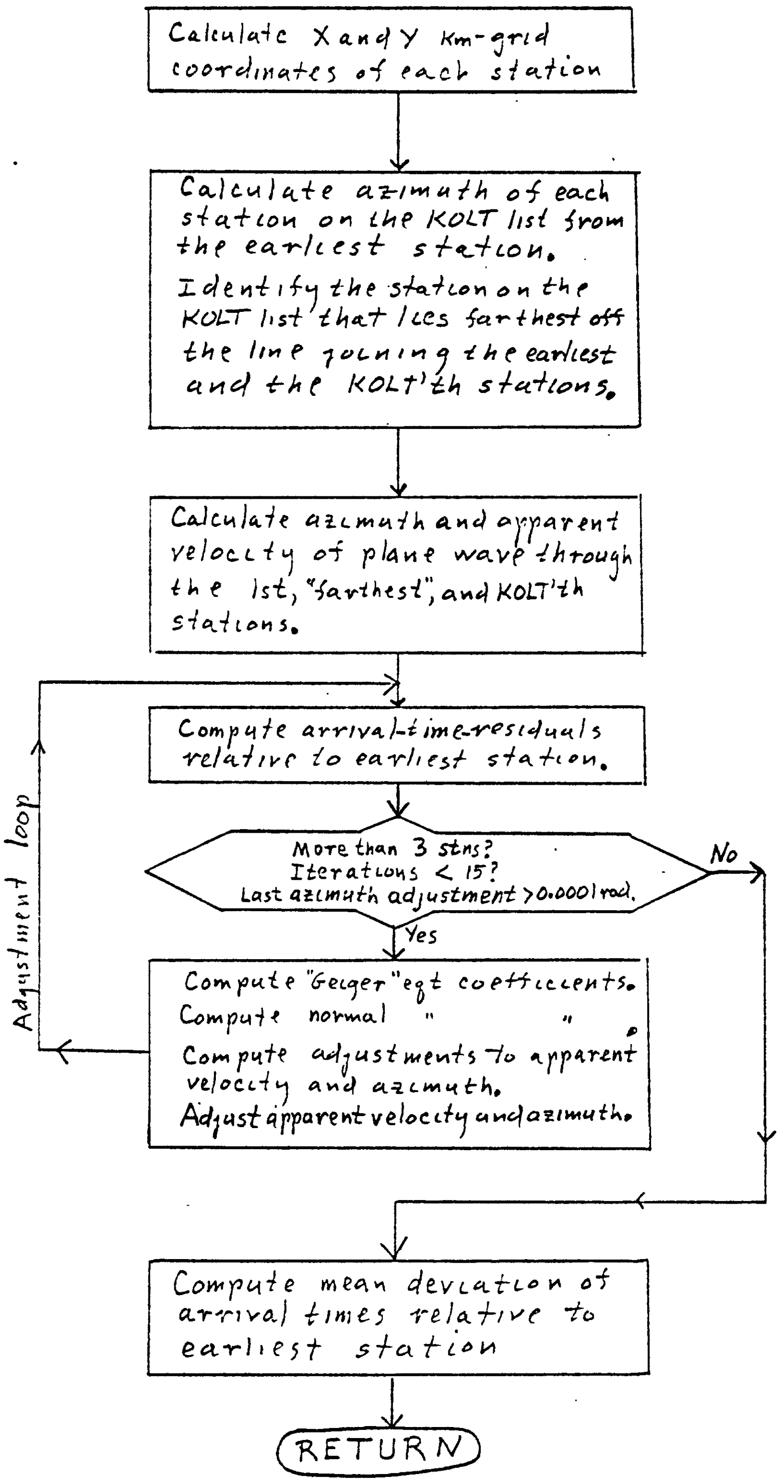
Subroutine TRVDRV



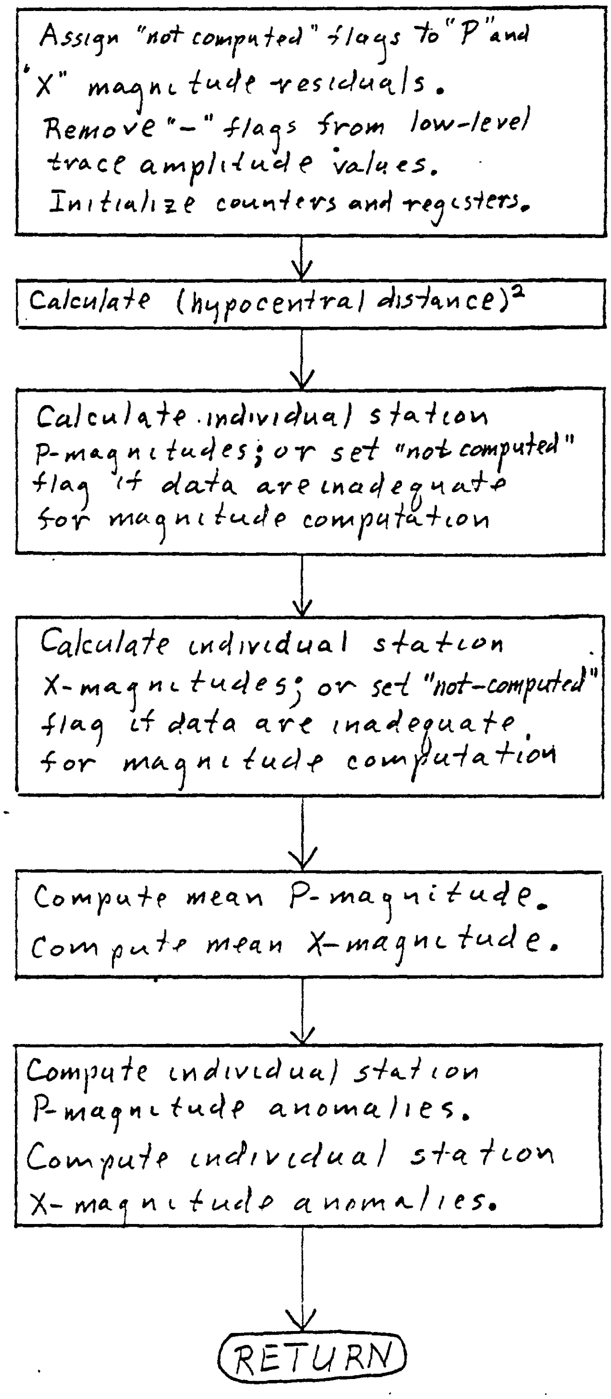
SUBROUTINE HYCOR



SUBROUTINE VELAZ



SUBROUTINE MAGNTD



Appendix 5

PROGRAM HYPOLAYR (1/13/69 — J P Eaton)

Dimension, common, and type block that is reproduced in all of the subroutines

Dimension and data statements for the statistical section of the main program

Collection of format statements

```
      $WATFOR
1          DIMENSION NSTA(2,99),LAT(2,99),YAT(2,99),LON(2,99),XON(2,99),
          1EL(2,99),DLY(2,99),MDL(2,99),MSTA(99),W(99),QSABE(99),KDATE(99),
          2JHR(99),JMIN(99),P(99),PRP(99),AMP(99),S(99),PRS(99),AMS(99),
          3PRX(99),AMX(99),RK(99),DT(99),CALP(99),CALS(99),CALX(99),TP(99),
          4DX(99),DY(99),DELTA(99),T(99),AX(99),AY(99),AH(99),ANIN(99),F(99),
          5PMAG(99),AT(99),BT(99),XH(99),YH(99),DIST1(99),TH1(99),FT1(99),
          6TS(99),AZ(99),V(26),DP(26),THK(26),TID(26,26),DID(26,26),TINJ(26),
          7DIDJ(26),TR(26),V1(26),DP1(26),THK1(26),TID1(26,26),DID1(26,26),
          8V2(26),DP2(26),THK2(26),TID2(26,26),DID2(26,26),A(4,4),B(4),Y(4),
          9C(4,4),D(3,3),AP(3,3),BP(3),G(99),PT(99),KO(99),XXMG(99)
2          DIMENSION EPMG(99),EXMG(99)
3          COMMON NSTA,LAT,YAT,LON,XON,EL,DLY,MDL,MSTA,W,QSABE,KDATE,JHR,
          1JMIN,P,PRP,AMP,S,PRS,AMS,PRX,AMX,RK,DT,CALP,CALS,CALX,TP,DX,DY,
          2DELTA,T,AX,AY,AH,ANIN,F,PMAG,AT,BT,XH,YH,DIST1,TH1,FT1,TS,AZ,V,
          3DP,THK,TID,DID,TINJ,DIDJ,TR,V1,DP1,THK1,TID1,DID1,V2,DP2,THK2,
          4TID2,DID2,A,B,Y,C,D,AP,BP,G,PT,KO,XXMG,EPMG,EXMG
4          COMMON/UNDM/HILO,CNST,PWRP,ZPMAG,PWRX,ZXMAG,KT,KSTA,VB,PPP,ISTS,
          1KSITE,NL1,NL2,LATR,YATTR,LOTR,XONTR,ZNOT,LARED,LORED,MODE,INST,
          2KREC,IHR,NEAR,PMIN,ORGS,QQ,ORG,LATEP,YATEP,LONEP,XONEP,Z,KZSW,
          3XEP,YEP,RAH,ASDX,ASDY,ASDZ,ASDT,MM,KOUT,XMAG,LOSW,PFI,VA,AAF,
          4LHY,KAZ,DETA,MFAR,PFAR,KALX,KOLT,SMP,XNEAR,XFAR,ZTR,ZRES,PPMG
5          REAL LAT,LON,LATR,LOTR,LARED,LORED,LATEP,LONEP
6          DIMENSION MPC(99),SCOF(99),SCOF2(99),AVRES(99),SDRES(99),SEM(99),
          1NOMIT(99),GW(99),MPCP(99),SCOP(99),SCOP2(99),AVREP(99),SDREP(99),
          2SEMP(99),MPCX(99),SCOX(99),SCOX2(99),AVREX(99),SDREX(99),SEMX(99)
7          DATA MPC/99*0/,SCOF/99*0.0/,SCOF2/99*0.0/,AVRES/99*-9.99/,
          1SDRES/99*-9.99/,SEM/99*-9.99/,MPCP/99*0/,SCOP/99*0.0/,
          2SCOP2/99*0.0/,AVREP/99*-9.99/,SDREP/99*-9.99/,SEMP/99*-9.99/,
          3MPCX/99*0/,SCOX/99*0.0/,SCOX2/99*0.0/,AVREX/99*-9.99/,
          4SDREX/99*-9.99/,SEMX/99*-9.99/
8     705 FORMAT(1H0,5X,'CODES (MODE LPC INST LOSW LHY KOUT KAZ)=(',
          17I2,')',5X,'ORGS=',F7.2,5X,'AV RESID=',F7.2,5X,'PMAG=',F7.2)
9     710 FORMAT(2X,A4,F2.0,F5.2,1X,F3.0,F5.2,1X,F4.0,1X,F5.2,1X,I1)
10    712 FORMAT(F7.3,F7.3)
11    715 FORMAT(3X,F2.0,1X,F5.2,2X,F3.0,1X,F5.2,2X,F5.2,2X,F2.0,1X,F3.0,
          12X,F6.1,2X,F5.2,2X,I1,1X,I1,1X,I1,1X,I1,1X,F7.5,1X,F7.5,1X,I1)
12    716 FORMAT(I2,3X,F5.2,2F5.0,9F5.2,2F5.3)
13    720 FORMAT(A4,A3,F2.1,I6,2I2,F5.2,F4.0,F3.2,F5.2,F4.0,F3.2,F4.0,F3.2,
          13F4.1,A3,F5.2)
14    820 FORMAT(F2.1,A4,A3,I6,2I2,F5.2,F3.0,F3.2,F5.2,F3.0,F3.2,5X,F3.0,
          1F3.2,5X,F4.1,A3,F5.2)
15    722 FORMAT(5X,I6,2X,2I2,2X,A4,1X,'NOT ON STATION LIST,REJECT QUAKE')
16    723 FORMAT(5X,I6,2X,2I2,2X,'INSUFFICIENT DATA FOR LOCATION')
17    748 FORMAT(4X,'DATE',4X,'ORIGIN',7X,'LAT',9X,'LONG',6X,'DEPTH',4X,
          1'AAF',4X,'SDP',3X,'SDX',3X,'SDY',3X,'SDZ',3X,'SDT',2X,
          2'KSTA',3X,'XMAG',3X,'II',2X,'KREC',3X,'VH')
18    750 FORMAT(3X,I6,1X,2I2,F6.2,F6.0,F6.2,F7.0,F6.2,F7.1,2F7.2,3F6.1,
```

```
      1F6.2,3X,I2,F8.2,3X,I2,3X,I2,3X,F6.2,3X/)
  755 FORMAT(I6,2I2,F5.2,F3.0,F5.2, F4.0,F5.2,F5.1,2F5.2,3F5.1,F5.2,
      1I2,F5.2,3I2)
  758 FORMAT(10X,'STATION',2X,'DELTA',3X,'AZI',3X,'ANIN',2X,'QSABE',2X,
      1'TP',6X,'TS',4X,'RESID',3X,'PMAG',2X,'RSPMG',3X,'XMAG',2X,'RSXMG',
      22X,'RMK',3X,'W',5X,'G')
  760 FORMAT(12X,A4,F6.1,2X,F5.0,1X,F6.1,3X,A3,1X,F6.2,2X,F6.2,
      12X,F6.2,1X,F6.2,1X,F6.2,1X,F6.2,1X,F6.2,2X,A3,1X,F5.2,1X,F5.2)
  765 FORMAT(6X,A4,F6.1,F5.0,F6.1,A3,4F6.2,A3,2F5.2,13X)
  770 FORMAT(////)
  780 FORMAT(5X,I6,1X,2I2,F5.2,3X,'STN',3X,'RESID',3X,'TH1(I)',2X,
      1'AZEP=',F8.2,1X,'VBAR=',F7.2,1X,'AAF=',F5.2,1X,'STNS N,F,X=',

      2A4,1X,A4,1X,A4,1X,'KAZ=',I1,1X,'II=',I2,1X,'KT=',I2)
  782 FORMAT(23X,A4,2X,F6.2,2X,F7.1,2X)
   30 L=0
   40 L=L+1
D1    READ(5,710)NSTA(1,L),LAT(1,L),YAT(1,L),LON(1,L),XON(1,L),
      1EL(1,L),DLY(1,L),MDL(1,L)
      IF(LAT(1,L))40,42,40
   42 KSITE=L-1
   43 DO 44 L=1,KSITE
      EL(1,L)=0.001*EL(1,L)
   44 CONTINUE
   45 L=0
   46 L=L+1
D2    READ(5,712) V1(L),DP1(L)
      IF(V1(L) .GT. 0.01)GO TO 46
   47 NL1=L-1
      L=0
   48 L=L+1
D3    READ(5,712) V2(L),DP2(L)
      IF(V2(L) .GT. 0.01) GO TO 48
   49 NL2=L-1
D4 50 READ(5,715)LATR,YATTR,LOTR,XONTR,ZTR,LARED,LORED,DELAZ,VB,MODE,
      1 LPC,INPRIN,IFMT,QQ,PPP,ISTS
      IF (QQ .LT. 0.1) QQ=1.8495
      IF (PPP .LT. 0.1) PPP=1.8576
D5    READ(5,716) KOLT,SMP,XNEAR,XFAR,HILO,CNST,PWRP,ZPMAG,PWRX,ZXMAG,
      1AVLT,AFLT,AFLP,ADLT,ADLP
      KLLT=KOLT
      KOMIT=0
  802 IF(ISTS .EQ. 0) GO TO 813
DX1 803 READ(5,809) TAAF,TFR,TWT,AMTST,IIT,KTTA,KOMIT
  809 FORMAT(4F10.3,3I5)
```

Read list of stations and station parameters

Convert station elevations from meters to kilometers

Read crustal model #1

Read crustal model #2

Read parameter cards (Trial values, constants, and options used in or controlling the main program and subroutines) (Parameters for statistical section)

```
      IF(KOMIT .EQ. 0) GO TO 813
DX2 804 READ(5,811)(NOMIT(L),L=1,KOMIT)
    811 FORMAT(1X,A4)
    813 IF(INPRIN .LT. 1) GO TO 52
     51 WRITE(6,840) KSITE
    840 FORMAT(10X,'KSITE = ',I3)
        WRITE(6,841) (NSTA(1,L),LAT(1,L),YAT(1,L),LON(1,L),XON(1,L),
       1EL(1,L),DLY(1,L),MDL(1,L), L=1,KSITE)
    841 FORMAT(10X,A4,F4.0,F7.2,3X,F5.0,F7.2,3X,F7.3,3X,F7.2,3X,I3)
        WRITE(6,842)NL1,NL2,LATR,YATTR,LOTR,XONTR,ZTR,LARED,LORED,DELAZ,
       1MODE,LPC,INPRIN,IFMT,KOLT,QQ,PPP,ISTS
        WRITE(6,862)SMP,XNEAR,XFAR,HILO,CNST,PWRP,ZPMAG,PWRX,ZXMAG,
       1AVLT,AFLT,AFLP,ADLT,ADLP
    842 FORMAT(10X,2I3,F6.0,F8.2,F7.0,2F8.2,F6.0,F7.0,F8.1,4I3,I4,2F9.5,
       1 I4)
        IF(ISTS .EQ. 0) GO TO 863
        WRITE(6,865) TAAF,TFR,TWT,AMTST,IIT,KTTA,KOMIT
    865 FORMAT(10X,4F10.3,3I5,/)
    862 FORMAT(10X,F6.2,2F7.0,9F7.2,2F7.3)
    863 WRITE(6,843) (V1(L),DP1(L), L=1,NL1)
        IF(NL2 .EQ. 0) GO TO 52
        WRITE(6,843) (V2(L),DP2(L), L=1,NL2)
    843 FORMAT(10X,F10.3,F10.3)
     52 CALL TPAR
        IF(INPRIN .LT. 5) GO TO 57
        IF(NL1 .GT. 10 .OR. NL2 .GT. 10) GO TO 57
     53 IF(NL1 .LT. 7 .AND. NL2 .LT. 7) GO TO 56
     54 WRITE(6,888)(THK1(J),(TID1(L,J),L=1,10),(DID1(L,J),L=1,10),
       1J=1,10)
        IF(NL2 .EQ. 0) GO TO 57
        WRITE(6,888)(THK2(J),(TID2(L,J),L=1,10),(DID2(L,J),L=1,10),
       1J=1,10)
    888 FORMAT(5X,21F6.2)
        GO TO 57
     56 WRITE(6,889)(THK1(J),(TID1(L,J),L=1,6),(DID1(L,J),L=1,6),
       1J=1,6)
        IF(NL2 .EQ. 0) GO TO 57
        WRITE(6,889)(THK2(J),(TID2(L,J),L=1,6),(DID2(L,J),L=1,6),
       1J=1,6)
    889 FORMAT(5X,13F8.3)
     57 L=0
```

(List of stations ignored in hypocenter adjustments)

Optional printout of station list and parameters

Subroutine to calculate arrays used in the TRVDRV subroutine

Optional printout of TPAR arrays

```
      KOLT=KLLT
   58 GO TO (59,559),IFMT
  559 L=L+1
D6-2  READ(5,720) MSTA(L),QSABE(L),W(L),KDATE(L),JHR(L),JMIN(L),P(L),
(D7) 1AMP(L),PRP(L),S(L),AMS(L),PRS(L),AMX(L),PRX(L),CALP(L),CALS(L),
     2CALX(L),RK(L),DT(L)
  560 IF(KDATE(L) .GT. 440000) GO TO 559 --> Read next phase card
  561 IF(KDATE(L) .GT. 110000) GO TO 900 --> Goto switch at end of M/Prog
  562 INST=JMIN(L)  ) Read INST and ZRES
      ZRES=P(L)     ) on execution card
  564 KREC=L-1
      IF(INPRIN .LT. 2) GO TO 566
  565 WRITE(6,846)KREC,INST,ZRES
      WRITE(6,867)(MSTA(L),KDATE(L),JHR(L),JMIN(L),QSABE(L),W(L),P(L),
     1AMP(L),PRP(L),S(L),AMS(L),PRS(L),AMX(L),PRX(L),
     2CALP(L),CALS(L),CALX(L),RK(L),DT(L), L=1,KREC)
  867 FORMAT(10X,A4,2X,I6,2X,2I2,2X,A3,2X,F3.0,F7.2,F5.0,F5.2,
     1F7.2,F5.0,F5.2,F5.0,F5.2,3F7.2,2X,A3,F7.2)
  566 IF(KREC .LT. 3) GO TO 96 --> Go to "no solution" printout
  567 IHR=24
      DO 570 J=1,KREC
      G(J)=1.0
      W(J)=(4.0-W(J))/4.0
      CSAB=ABS(CALS(J))
      IF(CSAB .LT. 0.01) CALS(J)=CALP(J)
  568 CXAB=ABS(CALX(J))
      IF(CXAB .LT. 0.01) CALX(J)=CALP(J)
  569 IF(JHR(J) .LT. IHR) IHR=JHR(J)
  570 CONTINUE
  572 GO TO 69
   59 L=L+1
      READ(5,820) W(L),MSTA(L),QSABE(L),KDATE(L),JHR(L),JMIN(L),
     1P(L),AMP(L),PRP(L),S(L),AMS(L),PRS(L),AMX(L),PRX(L),CALP(L),
     2RK(L),DT(L)
   60 IF(KDATE(L) .GT. 440000) GO TO 59
   61 IF(KDATE(L) .GT. 110000) GO TO 900
   62 INST=JMIN(L)
      ZRES=P(L)
   64 KREC=L-1
      IF(INPRIN .LT. 2) GO TO 66
   65 WRITE(6,846) KREC,INST,ZRES
  846 FORMAT(10X,'KREC=',I2,2X,'INST=',I2,2X,'ZRES=',F5.2)
      WRITE(6,847) (MSTA(L),QSABE(L),KDATE(L),JHR(L),JMIN(L),P(L),
     1AMP(L),PRP(L),S(L),AMS(L),PRS(L),AMX(L),PRX(L),CALP(L),
     2RK(L),DT(L), L=1,KREC)
  847 FORMAT(10X,A4,2X,A3,2X,I6,2X,2I2,F7.2,F5.0,F5.2,F7.2,F5.0,F5.2,
     15X,F5.0,F5.2,5X,F6.1,2X,A3,F7.2)
```

Format # 2 phase cards:

- Read phase cards
- Optional printout of phase list
- Convert external integer weights to internal fractional weights
- Set "S" and "X" calibration equal to "P" calibration if former are undefined
- Determine "hour" of earliest arrival

Read format #1

phase cards

```
   66 IF(KREC .LT. 3) GO TO 96
   67 IHR=24
      DO 68 J=1,KREC
      W(J)=(4.0-W(J))/4.0
      G(J)=1.0
      CALS(J)=CALP(J)
      CALX(J)=CALP(J)
      IF(JHR(J) .LT. IHR) IHR=JHR(J)
   68 CONTINUE
   69 DO 82 J=1,KREC
      DO 80 I=1,KSITE
      IF(MSTA(J) .EQ. NSTA(1,I)) GO TO 72
   70 IF(I .EQ. KSITE) GO TO 85
   71 GO TO 80
   72 LAT(2,J)=LAT(1,I)
      LON(2,J)=LON(1,I)
      YAT(2,J)=YAT(1,I)
      XON(2,J)=XON(1,I)
      DLY(2,J)=DLY(1,I)
      EL(2,J)=EL(1,I)
      MDL(2,J)=MDL(1,I)
      NSTA(2,J)=NSTA(1,I)
      GO TO 82
   80 CONTINUE
   82 CONTINUE
      GO TO 87
   85 WRITE(6,722) KDATE(J),JHR(J),JMIN(J),MSTA(J)
      WRITE(6,770)
      GO TO 57
   87 LOSW=0
      OSUM=0.0
      ORGS=0.0
      LL=0
      LWC=0
      DO 95 J=1,KREC
      TP(J)=FLOAT(3600*(JHR(J)-IHR)+60*JMIN(J))+P(J)+DT(J)
      PT(J)=TP(J)
      GW(J)=W(J)
      IF(KOMIT .EQ. 0) GO TO 88
      DO 815 K=1,KOMIT
      IF(NOMIT(K) .NE. MSTA(J)) GO TO 815
      W(J)=0.0
  815 CONTINUE
   88 IF(W(J)-0.3)95,95,89
   89 LWC=LWC+1
      IF(S(J))90,95,90
   90 ORGS=TP(J)-SMP*(S(J)-P(J))
```

Match phase and station lists

Reject quake if stn on phase list is not on station list

Set selected switches, sum registers, and counters

Calculate (reduced) P arrival times and set up ordering array

Set "0" weight for stations on the "OMIT" list

If P-weight <0.3, ignore S-P data

Calculate S-P origin time

```
      OSUM=OSUM+ORGS
      LL=LL+1
   95 CONTINUE
      IF(LWC-3)96,97,97
   96 WRITE(6,723)KDATE(1),JHR(1),JMIN(1)
      WRITE(6,770)
      GO TO 57
   97 XLL=FLOAT(LL)
      IF(LL .EQ. 0) GO TO 99
   98 LOSW=1
      ORGS=OSUM/XLL
   99 IF(LWC .LT. KOLT) KOLT=LWC
  100 DO 105 I=1,KOLT


      PTMN=9999.0
      IDX=1
      DO 104 J=1,KREC
      IF(W(J)-0.3) 104,104,102
  102 IF(PT(J)-PTMN) 103,104,104
  103 PTMN=PT(J)
      IDX=J
  104 CONTINUE
      PT(IDX)=99999.0
      KO(I)=IDX
  105 CONTINUE
      NEAR=KO(1)
      PMIN=TP(NEAR)
      MFAR=KO(KOLT)
      PFAR=TP(MFAR)
      KALX=MFAR
      II=0
      IF(INST .EQ. 8) GO TO 185
  113 IF(INPRIN .LT. 5) GO TO 115
  114 WRITE(6,848) IHR,MSTA(NEAR),LOSW,PMIN,ORGS
  848 FORMAT(10X,'IHR=',I2,2X,'1ST STN=',A4,2X,'LOSW=',I2,2X,
     1'PMIN=',F8.2,2X,'ORGS=',F8.2)
      WRITE(6,849) (MSTA(L),NSTA(2,L),LAT(2,L),YAT(2,L),LON(2,L),
     1XON(2,L),DLY(2,L),EL(2,L),MDL(2,L),TP(L),W(L), L=1,KREC)
  849 FORMAT(10X,A4,2X,A4,F4.0,F7.2,2X,F5.0,F7.2,F7.2,F7.2,I3,2F10.3)
  115 CALL PREHY
      IF( INPRIN .LT. 3) GO TO 118
  116 WRITE(6,850) MODE,LHY,LATEP,YATEP,LONEP, XONEP,Z,ORG,
     1MSTA(NEAR),MSTA(MFAR),MSTA(KALX)
  850 FORMAT(10X,'MODE=',I2,2X,'LHY=',I2,2X,'PREHY(LATT,LONG,DEPTH,',
     1'ORIG-STNS N,F,X)=',2X,F4.0,F7.2,2X,F5.0,2F7.2,F10.2,2X,
```

Calculate S-P origin time for station J

If fewer than 3 stns have P-weights ≥0.3, reject quake

Calculate average S-P origin time and flag its availability

"Order" earliest KOLT stations having P-weights greater than 0.3 in order of increasing P-wave arrival times

Specify 1st and Kolt'th stns and the corresponding arrival times

Define KALX temporarily

INST = 8 directs solution to the VELAZ routine

Optional printout of matched phase and station lists

Subroutine to fix preliminary hypocenter

Optional printout of the preliminary hypocenter

...unt for
...f solutions

Entry for repeat

Iteration entry point

```
      2A4,1X,A4,1X,A4/)
  118 DEDN=(XFAR-XNEAR)/0.9
      KAZ=0
```

Calculate coefficient used in the computation of the "distance" weighting factor

```
  119 AAF=10.0
      KZSW=1
      II=0
      IF(INST .EQ. 0 .OR. INST .EQ. 1 .OR. INST .EQ. 4
     1.OR. LOSW .EQ. 1) GO TO 124
  120 IF(INST-6) 121,123,124
  121 IF(INST-3) 122,123,122
  122 INST=1
      GO TO 124
  123 INST=4
  124 IF(INST .EQ. 1 .OR. INST .EQ. 4) Z=ZRES
```

Manipulation of switches controlling repeated solutions

```
  125 II=II+1
      XEP=60.0*(LONEP-LORED)+XONEP
      YEP=60.0*(LATEP-LARED)+YATEP
      DELMN=999.99
      DO 130 I=1,KREC
      ZLAT=(60.0*(LAT(2,I)+LARED)+YAT(2,I)+YEP)/(120.0*57.29578)
      PP=PPP*COS(ZLAT)
      DX(I)=(60.0*(LON(2,I)-LORED)+XON(2,I)-XEP)*PP
      DY(I)=(60.0*(LAT(2,I)-LARED)+YAT(2,I)-YEP)*QQ
      IF(DX(I)*DX(I) .LT. 0.000001) DX(I)=0.001
  126 IF(DY(I)*DY(I) .LT. 0.000001) DY(I)=0.001
  127 DELTA(I)=SQRT(DX(I)*DX(I)+DY(I)*DY(I))
      IF(DELTA(I) .LT. DELMN) DELMN=DELTA(I)
  130 CONTINUE
```

Calculate epicentral distances and determine smallest one

```
  131 IF(DELMN .GT. DELAZ .AND. II .GT. 5) GO TO 185
```

Go to VELAZ routine if event is too far from network

```
  132 CALL TRVDRV
```

Subroutine to calculate traveltimes, derivatives, and angles of incidence at the focus

```
  138 AAF1=AAF
      AAF=0.0
      ASUM=0.0
      BSUM=0.0
      KSTA=0
      WSTA=0.0
      AWF=0.0
      AWUM=0.0
```

Set switches, counters, and sum registers

```
      IF(II .LT. 5) GO TO 148
  139 DO 145 I=1,KREC
```

Do not weight arrivals according to distance before the 5th iteration

```
      IF(DELTA(I) .LT. XNEAR) GO TO 144
  140 IF(DELTA(I) .GT. XFAR) GO TO 143
```

```
  141 G(I)=1.0-(DELTA(I)-XNEAR)/DEDN
      GO TO 145
  143 G(I)=0.0
      GO TO 145
  144 G(I)=1.0
  145 CONTINUE
  148 DO 150 I=1,KREC
      F(I)=TP(I)-T(I)-DLY(2,I)-ORG
      IF(W(I)*G(I) .LT. 0.1) GO TO 150
  149 KSTA=KSTA+1
      ASUM=ASUM+ABS(F(I))
      BSUM=BSUM+F(I)
      WT=W(I)*G(I) ------> combined weight
      WSTA=WSTA+WT
      AWUM=AWUM+ABS(F(I)*WT)
  150 CONTINUE
      IF(KSTA .LT. 3) GO TO 96
      XSTA=FLOAT(KSTA)
      AAF=ASUM/XSTA ------> mean deviation
      AVR=BSUM/XSTA ------> average residual
      ABVR=ABS(AVR) ------> "  " modulus
      DAAF=AAF1-AAF ------> change in mean deviation
      AWF=AWUM/WSTA ------> weighted mean deviation
      IF(INST .NE. 9) GO TO 630
  616 WRITE(6,850) MODE,LHY,LATEP,YATEP,LONEP,XONEP,Z,ORG,
     1MSTA(NEAR),MSTA(MFAR),MSTA(KALX)
  617 WRITE(6,851) (MSTA(L),DELTA(L),T(L),AX(L),AY(L),AH(L),ANIN(L),
     1F(L), L=1,KREC)
  619 WRITE(6,620) AAF,AVR,AWF,XSTA,WSTA
  620 FORMAT(10X,'(AAF,AVR,AWF,XSTA,WSTA)=(',3F8.4,2F8.2,')')
  621 WRITE(6,770)
      GO TO 57
  630 IF(II .GT. 12) AVR=AVR1
      IF(INPRIN .LT. 4) GO TO 153
  151 IF(II .GT. 3) GO TO 153
  152 WRITE(6,851) (MSTA(L),DELTA(L),T(L),AX(L),AY(L),AH(L),ANIN(L),
     1F(L), L=1,KREC)
  851 FORMAT(10X,A4,F7.2,6F8.3)
  153 IF(INPRIN .LT.3) GO TO 155
  154 WRITE(6,852) YEP,XEP,Z,AAF,DAAF,KSTA,AWF,WSTA
  852 FORMAT(10X,3F8.2,2F8.3,2X,I3,2X,2F8.3)
  155 IF(II-12)161,156,300 ------> Terminate adjustment after 12 iterations
  156 II=13 ------>
      GO TO 158
  157 II=14 ------>
  158 AVR1=AVR
      ORG=ORG+AVR
```

Calculate distance-dependent weighting factors

Calculate arrival time residuals

Calculate parameters related to adequacy of current solution

Printout for INST=9 option, which uses program to compute distances, traveltimes, derivatives, and angles of incidence at the focus as well as residuals for a specified focus and origin time

Restore 12'th iteration AVR for printout

Optional printout of distances, traveltimes, derivatives, etc.

Optional printout of ambient focus and statistical parameters

→ Flag indicating termination after 12 iterations with subsequent adjustment of origin time

→ Flag indicating termination of a stationary solution with subsequent adjustment of origin time

```
      GO TO 138
  161 IF(KZSW .EQ. 1 .OR. II .LE. 4) GO TO 168
  162 IF(KSTA .EQ. MM .AND. ABVR .GT. AVLT .AND. KOUT .LT. 3) GO TO 168
  163 ABDAF=ABS(DAAF)
  164 IF(ABVR .GT. AVLT .AND. ABDAF .GT. ADLP) GO TO 168
  165 IF(AAF .LT. AFLT .AND. ABDAF .LT. ADLT .AND. ABVR .LT. AVLT)
     1GO TO 300
  166 IF(II .GT. 8 .AND. AAF .LT. AFLP .AND. ABDAF .LT. ADLP .AND.
     1ABVR .LT. AVLT) GO TO 300
  167 IF(II .GT. 8 .AND. AAF .LT. AFLP .AND. ABDAF .LT. ADLP .AND.
     1ABVR .GE. AVLT) GO TO 157
```

Tests for continuation or termination of iterations: specific tests permitting termination change as the number of iterations increases.

```
  168 DO 169 I=1,4
      B(I)=0.0
      DO 169 J=1,4
      A(I,J)=0.0
  169 CONTINUE
      DO 170 I=1,KREC
      WT=W(I)*G(I)
      A(1,1)=A(1,1)+AX(I)*AX(I)*WT
      A(1,2)=A(1,2)+AX(I)*AY(I)*WT
      A(1,3)=A(1,3)+AX(I)*AH(I)*WT
      A(1,4)=A(1,4)+AX(I)*WT
      A(2,2)=A(2,2)+AY(I)*AY(I)*WT
      A(2,3)=A(2,3)+AY(I)*AH(I)*WT
      A(2,4)=A(2,4)+AY(I)*WT
      A(3,3)=A(3,3)+AH(I)*AH(I)*WT
      A(3,4)=A(3,4)+AH(I)*WT
      A(4,4)=A(4,4)+1.0*WT
      B(1)=B(1)+F(I)*AX(I)*WT
      B(2)=B(2)+F(I)*AY(I)*WT
      B(3)=B(3)+F(I)*AH(I)*WT
      B(4)=B(4)+F(I)*WT
  170 CONTINUE
      A(2,1)=A(1,2)
      A(3,1)=A(1,3)
      A(4,1)=A(1,4)
      A(3,2)=A(2,3)
      A(4,2)=A(2,4)
      A(4,3)=A(3,4)
```

Calculate coefficients of normal equations used in computations of hypocentral adjustments

```
      AHMX=-1.0
      AHMN=+1.0
      DO 180 I=1,KREC
      IF(W(I)*G(I)-0.1) 180,180,171
  171 IF(AH(I)-AHMX)173,173,172
```

Calculate range of $\partial T/\partial z$

```
172 AHMX=AH(I)
173 IF(AH(I)-AHMN)174,180,180
174 AHMN=AH(I)
180 CONTINUE
    RAH=AHMX-AHMN
```

```
    IF(INPRIN .LT. 3) GO TO 182
181 WRITE(6,853) A(1,1), A(1,2),A(1,3),A(1,4),A(2,2),A(2,3),A(2,4),
   1A(3,3),A(3,4),A(4,4),B(1),B(2),B(3),B(4),RAH,INST
853 FORMAT(5X,15F8.4,2X,I3)
```

Optional printout of normal equation coefficients

```
182 CALL HYCOR
```

Subroutine to compute hypocentral adjustments

```
    IF(INPRIN .LT. 3) GO TO 184
183 WRITE(6,854) MM,KOUT,DETA,ASDX,ASDY,ASDZ,ASDT,Y(1),Y(2),Y(3),Y(4)
854 FORMAT(10X,I3,2X,I3,F14.10,8F10.4)
```

Optional printout of hypocentral adjustments and related parameters

```
184 IF(KOUT .NE. 5) GO TO 197
185 CALL VELAZ
```

Subroutine to compute velocity and azimuth of plane wave across net

```
    PSY=PFI+4.71239

189 IF(PSY-6.28318)191,191,190
190 PSY=PSY-6.28318
191 PSY=PSY*57.29578
    WRITE(6,780) KDATE(NEAR),JHR(NEAR),JMIN(NEAR),P(NEAR),
   1PSY,VA,AAF,MSTA(NEAR),MSTA(MFAR),MSTA(KALX),KAZ,II,KT
    DO 196 I=1,KREC
    IF(I .EQ. NEAR) GO TO 196
195 WRITE(6,782) MSTA(I),FT1(I),TH1(I)
196 CONTINUE
    WRITE(6,770)
```

Reduction of solution to standard format and printout for VELAZ subroutine

```
    IF(INST .LT. 3 .OR. INST .EQ. 8) GO TO 57
    Z=ZTR
    ORG=PMIN-2.0
    LONEP=LON(2,NEAR)
    XONEP=XON(2,NEAR)
    LATEP=LAT(2,NEAR)
    YATEP=YAT(2,NEAR)
    KAZ=0
    GO TO 412
```

Reset preliminary hypocenter to location of earliest station for further attempts to find a solution under certain INST controls

```
197 ABY3=ABS(Y(3))
    IF(Z+Y(3) .LE. 0.0 .AND. ABY3 .GT. 0.000001) GO TO 201
    GO TO 205
```

Test whether correction will put focus above ground

```
201 R=-0.6*Z/Y(3)
    Y(1)=Y(1)*(0.4+0.6*R)
    Y(2)=Y(2)*(0.4+0.6*R)
    Y(3)=Y(3)*R
    Y(4)=Y(4)*(0.4+0.6*R)
```

Restrict solution, if necessary, to avoid a negative focal depth

```
205 XONEP=XONEP+Y(1)/PP
```

Calculate corrected focal

iteration

```
      YATEP=YATEP+Y(2)/QQ
      Z = Z + Y(3)
      ORG=ORG+Y(4)
      VH=SQRT(Y(1)*Y(1)+Y(2)*Y(2))
      IF(INPRIN .LT. 3) GO TO 208
  206 WRITE(6,855) YATEP,XONEP,Z,ORG,VH,Y(1),Y(2),Y(3),Y(4)
  855 FORMAT(10X,5F8.2,22X,4F10.4//)
  208 KZSW=0
      IF(II .EQ. 4 .AND. RAH .LT. 0.02 .AND. INST .NE. 1 .AND.
     1INST .NE. 4) Z=ZTR
  209 IF(VH-10.0)215,210,210
  210 KZSW=1
  215 GO TO 125
  300 LREC=0
      ESUM=0.0
      DO 302 I=1,KREC
      IF(W(I)*G(I) .LT. 0.1) GO TO 302
  301 LREC=LREC+1
      ESUM=ESUM+F(I)*F(I)
  302 CONTINUE
      XREC=FLOAT(LREC-MM-1)
      IF(XREC-0.9)305,305,310
  305 SDP=77.77
      SDX=777.7
      SDY=777.7
      SDZ=777.7
      SDT=77.77
      GO TO 315
  310 SDP=SQRT(ESUM/XREC)
      SDX=SDP*SQRT(ASDX)
      SDY=SDP*SQRT(ASDY)
      SDZ=SDP*SQRT(ASDZ)

      SDT=SDP*SQRT(ASDT)
      GO TO (315,314,312,313,315), KOUT
  312 SDT=77.77
      GO TO 315
  313 SDT=77.77
  314 SDZ=777.7
  315 CONTINUE
      OSO=0.0
      OGS=0.0
      IF(LOSW .EQ. 1) OSO=ORGS-ORG
  320 IF(XONEP)322,325,325
```

Return for another

coordinates

Horizontal shift from last adjustment

Optional printout of focal corrections applied

If depth control has been lost, return focus to trial depth at end of 4'th iteration

Block depth adjustment on next iteration if VH > 10 km

Calculate statistical parameters of solution

```
  322 LONEP=LONEP-1.0
      XONEP=XONEP+60.0
      GO TO 320
  325 IF(XONEP-60.0)330,327,327
  327 LONEP=LONEP+1.0
      XONEP=XONEP-60.0
      GO TO 325
  330 IF(YATEP)332,335,335
  332 LATEP=LATEP-1.0
      YATEP=YATEP+60.0
      GO TO 330
  335 IF(YATEP-60.0)340,337,337
  337 LATEP=LATEP+1.0
      YATEP=YATEP-60.0
      GO TO 335
  340 KHR=ORG/3600.0
      FHR=KHR
      KMIN=ORG/60.0-60.0*FHR
      FMIN=KMIN
      SEC=ORG-3600.0*FHR-60.0*FMIN
      KHR=KHR+IHR
      IF(SEC)341,350,350
  341 SEC=SEC+60.0
      KMIN=KMIN-1
      IF(KMIN)342,350,350
  342 KMIN=KMIN+60
      KHR=KHR-1
```

Restore origin time, latitude, and longitude of earthquake to conventional format for printout

```
  350 DO 370 I=1,KREC
      TP(I)=TP(I)-ORG
      TS(I)=0.0
      IF(S(I))352,353,352
  352 TS(I)=TP(I)+(S(I)-P(I))
  353 IF(DY(I) .LE. 0) GO TO 356
  354 AZ(I)=-ATAN(DX(I)/DY(I))
      GO TO 357
  356 AZ(I)=3.14159-ATAN(DX(I)/DY(I))
  357 IF(AZ(I))358,358,359
  358 AZ(I)=AZ(I)+6.28318
  359 AZ(I)=57.29578*AZ(I)
  370 CONTINUE
```

Compute P-traveltimes, S-traveltimes, and epicenter-to-station azimuths for printout

```
      CALL MAGNTD
```

Subroutine to compute magnitudes from P+X data

```
      IF(LOSW .EQ. 1) OGS=SEC+OSO
```

S-P origin time for printout

```
  697 IF(ISTS .EQ. 0 .OR. INST .GT. 2) GO TO 698
  575 IF(AAF .GT. TAAF .OR. II .GT. IIT .OR. KSTA .LT. KTTA) GO TO 698
```

Tests for exclusion of event from summary

```
  576 DO 590 J=1,KREC
      WGJ=GW(J)*G(J)
      ABFJ=ABS(F(J))
  577 DO 582 K=1,KSITE
      IF(MSTA(J) .EQ. NSTA(1,K)) GO TO 585
```

```
  578 IF(K .EQ. KSITE) GO TO 590
  582 CONTINUE
  585 IF(ABFJ .GT. TFR .OR. WGJ .LT. TWT) GO TO 586
      MPC(K)=MPC(K)+1
      SCOF(K)=SCOF(K)+F(J)
      SCOF2(K)=SCOF2(K)+F(J)*F(J)
  586 ABEPM=ABS(EPMG(J))
      IF(ABEPM .GT. AMTST) GO TO 587
      MPCP(K)=MPCP(K)+1
      SCOP(K)=SCOP(K)+EPMG(J)
      SCOP2(K)=SCOP2(K)+EPMG(J)*EPMG(J)
  587 ABEXM=ABS(EXMG(J))
      IF(ABEXM .GT. AMTST) GO TO 590
      MPCX(K)=MPCX(K)+1
      SCOX(K)=SCOX(K)+EXMG(J)
      SCOX2(K)=SCOX2(K)+EXMG(J)*EXMG(J)
  590 CONTINUE
  698 WRITE(6,705) MODE,LPC,INST,LOSW,LHY,KOUT,KAZ,OGS,AVR,PPMG
      WRITE(6,748)
      WRITE(6,750) KDATE(   NEAR),KHR,KMIN,SEC,LATEP,YATEP,LONEP,XONEP,
     1Z,AAF,SDP,SDX,SDY,SDZ,SDT,KSTA,XMAG,II,KREC,VH
      IF(LPC .EQ. 0) GO TO 390
      KPLUS=0
  371 IF(LPC .EQ. 3) KPLUS=1
  372 WRITE(7,755) KDATE(   NEAR),KHR,KMIN,SEC,LATEP,YATEP,LONEP,XONEP,
     1Z,AAF,SDP,SDX,SDY,SDZ,SDT,KSTA,XMAG,II,KREC,KOUT
      IF(KPLUS .EQ. 0) GO TO 390
  373 KPLUS=0
      GO TO 372
  390 WRITE(6,758)
      DO 400 I=1,KREC
      WRITE(6,760) NSTA(2,I),DELTA(I),AZ(I),ANIN(I),QSABE(I),
     1TP(I),TS(I),F(I),PMAG(I),EPMG(I),XXMG(I),EXMG(I),RK(I),W(I),G(I)
      IF(LPC .EQ. 0 .OR. LPC .EQ. 2) GO TO 400
  392 WRITE(7,765) NSTA(2,I),DELTA(I),AZ(I),ANIN(I),QSABE(I),
     1TP(I),TS(I),F(I),PMAG(I),RK(I),W(I),G(I)
  400 CONTINUE
      WRITE(6,770)
      IF(LPC .EQ. 0) GO TO 404
      WRITE(7,777)
  777 FORMAT(6X,'$$$$')
  404 IF(INST .LT. 3) GO TO 57
  405 DO 410 I=1,KREC
      TP(I)=TP(I)+ORG
```

Sum registers for statistical summary:
- Test for exclusion of station from time summary, for this event
- Test for exclusion of station from P-mag summary, for this event
- Test for exclusion of station from X-mag summary, for this event

Principal printout section for line printer and card punch:
- Condition codes, etc
- Event summary on printer
- Event summary on card punch
- Punch duplicate summary if LPC=3
- Station-phase list on printer
- Station-phase list on card punch
- Skip lines to separate event on printer
- Write $$$$ card to separate event decks

```
  410 CONTINUE
  412 INST2=INST-2
      GO TO (415,415,416,417),INST2
  415 INST=0
      GO TO 119
  416 INST=1
      GO TO 119
  417 INST=4
      GO TO 119
```

Control section to manipulate INST variable to obtain desired sequence of solutions for the same earthquake

```
  900 IF(KDATE(L) .GT. 114400 ) GO TO 50
  910 IF(KDATE(L) .GT. 112200) GO TO 30
  915 IF(KDATE(L) .GT. 111500) GO TO 45
```

Switch section accessible from data deck to permit reentry at various points in program.

```
  950 IF(ISTS .EQ. 0) GO TO 999
```

→ Skip Statistical Routine

Calculation of statistical summary

```
  951 DO 960 K=1,KSITE
      IF(MPC(K) .LT. 2) GO TO 953
  952 XPC=FLOAT(MPC(K))

      AVRES(K)=SCOF(K)/XPC
      SDRES(K)=SQRT((XPC*SCOF2(K)-SCOF(K)*SCOF(K))/(XPC*(XPC-1.0)))
      SEM(K)=SDRES(K)/SQRT(XPC)
```

Calculate time residual statistics

```
  953 IF(MPCP(K) .LT. 2) GO TO 955
  954 XPP=FLOAT(MPCP(K))
      AVREP(K)=SCOP(K)/XPP
      SDREP(K)=SQRT((XPP*SCOP2(K)-SCOP(K)*SCOP(K))/(XPP*(XPP-1.0)))
      SEMP(K)=SDREP(K)/SQRT(XPP)
```

Calculate P-magnitude residual statistics

```
  955 IF(MPCX(K) .LT. 2) GO TO 960
      XPX=FLOAT(MPCX(K))
      AVREX(K)=SCOX(K)/XPX
      SDREX(K)=SQRT((XPX*SCOX2(K)-SCOX(K)*SCOX(K))/(XPX*(XPX-1.0)))
      SEMX(K)=SDREX(K)/SQRT(XPX)
```

Calculate X-magnitude residual statistics

```
  960 CONTINUE
      WRITE(6,976)
  976 FORMAT(////,20X,'TRAVELTIME  RESIDUALS',15X,
     1'P-MAGNITUDE  RESIDUALS',14X,'X-MAGNITUDE  RESIDUALS',/)
      WRITE(6,977)
      WRITE(6,978)(NSTA(1,K),AVRES(K),SDRES(K),SEM(K),MPC(K),AVREP(K),
     1SDREP(K),SEMP(K),MPCP(K),AVREX(K),SDREX(K),SEMX(K),MPCX(K),
     2K=1,KSITE)
  977 FORMAT(5X,'STATION',5X,'AVRES',2X,'S D RES',2X,'S E MEAN',
     12X,'N OBS',5X,'AVRES',2X,'S D RES',2X,'S E MEAN',2X,'N OBS',
     25X,'AVRES',2X,'S D RES',2X,'S E MEAN',2X,'N OBS')
  978 FORMAT(7X,A4,5X,F6.2,2X,F6.2,4X,F6.2,3X,I4,5X,F6.2,2X,F6.2,4X,
     1F6.2,3X,I4,5X,F6.2,2X,F6.2,4X,F6.2,3X,I4)
```

Printout of statistical summary

```
  962 IF(KOMIT .EQ. 0) GO TO 999
      WRITE(6,979)
      WRITE(6,980)(NOMIT(K),K=1,KOMIT)
  979 FORMAT(///,10X,'OMITTED',/)
  980 FORMAT(12X,A4)
  999 STOP
      END
```

Printout of list of stations that were omitted from hypocentral adjustment calculations

Subroutine to compute arrays, from model parameters, for use in the TRVDRV subroutine below

```
      SUBROUTINE TPAR
      DIMENSION NSTA(2,99),LAT(2,99),YAT(2,99),LON(2,99),XON(2,99),
     1EL(2,99),DLY(2,99),MDL(2,99),MSTA(99),W(99),QSABE(99),KDATE(99),
     2JHR(99),JMIN(99),P(99),PRP(99),AMP(99),S(99),PRS(99),AMS(99),
     3PRX(99),AMX(99),RK(99),DT(99),CALP(99),CALS(99),CALX(99),TP(99),
     4DX(99),DY(99),DELTA(99),T(99),AX(99),AY(99),AH(99),ANIN(99),F(99),
     5PMAG(99),AT(99),BT(99),XH(99),YH(99),DIST1(99),TH1(99),FT1(99),
     6TS(99),AZ(99),V(26),DP(26),THK(26),TID(26,26),DID(26,26),TINJ(26),
     7DIDJ(26),TR(26),V1(26),DP1(26),THK1(26),TID1(26,26),DID1(26,26),
     8V2(26),DP2(26),THK2(26),TID2(26,26),DID2(26,26),A(4,4),B(4),Y(4),
     9C(4,4),D(3,3),AP(3,3),BP(3),G(99),PT(99),KO(99),XXMG(99)
      DIMENSION EPMG(99),EXMG(99)
      COMMON NSTA,LAT,YAT,LON,XON,EL,DLY,MDL,MSTA,W,QSABE,KDATE,JHR,
     1JMIN,P,PRP,AMP,S,PRS,AMS,PRX,AMX,RK,DT,CALP,CALS,CALX,TP,DX,DY,
     2DELTA,T,AX,AY,AH,ANIN,F,PMAG,AT,BT,XH,YH,DIST1,TH1,FT1,TS,AZ,V,
     3DP,THK,TID,DID,TINJ,DIDJ,TR,V1,DP1,THK1,TID1,DID1,V2,DP2,THK2,
     4TID2,DID2,A,B,Y,C,D,AP,BP,G,PT,KO,XXMG,EPMG,EXMG
      COMMON/UNDM/HILO,CNST,PWRP,ZPMAG,PWRX,ZXMAG,KT,KSTA,VB,PPP,ISTS,
     1KSITE,NL1,NL2,LATR,YATTR,LOTR,XONTR,ZNOT,LARED,LORED,MODE,INST,
     2KREC,IHR,NEAR,PMIN,ORGS,QQ,ORG,LATEP,YATEP,LONEP,XONEP,Z,KZSW,
     3XEP,YEP,RAH,ASDX,ASDY,ASDZ,ASDT,MM,KOUT,XMAG,LOSW,PFI,VA,AAF,
     4LHY,KAZ,DETA,MFAR,PFAR,KALX,KOLT,SMP,XNEAR,XFAR,ZTR,ZRES,PPMG
      REAL LAT,LON,LATR,LOTR,LARED,LORED,LATEP,LONEP
```

This block is contained in the M/Prog and all of the subroutines

```
      KSW=1
    1 IF(KSW .EQ. 2) GO TO 5
    2 NL=NL1
      DO 3 K=1,NL
      V(K)=V1(K)
      DP(K)=DP1(K)
    3 CONTINUE
      GO TO 8
```

Load subroutine for model #1 calculations

```
    5 NL=NL2
      DO 7 K=1,NL
      V(K)=V2(K)
      DP(K)=DP2(K)
    7 CONTINUE
```

Load subroutine for model #2 calculations

```
C     COMPUTE THK(L)
    8 THK(NL)=0.0
      DO 10 K=2,NL
      L=K-1
      THK(L)=DP(K)-DP(L)
   10 CONTINUE
```

Compute layer thicknesses

```
C     COMPUTE INTERCEPTS AND CRITICAL DISTANCES FOR BOUNDARY FOCI
      DO 11 K=1,NL
      DO 11 L=1,NL
      TID(K,L)=0.0
      DID(K,L)=0.0
```

```
   11 CONTINUE
      N1=NL-1
      DO 15 M=2,NL
      M1=M-1
      SUM1=0.0
      SUMA=0.0
      DO 12 L=1,M1
      SQT=SQRT(V(M)*V(M)-V(L)*V(L))
      SUM1=SUM1 + THK(L)*SQT/(V(M)*V(L))
      SUMA=SUMA + THK(L)*V(L)/SQT
   12 CONTINUE
      TID(M,M)=SUM1
      DID(M,M)=SUMA
```

Compute intercepts of refracted waves and critical distances for waves with their sources lying on layer boundaries

```
   15 CONTINUE
      DO 20 M=2,NL
      M1=M-1
      SUM2=0.0
      SUMB=0.0
      DO 18 L=1,M1
      SQT=SQRT(V(M)*V(M)-V(L)*V(L))
      SUM2=SUM2 + THK(L)*SQT/(V(M)*V(L))
      SUMB=SUMB + THK(L)*V(L)/SQT
   18 CONTINUE
      TID(1,M)=2.0*SUM2
      DID(1,M)=2.0*SUMB
   20 CONTINUE
      DO 40 K=2,N1
      KK=K+1
      K1=K-1
      DO 40 M=KK,NL
      M1=M-1
      SUM1=0.0
      SUM2=0.0
      SUMA=0.0
      SUMB=0.0
      DO 30 L=1,K1
      SQT=SQRT(V(M)*V(M)-V(L)*V(L))
      SUM1=SUM1 + THK(L)*SQT/(V(M)*V(L))
      SUMA=SUMA + THK(L)*V(L)/SQT
   30 CONTINUE
      DO 35 L=K,M1
      SQT=SQRT(V(M)*V(M)-V(L)*V(L))
      SUM2=SUM2 + THK(L)*SQT/(V(M)*V(L))
```

```
      SUMB=SUMB + THK(L)*V(L)/SQT
   35 CONTINUE
      TID(K,M)=SUM1+2.0*SUM2
      DID(K,M)=SUMA+2.0*SUMB
   40 CONTINUE
      IF(KSW .EQ. 2) GO TO 44
   41 DO 42 K=1,NL
      THK1(K)=THK(K)
      DO 42 L=1,NL
      TID1(K,L)=TID(K,L)
      DID1(K,L)=DID(K,L)
   42 CONTINUE
      IF(NL2 .EQ. 0) GO TO 47
   43 KSW=2
      GO TO 1
   44 DO 46 K=1,NL
      THK2(K)=THK(K)
      DO 46 L=1,NL
      TID2(K,L)=TID(K,L)
      DID2(K,L)=DID(K,L)
   46 CONTINUE
   47 RETURN
      END
```

Transcribe model #1 results to appropriate arrays

Transcribe model #2 results to appropriate arrays

Subroutine to assign or compute the preliminary hypocenter to begin the adjustment procedure

```
      SUBROUTINE PREHY
      DIMENSION NSTA(2,99),LAT(2,99),YAT(2,99),LON(2,99),XON(2,99),
     1EL(2,99),DLY(2,99),MDL(2,99),MSTA(99),W(99),QSABE(99),KDATE(99),
     2JHR(99),JMIN(99),P(99),PRP(99),AMP(99),S(99),PRS(99),AMS(99),
     3PRX(99),AMX(99),RK(99),DT(99),CALP(99),CALS(99),CALX(99),TP(99),
     4DX(99),DY(99),DELTA(99),T(99),AX(99),AY(99),AH(99),ANIN(99),F(99),
     5PMAG(99),AT(99),BT(99),XH(99),YH(99),DIST1(99),TH1(99),FT1(99),
     6TS(99),AZ(99),V(26),DP(26),THK(26),TID(26,26),DID(26,26),TINJ(26),
     7DIDJ(26),TR(26),V1(26),DP1(26),THK1(26),TID1(26,26),DID1(26,26),
     8V2(26),DP2(26),THK2(26),TID2(26,26),DID2(26,26),A(4,4),B(4),Y(4),
     9C(4,4),D(3,3),AP(3,3),BP(3),G(99),PT(99),KO(99),XXMG(99)
      DIMENSION EPMG(99),EXMG(99)
      COMMON NSTA,LAT,YAT,LON,XON,EL,DLY,MDL,MSTA,W,QSABE,KDATE,JHR,
```

This block is contained in

```
     1JMIN,P,PRP,AMP,S,PRS,AMS,PRX,AMX,RK,DT,CALP,CALS,CALX,TP,DX,DY,
     2DELTA,T,AX,AY,AH,ANIN,F,PMAG,AT,BT,XH,YH,DIST1,TH1,FT1,TS,AZ,V,
     3DP,THK,TID,DID,TINJ,DIDJ,TR,V1,DP1,THK1,TID1,DID1,V2,DP2,THK2,
     4TID2,DID2,A,B,Y,C,D,AP,BP,G,PT,KO,XXMG,EPMG,EXMG
      COMMON/UNDM/HILO,CNST,PHRP,ZPMAG,PWRX,ZXMAG,KT,KSTA,VB,PPP,ISTS,
     1KSITE,NL1,NL2,LATR,YATTR,LOTR,XONTR,ZNOT,LARED,LORED,MODE,INST,
     2KREC,IHR,NEAR,PMIN,ORGS,QQ,ORG,LATEP,YATEP,LONEP,XONEP,Z,KZSW,
     3XEP,YEP,RAH,ASDX,ASDY,ASDZ,ASDT,MM,KOUT,XMAG,LOSW,PFI,VA,AAF,
     4LHY,KAZ,DETA,MFAR,PFAR,KALX,KOLT,SMP,XNEAR,XFAR,ZTR,ZRES,PPMG
      REAL LAT,LON,LATR,LOTR,LARED,LORED,LATEP,LONEP
      LHY=0
      MKEY=MODE+1
      GO TO (5,7,9),MKEY
    5 ORG=PMIN-2.0
      LONEP=LON(2,NEAR)
      XONEP=XON(2,NEAR)
      LATEP=LAT(2,NEAR)
      YATEP=YAT(2,NEAR)
      Z=ZTR
      IF(LOSW .EQ. 1 .AND. INST .GT. 1 .AND. INST .NE. 4) ORG=ORGS
      LHY=1
      GO TO 300
    7 ORG=PMIN-2.0
      LONEP=LOTR
      XONEP=XONTR
      LATEP=LATR
      YATEP=YATTR
      Z=ZTR
      IF(LOSW .EQ. 1 .AND. INST .GT. 1 .AND. INST .NE. 4) ORG=ORGS
      LHY=2
      GO TO 300
    9 ZHLAT=(60.0*LAT(2,NEAR)+YAT(2,NEAR))/(060.0*57.29578)
      PH=PPP*COS(ZHLAT)
      DO 11 I=1,KREC
      XH(I)=(60.0*(LON(2,I)-LORED)+XON(2,I))*PH
      YH(I)=(60.0*(LAT(2,I)-LARED)+YAT(2,I))*QQ
   11 CONTINUE
   16 DO 22 I=1,KREC
      IF(I .EQ. NEAR) GO TO 22
   17 DIST1(I)=SQRT((XH(I)-XH(NEAR))**2+(YH(I)-YH(NEAR))**2)
      DIV=(YH(I)-YH(NEAR))
      XNUM=(XH(NEAR)-XH(I))
      ABDIV=ABS(DIV)
      IF(ABDIV .LT. 0.000001) DIV=0.000001
   18 TH1(I)=ATAN(XNUM/DIV)
   19 IF(DIV .LT. 0.0) TH1(I)=TH1(I)+3.14159
   20 IF(TH1(I) .LT.0.0) TH1(I)=TH1(I)+6.28318
```

the M/Prog and all of the subroutines

Switch to select chosen mode of preliminary hypocenter determination

MODE=0: Set preliminary hypocenter at location of nearest station and depth ZTR (card DH); set preliminary origin time to the S-P origin time, if available, or to 2 seconds before the earliest arrival

MODE=1: Set preliminary hypocenter to the trial values assigned on card DH; set origin time as above.

MODE=2: Calculate preliminary hypocenter from P arrivals at selected stations

Calculate grid coordinates

Calculate azimuths of stations from earliest station

```
   22 CONTINUE
      KALMX=1
      KALMN=1
      ALTMX=-99.99
      ALTMN=99.99
      KLT=KOLT-1
      DO 32 J=2,KLT
      I=KO(J)
   28 ALT=DIST1(I)*SIN(TH1(I)-TH1(MFAR))
      IF(ALT-ALTMX)30,30,29
   29 ALTMX=ALT
      KALMX=I
   30 IF(ALT-ALTMN)31,32,32
   31 ALTMN=ALT
      KALMN=I
   32 CONTINUE
      QUES=ABS(ALTMX)-ABS(ALTMN)
      IF(QUES)33,34,34
   33 KALX=KALMN
      GO TO 35
   34 KALX=KALMX
   35 CONTINUE
```

Determine and identify stations lying farthest to the left and farthest to the right of the line connecting the earliest and the KOLT'th stations

```
   36 N=NEAR
      M=MFAR
      J=KALMN
      K=KALMX
      I=KALX
      IF(KOLT .LT. 4 .OR. INST .GT. 1 .AND. INST .NE. 4) GO TO 100
   37 AP(1,1)=XH(M)-XH(N)
      AP(1,2)=YH(M)-YH(N)
      AP(1,3)=VB*VB*(TP(M)-TP(N))
      AP(2,1)=XH(J)-XH(N)
      AP(2,2)=YH(J)-YH(N)
      AP(2,3)=VB*VB*(TP(J)-TP(N))
      AP(3,1)=XH(K)-XH(N)
      AP(3,2)=YH(K)-YH(N)
      AP(3,3)=VB*VB*(TP(K)-TP(N))
      BP(1)=0.5*((XH(M)**2+YH(M)**2)-(XH(N)**2+YH(N)**2)
     1-VB*VB*(TP(M)-TP(N))**2)
      BP(2)=0.5*((XH(J)**2+YH(J)**2)-(XH(N)**2+YH(N)**2)
     1-VB*VB*(TP(J)-TP(N))**2)
      BF(3)=0.5*((XH(K)**2+YH(K)**2)-(XH(N)**2+YH(N)**2)
     1-VB*VB*(TP(K)-TP(N))**2)
      DETAP=AP(1,1)*(AP(2,2)*AP(3,3)-AP(3,2)*AP(2,3))
     1-AP(2,1)*(AP(1,2)*AP(3,3)-AP(3,2)*AP(1,3))
```

(4 stations)

Use Richter's version of Inglada's method to eliminate depth and to compute the preliminary epicenter and origin time

```
          2+AP(3,1)*(AP(1,2)*AP(2,3)-AP(2,2)*AP(1,3))
729        ETAP=ABS(DETAP)
730        IF(ETAP .LT. 0.000001) GO TO 5
731        XNOT=(BP(1)*(AP(2,2)*AP(3,3)-AP(3,2)*AP(2,3))
          1-BP(2)*(AP(1,2)*AP(3,3)-AP(3,2)*AP(1,3))
          2+BP(3)*(AP(1,2)*AP(2,3)-AP(2,2)*AP(1,3)))/DETAP
732        YNOT=(AP(1,1)*(BP(2)*AP(3,3)-BP(3)*AP(2,3))
          1-AP(2,1)*(BP(1)*AP(3,3)-BP(3)*AP(1,3))
          2+AP(3,1)*(BP(1)*AP(2,3)-BP(2)*AP(1,3)))/DETAP
733        T1=(AP(1,1)*(AP(2,2)*BP(3)-AP(3,2)*BP(2))
          1-AP(2,1)*(AP(1,2)*BP(3)-AP(3,2)*BP(1))
          2+AP(3,1)*(AP(1,2)*BP(2)-AP(2,2)*BP(1)))/DETAP
734        LHY=3
735        DST2=(XH(N)-XNOT)**2+(YH(N)-YNOT)**2
736        ZSQ=VB*VB*T1*T1-DST2
```

Calculate Z_0 from the equation for the nearest station; use it if it is real and greater than half the distance of the nearest station

```
737        IF(ZSQ .LT. 0.0) GO TO 200
738        Z=SQRT(ZSQ)
739        DST1=SQRT(DST2)
740        IF(2.0*Z .LT. DST1) GO TO 200
741        GO TO 205
742    100 DET3=(YH(I)-YH(N))*(XH(M)-XH(N))-(YH(M)-YH(N))*(XH(I)-XH(N))
743        RP2=0.5*((XH(M)**2+YH(M)**2)-(XH(N)**2+YH(N)**2)
          1-(VB*(TP(M)-TP(N)))**2)
744        RP3=0.5*((XH(I)**2+YH(I)**2)-(XH(N)**2+YH(N)**2)
          1-(VB*(TP(I)-TP(N)))**2)
745        ET3=ABS(DET3)
746        IF(ET3 .LT. 0.000001) GO TO 5
747        G1=VB*VB*((YH(M)-YH(N))*(TP(I)-TP(N))
          1-(YH(I)-YH(N))*(TP(M)-TP(N)))/DET3
748        G2=((YH(I)-YH(N))*RP2-(YH(M)-YH(N))*RP3)/DET3
749        G3=VB*VB*((XH(I)-XH(N))*(TP(M)-TP(N))
          1-(XH(M)-XH(N))*(TP(I)-TP(N)))/DET3
750        G4=((XH(M)-XH(N))*RP3-(XH(I)-XH(N))*RP2)/DET3
751        IF(LOSW .EQ. 0) GO TO 150
752        T1=TP(N)-ORGS
753        XNOT=G1*T1+G2
754        YNOT=G3*T1+G4
755        LHY=4
756        GO TO 200
757    150 G5=G1*G1+G3*G3-VB*VB
758        G6=-2.0*(G1*(XH(N)-G2)+G3*(YH(N)-G4))
759        G7=(XH(N)-G2)**2+(YH(N)-G4)**2+ZTR*ZTR
```

(3 stations)

Eliminate depth by differencing equations and calculate the preliminary epicenter in terms of the traveltime to the nearest station

If S-P origin time is availabe, evaluate epicenter obtained above

If S-P origin time is not available,

```
      G8=G6**2-4.0*G5*G7
      IF(G8 .LT. 0.0) GO TO 5
  152 AG5=ABS(G5)
      IF(AG5 .LT. 0.000001) GO TO 5
  154 G9=SQRT(G8)
      T1P=-0.5*(G6+G9)/G5
      T1M=-0.5*(G6-G9)/G5
      QSM=G5*T1M*T1M+G6*T1M+G7
      AQSM=ABS(QSM)
      QSP=G5*T1P*T1P+G6*T1P+G7
      AQSP=ABS(QSP)
      IF(AQSP-AQSM)155,155,156
  155 IF(AQSP-0.001)160,160,5
  156 IF(AQSM-0.001)165,165,5
  160 T1=T1P
      GO TO 170
  165 T1=T1M
  170 XNOT=G1*T1+G2
      YNOT=G3*T1+G4
      LHY=5
      GO TO 200
  200 Z=ZTR
  205 LONEP=LORED
      XONEP=XNOT/PH
      LATEP=LARED
      YATEP=YNOT/QQ
      ORG=TP(N)-T1
  300 RETURN
      END
```

substitute epicenter and trial depth into station #1 (near) equation.

Solve the resulting quadratic for the traveltime to station #1 (near)

Select appropriate root of the quadratic, and evaluate the epicentral coordinates

Set depth equal to the trial depth (Card D1)

Put focal parameters in the form required by the M/Prog

Subroutine to compute traveltimes, derivatives, and angles of incidence at the focus

```
      SUBROUTINE TRVDRV
      DIMENSION NSTA(2,99),LAT(2,99),YAT(2,99),LON(2,99),XON(2,99),
     1EL(2,99),DLY(2,99),MDL(2,99),MSTA(99),W(99),QSABE(99),KDATE(99),
     2JHR(99),JMIN(99),P(99),PRP(99),AMP(99),S(99),PRS(99),AMS(99),
     3PRX(99),AMX(99),RK(99),DT(99),CALP(99),CALS(99),CALX(99),TP(99),
     4DX(99),DY(99),DELTA(99),T(99),AX(99),AY(99),AH(99),ANIN(99),F(99),
     5PMAG(99),AT(99),BT(99),XH(99),YH(99),DIST1(99),TH1(99),FT1(99),
     6TS(99),AZ(99),V(26),DP(26),THK(26),TID(26,26),DID(26,26),TINJ(26),
     7DIDJ(26),TR(26),V1(26),DP1(26),THK1(26),TID1(26,26),DID1(26,26),
     8V2(26),DP2(26),THK2(26),TID2(26,26),DID2(26,26),A(4,4),B(4),Y(4),
     9C(4,4),D(3,3),AP(3,3),BP(3),G(99),PT(99),KO(99),XXMG(99)
```

This block is contained in the M/Prog and all of

```
      DIMENSION EPMG(99),EXMG(99)
      COMMON NSTA,LAT,YAT,LON,XON,EL,DLY,MDL,MSTA,W,QSABE,KDATE,JHR,
     1JMIN,P,PRP,AMP,S,PRS,AMS,PRX,AMX,RK,DT,CALP,CALS,CALX,TP,DX,DY,
     2DELTA,T,AX,AY,AH,ANIN,F,PMAG,AT,BT,XH,YH,DIST1,TH1,FT1,TS,AZ,V,
     3DP,THK,TID,DID,TINJ,DIDJ,TR,V1,DP1,THK1,TID1,DID1,V2,DP2,THK2,
     4TID2,DID2,A,B,Y,C,D,AP,BP,G,PT,KO,XXMG,EPMG,EXMG
      COMMON/UNDM/HILO,CNST,PWRP,ZPMAG,PWRX,ZXMAG,KT,KSTA,VB,PPP,ISTS,
     1KSITE,NL1,NL2,LATR,YATTR,LOTR,XONTR,ZNOT,LARED,LORED,MODE,INST,
     2KREC,IHR,NEAR,PMIN,ORGS,QQ,ORG,LATEP,YATEP,LONEP,XONEP,Z,KZSW,
     3XEP,YEP,RAH,ASDX,ASDY,ASDZ,ASDT,MM,KOUT,XMAG,LOSW,PFI,VA,AAF,
     4LHY,KAZ,DETA,MFAR,PFAR,KALX,KOLT,SMP,XNEAR,XFAR,ZTR,ZRES,PPMG
      REAL LAT,LON,LATR,LOTR,LARED,LORED,LATEP,LONEP
      SRTBK(X,Y,Z)=SQRT((X*X)/(Y*Y)-(Z*Z))
      KEY=0
    5 KEY=KEY+1
      GO TO (10,20),KEY
   10 NL=NL1
      DO 15 K=1,NL
      THK(K)=THK1(K)
      DP(K)=DP1(K)
      V(K)=V1(K)
      DO 15 L=1,NL
      TID(K,L)=TID1(K,L)
      DID(K,L)=DID1(K,L)
   15 CONTINUE
      GO TO 51
   20 NL=NL2
      DO 25 K=1,NL
      THK(K)=THK2(K)
      DP(K)=DP2(K)
      V(K)=V2(K)
      DO 25 L=1,NL
      TID(K,L)=TID2(K,L)
      DID(K,L)=DID2(K,L)
   25 CONTINUE
C COMPUTE LAYER JL CONTAINING THE FOCUS
   51 L=0
   53 L=L+1
      IF(L .GT.NL) GO TO 56
      IF(DP(L)-Z)53,53,55
   55 JL=L-1
      GO TO 57
   56 JL=NL
   57 TKJ=Z-DP(JL)
      IF(JL .EQ.NL)GO TO 61
C COMPUTE INTERCEPT OF WAVE FROM FOCUS IN LAYER JL
C AND REFRACTED ALONG THE TOP OF LAYER L
   58 JJ=JL+1
      DO 60 L=JJ,NL
```

the subroutines

Statement function

Select model

Load subroutine for model #1 calculations

Load subroutine for model #2 calculations

Determine which layer contains the focus

Compute refracted wave intercepts for waves originating at depth Z

```
      SQT=SQRT(V(L)*V(L)-V(JL)*V(JL))
      TINJ(L)=TID(JL,L)-TKJ*SQT/(V(L)*V(JL))
      DIDJ(L)=DID(JL,L)-TKJ*V(JL)/SQT
   60 CONTINUE
C COMPUTE DELTA BEYOND WHICH ALL 1ST ARRIVALS ARE REFRACTIONS
      XOVMAX=V(JJ)*V(JL)*(TINJ(JJ)-TID(JL,JL))/(V(JJ)-V(JL))
   61 CONTINUE
C BEGIN LOOP OF COMPUTATIONS FOR VARIOUS DELTAS
      DO 300 I=1,KREC
      IF(MDL(2,I) .NE. KEY) GO TO 300
   90 IF(JL .EQ. NL) GO TO 210
  100 DO 102 M=JJ,NL
      TR(M)=TINJ(M)+DELTA(I)/V(M)
  102 CONTINUE
      TMIN=999.99
      M=JL
  104 M=M+1
      IF(TR(M)-TMIN)106,106,108
  106 IF(DIDJ(M) .GT. DELTA(I)) GO TO 108
  107 K=M
      TMIN=TR(M)
  108 IF(M .LT. NL) GO TO 104
  109 IF(DELTA(I)-XOVMAX)200,120,120
C CALCULATE TT AND DERIVATIVES FOR WAVES RECORDED BEYOND XOVMAX
  120 T(I)=TR(K)
      DTDD   =1.0/V(K)
      DTDH    =-SQRT(V(K)*V(K)-V(JL)*V(JL))/(V(K)*V(JL))
      ANIN(I)=3.141593-ARSIN(V(JL)/V(K))
      ANIN(I)=ANIN(I)*57.29578
      GO TO 298
C COMPUTE TT AND DERIVS OF DIRECT WAVE THROUGH LAYER JL
  200 IF(JL .NE. 1) GO TO 210
  201 SQT=SQRT(Z*Z+DELTA(I)*DELTA(I))
      TDJ1=SQT/V(1)
  203 IF(TDJ1-TMIN)205,120,120
  205 T(I)=TDJ1
      IF(SQT .LT. 0.000001) SQT=0.000001
  207 DTDD=DELTA(I)/(V(1)*SQT)
      DTDH    =Z/(V(1)*SQT)
      ZL=Z
      IF(ZL .LT. 0.000001) ZL=0.000001
  208 ANIN(I)=ATAN(DELTA(I)/ZL)
```

Compute distance beyond which all 1st arrivals are refracted waves

Compute refracted wave traveltimes

Determine earliest refracted wave at distance Δ

Test whether earliest refracted wave is 1st arrival

Calculate derivatives and angle of incidence and "load" arrays (if earliest arrival is a refracted wave)

Calculate traveltime, derivatives, and angle of incidence if focus lies in upper most layer and the direct wave is the 1st arrival.

Load appropriate arrays

```
      ANIN(I)=ANIN(I)*57.29578
      GO TO 298
  210 LL=0
C BEGIN ROUTINE TO FIND ROOT OF REFRACTION EQUATION
      IF(DELTA(I) .LT. 0.000001) DELTA(I)=0.000001
      IF(TKJ .LT. 0.000001) TKJ=0.000001
      IF(Z .LT. 0.000001) Z=0.000001
      XBIG=DELTA(I)
      XLIT=DELTA(I)*TKJ/Z
      UB=XBIG/SQRT(XBIG*XBIG+TKJ*TKJ)
      UL=XLIT/SQRT(XLIT*XLIT+TKJ*TKJ)
      ARGL=1.0-UL*UL
      IF(ARGL .LT. 0.00000001) ARGL=0.00000001
  212 ARGB=1.0-UB*UB
      IF(ARGB .LT. 0.00000001) ARGB=0.00000001
  213 DELBIG=TKJ*UB/SQRT(ARGB)
      DELLIT=TKJ*UL/SQRT(ARGL)
      J1=JL-1
```

Calculations for direct wave originating below the first layer

```
      DO 214 L=1,J1
      DELBIG=DELBIG+(THK(L)*UB)/SRTBK(V(JL),V(L),UB)
      DELLIT=DELLIT+(THK(L)*UL)/SRTBK(V(JL),V(L),UL)
  214 CONTINUE
  215 LL=LL+1
      IF(DELBIG-DELLIT .LT. 0.02) GO TO 231
  216 XTR=XLIT+(DELTA(I)-DELLIT)*(XBIG-XLIT)/(DELBIG-DELLIT)
      U=XTR/SQRT((XTR*XTR)+(TKJ*TKJ))
      ARGJ=1.0-U*U
      IF(ARGJ .LT. 0.00000001) ARGJ=0.00000001
  217 DELXTR=TKJ*U/SQRT(ARGJ)
      DO 220 L=1,J1
      DELXTR=DELXTR+(THK(L)*U)/SRTBK(V(JL),V(L),U)
  220 CONTINUE
      TEST=DELTA(I)-DELXTR
      IF(ABS(TEST)-0.02)233,233,221
  221 IF(TEST)222,233,226
  222 XBIG=XTR
      DELBIG=DELXTR
      GO TO 229
  226 XLIT=XTR
      DELLIT=DELXTR
  229 IF(1.0-U .LT. 0.0002 .AND. LL .GE. 10)GO TO 233
  230 IF(LL .LT. 25) GO TO 215
```

Find root of refraction equation

```
  231 XTR=0.5*(XBIG+XLIT)
      U=XTR/SQRT((XTR*XTR)+(TKJ*TKJ))
  233 CONTINUE
      IF(1.0-U .GT. 0.0002)GO TO 238
C IF U IS TOO NEAR 1.0 COMPUTE TDIR AS WAVE ALONG TOP OF LAYER JL
  235 TDC=TID(JL,JL)+DELTA(I)/V(JL)
      IF(JL .EQ. NL)GO TO 237
  236 IF(TDC-TMIN)237,120,120
  237 T(I)=TDC
      DTDD   =1.0/V(JL)
      DTDH   =0.0
      ANIN(I)=90.0
      GO TO 298
C COMPUTE TDIR AND DERIVS FROM ROOT OF DELTA(U) EQT
  238 TDIR=TKJ/(V(JL)*SQRT(1.0-U*U))
  239 DO 240 L=1,J1
      TDIR=TDIR+(THK(L)*V(JL))/(V(L)*V(L)*SRTBK(V(JL),V(L),U))
  240 CONTINUE
      IF(JL .EQ. NL) GO TO 245
  243 IF(TDIR-TMIN)245,120,120
  245 T(I)=TDIR
C COMPUTE DTDD    AND DTDH
      SRT=SQRT(1.0-U*U)**3
      ALFA=TKJ/SRT
      BETA=TKJ*U/(V(JL)*SRT)
      DO 247 L=1,J1
      STK=SRTBK(V(JL),V(L),U)**3
      ALFA=ALFA+THK(L)*V(JL)*V(JL)/(V(L)*V(L)*STK)
      BETA=BETA+THK(L)*V(JL)*U/(V(L)*V(L)*STK)
  247 CONTINUE
      DTDD   =BETA/ALFA
      DTDH   =(1.0-V(JL)*U*DTDD)/(V(JL)*SQRT(1.0-U*U))
      ANIN(I)=ARSIN(U)*57.29578
  298 AX(I)=-DTDD*DX(I)/DELTA(I)
      AY(I)=-DTDD*DY(I)/DELTA(I)
      AH(I)=DTDH

  300 CONTINUE
      IF(KEY .EQ. 2) GO TO 310
  301 IF(NL2 .EQ. 0) GO TO 310
  302 GO TO 5
  310 RETURN
      END
```

"Easy" solution — convergence … …

Degenerate solution for focus near top of layer

Calculate traveltimes, derivatives, and angle of incidence in non-degenerate case

Load derivative arrays

Switch to lead program through 2 models in succession

Subroutine to calculate hypocentral adjustments

```
      SUBROUTINE HYCOR
      DIMENSION NSTA(2,99),LAT(2,99),YAT(2,99),LON(2,99),XON(2,99),
     1EL(2,99),DLY(2,99),MDL(2,99),MSTA(99),W(99),QSABE(99),KDATE(99),
     2JHR(99),JMIN(99),P(99),PRP(99),AMP(99),S(99),PRS(99),AMS(99),
     3PRX(99),AMX(99),RK(99),DT(99),CALP(99),CALS(99),CALX(99),TP(99),
     4DX(99),DY(99),DELTA(99),T(99),AX(99),AY(99),AH(99),ANIN(99),F(99),
     5PMAG(99),AT(99),BT(99),XH(99),YH(99),DIST1(99),TH1(99),FT1(99),
     6TS(99),AZ(99),V(26),DP(26),THK(26),TID(26,26),DID(26,26),TINJ(26),
     7DIDJ(26),TR(26),V1(26),DP1(26),THK1(26),TID1(26,26),DID1(26,26),
     8V2(26),DP2(26),THK2(26),TID2(26,26),DID2(26,26),A(4,4),B(4),Y(4),
     9C(4,4),D(3,3),AP(3,3),BP(3),G(99),PT(99),KO(99),XXMG(99)
      DIMENSION EPMG(99),EXMG(99)
      COMMON NSTA,LAT,YAT,LON,XON,EL,DLY,MDL,MSTA,W,QSABE,KDATE,JHR,
     1JMIN,P,PRP,AMP,S,PRS,AMS,PRX,AMX,RK,DT,CALP,CALS,CALX,TP,DX,DY,
     2DELTA,T,AX,AY,AH,ANIN,F,PMAG,AT,BT,XH,YH,DIST1,TH1,FT1,TS,AZ,V,
     3DP,THK,TID,DID,TINJ,DIDJ,TR,V1,DP1,THK1,TID1,DID1,V2,DP2,THK2,
     4TID2,DID2,A,B,Y,C,D,AP,BP,G,PT,KO,XXMG,EPMG,EXMG
      COMMON/UNDM/HILO,CNST,PWRP,ZPMAG,PWRX,ZXMAG,KT,KSTA,VB,PPP,ISTS,
     1KSITE,NL1,NL2,LATR,YATTR,LOTR,XONTR,ZNOT,LARED,LORED,MODE,INST,
     2KREC,IHR,NEAR,PMIN,ORGS,QQ,ORG,LATEP,YATEP,LONEP,XONEP,Z,KZSW,
     3XEP,YEP,RAH,ASDX,ASDY,ASDZ,ASDT,MM,KOUT,XMAG,LOSW,PFI,VA,AAF,
     4LHY,KAZ,DETA,MFAR,PFAR,KALX,KOLT,SMP,XNEAR,XFAR,ZTR,ZRES,PPMG
      REAL LAT,LON,LATR,LOTR,LARED,LORED,LATEP,LONEP
    2 INST1=INST+1
    3 GO TO (5,200,300,300,200,300,300),INST1
    5 IF(RAH .LT. 0.02 .OR. KZSW .EQ. 1 .OR. KSTA .EQ. 3) GO TO 200
    7 DO 40 M=1,4
      DO 40 N=1,4
      K=0
   10 DO 35 I=1,4
      IF(I .EQ. M) GO TO 35
   12 K=K+1
      L=0
   20 DO 30 J=1,4
      IF(J .EQ. N) GO TO 30
   22 L=L+1
      D(K,L)=A(I,J)
   30 CONTINUE
   35 CONTINUE
      C(M,N)=((-1.0)**(M+N))*(D(1,1)*(D(2,2)*D(3,3)-D(3,2)*D(2,3))
     1 -D(1,2)*(D(2,1)*D(3,3)-D(3,1)*D(2,3))
     2 +D(1,3)*(D(2,1)*D(3,2)-D(3,1)*D(2,2)))
   40 CONTINUE
      DETA=A(1,1)*C(1,1)+A(2,1)*C(2,1)+A(3,1)*C(3,1)+A(4,1)*C(4,1)
      ETA=ABS(DETA)
      IF(ETA .LT. 0.00000001) GO TO 200
```

This block is contained in the M/Prog and all of the subroutines

Select proper adjustment routine INST control

Automatic control

Routine to solve 4x4 system of normal equations in "free" adjustment of x, y, z, and t₀

Construct cofactor matrix of matrix of coeff of unknowns in the normal equations

Evaluate and test the determinant of the matrix of coeff of unknowns

```
   42 DO 50 I=1,4
      Y(I)=(B(1)*C(1,I)+B(2)*C(2,I)+B(3)*C(3,I)+B(4)*C(4,I))/DETA
```

Solve for components of the correction vector

```
   50 CONTINUE
      MM=4
      KOUT=1
```

Flag 4x4 free solution

```
      ASDX=ABS(C(1,1)/DETA)
      ASDY=ABS(C(2,2)/DETA)
      ASDZ=ABS(C(3,3)/DETA)
      ASDT=ABS(C(4,4)/DETA)
      GO TO 500
```

Calculate elements of the principal diagonal of the inverse matrix of the normal equation "unknown" coeff

```
  200 A11=A(2,2)*A(4,4)-A(4,2)*A(2,4)
      A12=A(4,1)*A(2,4)-A(2,1)*A(4,4)
      A14=A(2,1)*A(4,2)-A(4,1)*A(2,2)
      A21=A(4,2)*A(4,1)-A(1,2)*A(4,4)
      A22=A(1,1)*A(4,4)-A(4,1)*A(1,4)
      A24=A(4,1)*A(1,2)-A(1,1)*A(4,2)
      A41=A(1,2)*A(2,4)-A(2,2)*A(4,1)
      A42=A(2,1)*A(1,4)-A(1,1)*A(2,4)
      A44=A(1,1)*A(2,2)-A(2,1)*A(1,2)
```

Routine to solve 3x3 system of equations in a "ZFIX" adjustment of the hypocenter

```
      DETA=A(1,1)*A11+A(2,1)*A21+A(4,1)*A41
      ETA=ABS(DETA)
      IF(ETA .LT. 0.00000001) GO TO 400
```

Evaluate and test determinant of coefficients of unknowns

```
  210 Y(1)=(B(1)*A11+B(2)*A21+B(4)*A41)/DETA
      Y(2)=(B(1)*A12+B(2)*A22+B(4)*A42)/DETA
      Y(3)=0.0
      Y(4)=(B(1)*A14+B(2)*A24+B(4)*A44)/DETA
```

Calculate correction vector

```
      MM=3
      KOUT=2
```

Flag "ZFIX" solution

```
      ASDX=ABS(A11/DETA)
      ASDY=ABS(A22/DETA)
      ASDZ=1.0
      ASDT=ABS(A44/DETA)
      GO TO 500
```

Calculate elements of the principal diagonal of the inverse matrix of coefficients of the unknowns in the normal equations

```
  300 IF(RAH .LT. 0.02 .OR. KZSW .EQ. 1) GO TO 350
  302 A11=A(2,2)*A(3,3)-A(3,2)*A(2,3)
      A12=A(3,1)*A(2,3)-A(2,1)*A(3,3)
      A13=A(2,1)*A(3,2)-A(3,1)*A(2,2)
      A21=A(3,2)*A(1,3)-A(1,2)*A(3,3)
      A22=A(1,1)*A(3,3)-A(3,1)*A(1,3)
      A23=A(3,1)*A(1,2)-A(1,1)*A(3,2)
      A31=A(1,2)*A(2,3)-A(2,2)*A(1,3)
      A32=A(2,1)*A(1,3)-A(1,1)*A(2,3)
      A33=A(1,1)*A(2,2)-A(2,1)*A(1,2)
```

Routine to solve 3x3 system of normal equations in a "TFIX" adjustment of the hypocenter

```
      DETA=A(1,1)*A11+A(2,1)*A21+A(3,1)*A31
      ETA=ABS(DETA)
      IF(ETA .LT. 0.00000001) GO TO 400
```

Evaluate and test determinant of coefficients of unknowns

```
  322 MM=3
      KOUT=3
```

Flag "TFIX" solution

```
      Y(1)=(B(1)*A11+B(2)*A21+B(3)*A31)/DETA
      Y(2)=(B(1)*A12+B(2)*A22+B(3)*A32)/DETA
      Y(3)=(B(1)*A13+B(2)*A23+B(3)*A33)/DETA
      Y(4)=0.0
```

Calculate correction vector

```
      ASDX=ABS(A11/DETA)
      ASDY=ABS(A22/DETA)
      ASDZ=ABS(A33/DETA)
      ASDT=1.0
      GO TO 500
```

Calculate elements of the principal diagonal of the inverse matrix of normal equation coefficients

```
  350 DETA=A(1,1)*A(2,2)-A(2,1)*A(1,2)
      ETA=ABS(DETA)
      IF(ETA .LT. 0.00000001) GO TO 400
  352 Y(1)=(B(1)*A(2,2)-B(2)*A(1,2))/DETA
      Y(2)=(A(1,1)*B(2)-A(2,1)*B(1))/DETA
      Y(3)=0.0
      Y(4)=0.0
```

Routine to solve 2x2 system of normal equations in a ZFIX-TFIX adjustment

Calculate correction vector

```
      MM=2
      KOUT=4
```

Flag "ZFIX-TFIX" solution

```
      ASDX=ABS(A(2,2)/DETA)
      ASDY=ABS(-A(1,1)/DETA)
      ASDZ=1.0
      ASDT=1.0
      GO TO 500
```

Calculate elements of the principal diagonal of the inverse matrix of normal equation coefficients

```
  400 KOUT=5
```

Flag "no solution", which calls VELAZ

```
  500 RETURN
      END
```

Subroutine to compute velocity and azimuth of approach of plane wave fitted to P-wave arrivals by least squares

```
      SUBROUTINE VELAZ
      DIMENSION NSTA(2,99),LAT(2,99),YAT(2,99),LON(2,99),XON(2,99),
     1EL(2,99),DLY(2,99),MDL(2,99),MSTA(99),W(99),QSABE(99),KDATE(99),
     2JHR(99),JMIN(99),P(99),PRP(99),AMP(99),S(99),PRS(99),AMS(99),
     3PRX(99),AMX(99),RK(99),DT(99),CALP(99),CALS(99),CALX(99),TP(99),
     4DX(99),DY(99),DELTA(99),T(99),AX(99),AY(99),AH(99),ANIN(99),F(99),
     5PMAG(99),AT(99),BT(99),XH(99),YH(99),DIST1(99),TH1(99),FT1(99),
     6TS(99),AZ(99),V(26),DP(26),THK(26),TID(26,26),DID(26,26),TINJ(26),
     7DIDJ(26),TR(26),V1(26),DP1(26),THK1(26),TID1(26,26),DID1(26,26),
     8V2(26),DP2(26),THK2(26),TID2(26,26),DID2(26,26),A(4,4),B(4),Y(4),
     9C(4,4),D(3,3),AP(3,3),BP(3),G(99),PT(99),KO(99),XXMG(99)
```

This block is contained in the

```
      DIMENSION EPMG(99),EXMG(99)
      COMMON NSTA,LAT,YAT,LON,XON,EL,DLY,MDL,MSTA,W,QSABE,KDATE,JHR,
     1JMIN,P,PRP,AMP,S,PRS,AMS,PRX,AMX,RK,DT,CALP,CALS,CALX,TP,DX,DY,
     2DELTA,T,AX,AY,AH,ANIN,F,PMAG,AT,BT,XH,YH,DIST1,TH1,FT1,TS,AZ,V,
     3DP,THK,TID,DID,TINJ,DIDJ,TR,V1,DP1,THK1,TID1,DID1,V2,DP2,THK2,
     4TID2,DID2,A,B,Y,C,D,AP,BP,G,PT,KO,XXMG,EPMG,EXMG
      COMMON/UNDM/HILO,CNST,PHRP,ZPMAG,PWRX,ZXMAG,KT,KSTA,VB,PPP,ISTS,
     1KSITE,NL1,NL2,LATR,YATTR,LOTR,XONTR,ZNOT,LARED,LORED,MODE,INST,
     2KREC,IHR,NEAR,PMIN,ORGS,QQ,ORG,LATEP,YATEP,LONEP,XONEP,Z,KZSW,
     3XEP,YEP,RAH,ASDX,ASDY,ASDZ,ASDT,MM,KOUT,XMAG,LOSW,PFI,VA,AAF,
     4LHY,KAZ,DETA,MFAR,PFAR,KALX,KOLT,SMP,XNEAR,XFAR,ZTR,ZRES,PPMG
      REAL LAT,LON,LATR,LOTR,LARED,LORED,LATEP,LONEP
```

M/Prog and in all of the subroutines

```
      IF(INST.EQ. 8) II=0
      IF(MODE .EQ. 2 .AND. INST .NE. 8) GO TO 26
    5 ZHLAT=(60.0*LAT(2,NEAR)+YAT(2,NEAR))/(060.0*57.29578)
      PH=PPP*COS(ZHLAT)
      DO 7 I=1,KREC
      XH(I)=(60.0*(LON(2,I)-LORED)+XON(2,I))*PH
      YH(I)=(60.0*(LAT(2,I)-LARED)+YAT(2,I))*QQ
    7 CONTINUE
      DO 20 I=1,KREC
      IF(I .EQ. NEAR) GO TO 20
    9 DIST1(I)=SQRT((XH(I)-XH(NEAR))**2+(YH(I)-YH(NEAR))**2)
      XNUM=(XH(NEAR)-XH(I))
      DIV=(YH(I)-YH(NEAR))
      ABDIV=ABS(DIV)
      IF(ABDIV .LT. 0.000001) DIV=0.000001
   13 TH1(I)=ATAN(XNUM/DIV)
   14 IF(DIV .LT. 0.0) TH1(I)=TH1(I)+3.14159
   15 IF(TH1(I) .LT. 0.0) TH1(I)=TH1(I)+6.28318
   20 CONTINUE
      KALX=1
      ALTMX=-99.99
      KLT=KOLT-1
      DO 25 J=2,KLT
      I=KO(J)
   22 ALT=DIST1(I)*SIN(TH1(I)-TH1(MFAR))
      ABALT=ABS(ALT)
      IF(ALTMX-ABALT)23,25,25
   23 ALTMX=ABALT
      KALX=I
   25 CONTINUE
```

Determine station on KOLT list that lies farthest from the line joining the 1st and the KOLT'th stations

```
   26 N=NEAR
      M=MFAR
      K=KALX
      GAM=((TP(K)-TP(N))*DIST1(M))/((TP(M)-TP(N))*DIST1(K))
      DENOM=COS(TH1(K))-GAM*COS(TH1(M))
      ADN=ABS(DENOM)
      IF(ADN .LT.0.0000001) DENOM=0.0000001
```

Calculate apparent velocity and azimuth of approach of plane wave through the 1st, KOLT'th, and "farthest off line" stations

```
27 PFI=ATAN((SIN(TH1(K))-GAM*SIN(TH1(M)))/DENOM)
28 IF(TH1(M)-PFI)29,30,30
29 PFI=PFI-3.14159
   GO TO 28
30 IF(TH1(M)-PFI -3.14159)32,32,31
31 PFI=PFI+3.14159
   GO TO 30
32 CONTINUE
33 VA=(DIST1(M)*SIN(TH1(M)-PFI))/(TP(M)-TP(N))
```

Set switches and sum registers

```
   KAZ=1
   KT=1
   Y2=1.0
   AAF=0.0
```

Adjustment loop

Compute residuals

```
36 DO 38 I=1,KREC
   IF(I .EQ. NEAR) GO TO 38
   FT1(I)=(TP(I)-TP(NEAR))-(DIST1(I)*SIN(TH1(I)-PFI))/VA
38 CONTINUE
```

Terminate adjustment if last change in azimuth <0.001 rad or iterations >15

```
   IF(KREC .LT. 4) GO TO 47
39 Y2AB=ABS(Y2)
40 IF(Y2AB .LT. 0.0001 .OR. KT .GE. 15) GO TO 47
```

Calculate normal equation coefficients

```
41 DO 43 I=1,KREC
   IF(I .EQ. NEAR) GO TO 43
42 AT(I)=-(DIST1(I)*SIN(TH1(I)-PFI))/(VA*VA)
   BT(I)=-(DIST1(I)*COS(TH1(I)-PFI))/VA
43 CONTINUE
   AT11=0.0
   AT12=0.0
   AT22=0.0
   BT1=0.0
   BT2=0.0
   DO 45 I=1,KREC
   IF(W(I) .LT. 0.1 .OR. I .EQ. NEAR) GO TO 45
44 AT11=AT11+AT(I)*AT(I)
   AT12=AT12+AT(I)*BT(I)
   AT22=AT22+BT(I)*BT(I)
   BT1=BT1+AT(I)*FT1(I)
   BT2=BT2+BT(I)*FT1(I)
45 CONTINUE
   AT21=AT12
```

Evaluate and test determinant of coefficients of the unknowns

```
   DEAT=AT11*AT22-AT21*AT12
   AEAT=ABS(DEAT)
   IF(AEAT .LT. 0.0000001) GO TO 47
```

Compute adjustments to apparent velocity and azimuth

```
46 Y1=(BT1*AT22-BT2*AT12)/DEAT
   Y2=(AT11*BT2-AT21*BT1)/DEAT
```

Adjust velocity and azimuth

```
   VA=VA+Y1
   PFI=PFI+Y2
   KT=KT+1
   GO TO 36
```

Compute mean deviation

```
47 KF=0
   DO 49 I=1,KREC
   IF(W(I) .LT. 0.1 .OR. I .EQ. NEAR) GO TO 49
48 KF=KF+1
   AAF=AAF+ABS(FT1(I))
49 CONTINUE
   IF(KF-2)50,50,51
50 AAF=0.0
   GO TO 52
51 XKF=FLOAT(KF)
   KAZ=2
   AAF=AAF/XKF
```

Convert azimuths to degrees

```
52 CONTINUE
   DO 54 I=1,KREC
   IF(I .EQ. NEAR) GO TO 54
53 TH1(I)=TH1(I)*57.29587
54 CONTINUE
   RETURN
   END
```

Subroutine to compute magnitudes from P-wave and X-wave amplitude and period data

```
1158       SUBROUTINE MAGNTD
1159       DIMENSION NSTA(2,99),LAT(2,99),YAT(2,99),LON(2,99),XON(2,99),
          1EL(2,99),DLY(2,99),MDL(2,99),MSTA(99),W(99),QSABE(99),KDATE(99),
          2JHR(99),JMIN(99),P(99),PRP(99),AMP(99),S(99),PRS(99),AMS(99),
          3PRX(99),AMX(99),RK(99),DT(99),CALP(99),CALS(99),CALX(99),TP(99),
          4DX(99),DY(99),DELTA(99),T(99),AX(99),AY(99),AH(99),ANIN(99),F(99),
          5PMAG(99),AT(99),BT(99),XH(99),YH(99),DIST1(99),TH1(99),FT1(99),
          6TS(99),AZ(99),V(26),DP(26),THK(26),TID(26,26),DID(26,26),TINJ(26),
          7DIDJ(26),TR(26),V1(26),DP1(26),THK1(26),TID1(26,26),DID1(26,26),
          8V2(26),DP2(26),THK2(26),TID2(26,26),DID2(26,26),A(4,4),B(4),Y(4),
          9C(4,4),D(3,3),AP(3,3),BP(3),G(99),PT(99),KO(99),XXMG(99)
1160       DIMENSION EPMG(99),EXMG(99)
1161       COMMON NSTA,LAT,YAT,LON,XON,EL,DLY,MDL,MSTA,W,QSABE,KDATE,JHR,
          1JMIN,P,PRP,AMP,S,PRS,AMS,PRX,AMX,RK,DT,CALP,CALS,CALX,TP,DX,DY,
          2DELTA,T,AX,AY,AH,ANIN,F,PMAG,AT,BT,XH,YH,DIST1,TH1,FT1,TS,AZ,V,
          3DP,THK,TID,DID,TINJ,DIDJ,TR,V1,DP1,THK1,TID1,DID1,V2,DP2,THK2,
          4TID2,DID2,A,B,Y,C,D,AP,BP,G,PT,KO,XXMG,EPMG,EXMG
1162       COMMON/UNDM/HILO,CNST,PWRP,ZPMAG,PWRX,ZXMAG,KT,KSTA,VB,PPP,ISTS,
          1KSITE,NL1,NL2,LATR,YATTR,LOTR,XONTR,ZNOT,LARED,LORED,MODE,INST,
          2KREC,IHR,NEAR,PMIN,ORGS,QQ,ORG,LATEP,YATEP,LONEP,XONEP,Z,KZSW,
          3XEP,YEP,RAH,ASDX,ASDY,ASDZ,ASDT,MM,KOUT,XMAG,LOSW,PFI,VA,AAF,
          4LHY,KAZ,DETA,MFAR,PFAR,KALX,KOLT,SMP,XNEAR,XFAR,ZTR,ZRES,PPMG
1163       REAL LAT,LON,LATR,LOTR,LARED,LORED,LATEP,LONEP
```

This block is contained in the M/Prog and in all of the subroutines

```
1164       DO 20 J=1,KREC
1165       EPMG(J)=-9.99
1166       EXMG(J)=-9.99
```

Initialize registers

```
1167       IF(AMP(J))5,10,10
1168     5 AMP(J)=-HILO*AMP(J)
1169    10 IF(AMX(J))15,20,20
1170    15 AMX(J)=-HILO*AMX(J)
1171    20 CONTINUE
```

Remove "—" flags from low level amplitude entries

```
1172       MC=0
1173       MP=0
1174       SXMAG=0.0
1175       SPMAG=0.0
```

Set counters and sum registers

```
1176       DO 100 J=1,KREC
1177       RAD2=(DELTA(J)*DELTA(J)+Z*Z)
1178       IF(RAD2 .LT. 1.1) GO TO 100
```

Calculate hypocentral distance (squared)

```
1179       IF(AMP(J) .LT. 0.01) GO TO 40
1180       IF(CALP(J))40,40,30
1181    30 ARGP=AMP(J)*CNST*PRP(J)/CALP(J)
1182       IF(ARGP .LT. 0.000001) GO TO 40
1183       PMAG(J)=ALOG10(ARGP*RAD2**PWRP)-ZPMAG
1184       MP=MP+1
1185       SPMAG=SPMAG+PMAG(J)
1186       GO TO 42
```

P magnitude calculation for stn J

X magnitude calculation for stn J

```
   40 PMAG(J)=-9.99
   42 IF(CALX(J))90,90,45
   43 IF(AMX(J) .LT. 0.01) GO TO 90
   45 ARGX=AMX(J)*CNST*PRX(J)/CALX(J)
      IF(ARGX .LT. 0.000001) GO TO 90
      MC=MC+1
      XXMG(J)=ALOG10(ARGX*RAD2**PWRX)-ZXMAG
      SXMAG=SXMAG+XXMG(J)
   85 GO TO 100
   90 XXMG(J)=-9.99
```

Compute mean P magnitude

```
  100 CONTINUE
      IF(MP .EQ. 0) GO TO 103
      XMP=FLOAT(MP)
      PPMG=SPMAG/XMP
      GO TO 105
  103 PPMG=-9.99
```

Compute mean X magnitude

```
  105 IF(MC .EQ. 0) GO TO 110
      SMC=MC
      XMAG=SXMAG/SMC
      GO TO 115
  110 XMAG=-9.99
```

Compute P-magnitude residuals

```
  115 IF(PPMG .LT. -9.00) GO TO 130
  117 DO 125 J=1,KREC
      IF(PMAG(J) .LT.-9.00) GO TO 125
  120 EPMG(J)=PMAG(J)-PPMG
  125 CONTINUE
```

Compute X-magnitude residuals

```
  130 IF(XMAG .LT. -9.00) GO TO 150
  132 DO 145 J=1,KREC
      IF(XXMG(J) .LT. -9.00) GO TO 145
  135 EXMG(J)=XXMG(J)-XMAG
  145 CONTINUE
  150 RETURN
      END
```

```
$DATA
KSITE =  20
  GF 35.   49.88    120.  21.18     0.436      0.00     2
   1 35.   45.35    120.  18.73     0.372     -0.04     1
   2 35.   47.46    120.  21.44     0.378     -0.07     1
   3 35.   43.20    120.  16.85     0.418      0.01     1
   4 35.   48.84    120.  16.07     0.485     -0.01     2
   5 35.   42.59    120.  22.72     0.448      0.10     1
   6 35.   40.30    120.  12.65     0.640     -0.07     1
   7 35.   39.06    120.  19.22     0.466      0.10     1
  8A 35.   47.18    120.  11.00     0.492     -0.08     2
  8B 35.   47.39    120.  10.55     0.518     -0.08     2
   9 35.   52.79    120.  24.72     0.469      0.09     2
  10 35.   49.47    120.  26.31     0.646     -0.07     1
  11 35.   49.88    120.  21.18     0.436     -0.07     2
  12 35.   53.33    120.  20.55     0.549      0.11     2
  13 35.   55.09    120.  28.69     0.603     -0.12     1
EML1 35.   56.97    120.  28.28     0.538      0.25     2
EML2 35.   49.23    120.  30.87     0.460      0.03     1
EML3 35.   51.10    120.  36.50     0.460      0.10     1
EML4 35.   54.50    120.  28.17     0.515     -0.18     1
EML5 35.   55.53    120.  29.63     0.578     -0.26     1
  6  7   35.    0.00   120.    0.00    5.00   35.    120.    25.0  2  0  3  1   7  1.84950  1.85760  1
  1.37    50.     51.  32.00  1.03   0.85   1.55   0.85   1.70   0.03  0.10   0.30  0.010  0.002
     0.150     0.300      0.500      1.000   12    5    0

     1.700     0.000
     2.800     0.280
     5.000     1.550
     6.000     3.740
     6.800    15.000
     8.050    25.000
     2.360     0.000
     3.340     0.180
     4.620     1.240
     5.620     2.760
     6.000     4.440
     6.800    15.000
     8.050    25.000
KREC=13  INST= 0  ZRES= 0.00
```

```
    48.12   20.57    3.76   0.029   0.001   11      0.029  11.000
0.1262  0.0400 -0.0066 -0.0991  0.1680 -0.0143 -0.0988  0.0308  0.3398 11.0000  0.0005 -0.0005  0.0007 -0.0085  0.1292   0
     4     1  0.0041759050      8.6155      6.6731   51.1106     0.1385     0.0050   -0.0018    0.0454   -0.0021
    48.12   20.57    3.80  374.03     0.01                                  0.0050   -0.0018    0.0454   -0.0021


    48.12   20.57    3.80   0.030  -0.000   11      0.030  11.000
0.1221  0.0397 -0.0189 -0.1076  0.1674 -0.0151 -0.0997  0.0355  0.2754 11.0000 -0.0000 -0.0005 -0.0022  0.0005  0.1930   0
     4     1  0.0053487710      9.4640      6.5811   38.3488     0.1130    -0.0093   -0.0073   -0.0851    0.0020
    48.12   20.57    3.72  374.03     0.01                                 -0.0093   -0.0073   -0.0851    0.0020


    48.12   20.57    3.72   0.030  -0.000   11      0.030  11.000

  CODES (MODE LPC  INST LOSW LHY KOUT KAZI)=( 2 0 0 0 3 1 0)     ORGS=    0.00      AV RESID=  -0.00      PMAG=   0.65
 DATE     ORIGIN         LAT          LONG         DEPTH    AAF     SDP    SDX    SDY    SDZ   SDT  KSTA    XMAG   II  KREC    VH
660914  0 6 14.03    35. 48.12     120. 20.57        3.7    0.03    0.05    0.1    0.1    0.3  0.02   11     0.49    5   11     0.01
```

STATION	DELTA	AZI	ANIN	QSABE	TP	TS	RESID	PMAG	RSPMG	XMAG	RSXMG	RMK	W	G
GH	3.4	344.	54.8	IP-	1.17	0.00	-0.02	-9.99	-9.99	-9.99	-9.99		1.00	1.00
1	5.8	152.	123.6	IP-	1.70	0.00	-0.04	0.51	-0.14	0.62	0.13		1.00	1.00
2	1.8	227.	32.1	IP-	1.12	0.00	0.03	0.55	-0.10	0.55	0.05		1.00	1.00
4	6.9	79.	76.7	IP&	1.74	0.00	-0.01	0.83	0.18	0.50	0.00		1.00	1.00
5	10.7	198.	123.6	IP-	2.64	0.00	-0.05	1.09	0.44	1.15	0.66		1.00	1.00
7	16.9	173.	123.6	IP-	3.77	0.00	0.05	1.05	0.40	0.80	0.31		1.00	1.00
88	15.2	95.	85.5	IP&	3.16	0.00	0.02	0.65	0.00	0.33	-0.16		1.00	1.00
9	10.7	324.	82.9	IP-	2.47	0.00	-0.04	0.28	-0.37	0.09	-0.41		1.00	1.00
10	9.0	286.	123.6	IP&	2.23	0.00	-0.01	0.23	-0.42	-0.09	-0.58		1.00	1.00
12	9.6	0.	81.8	IP-	2.36	0.00	0.01	-9.99	-9.99	-9.99	-9.99		1.00	1.00
13	17.8	317.	123.6	P-	3.69	0.00	0.04	-9.99	-9.99	-9.99	-9.99		1.00	1.00