# DETERMINATION OF THREE-DIMENSIONAL VELOCITY ANOMALIES WITHIN THE UPPER CRUST IN THE VICINITY OF SOCORRO, NEW MEXICO USING FIRST P-ARRIVAL TIMES FROM LOCAL EARTHQUAKES

by

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## Abstract

P-wave arrival times associated with local events are inverted to determine an accurate three-dimensional seismic velocity model for the Rio Grande rift zone in the vicinity of Socorro, New Mexico. Both resolution information and estimated errors are a part of the complete solution of the problem. In addition, an improved set of hypocenter parameters and a set of station corrections (adjustments to the arrival times to compensate for near-surface effects) are also obtained.

Modified forms of the classical least squares approach (generalized and damped least squares) are used to stabilize the inversion process by suppressing model changes in those parameters poorly defined by the data. Expanding on techniques formulated by others, inversion schemes are developed, described, tested and applied to the data of the local array.

A mobile array of eight short-period seismographs provided the arrival time data (262 P-wave observations associated with 40 events) for this study. The initial attempt to model these data resulted in a representative half-space velocity of 5.85 km/sec. Analyzing the data for possible azimuthal velocity variations revealed that the resulting velocity distribution was not significantly different from the half-space solution.

In order to determine if lateral and/or vertical variations in the velocity existed, the area under consideration was subdivided at depth (4km) and into blocks one-tenth of a degree on a side. The resulting model showed that a lower block approximately 15 km WSW of Socorro had an average velocity of 5.17 $\pm$.11(s.d.) km/sec (.68 km/sec less than the half-space velocity). Other blocks were found to have smaller anomalies, but still significant, relative to the half-space velocity. The preferred explanation for anomalously low velocity is that the associated block represents a site of magmatic intrusion into the upper crust.

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# Introduction

## Purpose and Scope

Constructing accurate three-dimensional seismic velocity models of the crust is a major objective of seismology. Accurate velocity information is necessary for a variety of purposes, including improving the accuracy of the location of earthquakes, determining crustal structure, and the detection of time-dependent velocity anomalies.

A small array of short-period seismographs, established for the purpose of studying local seismicity, can provide a source of velocity and structure information. Earthquakes occurring at a variety of depths and epicentral locations within the volume beneath the array provide diverse travel paths through that volume. The calculated hypocentral parameters of each event are independent, but do depend on the velocity model used to obtain calculated travel times. The arrival times of the set of events carry information on the velocity structure. The random departures of observed from calculated arrival times (residuals) reflect (random) errors in the data which provide limits for any modeling process. The systematic residuals reflect model inaccuracies, and provide information which may be used to correct the initial velocity model. In addition to four source parameters (epicenter coordinates, focal depth, and

origin time), each earthquake makes available independent data (as much as the number of observed arrivals in excess of four) for the refinement of the velocity model.

The purpose of this study was to describe and compare least squares techniques for extracting velocity information from a set of earthquake arrival times, and to apply these techniques to data obtained by a local array in the Rio Grande rift near Socorro, New Mexico. The calculations were formulated as modified inverse problems containing elements of the formulations of Backus and Gilbert (1968), Wiggins (1972), Jackson (1972), Crosson (1976), and Aki et al. (1977). Both resolution information and estimated errors were a part of the complete solution of the problem. In addition, an improved set of hypocenter parameters and a set of station corrections were also obtained.

Following Aki et al. (1977), the volume beneath the array was divided into blocks and each block was assigned a parameter describing the slowness (reciprocal of velocity) within that block. Assuming an initial model, a linearized equation for the difference between an observed and calculated value of a given arrival time was written in terms of perturbations to the initial source and model parameters. Using the set of linearized equations for all arrivals, the source parameters for all events and the model

parameters of all blocks penetrated by the P-wave were determined simultaneously. The results were then evaluated using standard error and resolution analysis.

Modifications to the classical least squares (CLS) approach become necessary when an instability in the inversion process results from an attempt to model parameters poorly defined by the data. In such situations, two differing techniques can be used to stabilize the inversion process by suppressing model changes in the poorly defined parameters. The generalized least squares (GLS) approach produces the desired effect by removal of the eigenvalues and eigenvectors associated with the poorly defined parameters and thus constrains these parameters to values given by the initial model. In the other approach, damped least squares (DLS), the desired effect is accomplished by smoothing to a constant value the small eigenvalues associated with the poorly defined parameters and thus suppressing, but not eliminating completely, changes to these parameters.

In this study, the various inverse methods used were tested by using artificial data generated for known source and velocity models to examine stability and the effectiveness of the measures for resolution and error. The techniques developed were then applied to the investigation

of the upper crustal structure of the Rio Grande rift in the vicinity of Socorro, New Mexico leading to the most accurate and detailed seismic velocity model of the region to date.

Previous work involving the development and applications of these techniques to velocity modeling problems have been authored by Crosson (1976), Aki et al. (1977), and Aki and Lee (1976).

Crosson (1976) used a DLS modeling procedure to obtain a layered velocity model of the Puget Sound region in western Washington. Using the P-wave data of 40 local events (distributed in depth from near the surface to over 50 km and recorded by a 14 station network), he was able to obtain a model that indicated the presence of a low-velocity zone at a depth of 40 kilometers near the base of the crust. However, he was unable to obtain the exact configuration of the zone due to the lack of resolving power at critical depths.

Aki et al. (1977) started with a layered medium, but divided each layer into many blocks which were then assigned a parameter which described the velocity fluctuations from the layer average. Both GLS and DLS methods were applied to 1496 teleseismic P-wave residuals obtained from 93 events at 22 subarrays in order to obtain a velocity model beneath the Norwegian Seismic Array (NORSAR) to a depth of 126 km. The resulting model showed the existence of strong

inhomogeneities (differences of several tenths of km/sec on a scale of thousands of square kilometers) to the bottom of the lithosphere. However, problems of vertical smoothing were encountered due to the intrinsic nonuniqueness associated with the near-vertical travel paths of the teleseismic arrivals. Three-dimensional modeling of teleseismic arrivals is restricted to obtaining velocity perturbations within individual layers, with independent data being required to determine the average velocity of each layer.

The techniques developed by Aki et al. (1977) have been used by others (Husebye et al., 1976; Ellsworth and Koyanagi, 1977; Mitchell et al., 1977; Reasenberg et al., 1980; Romanowicz, 1980) for the inversion of teleseismic arrivals at other arrays, with the same problems inherent in the use of teleseismic arrivals.

Aki and Lee (1976) used a DLS modeling procedure, which used only one iteration, to obtain a three-dimensional velocity structure of the San Andreas fault zone in the vicinity of Bear Valley, California. The data from 1218 P-wave arrivals associated with 32 local events were inverted to produce a velocity model. The resulting velocity distribution in the upper 5 kilometers showed a horizontally narrow, low-velocity zone with a P-wave velocity of about 5 km/sec in the San Andreas fault zone

sandwiched between high-velocity regions of about 6 km/sec. However, for both this approach and that of Aki et al. (1977), a solution based on a single-step iteration of an oversimplified initial model may possess errors inherent in the linearization of a non-linear problem. In addition, for both these approaches, errors may also result from the simplified method they used to calculate travel path lengths within blocks.

Initial attempts to model synthetic data (representative of the true data) using the formulations developed by these investigators demonstrated certain inadequacies. A single iteration was not sufficient to reduce errors inherent in the linearization of the non-linear problem, as demonstrated by an inability to adequately reproduce the true model. However, a multi-step iterative procedure demonstrated additional instability due to the method used by Aki and Lee (1976) and Aki et al. (1977) to calculate travel path lengths within blocks. Their oversimplified method was to minimize the number of penetrated blocks by assuming either vertical or horizontal approximations for the true travel paths (see Aki and Lee, 1977). This study makes no such approximation, as the path length within any block is calculated exactly, with no approximations save that it is assumed the ray is unrefracted at block boundaries. This is reasonable, as

these boundaries are arbitrary and do not represent true velocity interfaces. This modification, in conjunction with an iterative procedure, markedly improved the performance of the inversion process when tested on synthetic data.

A further modification incorporated in this study involved using an eigenvalue/eigenvector decomposition approach (GLS), instead of a DLS, because GLS provided greater latitude in the choice of smoothed parameters to be used in the modeling of the data. It should be noted that a similar formulation involving eigenvalue/eigenvector decomposition by Aki et al. (1977) was used only for maximizing resolution rather than for shaping the resolving kernels, as it was in this study. In addition, the programs used in this study allowed for the inclusion of constraints on parameters known independently of the data. The resulting improvements to the basic formulations allowed for accurate velocity information to be obtained from the data, as demonstrated by applications to synthetic data.

## Geological and Geophysical Background

The geographic area of interest in this study lies within the central region of the Rio Grande rift zone. The Rio Grande rift is a nearly north to south linear structure penetrating the southern Rocky Mountains as far north as

Leadville, Colorado and merging with the Basin and Range province to the south. The southern extent of the rift is poorly defined, but may extend as far south as Chihuahua, Mexico (Chapin, 1971). Fig. 1 is a generalized map of the rift zone and physiographic provinces within the state of New Mexico. In central New Mexico, the rift is bounded by the Great Plains province on the east and by the Colorado Plateau on the west. Of interest in this study is that portion of the central rift that extends from approximately 40 kilometers north to 20 kilometers south of Socorro, New Mexico (see Fig. 2). Within this area the character of the rift changes at the northern boundary from that of a single basin with raised margins to that of a rift with a series of parallel basins and ranges. In addition, the total width of the rift increases to 2.5 times that of the single basin to the north. The central ranges within this area are intragraben horsts that formed relatively late in the history of the rift, i.e., 9-10 m.y. ago (Chapin and Seager, 1975). The formation of such horsts through several thousand feet of sedimentary fill occurs at only one other locality within the rift, namely at Las Cruces, New Mexico. Notable features within the area of interest are (1) alluvial basins which are 3 to 5 km deep (Sanford, 1968; and Chapin and Seager, 1975), (2) boundary faults of Quaternary age that strike NNE to NNW (Sanford et al., 1972), (3) raised structural margins, especially on the the

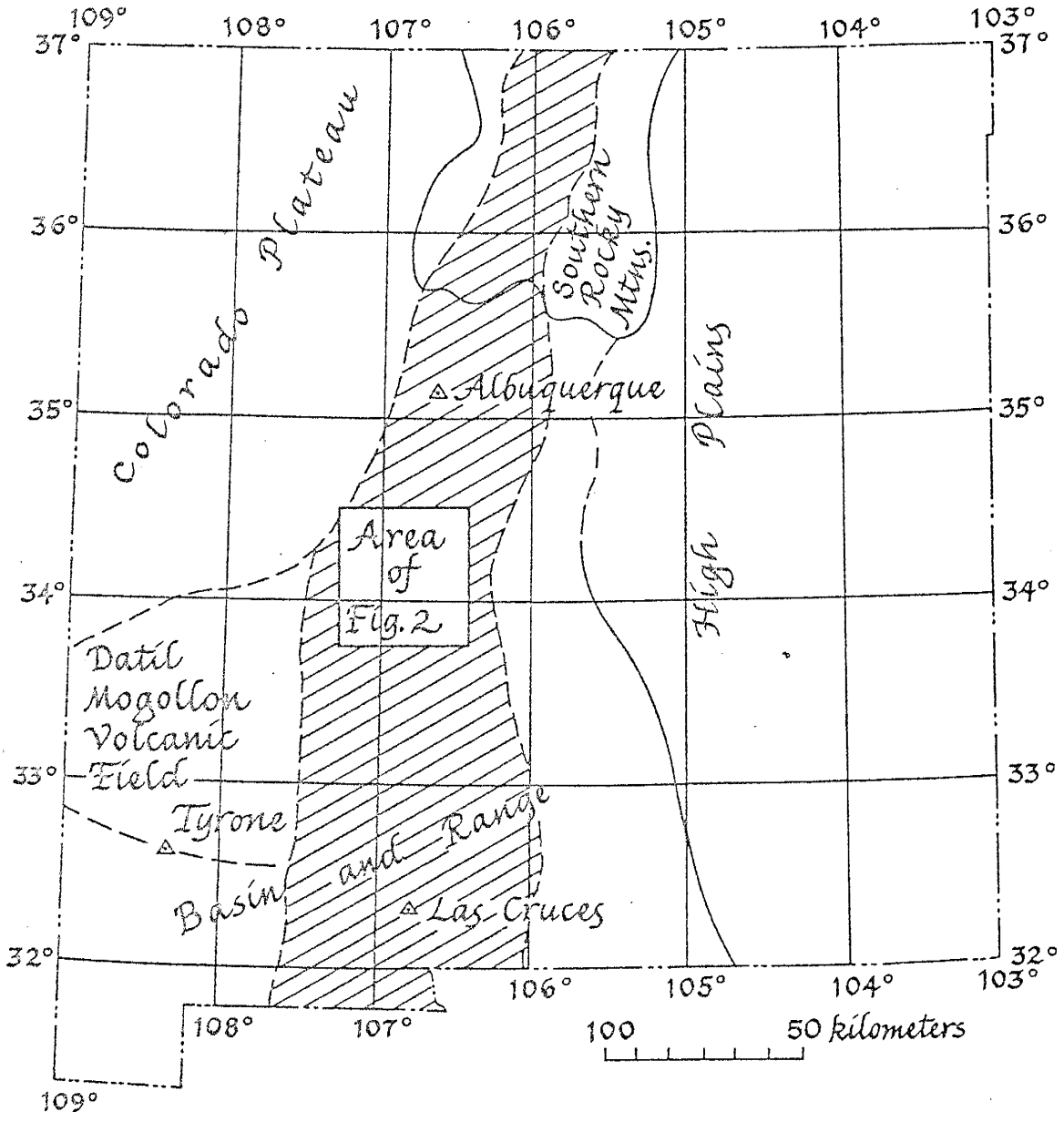



Figure 1. Physiographic provinces and the Rio Grande rift in New Mexico (after Chapin, 1971).

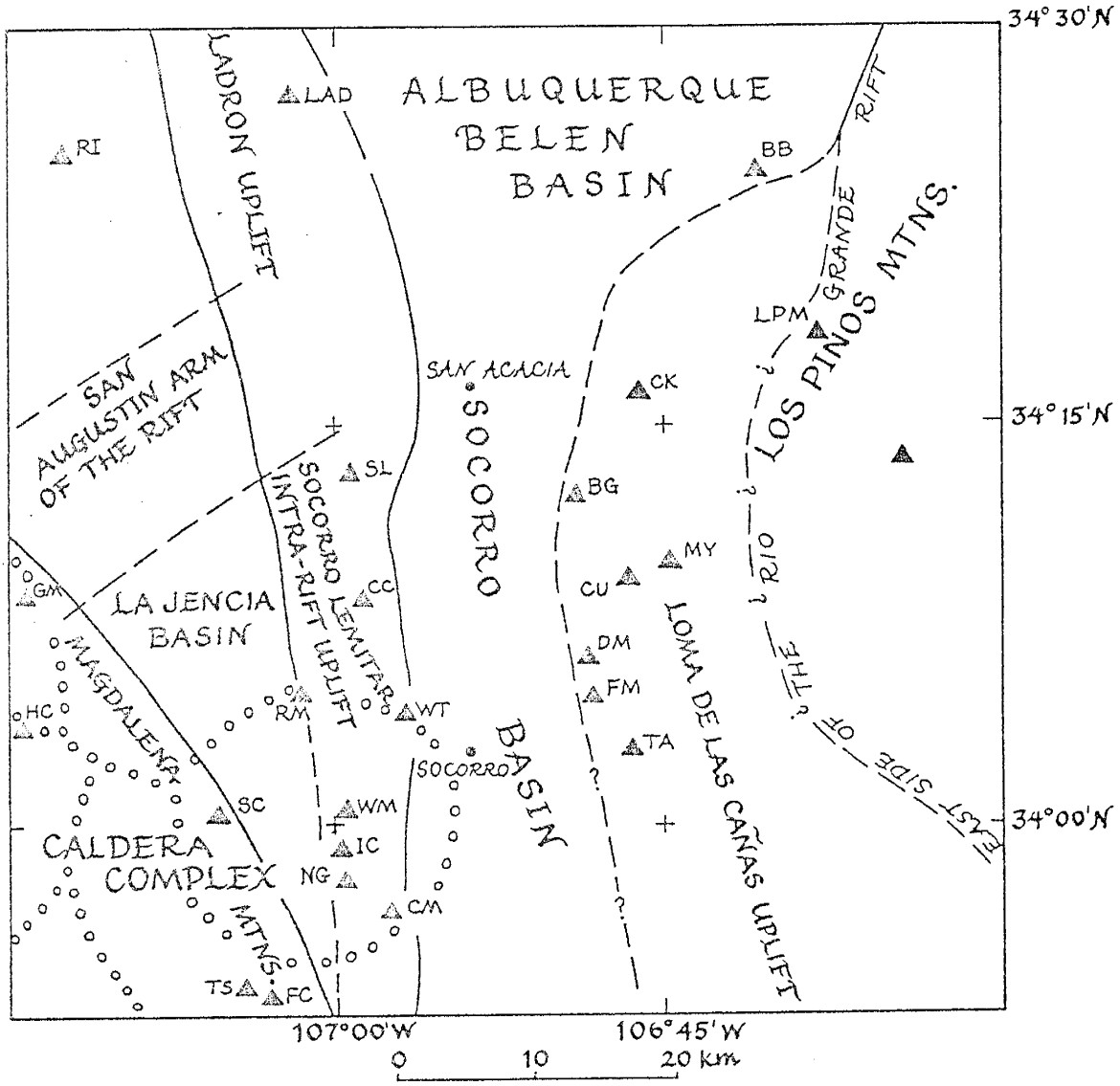



Figure 2. Major physical features near Socorro and locations of the seismic recording stations (from Rinehart et al. 1979).

eastern side of the rift (Chapin, 1971), (4) several intrarift uplifts (Chapin and Seager, 1975), and (5) the intersection of two volcanic lineaments, one of which is postulated to be a deep-seated transverse shear zone (Chapin et al., 1978).

In response to east - west crustal extension, rifting began between 32 and 27 m.y. ago and continues to the present (Chapin, 1971). A great deal of volcanic activity has accompanied the formation of the rift, with the two periods of greatest activity being from 26 to 20 m.y. ago and from 5 m.y. ago to present (Chapin and Seager, 1975). Basaltic andesites were most abundant during the first period of volcanism, whereas true basalts dominate the later period. The youngest basaltic flows in the Socorro area have been dated at 4 m.y. (Bachman and Mehnert, 1978).

Beneath the area of interest, at a mid-crustal depth of 19 kilometers, is an extensive, sill-like magma body (Rinehart et al., 1979). The magma body appears to terminate to the south against a northeast-trending transverse shear zone and may be leaking magma along it to form shallow, upper-crustal reservoirs (Chapin, 1979).

Additional geophysical observations associated with the area of interest, all possibly related to the intrusion of magma into the upper crust, are high seismicity, high

temperature gradients and heat flows, and surface uplift. The area above the magma body is an area of concentrated seismic energy release (often in swarm-like events) sandwiched between essentially aseismic portions of the rift (Sanford et al., 1979). The activity over the magma body is diffusely distributed and is not correlated with known major faults (Sanford, 1978). Within the Socorro mountain block, temperature gradients as high as 241 °C/km, and heat flows as high as 11.7 HFU have been measured (Sanford, 1977; Reiter and Smith, 1977). Using level-line data, Reilinger et al. (1979) were able to identify an extremely rapid (2 to 6 mm/yr) uplift centered over the magma body with a maximum rate of uplift of 6 mm/yr occurring 20 km north of Socorro.

In addition, P and S waves from local microearthquakes and mining explosions have been used by many investigators to infer magma bodies at shallow levels within the upper crust in the vicinity of Socorro (Shuleski, 1976; Caravella, 1976; Johnston, 1978; Fender, 1978; Guynn, 1978). Shuleski (1976) and Johnston (1978) were able to define regions of higher-than-normal S-phase absorption within the upper crust. Caravella (1976) and Fender (1978) determined a spatial distribution of Poisson's ratio and Guynn (1978) obtained estimates of Q for crustal rock within the array. When reviewing these studies, Sanford and Schlue (1980) concluded that only a small amount of magma resides

at high levels within the crust, occurring in a complex network of dikes and sills. They also concluded that the most likely localities for such shallow magma bodies were (1) between stations "WT", "SC", and "CM", (2) ESE of station "WT" and (3) SW of station "BG" (see Fig. 2).

It was the purpose of this study to determine efficient methods for extracting velocity information from a set of arrival times and to use these techniques to construct an accurate three-dimensional seismic velocity model for the Rio Grande rift zone in the vicinity of Socorro, New Mexico. In addition, it was also the purpose of this study to examine resulting velocity anomalies in conjunction with the likely localities for magmatic intrusions as proposed by other investigators. Expanding on the modified least squares techniques formulated by others, inversion schemes were developed, tested and applied to the data of the local array.

## Data

In an effort to obtain more detailed knowledge of the geophysical properties of the upper crust in the Socorro area, a very localized microearthquake study was undertaken in May, 1975 (Sanford et al., 1977). During the subsequent 316 recording days extending over 33 months, more than 1200 events were recorded. Of these, 40 events, yielding 262 P-wave observations, were selected for this study. Two important criteria used for selection were sharp, clear, unambiguous P-arrivals at six or more stations of the array per event, and a good distribution of hypocenters over the area of the network. Care was taken to eliminate events from the same swarm which, although they were well recorded, provided neither independent nor unique information. A listing of the events so chosen is given in Appendix 1, with the spatial distribution of these events presented in Fig. 3.

In order to determine the four source parameters (latitude, longitude, depth and origin time) using first P-wave arrivals, it is necessary to have a minimum of four stations recording the event. Therefore, an event recorded by N stations provides N-4 observations for the determination of the velocity (path) parameters. For this reason, only events recorded by 6 stations or more were included in this study.

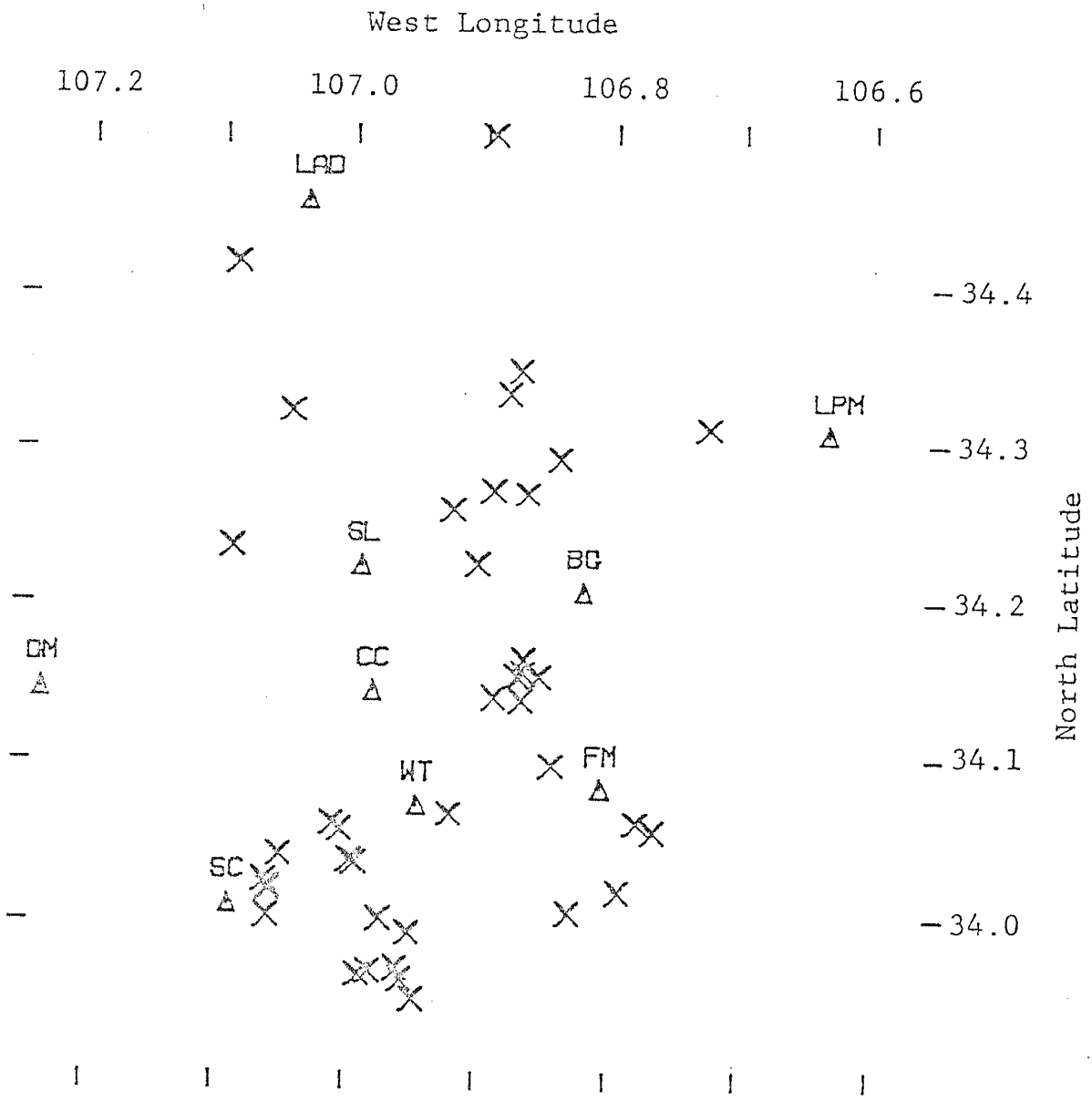



Figure 3. Spatial distribution of the events used in the study.

It is to be expected that the quality of the results will depend critically on the distribution of travel paths available. Simply overdetermining the system is not sufficient to ensure results, as many observations do not provide independent, unique information. Therefore, it was necessary to select events that provided a good distribution of travel paths.

During initial attempts to use these data to model a representative half-space velocity, it became apparent from occasional large residuals that errors continued to contaminate the data. These large residuals were used as a basis for rechecking and correcting the data, and for eliminating any obvious data errors.

Uncertainties were assigned to the P-wave arrival readings on an *a priori* basis, depending on the subjective quality of each arrival. A minimum uncertainty of .03 secs was assumed for all readings. The assigned uncertainty was incremented in steps of .03 secs for arrivals which were weaker than normal.

Instrumentation

Most of the microearthquake seismograms used in this study were recorded with a movable array of six Sprengnether MEQ-800 seismic recording systems. After April, 1977, this network was supplemented by two Sprengnether DR-100 digital recording systems. In addition, starting in 1977 telemetered signals were available from Albuquerque Seismological Laboratory (U.S.G.S.) for stations "LAD" and "LPM".

MEQ-800 Seismograph: The Sprengnether MEQ-800 is a self-contained, portable, analog seismic recording system with a wide sensitivity range. Some filtering of the signal above 30 Hz was necessary to reduce noise caused by near-surface atmospheric disturbances. For some quiet stations located in mines or caves the signal was recorded without filters. After amplification, a helical recording of the seismic signal was made on smoked paper at a rate of 120 $\pm$1.0mm/min. Time marks at 60 second intervals were produced by self-contained, quartz crystal chronometers. These clocks were synchronized at the begining of each recording week with the WWV standard time signal. At the end of each recording week the internal time signals were again simultaneously recorded with the WWV standard time

signal to correct for clock drift. To complete the MEQ-800 system, either a Mark Products vertical L4-C geophone or, occasionally, a Willmore vertical geophone was used.

DR-100 Seismograph: The Sprengnether DR-100 system is a precision 12-bit digital seismic recorder. It continually monitors the seismic signal at 100 samples per second until triggered by an event whose signal has a short-term average larger, by a prescribed amount, than the long-term signal average preceding the event. At this time, the event signal and timing information, supplied by a quartz crystal chronometer, are recorded on magnetic tape. The available amplification and filter settings are identical to the MEQ-800 system. The geophone used with this system is the same as used with the MEQ-800 system (Marks Products L4-C). A companion play-back system (Sprengnether DP-100) provided both analog and digital output for subsequent data processing and analysis.

## Arrays

The eight Sprengnether systems were available for use in a movable array which could occupy any of the 25 station sites shown in Fig. 2 and listed in Table 1. Given the general locality of a new station location, protection from

TABLE 1. SEISMOGRAPH STATION LOCATIONS AND STATION CORRECTIONS

| STATION | LATITUDE | LONGITUDE | ELEVATION(m) | STATION CORRECTION(sec) |
|---|---|---|---|---|
| BB | 34.4090 | 106.6818 | 1615 | -.04 |
| BG | 34.2068 | 106.8205 | 1516 | -.01 |
| CC | 34.1442 | 106.9819 | 1649 | -.15 |
| CK | 34.2725 | 106.7702 | 1578 | -.04 |
| CM | 33.9501 | 106.9576 | 1640 | .13 |
| CU | 34.1573 | 106.7785 | 1585 | -.10 |
| DM | 34.1075 | 106.8079 | 1536 | -.01 |
| FC | 33.8950 | 107.0504 | 1850 | .26 |
| FM | 34.0829 | 106.8047 | 1537 | .00 |
| GM | 34.1454 | 107.2345 | 1945 | -.06 |
| HC | 34.0658 | 107.2361 | 2240 | .16 |
| IC | 33.9870 | 106.9967 | 1730 | .08 |
| LAD | 34.4583 | 107.0375 | 1768 | -.25 |
| LPM | 34.3076 | 106.6336 | 1737 | -.24 |
| MY | 34.1667 | 106.7459 | 1645 | -.09 |
| NG | 33.9648 | 106.9933 | 1730 | .14 |
| RI | 34.4234 | 107.2075 | 1530 | -.01 |
| RM | 34.0812 | 107.0069 | 1719 | .11 |
| SC | 34.0100 | 107.0894 | 2073 | .15 |
| SL | 34.2234 | 106.9910 | 1615 | -.11 |
| TA | 34.0498 | 106.7751 | 1558 | .09 |
| TD | 34.2339 | 106.5778 | 1850 | -.09 |
| TS | 33.9012 | 107.0662 | 1860 | .28 |
| WM | 34.0120 | 106.9929 | 1673 | .12 |
| WT | 34.0722 | 106.9459 | 1555 | -.11 |

atmospheric noise was a main consideration in the actual site selection. In most cases, caves and abandoned mines were used, and when possible, the geophone was buried. The majority of the recording time was spent with arrays in the southern portion of the area until Fall, 1977, when the instruments were moved to the more northerly stations.

## Theory

Within this section is the general development of the inversion schemes used in this study. Three basic approaches, classical least squares, damped least squares and generalized least squares (eigenvector/eigenvalue decomposition) are examined. The application of these three analytical procedures for obtaining velocity models of the Rio Grande valley in the Socorro region are presented in later sections.

The following notation is used in the discussion of the inversion schemes. Underlined capital letters represent entire matrices, while subscripted capital letters represent single matrix elements. Underlined lower case letters represent single columns of larger multi-dimensional vectors. The superscripts "ob" and "t" designate observed data and theoretically calculated values, respectively. The superscript "T" indicates the transpose of a matrix.

The basic approach of all three schemes is to minimize the difference between the observed data and data from an initial model (theoretical data) by calculating appropriate adjustments to the parameters of the initial model.

Theoretical data are calculated numerically from an assumed model $(x_1, x_2, \ldots, x_m)$ according to a functional $F_i$,

$$T_i^t = F_i\ (x_1, x_2, \ldots, x_m) \qquad (1)$$

or, in matrix notation

$$\underline{T}^t = F\ (\underline{x})$$

where $\underline{x}$ is a vector containing all parameters and $\underline{T}^t$ is a vector of all theoretical data.

If the functional F is non-linear, as it is for this problem, the assumption is made that $T_i$ can be expanded in a Taylor series about some initial model $\underline{x}^\circ$ in order to obtain the difference $\Delta T_i$ between the observed and theoretical values. The resulting expansion is as follows:

$$T_i^{ob} = F_i\ (\underline{x}^\circ) + \sum_{k=1}^{m} \frac{\partial F_i(x)}{\partial x_k} (x_k - x_k^\circ)$$

$$+ \tfrac{1}{2} \sum_{k=1}^{m} \sum_{j=1}^{m} \frac{\partial F_i(x)}{\partial x_k \partial x_j} (x_k - x_k^\circ)(x_j - x_j^\circ)$$

$$+ \ldots,\ i = 1, \ldots, n$$

where

$T_i^{ob} = i^{th}$ Observed Datum

$F_i(\underline{x}) = i^{th}$ Theoretical Datum

$\frac{\partial F_i(\underline{x})}{\partial x_k} =$ Change of the ith theoretical datum with respect to the kth parameter

$(x_k - x_k^\circ) = \Delta x_k =$ Change to be applied to the kth parameter

$n =$ Total number of observations

$m =$ Total number of model parameters

By making the assumption of linearity i.e., that the initial model $\underline{x}^\circ$ is close enough to the final model $\underline{x}$ so that second

order terms can be ignored, the equation may be written

$$T_i^{ob} - F_i(\underline{x}^\circ) = \sum_{k=1}^{m} \frac{\partial F_i(x_k)}{\partial x_k} \Delta x_k + \varepsilon_i \qquad (2)$$

where

$\varepsilon_i$ = Higher order terms and errors in observation.

Substituting from expression (1) and ignoring higher-order terms and errors, the entire set of equations can be presented in the matrix notation by

$$\underline{\Delta T} = \underline{A}\,\underline{\Delta x} \qquad (3)$$

Where $\underline{A}$ is the matrix of partial derivatives. The elements of the columns of the n x m matrix $\underline{A}$ are the partial derivatives of the functional $F(x_k)$ with respect to the particular parameter $x_i$, evaluated at $x^\circ_i$. The elements of the rows of $\underline{A}$ are then partial derivatives associated with a particular observation and evaluated at $\underline{x}^\circ$. An element of

the matrix $\underline{A}$ can be represented by

$$A_{ki} = \left[ \frac{\partial F(x_k)}{\partial x_i} \right]_{x^\circ} .$$

The solution of expression (3) requires an operator $\underline{H}$, the 'inverse of $\underline{A}$' such that

$$\underline{\hat{\Delta x}} = \underline{H}\,\underline{\Delta T} \qquad (4).$$

The resulting correction vector $\underline{\hat{\Delta x}}$ is then applied to $\underline{x}^\circ$ to produce the new set of model parameters $\underline{x}$. For small $\underline{\hat{\Delta x}}$, the problem is quasi-linear and the higher order terms in the expansion may be safely ignored. If the higher order terms cannot be ignored, $\underline{x}$ is then used as the new initial estimate and the inversion is repeated. These iterations continue until the resulting $\underline{\Delta x}$ converges to zero.

Three differing approaches to finding an inverse matrix $\underline{H}$ were examined in a effort to find the most suitable 'inverse of $\underline{A}$'. Each of these schemes will now be discussed and developed separately.

Classical Least Squares

For classical least squares, the most general case is where there are at least as many data as unknown parameters ($n \geq m$). For this case it is reasonable to assume that a final model will not fit the data exactly unless n=m, i.e.,

$$\Delta T_i - A_{ij} \Delta x_j = \varepsilon_i$$

where $\varepsilon_i$ is the residual "error" associated with the ith datum. These errors are due to noisy data and/or poor parametization of the model.

The classical least squares approach is to find the set of $\hat{\Delta x_j}$'s for which the $\varepsilon_i$'s are minimized. Following the general development of Draper and Smith (1966) the procedure is to minimize the sum of squares of the residuals with respect to the unknown parameters.

The entire set of errors is given by

$$\underline{\varepsilon} = \underline{\Delta T} - \underline{A}\,\underline{\Delta x} \ ,$$

and thus the square of the set of residuals is given by

$$|\varepsilon|^2 = \underline{\varepsilon}^T \underline{\varepsilon} = (\underline{\Delta T} - \underline{A}\,\underline{\Delta x})^T (\underline{\Delta T} - \underline{A}\,\underline{\Delta x}) \ .$$

Expanding this expression gives

$$|\mathcal{E}|^2 = \underline{\Delta T}^T \underline{\Delta T} - \underline{\Delta T}^T \underline{A}\underline{\Delta x} - \underline{\Delta x}^T \underline{A}^T \underline{\Delta T} + \underline{\Delta x}^T \underline{A}^T \underline{A}\underline{\Delta x} \quad .$$

Noting that

$$\underline{\Delta T}^T \underline{A}\underline{\Delta x} = (\underline{A}^T \underline{\Delta T})^T \underline{\Delta x}$$

and

$$(\underline{A}^T \underline{\Delta T})^T \underline{\Delta x} = \underline{\Delta x}^T \underline{A}^T \underline{\Delta T},$$

the expression for $|\mathcal{E}|^2$ can be written as

$$|\mathcal{E}|^2 = \underline{\Delta T}^T \underline{\Delta T} - 2\,\underline{\Delta x}^T \underline{A}^T \underline{\Delta T} + \underline{\Delta x}^T \underline{A}^T \underline{A}\underline{\Delta x} \quad .$$

In order to simplify this expression further, the following substitutions are made:

$$S = \underline{\Delta T}^T \underline{\Delta T} \qquad \text{(scalar)}$$

$$\underline{V} = \underline{A}^T \underline{\Delta T} \qquad \text{(vector)}$$

$$\underline{M} = \underline{A}^T \underline{A} \qquad \text{(matrix)}$$

leading to

$$|\mathcal{E}|^2 = S - 2\underline{\Delta X}^T\ \underline{V} + \underline{\Delta X}^T\ \underline{M}\underline{\Delta X} \quad .$$

In subscript notation this becomes

$$|\mathcal{E}|^2 = S - 2\sum_{j=1}^{m} V_j\ \Delta x_j + \sum_{j,k}^{m} M_{jk}\Delta x_j\ \Delta x_k \quad .$$

Differentiating this expression leads to

$$\frac{\partial|\mathcal{E}|^2}{\partial x_l} = -2\sum_{j=1}^{m} V_j\ \delta_{jl} + \sum_{j=1}^{m}\sum_{k=1}^{m} M_{jk}\{\Delta x_k\ \delta_{jl} + \Delta x_j\ \delta_{kl}\} \quad ,$$

which can be reduced to

$$\frac{\partial|\mathcal{E}|^2}{\partial x_l} = -2V_l + \sum_{k=1}^{m} M_{lk}\Delta x_k + \sum_{j=1}^{m} M_{lk}\Delta x_j \quad ,$$

and since $\underline{M}$ is symmetric it follows that

$$\frac{\partial|\mathcal{E}|^2}{\partial x_l} = -2V_l + 2\sum_{j=1}^{m} M_{lj}\Delta x_j \quad .$$

Returning from subscript notation to matrix notation and setting the expression equal to zero gives

$$\frac{\partial|\mathcal{E}|^2}{\partial x} = -2\underline{V} + 2\underline{M}\ \underline{\Delta X} = 0$$

leading to

$$\underline{M}\,\underline{\Delta X} = \underline{V}$$

Replacing earlier substitutions gives

$$\underline{A}^T\,\underline{A}\underline{\Delta X} = \underline{A}^T\,\underline{\Delta T} \quad .$$

If $\underline{A}^T\,\underline{A}$, a square (m x m) matrix, is non-singular, then $(\underline{A}^T\,\underline{A})^{-1}$ exists leading to the least squares solution of the expression (4), given by

$$\underline{\hat{\Delta X}} = \underline{H}\,\underline{\Delta T} = (\underline{A}^T\,\underline{A})^{-1}\,\underline{A}^T\underline{\Delta T} \qquad (5)$$

For the special case where n = m,

$$(A^T A)^{-1} = A^{-1}\,(A^T)^{-1}$$

leading to a solution of the form

$$\underline{\Delta X} = \underline{A}^{-1}\,\underline{\Delta T} \quad .$$

The classical least squares approach reduces the original system of equations $\underline{A}$, which has no inverse, to an m x m system $\underline{A}^T\underline{A}$ which may have an inverse. For the quasi-linear problem, iterative solutions are carried out until a prescribed convergence condition is satisfied. For example, $\underline{\hat{\Delta x}}$ or $\underline{\Delta T}^T\underline{\Delta T}$ may be examined for 'smallness' after each iteration. Experience in actual calculations is invariably necessary to determine a useful convergence criterion.

A measure of the independence from the starting model a particular unknown has after inversion is given by the R matrix or "resolution matrix" where

$$\underline{R} \equiv \underline{H}\underline{A} \ .$$

In theory, when classical least squares is used, the new model parameters are totally independent of the starting model. This can be seen by examining the resolution matrix $\underline{R}$, where

$$\underline{\hat{\Delta X}} = \underline{H}\,\underline{\Delta T} = \underline{H}\underline{A}\underline{\Delta x} = \underline{R}\underline{\Delta x} \ .$$

If $\underline{R}=\underline{I}$ (the identity matrix), then the solution $\underline{\hat{\Delta x}}$ is unique (i.e., cannot depend upon the initial model).

The rows of $\underline{R}$ are the resolving kernels that show how the real parameters are averaged or "blurred" to obtain the estimated parameters. The resolution of the kth parameter is given by examining the kth row of the $\underline{R}$ matrix. The degree to which $\underline{R}$ approximates the identity matrix is a measure of the resolution obtained from the data, with a null or zero resolving kernel showing model dependence for the associated parameter (Jackson, 1972).

In practice, difficulties are often encountered with classical least squares since the matrix $\underline{A}^T \underline{A}$ may often be singular or nearly singular. These difficulties arise because the data may carry no information about one or more of the model parameters.

Symptoms of lack of information, as found in practice, are large and unstable or oscillating changes in the solution vector from iteration to iteration. The source of difficulty is easily seen when a fundamental decomposition theorem (Lanczos, 1961) is applied to the normal equation matrix.

Generalized Eigenvector/Eigenvalue Analysis

The basis for the decomposition approach used in this paper was developed by Lanczos (1961) and explained in detail by Jackson (1972) and Wiggins (1972).

If $\underline{A}$ is an arbitrary n x n square matrix, then the equation

$$\underline{A}\,\underline{u}_i = \lambda \underline{u}_i$$

is the eigenvalue equation associated with $\underline{A}$. The scalars $\lambda_1, \lambda_2, \lambda_3 \ldots, \lambda_n$ are called the eigenvalues of $\underline{A}$ while the vectors $u_{1i}, u_{2i}, u_{3i} \ldots, u_{ni}$ are called the normalized eigenvectors or principal axes of $\underline{A}$. For an n x n symmetric matrix the eigenvalues are always real and the eigenvectors are orthogonal. An orthogonal matrix $\underline{U}$ has the property

$$\underline{U}^T\underline{U} = \underline{I} = \underline{U}\underline{U}^T \quad .$$

The set of eigenvalue equations for a symmetric matrix $\underline{S}$ can be written

$$\underline{S}\underline{U} = \underline{U}\underline{\Lambda}$$

where $\underline{U}$ is the orthogonal matrix of eigenvectors and $\underline{\Lambda}$ is the diagonal matrix of eigenvalues. Post-multiplying by $\underline{U}^T$ gives

$$\underline{S} = \underline{U}\,\underline{\Lambda}\,\underline{U}^T$$

as the decomposed form of the symmetric matrix $\underline{S}$.

An arbitrary linear n x m system

$$\underline{A}\underline{x} = \underline{b}$$

can be combined with its adjoint m x n system

$$\underline{A}^T\,\underline{y} = \underline{c}$$

to provide a (n + m) x (m + n) symmetric system

$$\underline{S}\,\underline{z} = \underline{a}$$

where

$$\underline{S} \equiv \left[\begin{array}{c|c} O & \underline{A} \\ \hline \underline{A}^T & O \end{array}\right]$$

$$\underline{z} \equiv \left\{\begin{array}{c} \underline{y} \\ \hline \underline{x} \end{array}\right\}$$

and

$$\underline{a} \equiv \left\{ \begin{array}{c} \underline{b} \\ \hline \underline{c} \end{array} \right\}$$

The eigenvalue equation of a symmetric matrix $\underline{S}$ can be written in a similar form

$$\underline{S}\,\underline{w} = \lambda\,\underline{w}$$

where

$$\underline{w} = \left\{ \begin{array}{c} \underline{u} \\ \hline \underline{v} \end{array} \right\}$$

or

$$\left[ \begin{array}{c|c} O & \underline{A} \\ \hline \underline{A}^T & O \end{array} \right] \quad \left\{ \begin{array}{c} \underline{u} \\ \hline \underline{v} \end{array} \right\} = \lambda \quad \left\{ \begin{array}{c} \underline{u} \\ \hline \underline{v} \end{array} \right\} .$$

This is equivalent to

$$\underline{A}\,\underline{v} = \lambda\,\underline{u} \qquad (6)$$

and

$$\underline{A}^T \underline{u} = \lambda \underline{v} \quad . \qquad (7)$$

Premultiplying (6) by $\underline{A}^T$ leads to

$$\underline{A}^T \underline{A} \underline{v} = \underline{A}^T \lambda \underline{u}$$

and substituting with expression (7) leads to

$$\underline{A}^T \underline{A} \underline{v} = \lambda^2 \underline{v} \quad .$$

From this expression it can be seen that $\underline{v}$ is an eigenvector of $\underline{A}^T \underline{A}$. Similarly, premultiplying (7) by $\underline{A}$ leads to

$$\underline{A} \underline{A}^T \underline{u} = \lambda^2 \underline{u}$$

and it is seen that $\underline{u}$ is an eigenvector of $\underline{A}\underline{A}^T$.

The two equations $\underline{A}\underline{v} = \lambda \underline{u}$ and $\underline{A}^T\underline{u} = \lambda \underline{v}$ can be written in the matrix equations

$$\underline{A} \underline{V} = \underline{U} \underline{\Lambda} \qquad (8)$$

and

$$\underline{A}^T \underline{U} = \underline{V} \underline{\Lambda}$$

Post-multiplying (8) by $\underline{V}^T$ leads to

$$\underline{A}\,\underline{V}\underline{V}^T = \underline{U}\underline{\Lambda}\underline{V}^T$$

or

$$\underline{A} = \underline{U}\underline{\Lambda}\underline{V}^T \quad .$$

From this it can be seen that an arbitrary n x m matrix $\underline{A}$ can be decomposed into $\underline{U}$, $\underline{V}$ and $\underline{\Lambda}$. For the problem under investigation the columns of $\underline{U}$ are the eigenvectors associated with the unknown parameters, the columns of $\underline{V}$ are the eigenvectors associated with the data, and $\underline{\Lambda}$ is a diagonal m x m matrix containing the eigenvalues of $\underline{A}$.

Expanding expression (5), the decomposed form of the 'inverse of $\underline{A}$' becomes

$$\underline{H} = \underline{V}\underline{\Lambda}^{-1}\underline{U}^T \quad .$$

If certain parameters in the starting model are poorly defined by the given data, their associated eigenvalues will be zero or near zero. The strength of the decomposition approach over classical least squares lies in the fact that these poorly defined parameters can be eliminated by

discarding the eigenvalues and eigenvectors associated with these parameters, thereby reducing the rank or degrees of freedom of $\underline{\Lambda}$ to p instead of m, where p is the number of resolvable parameters. Using only p degrees of freedom the decomposed form of the inverse of $\underline{A}$ becomes

$$\underset{(n\times m)}{\underline{H}} \equiv \underset{(n\times p)}{\underline{V}}\ \underset{(p\times p)}{\underline{\Lambda}^{-1}}\ \underset{(p\times m)}{\underline{U}^{T}} \quad ,$$

leading to

$$\underline{\hat{\Delta X}} = \underset{(n\times p)}{\underline{V}}\ \underset{(p\times p)}{\underline{\Lambda}^{-1}}\ \underset{(p\times m)}{\underline{U}^{T}}\ \underline{\Delta T}$$

which for p = m is identical to the classical least squares approach. The elements of the correction vector associated with the removed eigenvalues will be zero or near zero. The effect that the removal of a given eigenvalue will have on the correction vector can be obtained from an examination of the corresponding row (resolving kernel) of the resolution matrix

$$\underline{R} \equiv \underline{V}_p \underline{V}_p^{T} \qquad (9)$$

with a null or zero resolving kernel showing nearly complete model dependence for the associated parameter.

Damped Least Squares

From an examination of the decomposition approach and the associated expanded form of expression (5)

$$\underline{\hat{\Delta x}} = \underline{V}\underline{\Lambda}^{-1}\,\underline{U}^{T}\,\underline{\Delta T} \quad ,$$

it can be seen that, since $\hat{\Delta x}_i$ involves division by $\lambda_i$, very small $\lambda_i$'s result in large and unstable changes in one or more of the components of the correction vector $\underline{\hat{\Delta x}}$. If an iterative inversion is necessary, the small $\lambda_i$'s may cause the problem itself to become unstable as the partial derivatives of $\underline{A}$ and the $\underline{\Delta T}$ residuals are recalculated.

In the decomposition approach, parameters with zero or near-zero eigenvalues were constrained to values given by the initial model in order to stabilize the problem. A different approach is to suppress, but not eliminate completely, changes in those parameters that are poorly defined in the observation space.

The procedure in this approach is to minimize the weighted sum of the residual and solution vectors (Levenberg, 1944). That is, minimize $|\varepsilon|^2$ where

$$|\varepsilon|^2 \equiv (\underline{A}\underline{\Delta x} - \underline{\Delta T})^T (\underline{A}\underline{\Delta x} - \underline{\Delta T}) + \theta^2 \underline{\Delta x}^T \underline{\Delta x}$$

and where $\theta^2$ is a weighting coefficient to be adjusted to the requirements of the problem to control the resolving and variance characteristics of the inversion procedure.

Following the approach used in the development of classical least squares leads to

$$|\varepsilon|^2 = \underline{A}^T \underline{\Delta x}^T \underline{A}\underline{\Delta x} - \underline{A}^T \underline{\Delta x}^T \Delta T - \underline{\Delta T}^T \underline{A}\underline{\Delta x}$$

$$+ \underline{\Delta T}^T \underline{\Delta T} + \theta^2 \underline{\Delta x}^T \underline{\Delta x} \quad .$$

Again, let

$$S \equiv \underline{\Delta T}^T \underline{\Delta T}$$

$$\underline{V} \equiv \underline{A}^T \underline{\Delta T}$$

$$\underline{M} \equiv \underline{A}^T \underline{A} \quad ,$$

which leads to

$$|\varepsilon|^2 = S - 2 \underline{\Delta x}^T \underline{V} + \Delta x^T \underline{M}\, \underline{\Delta x} + \theta^2 \underline{\Delta x}^T \underline{\Delta x} \quad .$$

In subscript notation this becomes

$$|\varepsilon|^2 = S - 2\sum_{j=1}^{m} V_j x_j + \sum_{j,k} M_{jk} x_j x_k + \theta^2 \sum_{j,k} x_j x_k \ .$$

Differentiating this expression leads to

$$\frac{\partial |\varepsilon|^2}{\partial x_l} = -2\sum_{j=1}^{m} V_j \delta_{jl} + \sum_{j=1}^{m}\sum_{k=1}^{m} M_{jk}\{\Delta x_k \delta_{jl} + \Delta x_j \delta_{kl}\}$$
$$+ \theta^2 \sum_{j=1}^{m}\sum_{k=1}^{m} \{\Delta x_k \delta_{jl} + \Delta x_j \delta_{kl}\}$$

which can be reduced to

$$\frac{\partial |\varepsilon|^2}{\partial x_l} = -2V_l + \sum_{k=1}^{m} M_{lk}\Delta x_k + \sum_{j=1}^{m} M_{jk}\Delta x_j$$
$$+ \theta^2 \sum_{k=1}^{m} \Delta x_k + \theta^2 \sum_{j=1}^{m} \Delta x_j$$

Since M is symmetric it follows that

$$\frac{\partial |\varepsilon|^2}{\partial x_l} = -2V_l + 2\sum_{j=1}^{m} M_{lj}\Delta x_j + 2\theta^2 \sum_{j=1}^{m} \Delta x_j$$

or

$$\frac{\partial |\mathcal{E}|^2}{\partial x} = -2\underline{V} + 2\underline{M}\,\Delta x + 2\theta^2\,\underline{\Delta x} \quad .$$

Combining terms leads to

$$\frac{\partial |\mathcal{E}|^2}{\partial x} = -2\underline{V} + 2\,(\underline{M} + \theta^2\,\underline{I})\,\underline{\Delta x} \quad .$$

Setting the expression equal to zero yields

$$(\underline{M} + \theta^2\,\underline{I})\,\underline{\Delta x} = \underline{V}$$

or finally

$$(\underline{A}^T\underline{A} + \theta^2\underline{I})\,\underline{\Delta x} = \underline{A}^T\,\underline{\Delta T} \quad . \qquad (10)$$

Since $\theta^2$ will always be nonzero, the inverse of $(\underline{A}^T\underline{A} + \theta^2\underline{I})$ exists, and

$$\underline{\hat{\Delta x}} = (\underline{A}^T\underline{A} + \theta^2\underline{I})^{-1}\,\underline{A}^T\,\underline{\Delta T} \quad .$$

Comparing this expression with expression (5) shows that the DLS approach, relative to the CLS approach, introduces a bias, given by

$$E\{\underline{\hat{\Delta x}}\} = \underline{\Delta x}\,[\underline{I} - \theta^2\underline{I}\,(\underline{A}^T\underline{A} + \theta^2\,\underline{I})^{-1}]$$

into the solution by the use of the damping factor. As $\theta^2$ is always positive the bias is always negative, and adjustments to initial estimates will be less for the DLS approach than for the CLS approach. The DLS approach alters the eigenvalue spectrum of the original matrix $\underline{A}$ to suppress large correction vector components arising from small eigenvalues. This can be seen by applying the fundamental decomposition theorem to $\underline{A}$ in expression (10), giving

$$(\underline{V}\underline{\Lambda}^2\underline{V}^T + \theta^2\underline{I})\,\underline{\Delta X} = \underline{V}\underline{\Lambda}\,\underline{U}^T\,\underline{\Delta T} \quad .$$

Premultiplying the above expression by $\underline{V}^T$ gives

$$(\underline{\Lambda}^2\underline{V}^T + \theta^2\underline{V}^T)\,\underline{\Delta X} = \underline{\Lambda}\,\underline{U}^T\,\underline{\Delta T}$$

leading to

$$(\underline{\Lambda}^2 + \theta^2\underline{I})\,\underline{V}^T\underline{\Delta X} = \underline{\Lambda}\,\underline{U}^T\,\underline{\Delta T} \quad .$$

It follows that

$$\underline{V}^T\underline{\hat{\Delta X}} = (\underline{\Lambda}^2 + \theta^2\underline{I})^{-1}\underline{\Lambda}\,\underline{U}^T\underline{\Delta T}$$

and premultiplying by $\underline{V}$ gives

$$\underline{\hat{\Delta X}} = \underline{V}\,[(\underline{\Lambda}^2 + \theta^2\underline{I})^{-1}\underline{\Lambda}]\,\underline{U}^T\underline{\Delta T}$$

which is the damped least squares solution in the eigenspace. The quantity in brackets is a diagonal matrix whose typical element is

$$\lambda_i / (\lambda_i^2 + \theta^2) \quad .$$

Figure (4) (Crosson, 1976) is an illustration of the change component as a function of the eigenvalue size. From the figure it can be seen that for classical least squares the change component increases without bound as $\lambda$ decreases. Conversely, for the damped least squares method, the change component is smoothly tapered to zero as $\lambda$ decreases, with the degree of tapering dependent upon the size of $\theta^2$. Thus, for the damped least squares, the inverse always exists, even when zero eigenvalues are present. In addition, further advantages of the damped least squares method are that the eigenvector/eigenvalue decomposition of $\underline{A}$ need not be performed explicitly and a decision regarding the rank of matrix $\underline{A}$ need not be made.

Use of the damped least squares approach may be compared with the decomposition approach presented by Wiggins (1972), in which a sharp cutoff criterion is used to truncate the eigenvalue spectrum and thus avoid instability. Both methods cause a modification of the resolving matrix,

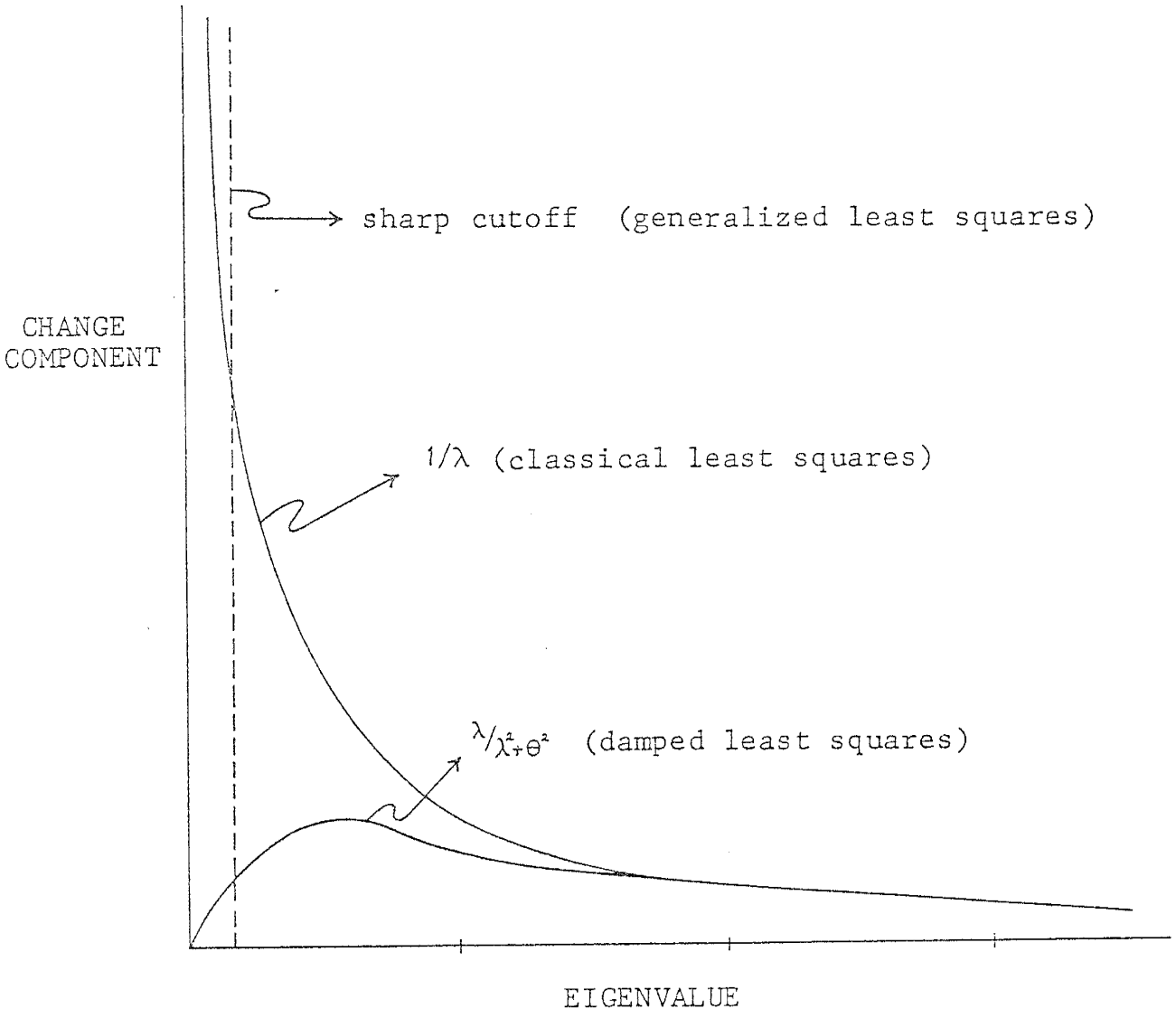



Figure 4. Schematic representation of a change component as a function of the eigenvalue size for the classical squares, damped least squares, and generalized least squares (from Crosson, 1976a).

so that it is no longer an identity matrix as in the case of classical least squares. Each estimated parameter, in fact, represents a linear combination of the true parameters (i.e., smoothed version of the true model). For both cases, when the eigenvalue spectrum is shaped to achieve a stable inverse, there is a tradeoff between resolution and estimate variance which is controlled by the particular shaping adopted.

The selection of $\theta^2$ for the damped least squares approach is important in controlling the resolving and variance characteristics of the inversion procedure. As $\theta^2$ increases, the variance values decrease as the rows of $\underline{R}$

$$\underline{R} = \underline{V}\left[(\underline{\Lambda}^2 + \theta \underline{I})^{-1}\underline{\Lambda}^2\right]\underline{V}^T \qquad (11)$$

become less delta-like (Crosson, 1976). Therefore, it is desirable to choose $\theta^2$ as small as possible to achieve maximum resolution, yet large enough to achieve appropriate stability and variance estimates. Crosson (1976) found that an appropriate value is easily found by trial and error to be the minimum value consistent with a stable inverse.

Error Analysis

Ideally, the least squares solution results in a set of residuals which are randomly (and normally) distributed about the "best" model. These residuals can be considered to be a measure of the errors in the observations. If an a priori estimate of the possible error associated with a given observation can be made, then that observation should be weighted accordingly, to prevent 'pulling' the solution when a large residual is present.

The assumption is made that each measurement is independent, and that repeated measurements are "normally" distributed about a mean value with a "standard deviation" $\sigma$.

If y is a random variable, the mean, $\bar{y}$, or expectation E of y, is given by

$$\bar{y} = E(y) \quad .$$

The variance ($\sigma^2$) of y is given by

$$\sigma_y^2 = E\{(y-\bar{y})^2\}$$

and the covariance between two distinct random variables, x

and y, is defined by

$$C_{xy} = E\left\{(x-\bar{x})(y-\bar{y})\right\} \quad .$$

For a large number of attempts to measure the variable y, it would be found that 68% would fall between $(y - \sigma)$ and $(y + \sigma)$, and about 95% of the measurements would fall between $(y - 2\sigma)$ and $(y + 2\sigma)$.

If the mean values of a set of random variables such as $\underline{\hat{x}}$ are zero, as is the ideal case for residuals and correction vector components, then the corresponding cross product array is given by

$$\underline{\hat{X}}\,\underline{\hat{X}}^T = \begin{bmatrix} \hat{X}_1\hat{X}_1 & \hat{X}_1\hat{X}_2 \cdots \\ \vdots & \\ \hat{X}_m\hat{X}_1 & \end{bmatrix} \quad .$$

The covariance array for all estimates is then given by

$$C_{\underline{\hat{x}}\underline{\hat{x}}} = E\left\{\underline{\hat{X}}\,\underline{\hat{X}}^T\right\} = \begin{bmatrix} E\{\hat{X}_1\hat{X}_1\} & E\{\hat{X}_1\hat{X}_2\} \cdots \\ \vdots & \end{bmatrix}$$

where the expectation operator can be viewed as operating on each element in the array independently.

If $\underline{y}$ is the set of observations then $\hat{\underline{x}} = \underline{H}\underline{y}$ and the transpose is given by

$$\hat{\underline{X}}^T = (\underline{H}\underline{y})^T = \underline{y}^T \underline{H}^T \quad .$$

Forming

$$\hat{\underline{X}}\hat{\underline{X}}^T = \underline{H}\underline{y}\underline{y}^T\underline{H}^T$$

leads to the covariance array

$$\underline{C}_{\hat{\underline{X}}\hat{\underline{X}}} = E\{\hat{\underline{X}}\hat{\underline{X}}^T\} = E\{\underline{H}\underline{y}\underline{y}^T\underline{H}^T\} \ ,$$

but the elements are constant coefficients and only y, the observation, are random variables. Thus, the expectation operator should operate only on $\underline{y}\underline{y}^T$ leading to

$$\underline{C}_{\hat{\underline{X}}\hat{\underline{X}}} = \underline{H}\, E\{\underline{y}\underline{y}^T\}\, \underline{H}^T \quad .$$

If the observations are independent and uncorrelated random variables with constant variance then

$$E\{\underline{y}\underline{y}^T\} = \underline{C}_{\underline{y}\underline{y}^T} = \sigma_y^2\, \underline{I}$$

and

$$\underline{C}_{\hat{\underline{X}}\hat{\underline{X}}} = \sigma_Y^2 \, \underline{H}\underline{H}^T \quad .$$

If the data have been statistically weighted so that they have unit variance, $\sigma_Y = 1$, then

$$\underline{C}_{\hat{\underline{X}}\hat{\underline{X}}} = \underline{H}\underline{H}^T \quad .$$

The variance/covariance values so obtained give a simple, standard measure of the uncertainties of the estimated parameters with the square root of the diagonal elements of $\underline{C}_{\hat{\underline{X}}\hat{\underline{X}}}$ being the standard deviations associated with the estimated parameters.

In order to obtain a $\sigma_Y^2 = 1$, an a priori estimate of the possible error, $\sigma_i$ , associated with the ith observation is used to weight that observation by

$$\frac{Y_i}{\sigma_i} = \sum_k \frac{A_{ik}}{\sigma_i} X_k$$

leading to

$$Y_i' = \sum A_{ik}' X_k \quad .$$

Problem Formulation

Having developed the general form of the inversion schemes to be used, the task now becomes one of formulating expression (3) in terms of differing velocity models and observed travel times. The initial formulation to be developed will be for the simultaneous location of 40 events and the determination of a representative half-space velocity for the volume beneath the recording array.

For the development of this formulation, the following definitions are necessary:

$(x,y,z) \equiv$ station location

$(X,Y,Z) \equiv$ event location

$T \equiv$ origin time

$t \equiv$ arrival time

and $V \equiv$ half-space velocity.

An expression involving these definitions and relating the travel distance to the velocity and the travel time is given by

$$\left[(x-X)^2 + (y-Y)^2 + (z-Z)^2\right]^{1/2} = V(t-T) . \qquad (12)$$

If an initial estimate of x is made for the unknown X parameter, the correction to the initial estimate is then defined as

$$\Delta X = X - X_o \quad .$$

The unknown parameter X is represented as the sum of initial estimate x and the unknown correction $\Delta x$,

$$X = \Delta X + X_o$$

Similarly, the other unknowns can then be written as

$$Y = \Delta Y + Y_o$$
$$Z = \Delta Z + Z_o$$
$$T = \Delta T + T_o$$
$$V = \Delta V + V_o$$

Substituting these into expression (12) gives

$$\left[(x-\Delta X-X_o)^2 + (y-\Delta Y-Y_o)^2 + (z-\Delta Z-Z_o)^2\right]^{1/2} = (\Delta V+V_o)(t-\Delta T-T_o) \quad .$$

Expanding this expression, combining terms and ignoring those terms involving multiple $\Delta$'s leads to

$$(X_o-X)\Delta X + (Y_o-Y)\Delta Y + (Z_o-Z)\Delta Z - V_o T^2 \Delta V + V_o^2 T \Delta T$$
$$= .5\left[-(x-X_o)^2 - (y-Y_o)^2 - (z-Z_o)^2 + V_o T^2\right]$$

where T is the travel time between the station and event based on T . Dividing both sides of the expression by $v_o^2 T$ leads to

$$-\frac{X-X_o}{V_o^2 T}\Delta X - \frac{Y-Y_o}{V_o^2 T}\Delta Y - \frac{Z-Z_o}{V_o^2 T}\Delta Z - \frac{T}{V_o}\Delta V + \Delta T$$

$$= .5\left[-\frac{[(X-X_o)^2+(Y-Y_o)^2+(Z-Z_o)^2]}{V_o^2 T} + T\right] . \qquad (13)$$

If the travel time residual is defined as

$$R \equiv T - T_o$$

where $T_o$ is the travel time based on the initial model, then the right-hand side of expression (13) can be simplified as

$$.5\left[-\frac{(T-R)^2}{T} + T\right] \approx T - T_o = R .$$

A general form of the expression (13) for event j recorded at station i is then given by

$$R_{ij} = \left(\frac{\partial T}{\partial x}\right)_{ij}\Delta x_j + \left(\frac{\partial T}{\partial y}\right)_{ij}\Delta y_j + \left(\frac{\partial T}{\partial z}\right)_{ij}\Delta z_j$$

$$+ \left(\frac{\partial T}{\partial v}\right)_{ij}\Delta V + \Delta T + \varepsilon_{ij} \qquad (14)$$

The derivatives of travel time with respect to the x, y, and z coordinates and velocity are calculated for the initial model as

$$\left(\frac{\partial T}{\partial x}\right)_{ij} = -\left(x_i - x_{oj}\right) / V_o^2 T_{ij}$$

$$\left(\frac{\partial T}{\partial y}\right)_{ij} = -\left(y_i - y_{oj}\right) / V_o^2 T_{ij}$$

$$\left(\frac{\partial T}{\partial z}\right)_{ij} = -\left(z_i - z_{oj}\right) / V_o^2 T_{ij}$$

$$\left(\frac{\partial T}{\partial v}\right)_{ij} = -T_{ij} / V_o$$

The terms $\Delta x_j$, $\Delta y_j$, $\Delta z_j$, and $\Delta T_j$ are corrections to the source parameters of the jth event. The term $\Delta v$ is the correction to the single path parameter of the problem.

A reexamination of expression (2)

$$T_i^\circ - F_i\left(\underline{x}^\circ\right) = \sum_k \frac{\partial F_i\left(x_k\right)}{\partial x_k} \Delta x_k + \varepsilon_{ii} \qquad (2)$$

shows it to be a more general form of expression (14). Therefore, a set of n arrivals for q events recorded at p

stations can be represented in matrix notation by expression (3)

$$\underline{\Delta T} = \underline{A}\,\underline{\Delta x} \quad , \qquad (3)$$

where $\underline{\Delta T}$ is an n-dimensional column vector of the travel time residuals, $\underline{A}$ is n x (4q + 1) partial derivative matrix, and $\underline{\Delta x}$ is a (4q + 1) dimensional column vector of the unknowns.

The system of equations in expanded matrix form is set forth as

$$\begin{bmatrix} \Delta T_{11} \\ \vdots \\ \Delta T_{1p} \\ \Delta T_{21} \\ \vdots \\ \Delta T_{2p} \\ \vdots \\ \Delta T_{q1} \\ \vdots \\ \Delta T_{qp} \end{bmatrix} = \begin{bmatrix} \frac{\partial T_{11}}{\partial x_{11}} \cdots \frac{\partial T_{11}}{\partial x_{41}} & & & \frac{\partial T_{11}}{\partial v} \\ \vdots & & & \vdots \\ \frac{\partial T_{1p}}{\partial x_{11}} \cdots \frac{\partial T_{1p}}{\partial x_{41}} & & & \frac{\partial T_{1p}}{\partial v} \\ & \frac{\partial T_{21}}{\partial x_{12}} \cdots \frac{\partial T_{21}}{\partial x_{42}} & & \\ & \vdots & & \\ & \frac{\partial T_{2p}}{\partial x_{12}} \cdots \frac{\partial T_{2p}}{\partial x_{42}} & & \\ & & & \\ & & & \\ & & & \frac{\partial T_{qp}}{\partial v} \end{bmatrix} \begin{bmatrix} \Delta x_{11} \\ \vdots \\ \Delta x_{41} \\ \Delta x_{12} \\ \vdots \\ \Delta x_{42} \\ \Delta x_{13} \\ \vdots \\ \Delta x_{43} \\ \vdots \\ \Delta x_{4q} \\ \Delta v \end{bmatrix}$$

The right-hand column of A, consisting of the partial derivatives of travel time with respect to the path parameter v, couple across individual events, since path parameters are common to all events. If this column were zero, the system would revert to q separate hypocenter location problems.

Obtaining a suitable inverse for A, and the resulting solution, will be discussed in a later section in which the program is developed and applied to the data.

In addition to finding a single representative velocity, a formulation was developed for a multiple block system. In this formulation expression (14) becomes

$$R_{ij} = \left(\frac{\partial T}{\partial x}\right)_{ij} \Delta x_j + \left(\frac{\partial T}{\partial y}\right)_{ij} \Delta y + \left(\frac{\partial T}{\partial z}\right)_{ij} \Delta z_j + \sum_k T_{ij}^{k} F_k + \Delta T_j + \varepsilon_{ij}$$

where the fourth term on the right-hand side has become $\sum_k T_{ij}^{(k)} F_k$. This term expresses the travel time variation due to the perturbation of wave slowness (Aki and Lee, 1976). $F_k$ represents the fractional perturbation of slowness in

block k from the initial value $v_o^{-1}$

$$F_k = \frac{(V^{-1} - V_o^{-1})}{V_o^{-1}} \approx -\frac{V - V_o}{V_o}$$

Along a given ray path (i,j) connecting the ith station with the initial location of the jth event the travel time $T_{ij}^{(k)}$ spent within each penetrated block is determined. Thus $T_{ij}^{(k)}$ is the time spent in block k by the ray (i,j), and the summation is made over all blocks penetrated by ray (i,j).

The third formulation used in this study investigates the possibility of an azimuthal velocity distribution within the volume beneath the array. The form of the velocity function used in this approach is given by

$$V(\phi) = A + B\cos 2\phi + C\sin 2\phi + D\cos 4\phi + E\sin 4\phi$$

where $\phi$ is the azimuth (Backus, 1965). Returning to expression (11), the right-hand side may be expanded to include an azimuthal velocity function:

$$(\Delta V(\phi) + V_o(\phi))(t - \Delta T - T_o) = [(\Delta A + A_o) + (\Delta B + B)\cos 2\phi + (\Delta C + C_o)\sin 2\phi + (\Delta D + D_o)\cos 4\phi + (\Delta E + E_o)\sin 4\phi] \times (t - \Delta T - T_o)$$

where

$$\Delta V(\phi) = \Delta A + \Delta B \cos 2\phi + \Delta C \sin 2\phi + \Delta D \cos 4\phi + \Delta E \sin 4\phi$$

As before, expanding, combining and ignoring terms involving more than one $\Delta$ leads to

$$\Delta X (X_o - X) + \Delta Y (Y_o - Y) + \Delta Z (Z_o - Z) - \Delta V(\phi) V_o(\phi) T^2 + V_o(\phi) T \Delta T = .5 \left[ (X - X_o) - (Y - Y_o) - (Z - Z_o) + V_o(\phi)^2 T^2 \right] .$$

Dividing this expression by $v_o(\phi)^2 T$ and expanding the term involving $\Delta v(\phi)$ leads to

$$-\frac{X - X}{V_o(\phi)^2 T} \Delta X - \frac{Y - Y}{V_o(\phi)^2 T} \Delta Y - \frac{Z - Z}{V_o(\phi)^2 T} \Delta Z - \frac{T}{V_o(\phi)} \Delta A$$

$$-\frac{T \cos 2\phi}{V_o(\phi)} \Delta B - \frac{T \sin 2\phi}{V_o(\phi)} \Delta C - \frac{T \cos 4\phi}{V_o(\phi)} \Delta D$$

$$-\frac{T \sin 4\phi}{V_o(\phi)} \Delta E + \Delta T = R$$

where R, the travel time residual, is as defined above.

The general form of expression (14) for the azimuthal velocity case for and event j recorded at station i is then given by

$$R_{ij} = \left(\frac{\partial T}{\partial x}\right)_{ij} \Delta x_j + \left(\frac{\partial T}{\partial y}\right)_{ij} \Delta y_j + \left(\frac{\partial T}{\partial z}\right)_{ij} \Delta z_j$$

$$+ \left(\frac{\partial T}{\partial A}\right)_{ij} \Delta A + \left(\frac{\partial T}{\partial B}\right)_{ij} \Delta B + \left(\frac{\partial T}{\partial C}\right)_{ij} \Delta C$$

$$+ \left(\frac{\partial T}{\partial D}\right)_{ij} \Delta D + \left(\frac{\partial T}{\partial E}\right)_{ij} \Delta E + \Delta T + \varepsilon_{ij} \quad .$$

The derivatives of travel time with respect to the x, y, and z coordinates are as given before. Those associated with the components of the azimuthal velocity are calculated for the initial model as

$$\left(\frac{\partial T}{\partial A}\right)_{ij} = -\frac{T}{V_o(\phi)}, \left(\frac{\partial T}{\partial B}\right)_{ij} = -\frac{T}{V_o(\phi)} \cos 2\phi$$

$$\left(\frac{\partial T}{\partial C}\right)_{ij} = -\frac{T}{V_o(\phi)} \sin 2\phi \ , \ \left(\frac{\partial T}{\partial D}\right)_{ij} = -\frac{T}{V_o(\phi)} \cos 4\phi$$

$$\left(\frac{\partial T}{\partial E}\right)_{ij} = -\frac{T}{V_o \phi} \sin 4\phi$$

with their associated $\Delta$'s being corrections to the path parameters of the problem.

Having determined the form of the $\underline{A}$ matrix for the three velocity models under investigation, the problem becomes one of finding suitable inverses for these matrices so that the appropriate correction vectors may be found and velocity models obtained.

## Velocity Modeling

In implementing the theory described above for solving the joint velocity-hypocenter model problem, computer programs were written for the DEC-20 computer (Appendix 7). In addition to the velocity parameters and source parameters, initially a set of station corrections were included in the list of parameters to estimate.

In addition to attempting to model real data, a sequence of numerical tests on generated data was undertaken to determine the ability of the differing approaches to model the data given the existing source distribution and assumed data error. The results obtained in these tests provided some insight into the uncertainties expected when working with real data, as well as guidance in the selection of control parameters. Test data (P-arrival times) were calculated for prescribed velocity models using the event and station distributions of the real data (see section Testing with Artificial Data).

### Station Corrections and Half-Space Velocity

One of the problems encountered in this study was that many of the stations were on unknown thicknesses of relatively low velocity material. To compensate for these

near-surface effects, relative station corrections (adjustments to the arrival times) for each of the 25 stations were found. Only relative station corrections can be determined, since the same constant can be added to, or subtracted from, all station corrections without affecting the results. The initial estimates of station corrections for 14 of the 25 stations (Appendix 3) used in the iterative procedure were obtained from explosion sources located approximately four kilometers SW of station "WT" (A. R. Sanford, personal communication). Corrections for the remaining 11 stations were initially assumed to be zero. These initial estimates of the station corrections were modified in successive steps in an effort to reduce the mean travel-time residual associated with each station. The final set of station corrections varied between $\pm 0.25$ seconds, with those stations located on Precambrian basement generally having large negative values, and those stations located on thick sections of low-velocity valley fill or caldera deposits generally having large positive values.

The first step in refining the initial estimates of the station corrections was to use the classical least squares approach to simultaneously locate in time and space 40 events (160 unknowns), while assuming a constant half-space velocity of 5.84 km/sec. This value for the half-space velocity was chosen because it was the best estimate

available from earlier attempts to model arrival time data of local events. Each run consisted of three iterations, after which the travel-time residuals associated with the resulting model were then examined and appropriate adjustments to the set of stations corrections made. This procedure was repeated until the changes in the station corrections so determined were small, i.e., on the order of .01 seconds. Using the resulting station corrections as initial estimates, the same procedure was repeated while allowing both the half-space velocity and station corrections to vary. The resulting half-space velocity obtained from this approach was 5.84 $\pm$.027(s.d.) km/sec, with the final set of station corrections and intermediate results presented in Appendix 3.

Independent depth information, based on S-to-S reflections from the upper surface of an extensive magma body at a depth of 18 to 19 kilometers beneath the array (Rinehart, 1979), was available for 20 of the 40 events used. To take advantage of this additional information, a second approach, using eigenvalue/eigenvector decomposition (Jackson, 1972), was used to control large changes in the "known" depths. Depths were weighted by *a priori* estimates (Jackson, 1972) of $\pm$1.0 kilometer for the "known" depths (Rinehart, 1979), and $\pm$3.0 kilometers for depths for which there was no *a priori* information. Given these *a priori*

weights, eigenvalues and eigenvectors associated with those depths which varied beyond prescribed limits ($\pm$3km) were eliminated. In addition, to maintain numerical stability, those eigenvalues with a value less than one-hundredth of the largest eigenvalue were also eliminated. The result of these measures was to constrain the "known" depths to within 3 kilometers of their initial estimates. As before, a constant half-space velocity of 5.84 km/sec was used until the changes in the station corrections were small, at which time the velocity as well as the station corrections were allowed to vary. The resulting half-space velocity obtained from this approach was 5.85 $\pm$.018(s.d.) km/sec, with the final set of station corrections presented in Table 1 and intermediate results in Appendix 3. These results are comparable to those of the first approach, with only relatively small modifications to the initial estimates obtained from explosion data being necessary.

In order to test the approaches used, theoretical travel times were determined for a hypothetical 5.85 km/sec half-space velocity model using the event and station distribution of the real data set. To approximate real data with observational errors, normally distributed noise, scaled by the observational weighting assumed for the real data, was applied to the synthetic arrivals. Finally, erroneous station corrections were applied to the synthetic

data set, with the magnitude of these corrections being similar to the adjustments made to the initial estimates of the station corrections associated with the real data. An attempt was then made to determine these erroneous station corrections by applying the methods outlined above, with the results being presented in Appendix 4.

The results of the testing (Appendix 4) indicate that the decomposition approach, with the inclusion of the additional depth information, is the better of the two basic approaches as it did a better job of defining the applied station corrections. In addition, it is not unreasonable to infer from these results an uncertainty in the station corrections of a few hundredths of a second for those stations where more than three arrivals are available.

When comparing the results associated with the real and synthetic data sets, the effects of differing a priori knowledge of the solutions should be considered. It should be noted that the depths for all events of the test data were known while only 20 of a total of 40 depths were known for the real data. In addition, the initial estimates of the locations for the synthetic data set were determined by applying noise to the correct locations while for the real data set the best available estimate was used. The applied noise was of a normal distribution scaled by the appropriate parameter weight (Appendix 1). It is assumed that the

differences between the approaches used on the real data and on the synthetic data were of little consequence and did not affect the resulting comparison.

The resulting station corrections obtained from using the decomposition approach on real data (Table 1) provided the necessary adjustments to the arrival times to account for near-surface effects. With near-surface control, additional refinements in the velocity model could be made. The resulting model (half-space velocity, source parameters and station corrections) was subsequently used as the initial model for all of the following inversions. This choice for an initial model was convenient, but it should be noted that further experimentation indicated that the resultant models were generally independent of the starting models when the calculations were stable and convergent.

The initial step in refining the half-space velocity model was to determine if the P-wave velocity within the area of interest is azimuthally dependent. Subsequent refinements involved subdividing the area of interest into blocks and determining a representative average velocity for each of these volumes. The following is a description of these refinements and the resulting velocity models obtained.

Azimuthal Velocity Model

The determination of a representative azimuthal velocity distribution for the volume beneath the array presented a major problem. If an azimuthal velocity distribution exists, accurate station corrections could be determined for only those stations with arrivals well distributed in azimuth, implying possible errors in the set of station corrections previously determined. However, trial runs showed that accurate station corrections for 17 stations, centrally located within the array, could be determined, as these stations had arrivals that were well distributed in azimuth. The real data set was then modified to include only those events for which five or more arrivals were recorded by these stations. The resulting modified data set was comprised of 132 arrivals associated with 23 events.

In order to learn if the resulting data set provided sufficient information for resolving an azimuthal velocity distribution, a synthetic data set, constructed for the same travel path distribution and a prescribed azimuthal velocity distribution, was inverted using the classical least squares approach. The resulting velocity model, uncertainties, and true velocity model are presented in Table 2. In addition, Table 2 also presents the uncertainties in terms of the uncertainty in the model as a function of ten degree

increments of azimuth. The deviation of the resulting model from a half-space velocity (5.85 km/sec), due to the azimuthal terms of the calculated velocity function, is displayed graphically in Fig. 5. An examination of Fig. 5 and Table 2 shows that the resulting model does include the true solution (at one standard deviation). Therefore, it can be concluded that there is sufficient information in the reduced data set to determine, at acceptable levels of uncertainty, an azimuthal velocity distribution by the CLS approach.

The CLS approach was then applied to the 132 arrivals of the modified real data set in order to determine the 92 source parameters and the 5 model parameters. The resulting model and the associated uncertainties, at ten degree intervals of azimuth, are presented in Table 3. The deviation of the resulting model from a half-space velocity (5.85 km/sec), due to the azimuthal terms of the resulting velocity model, is presented in Fig. 6. An examination of Fig. 6 and Table 3 shows that the azimuthal variations are not significantly different from the half-space velocity of 5.85 km/sec obtained by the classical inversion of the total data set. In addition, the maximum deviation from a half-space velocity model, at two standard deviations, for any azimuth is 0.08 km/sec.

TABLE 2. AZIMUTHAL VELOCITY MODEL (SYNTHETIC DATA)

TRUE VELOCITY FUNCTION $\Rightarrow$ $V(\phi) = 5.85 + .1\cos 2\phi$

CALCULATED VELOCITY

$$V(\phi) = A + B\cos 2\phi + C\sin 2\phi + D\cos 4\phi + E\sin 4\phi$$

$A = 5.753 \pm .079$ (s.d.) km/sec

$B = .085 \quad .017$

$C = .006 \quad .023$

$D = .011 \quad .011$

$E = .004 \quad .013$

| AZIMUTH (Ø) | CALCULATED VARIATIONS IN VELOCITY (km/sec) (due to Ø) | TRUE VARIATIONS IN VELOCITY (km/sec) (due to Ø) |
|---|---|---|
| 0 | 0.10 ±.03 (s.d.) | 0.10 |
| 10 | 0.09 .04 | 0.09 |
| 20 | 0.07 .04 | 0.08 |
| 30 | 0.05 .04 | 0.05 |
| 40 | 0.01 .04 | 0.02 |
| 50 | -0.02 .04 | -0.02 |
| 60 | -0.05 .04 | -0.05 |
| 70 | -0.06 .04 | -0.08 |
| 80 | -0.07 .04 | -0.09 |
| 90 | -0.07 .03 | -0.10 |
| 100 | -0.07 .04 | -0.09 |
| 110 | -0.06 .04 | -0.08 |
| 120 | -0.05 .04 | -0.05 |
| 130 | -0.03 .04 | -0.02 |
| 140 | 0.00 .04 | 0.02 |
| 150 | 0.03 .04 | 0.05 |
| 160 | 0.06 .04 | 0.08 |
| 170 | 0.08 .04 | 0.09 |

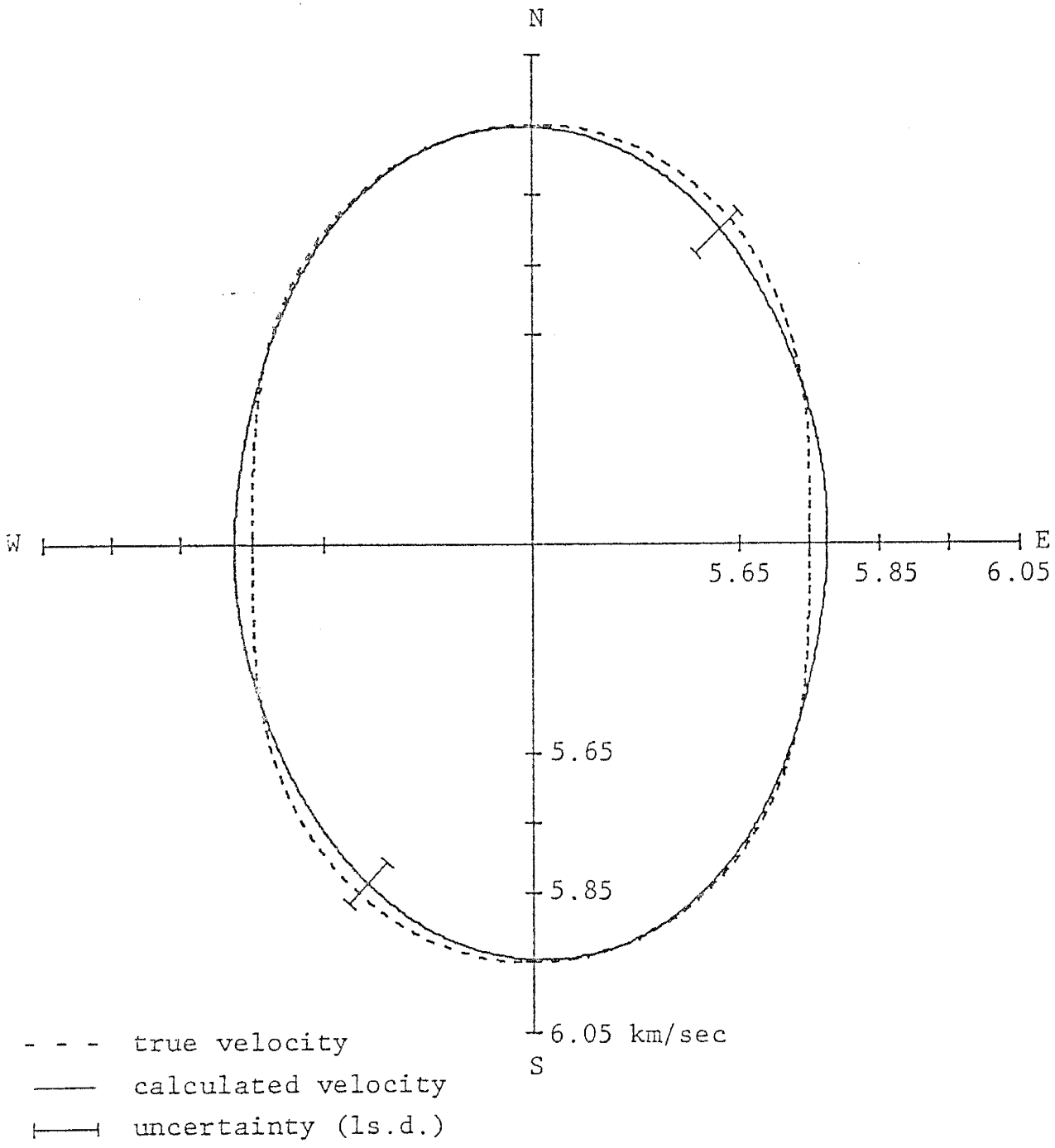



Figure 5. Graphical representation of the azimuthal velocity function obtained by CLS inversion of the synthetic data.

TABLE 3. AZIMUTHAL VELOCITY MODEL (REAL DATA)

$$V(\emptyset) = A + B\cos 2\emptyset + C\sin 2\emptyset + D\cos 4\emptyset + E\sin 4\emptyset$$

$A = 5.736 \pm .070$ (s.d.) km/sec

$B = -.003 \quad .016$

$C = -.012 \quad .022$

$D = \quad .002 \quad .011$

$E = -.029 \quad .013$

| AZIMUTH (Ø) | VARIATIONS IN VELOCITY (km/sec) (due to Ø) |
|---|---|
| 0 | 0.00 ±.03 (s.d.) |
| 10 | -0.02 .04 |
| 20 | -0.04 .04 |
| 30 | -0.04 .04 |
| 40 | -0.02 .04 |
| 50 | 0.00 .04 |
| 60 | 0.02 .04 |
| 70 | 0.02 .04 |
| 80 | 0.02 .04 |
| 90 | 0.00 .03 |
| 100 | -0.02 .04 |
| 110 | -0.02 .04 |
| 120 | -0.02 .04 |
| 130 | 0.00 .04 |
| 140 | 0.02 .04 |
| 150 | 0.03 .04 |
| 160 | 0.04 .04 |
| 170 | 0.02 .04 |

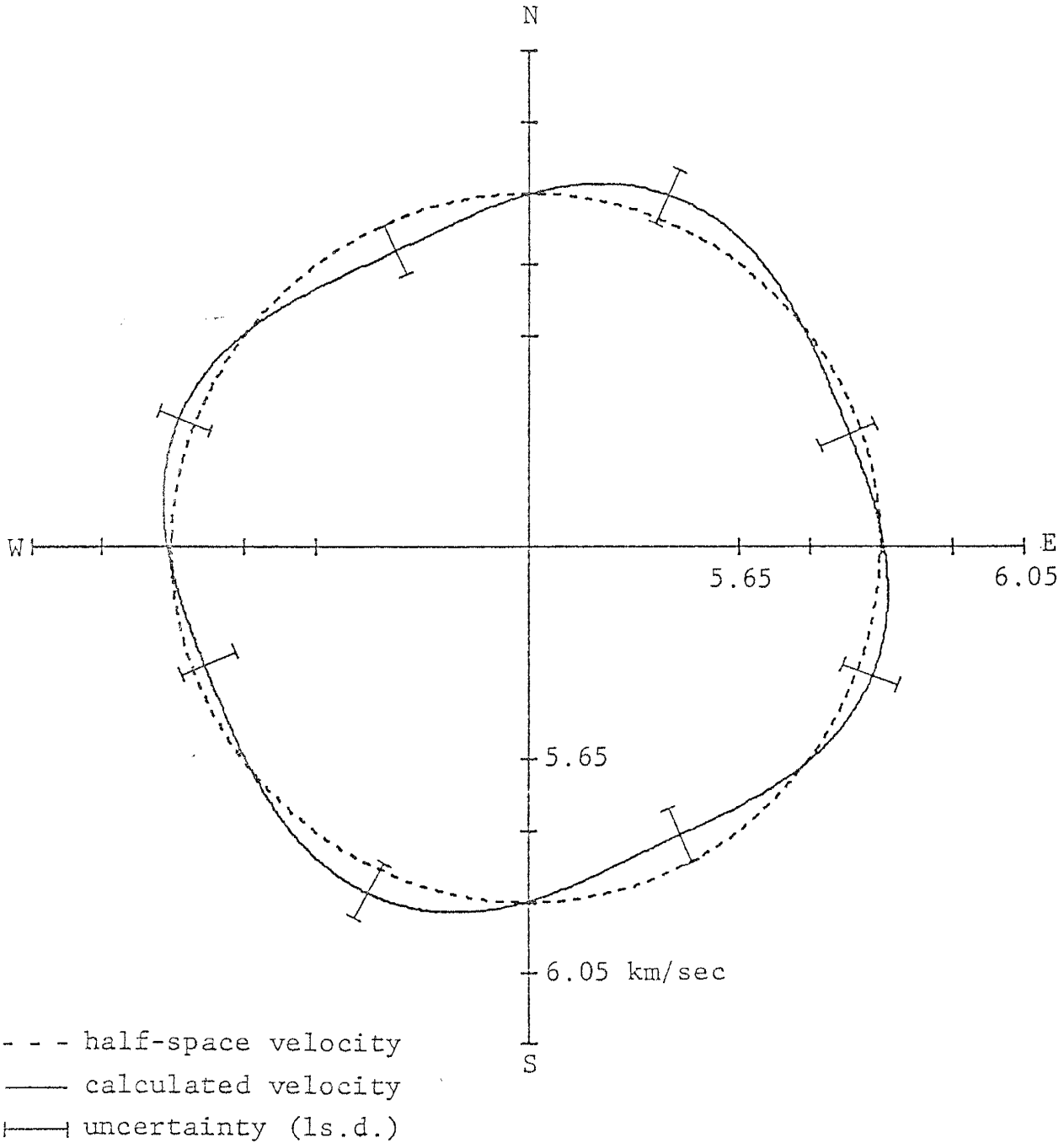



Figure 6. Graphical representation of the deviation of the calculated azimuthal velocity function (real data) from a half-space velocity.

From these results, it is concluded that there may exist a small azimuthal velocity distribution, with a maximum variation of less than one-tenth of a km/sec. As this variation is within the noise of the data, it shall be assumed that the effect of the azimuthal velocity distribution is of second order, and can therefore be ignored in subsequent calculations. In addition, due to the lack of a significant azimuthal dependence of the velocity, all station corrections previously determined will be used in obtaining subsequent models.

## Thirty-Six Block Model

The next step in the modeling procedure was to divide the volume of interest into blocks (right rectangular prisms) one-tenth of a degree on a side at the surface and to a depth of the deepest ray penetrating each block. It must be noted that the position of these boundaries may influence the final model. However, after many trials with differing block configurations, it was demonstrated that differing configurations produced statistically equivalent solutions at uncertainties of two standard deviations. Aki et al. (1977) attempted to reduce the influence of the block boundaries by averaging two models in which the blocks were displaced diagonally by one-half block length. This

introduced a smoothing of the velocities of the differing configurations, which they claimed was an improved velocity model, suitable for contouring, with the effect of the boundaries reduced. However, the resolution and uncertainty information of the differing block configurations could not be smoothed as the velocities were. Therefore, since differing configurations produced statistically equivalent solutions, and since a smoothed velocity model would not have the resolution and uncertainty information considered necessary for interpretation, smoothing of differing block configurations in the sense of Aki et al. (1977) was not undertaken in this study.

The resulting 6 x 6 grid (Fig. 7) represents (relative to the half-space model) an increase in the number of unknown velocity parameters from 1 to 36 and an increase in the total number of unknown parameters from 161 to 196. When referring to a particular block its location within the gridwork is referenced first by its row and then by its column. In later block configurations a third number is used to denote the layer in which the block is located.

The initial attempt to model the data by means of a CLS approach demonstrated that this technique was no longer stable for a model of this configuration and complexity. It was therefore necessary to use modified forms of this inversion procedure (i.e., GLS and DLS) to obtain stable models.

Generalized Least Squares: The GLS procedure was applied to the 262 travel-time residuals comprising the data set. After several trials it was determined that keeping 175 of the 196 eigenvalues and associated eigenvectors produced a stable inverse with an acceptable balance between uncertainties and resolution. If care is not taken in obtaining a balance, the ensuing model may have unnecessarily large uncertainties resulting from an effort to model features poorly defined by the data. Since the removal of eigenvalues leads to solutions for which both the resolution and uncertainties of the associated parameters are decreased, a point of acceptable trade-off must be found. Given the assumed accuracy of the observations and the dimensions of the blocks, one has a lower limit on the uncertainty. Using this lower limit in conjunction with desired resolvability, the optimum number of eigenvalues to retain can be determined. The resulting velocity model for this block configuration and approach is presented in Fig. 7. In addition to the average velocity of each block, an estimate of the uncertainty (1 standard deviation) is also presented.

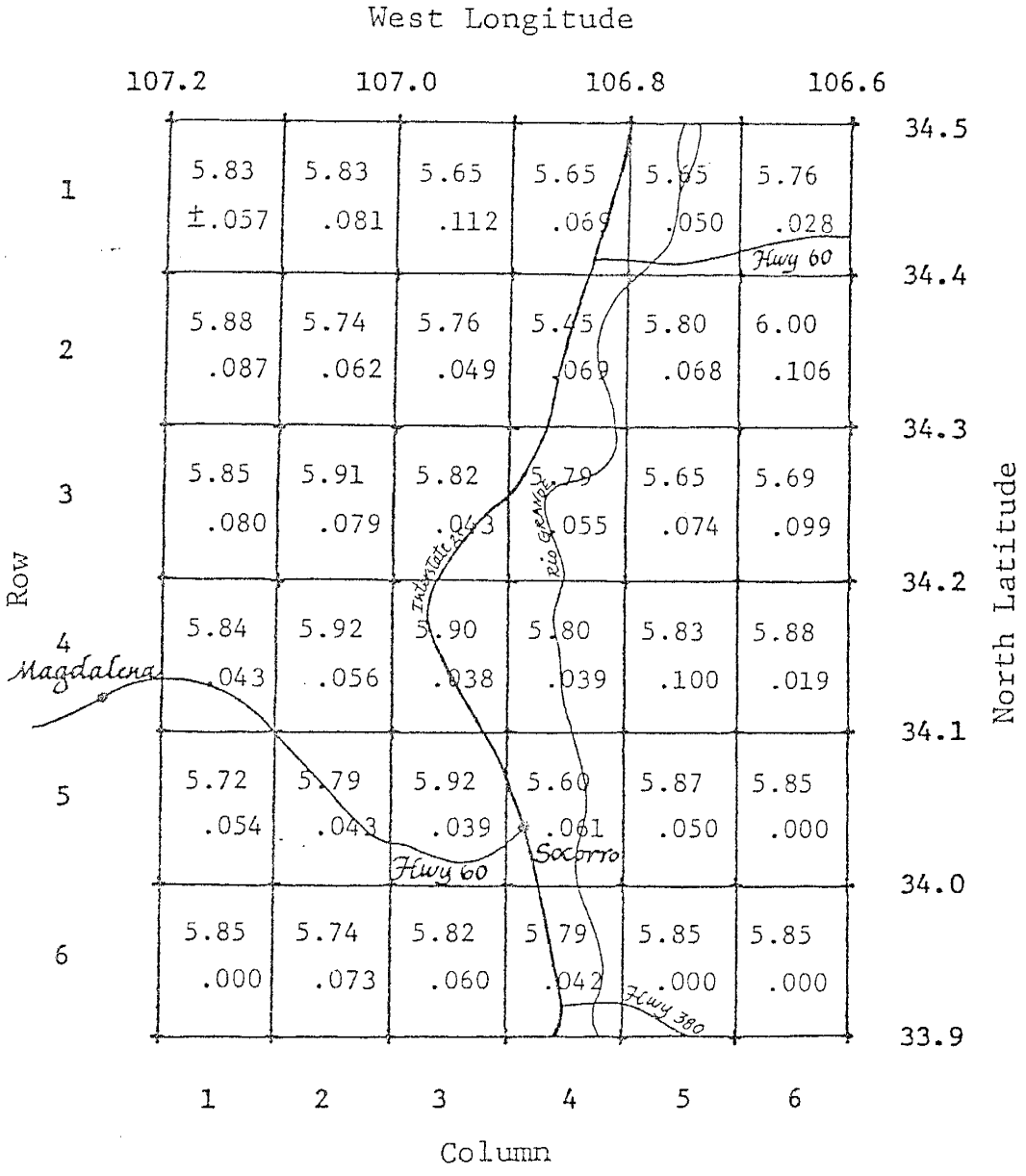



Figure 7. Calculated velocities and uncertainties for the thirty-six block velocity model of the real data --- GLS. Velocities are given in km/sec.

As in the case of the half-space model, independent depth information based on the S-to-S reflections was incorporated by removing those eigenvalues and eigenvectors associated with those 8 "known" depths which varied beyond prescribed limits, thus suppressing changes in those depths.

For a given travel path, the difference between the observed and theoretical travel times is the travel-time residual. When the entire set of travel-time residuals for this model (Appendix 2) was examined, it was determined that the average of the residuals had a standard deviation of .035 seconds as compared to a value of .040 seconds obtained for the half-space model. This decrease demonstrates the expected ability of the more complicated velocity structure to model a greater portion of the travel-time residuals relative to the half-space model.

The question of whether or not this was a significant decrease given the greater complexity of the 36 block model was tested using the classic F-test. The F-test was used to evaluate the null hypothesis of no difference between the variance of the residuals of this model and the variance of the residuals of the half-space model. If $SSR_k$ is the sum of the squares of the residuals when k variables are used and $SSR_r$ is the sum of the squares of the residuals when (r-k) variables are added to the original k parameters, then

for m observations

$$F = \frac{\left[SSR_k - SSR_r\right]\ (m-r-1)}{(r-k)SSR_r}$$

with (r-k) and (m-r-1) degrees of freedom (Anderson and Bancroft, 1952). The 36 block model had a total of 86 degrees of freedom, 14 fewer than the half-space model. The resulting F value was 1.88 with 14 and 86 degrees of freedom. Comparing this value to standard tables of F indicated that adding the additional variables was significant at the 95 per cent confidence level.

As it is of interest in this study to delineate regions of anomalous velocity, it is important to view the resulting average velocities in terms of their uncertainties and the degree to which they can be resolved from the data. A good measure of the ability to resolve a particular average velocity from the data is given by the associated diagonal element of the resolving kernel (Wiggins, 1972). In addition to the diagonal elements associated with the average velocities, Table 4 also presents the percentage of the total travel path length contained within each block.

A classification scheme, depicting the ability of the inversion to resolve the average velocity of a given block from the data, was developed by examining the results of the

TABLE 4. DIAGONAL ELEMENTS OF RESOLVING KERNELS
(GLS INVERSION OF 36 BLOCK MODEL)

(REAL DATA)

| BLOCK | DIAG. ELEMENT | % TOTAL TRAVEL PATH |
|---|---|---|
| (1,1) | .53 | .0063 |
| (1,2) | .68 | .0270 |
| (1,3) | .65 | .0164 |
| (1,4) | .27 | .0066 |
| (1,5) | .20 | .0027 |
| (1,6) | .05 | .0015 |
| (2,1) | .71 | .0056 |
| (2,2) | .92 | .0269 |
| (2,3) | .85 | .0363 |
| (2,4) | .76 | .0244 |
| (2,5) | .75 | .0199 |
| (2,6) | .79 | .0114 |
| (3,1) | .69 | .0042 |
| (3,2) | .96 | .0233 |
| (3,3) | .96 | .0484 |
| (3,4) | .93 | .0549 |
| (3,5) | .74 | .0281 |
| (3,6) | .91 | .0204 |
| (4,1) | .97 | .0345 |
| (4,2) | .93 | .0313 |
| (4,3) | .98 | .0744 |
| (4,4) | .97 | .0807 |
| (4,5) | .93 | .0118 |
| (4,6) | .03 | .0008 |
| (5,1) | .96 | .0246 |
| (5,2) | .97 | .1024 |
| (5,3) | .98 | .1107 |
| (5,4) | .96 | .0607 |
| (5,5) | .20 | .0141 |
| (5,6) | .00 | .0000 |
| (6,1) | .00 | .0000 |
| (6,2) | .89 | .0227 |
| (6,3) | .93 | .0585 |
| (6,4) | .07 | .0023 |
| (6,5) | .00 | .0000 |
| (6,6) | .00 | .0000 |

synthetic data studies (see section Testing with Artificial Data). This scheme uses the respective diagonal element of the resolution matrix to classify those average velocities having a diagonal element greater than or equal to .75 as having 'acceptable' resolution, those having a diagonal element greater than or equal to .85 as having 'good' resolution, and those having a diagonal element greater than or equal to .95 as having 'excellent' resolution. It is important to note that the velocity parameter representing the average velocity of a block is not necessarily the true average velocity of that block, but rather the average velocity of a block configuration as represented by the resolving kernel of that velocity parameter. Nevertheless, average velocities with 'acceptable' resolution are considered resolvable even though average velocities with 'excellent' resolution are more representative of the true average velocities of their respective blocks. Only if the diagonal element of the resolving kernel is 1.0 does the calculated velocity represent the average velocity of the block (as is the case in the CLS approach).

For brevity and clarity in the presentation of the following results, a given block will be called "resolvable" when in fact it is the average velocity of that block which is resolvable. In addition, only those average velocities

which are resolvable will be compared, and refering to such a comparison as statistically significant will imply a 95% confidence level unless otherwise stated.

Using this classification scheme, an examination of Table 4 shows that the resulting model (Fig. 7) has 20 blocks which can be classified as having 'acceptable' or better velocity resolution, 17 blocks with 'good' or better velocity resolution, and 9 blocks which have 'excellent' velocity resolution.

An examination of Fig. 7 shows several blocks, primarily blocks (2,4) and (5,4), which appear to have resolvable velocities that are anomalously low relative to the velocities of surrounding blocks. However, these velocities must be viewed in conjunction with their associated uncertainties. The lowest velocity obtained for any block is 5.45 $\pm$.069(s.d.) km/sec for block(2,4). If a maximum uncertainty of two standard deviations (95% confidence interval) is taken for this and all other blocks, the resulting value is still lower than the minimum velocity obtainable for all adjacent blocks and most non-adjacent blocks, leading to the conclusion that block(2,4) defines a region of depressed velocity. Conversely, the velocity of block(5,4) (5.60 $\pm$.061 km/sec) is lower, at two standard deviations, than the minimum velocity of only two of its surrounding blocks, blocks (4,3) and (5,3). It is also of interest to note (for comparison to later, more complicated

models) that the velocity of block(5,2) does not have a maximum velocity that is anomalously low when compared to the minimum velocities of any of its surrounding blocks.

After an examination of all resolvable velocities, it is seen (in a statistical sense) that only one block (block(2,4)) of this model has a uniquely low velocity relative to the velocities of all adjacent blocks, while many blocks have anomalously low velocities relative to some, but not all, adjacent blocks.

Damped Least Squares: The DLS procedure was applied to the data set using the same 36 block configuration as the previous model. After trying several values for the damping factor $\theta^2$, it was found that a damping factor of 0.5 produced a stable inverse as well as the desired balance between uncertainties and resolution. As a comparison with the GLS approach, where 89% of the eigenvalues were retained, 88% of the eigenvalues exceeded a damping factor value of 0.5 for the DLS.

The independent depth information (incorporated into the GLS approach by removal of the associated eigenvalues and eigenvectors) was incorporated into the DLS approach by increasing the damping factor from 0.5 to 5.0 for those four depths which preliminary results showed varied beyond

prescribed limits. This decrease in the number of depths which varied beyond prescribed limits, relative to the 8 depths of the GLS approach, is a result of the increased smoothing inherent in the DLS approach. It was found that increasing the damping factor to values above 5.0 produced large negative side lobes in the associated resolving kernels, which thereby introduced an instability in the resulting inversion. By using a damping value of 5.0, changes to the initial estimates of these depths were comparable to those obtained by the GLS technique. The resulting velocity model and uncertainties obtained from damped least squares are presented in Fig. 8, with the diagonal elements of the associated resolving kernels given in Table 5.

The average of the travel-time residuals of the resulting model (Appendix 2) had a standard deviation of .032 seconds, as compared to a value of .035 seconds obtained for the generalized inversion. This difference is a direct result of the dissimilar smoothing procedures employed by the differing techniques. A comparison of Tables 4 and 5 shows that, relative to the generalized inverse approach, the damped inverse approach models a greater percentage of the data with those parameters poorly defined by the data, at the expense of other parameters.

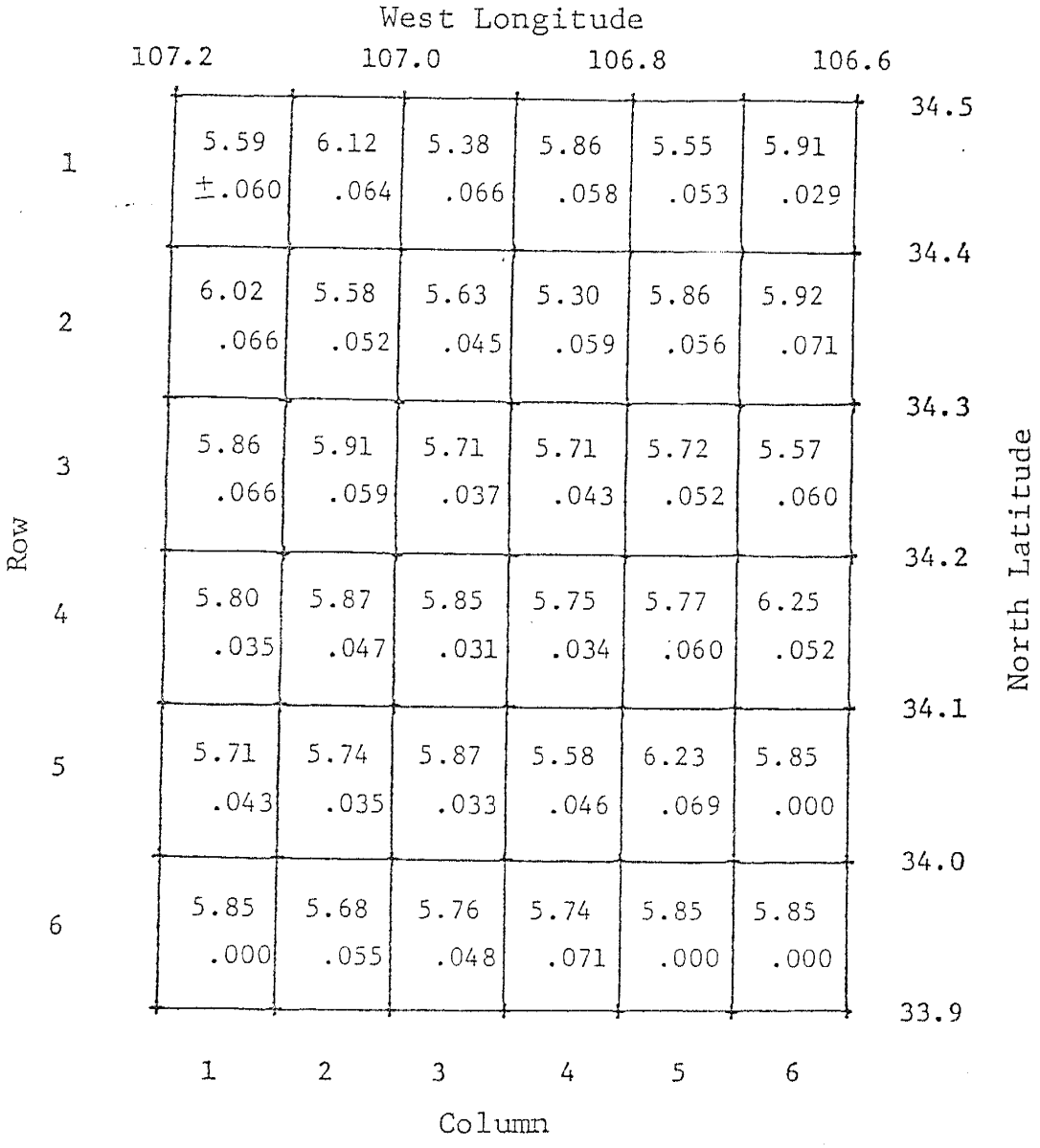



Figure 8. Calculated velocities and uncertainties for the thirty-six block velocity model of the real data --- DLS.

TABLE 5. DIAGONAL ELEMENTS OF RESOLVING KERNELS
(DLS INVERSION OF 36 BLOCK MODEL)

(REAL DATA)

| BLOCK | DIAG. ELEMENT |
|---|---|
| (1,1) | .54 |
| (1,2) | .65 |
| (1,3) | .54 |
| (1,4) | .31 |
| (1,5) | .24 |
| (1,6) | .06 |
| (2,1) | .60 |
| (2,2) | .86 |
| (2,3) | .86 |
| (2,4) | .77 |
| (2,5) | .81 |
| (2,6) | .64 |
| (3,1) | .67 |
| (3,2) | .82 |
| (3,3) | .92 |
| (3,4) | .89 |
| (3,5) | .83 |
| (3,6) | .77 |
| (4,1) | .94 |
| (4,2) | .89 |
| (4,3) | .95 |
| (4,4) | .95 |
| (4,5) | .77 |
| (4,6) | .13 |
| (5,1) | .91 |
| (5,2) | .94 |
| (5,3) | .94 |
| (5,4) | .89 |
| (5,5) | .34 |
| (5,6) | .00 |
| (6,1) | .00 |
| (6,2) | .83 |
| (6,3) | .87 |
| (6,4) | .28 |
| (6,5) | .00 |
| (6,6) | .00 |

It is therefore important to note that this decrease in the standard deviation of the average residual is not indicative of the one model being "better" than the other.

As in the case of the generalized inverse, an F-test was used to test whether the new parametization was a significant improvement over the half-space model. It must be noted that for the DLS approach it is not possible to determine the exact number of degrees of freedom associated with a given damping factor, leading to a possible error in the determination of the F value. For this reason the same degrees of freedom used in the F-test for the GLS method were used to obtain the F value for the damped least squares. A resulting F value of 3.46 with 14 and 86 degrees of freedom was obtained. Comparing this value to standard tables of F indicated that adding the additional velocity terms was significant at the 99 per cent confidence level. This increase in the confidence level relative to that obtained in the generalized inverse approach could be due to an error in the number of degrees of freedom used for determining the F value of this model and/or differences in the smoothing procedures.

An examination of Table 5 shows that the resulting model (Fig. 8) has 20 blocks whose associated average velocities are classified as having 'acceptable' or better resolution, 13 with 'good' or better resolution, and two with 'excellent' resolution. This compares to 20, 17, and 9

blocks, respectively, when the GLS technique was used. This decrease in the number of 'good' and 'excellent' velocities is a consequence of the increased smoothing inherent in damped least squares. This difference is easily seen when the respective expressions for the resolution matrix are compared (equations (9) and (11)). An examination of Fig. 8 shows that the reduction in resolution associated with the DLS is accompanied by a reduction in the uncertainties of the resulting velocities. A comparison of the two models (Figs 7 and 8) shows considerable agreement, with the discrepancies being due to the dissimilar smoothing procedures employed by the differing techniques.

An examination of Fig. 8 shows the average velocity of block(2,4) is 5.30 $\pm$.059(s.d.) km/sec with a resolution that is 'acceptable'. At two standard deviations, the maximum velocity of this block is still lower than the minimum velocity obtainable for all adjacent blocks as well as all of the non-adjacent blocks. Therefore, both the generalized and damped inverses lead to the same result, namely that block(2,4) defines a region of low-velocity relative to surrounding blocks.

An examination of block(5,4) shows a velocity of 5.58 .046(s.d.) km/sec which, as was the case for the ...ralized inverse, is lower than the minimum velocity of ...wo of its surrounding blocks, blocks (4,3) and (5,3).

In addition, the velocity of block(5,2) cannot be resolved as either a uniquely low or high velocity relative to any of the velocities of the surrounding blocks. Therefore, as in the case of the generalized inverse, only one block (block(2,4)) of this model can be shown to have a uniquely low velocity relative to the velocities of all adjacent resolvable blocks

It is important to note that a block-by-block comparison of the two models shows corresponding blocks to be statistically equivalent. That is, the velocity of any given resolvable block in one model is not statistically different from the velocity of the corresponding resolvable block in the other model at two standard deviations. The small differences that do exist in the average velocities, uncertainties and resolution of the two models can be explained in terms of the smoothing procedures inherent in the different modelling approaches.

## Forty-Eight Block Model

In order to further refine the velocity model, the number of blocks was increased from 36 to 48. The additional 12 blocks were constructed by subdividing the twelve well resolved central blocks with an interface at depth. After several trials, it was determined that placing

an interface at a depth of four kilometers provided the best velocity resolution within all blocks. The twelve central blocks were the only ones subdivided, as there were insufficient travel paths at depth within the other blocks to provide sufficient velocity resolution.

Generalized Least Squares: The GLS procedure was again applied to the 262 travel-time residuals comprising the data set. After several initial inversions, it was determined that retaining 183 of the total 208 eigenvalues and associated eigenvectors produced a stable inverse with an acceptable balance between uncertainties and resolution. The resulting velocity model and uncertainties are presented in Fig. 9, with the diagonal elements of the corresponding resolving kernels presented in Table 6. In addition, Table 6 also presents the percentage of total travel path length contained within each block of the 48 block model.

The average of the travel-time residuals of the resulting model (Appendix 2) had a standard deviation of .032 seconds, an improvement of .003 seconds over that which was obtained for the 36 block model. In addition, it should be noted that this value is in excellent agreement with the value of .031 seconds, expected from the estimates of observational error. As in the case of previous models, an F-test was used to decide whether the new parametization was

Layer #1

| | 107.2 | 107.0 | 106.8 | | 106.6 | |
|---|---|---|---|---|---|---|
| | | | | | | 34.5 |
| 1 | 5.84 ±.055 | 5.89 .086 | 5.73 .079 | 5.95 .076 | 5.83 .072 | 5.80 .043 |
| | | | | | | 34.4 |
| 2 | 5.88 .078 | 5.48 .092 | 5.79 .077 | 5.45 .112 | 5.85 .079 | 6.06 .118 |
| | | | | | | 34.3 |
| 3 | 5.87 .068 | 5.84 .093 | 5.83 .058 | 5.72 .068 | 5.77 .085 | 5.54 .104 |
| | | | | | | 34.2 |
| 4 | 5.91 .052 | 5.78 .083 | 5.85 .045 | 5.66 .057 | 5.90 .110 | 5.82 .031 |
| | | | | | | 34.1 |
| 5 | 5.72 .055 | 5.90 .052 | 5.81 .052 | 5.59 .079 | 5.93 .055 | 5.85 .000 |
| | | | | | | 34.0 |
| 6 | 5.85 .000 | 5.48 .081 | 5.84 .067 | 6.10 .027 | 5.85 .000 | 5.85 .000 |
| | | | | | | 33.9 |
| | 1 | 2 | 3 | 4 | 5 | 6 |

Layer #2

| | | | |
|---|---|---|---|
| 1 | | | |
| 2 | 5.90 ±.116 | 5.80 .097 | 5.77 .155 |
| 3 | 5.96 .106 | 6.09 .128 | 6.15 .116 |
| 4 | 6.24 .109 | 6.05 .118 | 5.75 .117 |
| 5 | 5.17 .114 | 5.83 .086 | 5.51 .132 |
| 6 | | | |
| | 1 | 2 | 3 |

9. Calculated velocities and uncertainties for the forty-eight block velocity model of the real data --- GLS.

TABLE 6. DIAGONAL ELEMENTS OF RESOLVING KERNELS
(GLS INVERSION OF 48 BLOCK MODEL)

(REAL DATA)

| BLOCK | DIAG. ELEMENT | % TOTAL TRAVEL PATH |
|---|---|---|
| (1,1,1) | .50 | .0063 |
| (1,2,1) | .55 | .0270 |
| (1,3,1) | .53 | .0164 |
| (1,4,1) | .34 | .0066 |
| (1,5,1) | .26 | .0027 |
| (1,6,1) | .08 | .0015 |
| (2,1,1) | .67 | .0056 |
| (2,2,1) | .84 | .0122 |
| (2,3,1) | .79 | .0185 |
| (2,4,1) | .70 | .0049 |
| (2,5,1) | .87 | .0199 |
| (2,6,1) | .76 | .0114 |
| (3,1,1) | .60 | .0042 |
| (3,2,1) | .72 | .0113 |
| (3,3,1) | .95 | .0263 |
| (3,4,1) | .89 | .0367 |
| (3,5,1) | .80 | .0281 |
| (3,6,1) | .90 | .0204 |
| (4,1,1) | .93 | .0345 |
| (4,2,1) | .88 | .0162 |
| (4,3,1) | .93 | .0569 |
| (4,4,1) | .95 | .0464 |
| (4,5,1) | .92 | .0118 |
| (4,6,1) | .04 | .0008 |
| (5,1,1) | .96 | .0246 |
| (5,2,1) | .92 | .0397 |
| (5,3,1) | .95 | .0595 |
| (5,4,1) | .93 | .0285 |
| (5,5,1) | .16 | .0141 |
| (5,6,1) | .00 | .0000 |
| (6,1,1) | .00 | .0000 |
| (6,2,1) | .92 | .0227 |
| (6,3,1) | .88 | .0585 |
| (6,4,1) | .04 | .0023 |
| (6,5,1) | .00 | .0000 |
| (6,6,1) | .00 | .0000 |
| (2,2,2) | .81 | .0147 |
| (2,3,2) | .72 | .0178 |
| (2,4,2) | .61 | .0195 |
| (3,2,2) | .47 | .0120 |
| (3,3,2) | .87 | .0220 |
| (3,4,2) | .84 | .0182 |
| (4,2,2) | .75 | .0151 |
| (4,3,2) | .87 | .0175 |
| (4,4,2) | .91 | .0343 |
| (5,2,2) | .95 | .0627 |
| (5,3,2) | .98 | .0512 |
| (5,4,2) | .85 | .0322 |

a significant improvement over the previous model. An F value of 1.91 with 8 and 78 degrees of freedom was obtained. Comparing this value to standard tables of F indicated that adding the additional parameters was significant at the 90 per cent confidence level.

An examination of Table 6 shows that the resulting model (Fig. 9) has 28 blocks for which average velocities can be resolved at 'acceptable' levels or better. Of the twelve lower blocks, nine had velocities which could be resolved at 'acceptable' levels or better. Of these nine, six are classified as having 'good' or better resolution, and two as having 'excellent' resolution. One of the two blocks with 'excellent' velocity resolution is block(5,2,2). At 5.17 $\pm$.11(s.d.) km/sec relative to 5.90 $\pm$.05(s.d.) km/sec of the block above it, this block defines a region of extremely low velocity. In addition, the maximum velocity of 5.40 km/sec is significantly lower than the minimum velocity of all other lower blocks, with the exception of of block(5,4,2).

Of the remaining eight resolvable velocities associated with lower blocks, three differ statistically at two standard deviations from the velocity of the block above. These three velocities are 5.90 $\pm$.11, 6.15 $\pm$.12 and 6.24 $\pm$.11(s.d.) km/sec, associated with blocks (2,2,2), (3,4,2), and (4,2,2) respectively. Unlike the velocity of

block(5,2,2) relative to the velocity of the block above, these three velocities are higher than those of their associated upper blocks.

While four of the velocities of the lower blocks differ statistically from the velocities of their respective upper blocks, others can be shown to differ statistically from the 'acceptable' velocities of other lower blocks. For example, block(5,4,2), with a velocity of 5.51 $\pm$.13(s.d.) km/sec, depicts (at two standard deviations) a region of anomalously low velocity relative to blocks (4,3,2), (4,2,2), (3,4,2), and (3,3,2) (which have velocities of 6.05 $\pm$.12, 6.24 $\pm$.11, 6.15 $\pm$.12, and 6.09 $\pm$.13(s.d.) km/sec respectively). It is also of interest to note that block(4,4,2), located between blocks (5,4,2) and (3,4,2), has a velocity (5.75 $\pm$.12 km/sec) that is statistically equivalent to the velocity of either of these anomalous blocks.

Of the twelve upper blocks, only two blocks, blocks (3,2,1) and (2,4,1), have associated with them velocities that are not resolvable at 'acceptable' levels. The velocities of their associated lower blocks, blocks (3,2,2) and (2,4,2) respectively, are also not resolvable at 'acceptable' levels. When blocks (3,2,1) and (3,2,2) are combined, they represent block(3,2) of the 36 block model which had an 'excellently' resolved velocity. When blocks (2,4,1) and (2,4,2) are combined, they represent block(2,4)

of the 36 block model, which had a velocity with 'acceptable' resolution and was the only block of the 36 block model which defined a region of depressed velocity relative to all surrounding resolvable blocks. This inability to resolve the velocities of these subdivided blocks is a result of the reduced travel path lengths within the subdivided blocks and the changed smoothing procedure inherent in the reparametization.

Of the twelve upper blocks, not one can be shown to have a velocity that is statistically different from the velocities of adjacent blocks. However, some of the blocks do have velocities that are statistically different from those of non-adjacent blocks.

One of the previously unresolvable velocities associated with an outer block (block(3,5)) of the 36 block model was resolved in the 48 block model. However, this reclassification is the result of a relatively small increase in the associated diagonal element of the resolving kernel, from 0.74 to 0.80. This apparent change in the ability to resolve the average velocity of a dimensionally unchanged block is a result of changes in smoothing inherent in the changes in the eigenvalue spectrum of the new model relative to previous models. A comparison of the velocities of the dimensionally unchanged blocks of the 48 block model

with the average velocities of the corresponding blocks of the 36 block model shows, as expected, that in a statistical sense they have not changed.

Damped Least Squares: The DLS procedure was applied to the data set using the same 48 block configuration of the previous model. As for the case of the 36 block model, it was found that a damping factor of 0.5 produced a stable inverse, as well as the desired acceptable balance between uncertainties and resolution. As a comparison to the GLS approach, where 88% of the eigenvalues were retained, 84% of the eigenvalues exceeded a damping factor value of 0.5 for the DLS approach.

The independent depth information was incorporated into the 48 block model, as it was in the 36 block model, by increasing the damping factor from 0.5 to 5.0 for the same four depths determined independently of the travel time data and which varied beyond prescribed limits.

The average of the travel-time residuals of the resulting model had a standard deviation of .031 seconds as compared to a value of .032 seconds for the 36 block model. An F-test was used to decide whether the new parametization was a significant improvement over the 36 block model. An F value of 0.64 with 8 and 78 degrees of freedom was obtained. Comparing this value to standard tables of F indicated that

adding the additional velocity terms was not significant. Therefore, it can be concluded that, of the models attempted, the 36 block model represents the most refined velocity model that can be obtained from the data with this approach.

## Event Locations

The event locations associated with these velocity models are presented in Appendix 5, with those associated with the generalized inversion of the 48 block model representing the most refined set of locations obtained. A comparison of these locations with their initial estimates (locations from the half-space model) shows that, for the most part, only small changes have occurred. However, as expected, the difference between an initial and final location increases as the complexity of the model increases. For those few events where large changes in depth and origin time did occur, examining the station locations relative to the corresponding event locations shows they had poor azimuthal station distributions. Also, the inability to constrain three of the depths to within three kilometers of the known values may reflect inaccuracies in the velocity model used to determine these "known" depths. However, as these depths were within four kilometers of the assumed

known value, the resulting error is not considered significant. As the complexity of the velocity model increases, small adjustments (improvements) to the event locations are realized. However, in view of the magnitude of these adjustments, a half-space model provides suitable initial estimates of these locations, with the greatest error occurring in depths and origin times.

## Testing with Artificial Data

In order to obtain insight into the problems which can be expected in working with real data, a sequence of numerical tests on generated data was undertaken. Test data (P-arrival times) were calculated for prescribed velocity models using the event and station distributions of the real data (Appendix 1). The velocity models used were based on the same block configurations used to model the real data: a 5.85 km/sec half-space model, a 36 block model (Fig. 10) and a 48 block model (Fig. 13). To approximate real data with observational errors, normally distributed noise, scaled by the observational weighting assumed for the real data, was applied to the synthetic arrivals. The initial estimates of the source parameters were obtained by adding normally distributed noise (scaled by the assumed parametric weighting) to the true values.

### Half-Space Model

For the case of the half-space model, it was found that the classical least squares approach provided a stable inverse, and that it was not necessary to use a modified form of this approach to insure stability. The only reason that a modified least squares approach might be used for

this half-space model would be to control parameters known independently of the data, as was the case for the real data.

The resulting velocity obtained for the half-space model was 5.84 $\pm$.023(s.d.) km/sec. The resulting average of the travel-time residuals had a standard deviation of .017 seconds as compared to a value of .029 seconds for the applied noise. This modeling of a portion of the applied noise is a consequence of the fact that the arrivals are not truly independent, being grouped in events. That is, for a given event, the mean value of the applied noise could be absorbed by the origin time of that event without affecting the other parameters. However, it is more likely that a portion of the applied noise is absorbed in a more complicated way by all of the associated parameters. Repeated trials showed, as expected, that the amount of noise modeled varied for different synthetic data sets, while the resulting models remained comparable.

## Thirty-Six Block Model

For the 36 block model it was determined that the classical least squares approach was not stable. The generalized least squares and damped least squares were then used to model the synthetic data of the 36 block configuration.

Generalized Least Squares: The GLS approach was applied to the 262 travel-time residuals comprising the synthetic data set of this block configuration. In order to duplicate, as closely as possible, the set of smoothed parameters used to model the real data, 175 of the 196 eigenvalues and associated eigenvectors were retained, as was the case for the real data. The resulting velocity model and associated uncertainties are presented in Fig. 11, with the diagonal element of the resolving matrix associated with each average velocity presented in Table 7. The actual errors in the resulting velocity model and the calculated uncertainties, at two standard deviations, are given in Table 8. An examination of Table 8 shows that for this model and approach, all calculated velocities are within two standard deviations of the true values. The resulting average of the travel-time residuals had a standard deviation of .016 seconds as compared to a value of .029 seconds for the applied noise. As in the case of the half-space model, a considerable amount of the applied noise was modeled, again demonstrating the non-independence of the data.

Damped Least Squares: The DLS approach was applied to the travel-time residuals comprising the synthetic data of the 36 block model. As was the case of the application of

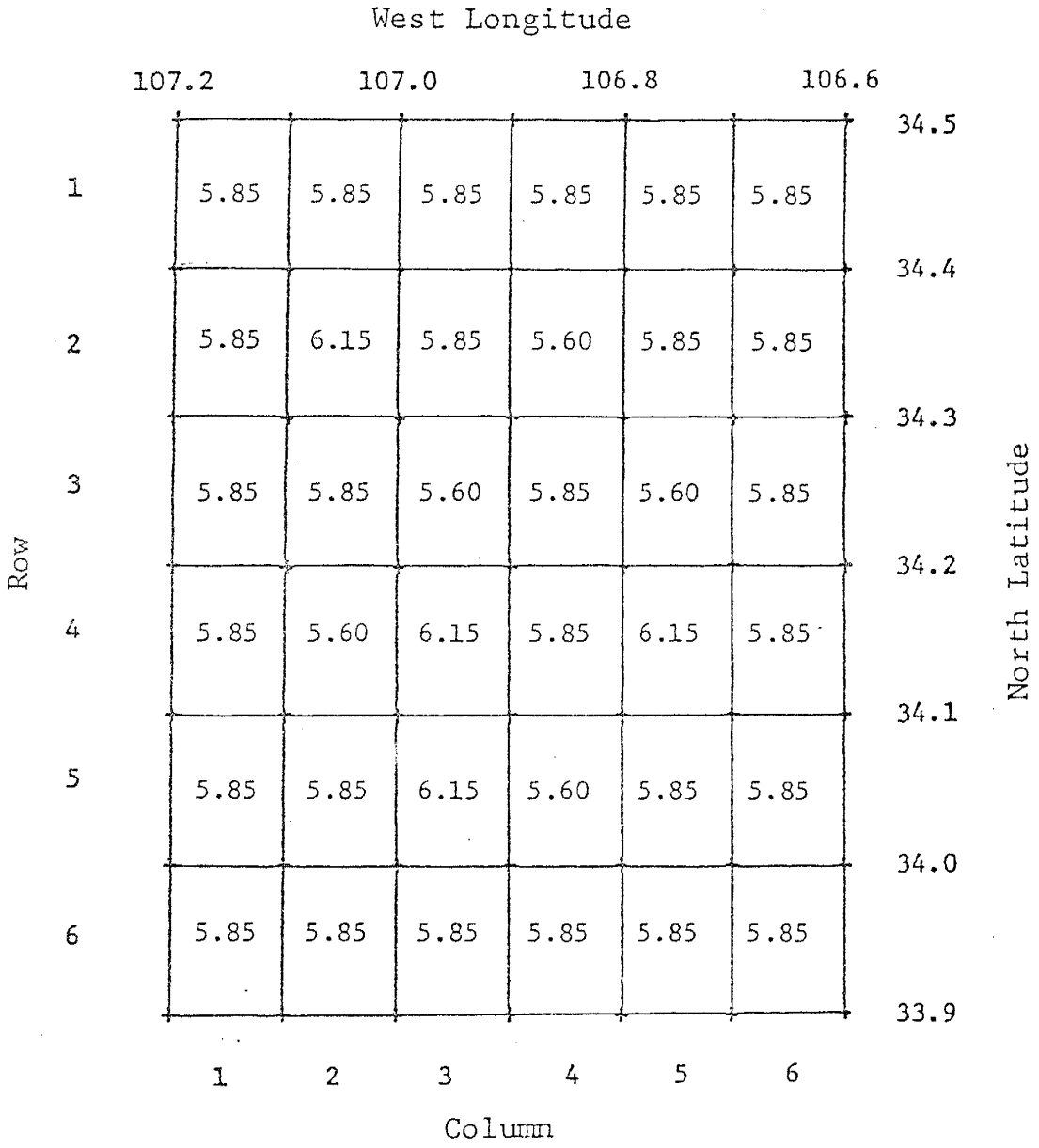



Figure 10. Thirty-six block model used for the generation of the synthetic data.

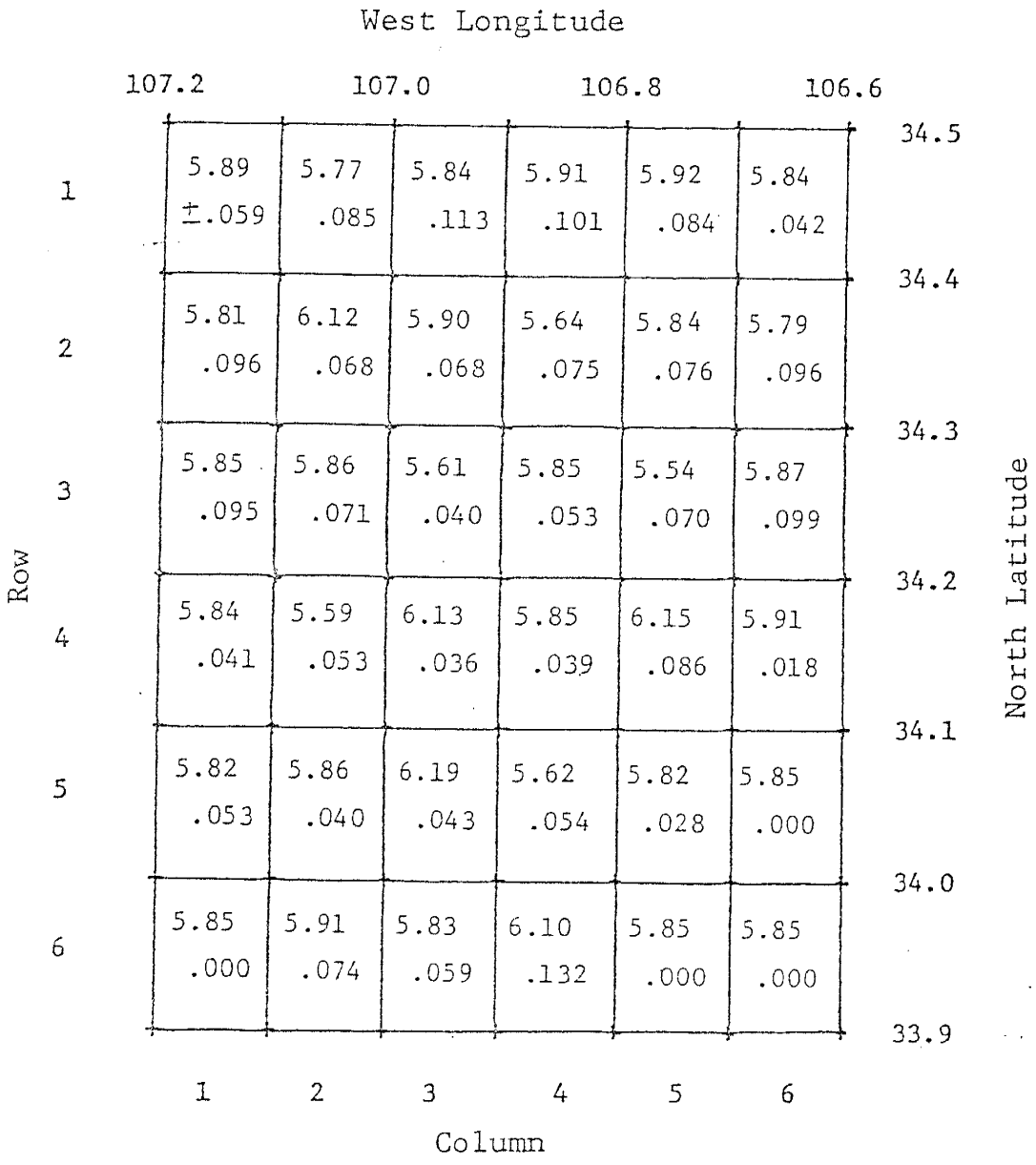



Figure 11. Calculated velocities and uncertainties for the thirty-six block velocity model of the synthetic data --- GLS.

TABLE 7. DIAGONAL ELEMENTS OF RESOLVING KERNELS
(GLS INVERSION OF 36 BLOCK MODEL)

(SYNTHETIC DATA)

| BLOCK | DIAG. ELEMENT |
|---|---|
| (1,1) | .52 |
| (1,2) | .71 |
| (1,3) | .68 |
| (1,4) | .37 |
| (1,5) | .28 |
| (1,6) | .07 |
| (2,1) | .77 |
| (2,2) | .93 |
| (2,3) | .93 |
| (2,4) | .84 |
| (2,5) | .88 |
| (2,6) | .79 |
| (3,1) | .78 |
| (3,2) | .89 |
| (3,3) | .93 |
| (3,4) | .92 |
| (3,5) | .92 |
| (3,6) | .94 |
| (4,1) | .95 |
| (4,2) | .90 |
| (4,3) | .98 |
| (4,4) | .97 |
| (4,5) | .88 |
| (4,6) | .03 |
| (5,1) | .95 |
| (5,2) | .98 |
| (5,3) | .98 |
| (5,4) | .95 |
| (5,5) | .08 |
| (5,6) | .00 |
| (6,1) | .00 |
| (6,2) | .91 |
| (6,3) | .93 |
| (6,4) | .43 |
| (6,5) | .00 |
| (6,6) | .00 |

TABLE 8. ABSOLUTE DIFFERENCE BETWEEN CALCULATED AND TRUE VELOCITIES (GLS INVERSION OF 36 BLOCK MODEL -- SYNTHETIC DATA)

| BLOCK | ABSOLUTE DIFFERENCE (KM/SEC) | CALCULATED UNCERTAINTY (2S.D.) |
|---|---|---|
| (1,1) | .04 | .12 |
| (1,2) | .08 | .17 |
| (1,3) | .01 | .23 |
| (1,4) | .06 | .20 |
| (1,5) | .07 | .17 |
| (1,6) | .01 | .08 |
| (2,1) | .04 | .19 |
| (2,2) | .03 | .14 |
| (2,3) | .05 | .14 |
| (2,4) | .04 | .15 |
| (2,5) | .01 | .15 |
| (2,6) | .06 | .19 |
| (3,1) | .00 | .19 |
| (3,2) | .01 | .14 |
| (3,3) | .01 | .08 |
| (3,4) | .00 | .11 |
| (3,5) | .06 | .14 |
| (3,6) | .02 | .20 |
| (4,1) | .01 | .08 |
| (4,2) | .01 | .11 |
| (4,3) | .02 | .07 |
| (4,4) | .00 | .08 |
| (4,5) | .00 | .17 |
| (4,6) | .06 | .04 |
| (5,1) | .03 | .11 |
| (5,2) | .01 | .08 |
| (5,3) | .04 | .09 |
| (5,4) | .02 | .11 |
| (5,5) | .03 | .06 |
| (5,6) | .00 | .00 |
| (6,1) | .00 | .00 |
| (6,2) | .06 | .15 |
| (6,3) | .02 | .12 |
| (6,4) | .25 | .26 |
| (6,5) | .00 | .00 |
| (6,6) | .00 | .00 |

this approach to the real data, a damping factor of 0.5 was used. The resulting velocity model, along with the uncertainties and the true velocity model are presented in Fig. 12, with the diagonal elements of the resolving kernels presented in Table 9. The actual errors in the calculated velocities and the calculated uncertainties, at two standard deviations, are given in Table 10. An examination of Table 10 shows that there are five blocks, blocks (1,2), (2,3), (2,4), (4,6) and (6,4), which have calculated velocities that, when viewed in terms of two standard deviations, are not equivalent to the true values. The diagonal elements of the resolving kernels associated with these average velocities are .71, .86, .73, .14 and .37, respectively. It should be noted that the two blocks with the largest diagonal elements have associated average velocities that miss by only a few hundredths of a km/sec at two standard deviations of encompassing the true values. It should also be noted that two of the blocks, blocks (1,2) and (4,6), with diagonal elements of .71 and .14 respectively, have calculated velocities that, when viewed in terms of three standard deviations, are still not equivalent to the true values. The resulting average of the travel-time residuals had a standard deviation of .016 seconds as compared to a value of .029 seconds for the applied noise, with a portion of the applied noise again being modeled.

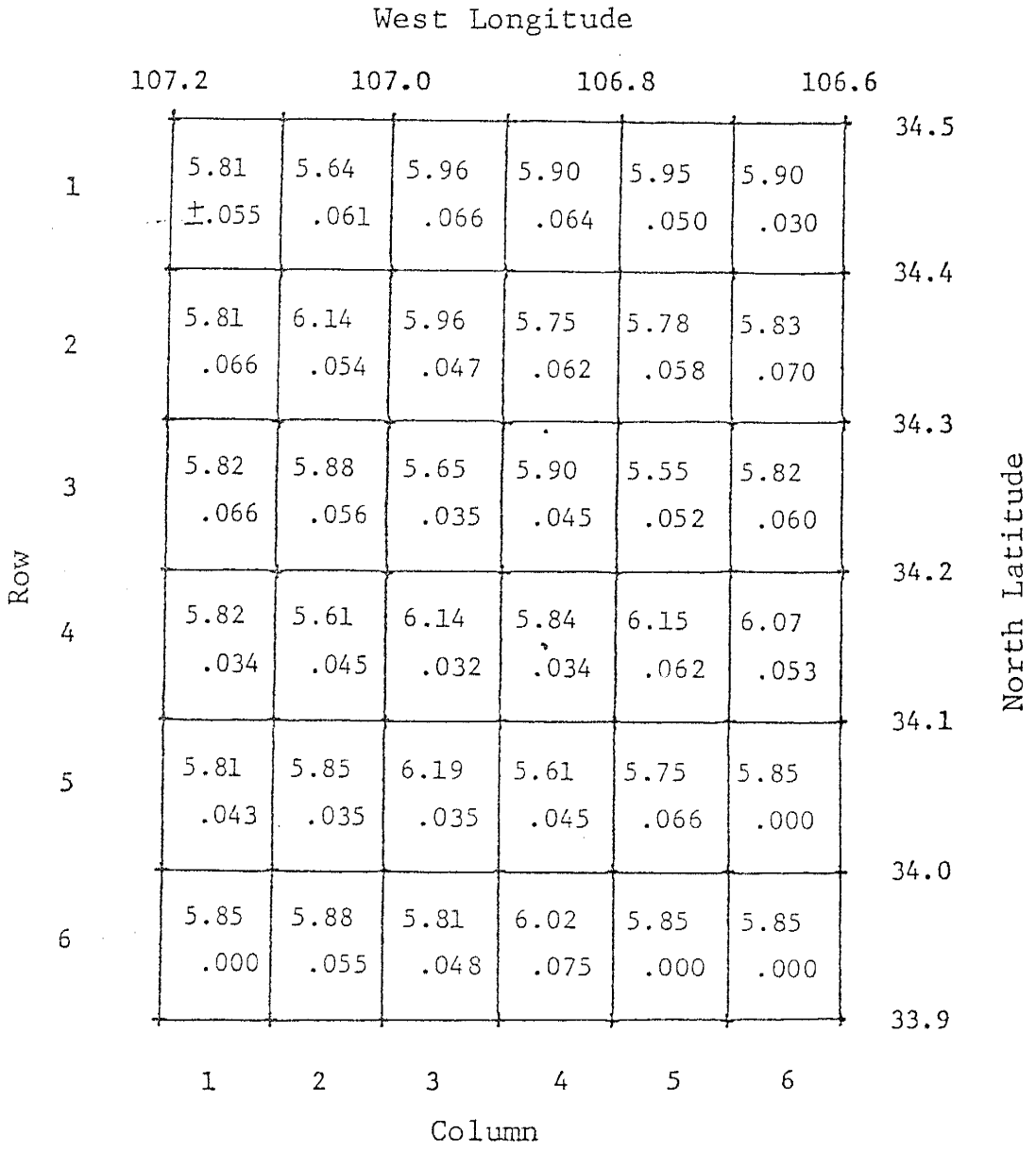



Figure 12. Calculated velocities and uncertainties for the thirty-six block velocity model of the synthetic data --- DLS.

TABLE 9. DIAGONAL ELEMENTS OF RESOLVING KERNELS
(DLS INVERSION OF 36 BLOCK MODEL)

(SYNTHETIC DATA)

| BLOCK | DIAG. ELEMENT |
|---|---|
| (1,1) | .49 |
| (1,2) | .71 |
| (1,3) | .52 |
| (1,4) | .35 |
| (1,5) | .24 |
| (1,6) | .06 |
| (2,1) | .62 |
| (2,2) | .84 |
| (2,3) | .86 |
| (2,4) | .73 |
| (2,5) | .80 |
| (2,6) | .66 |
| (3,1) | .68 |
| (3,2) | .83 |
| (3,3) | .93 |
| (3,4) | .88 |
| (3,5) | .85 |
| (3,6) | .77 |
| (4,1) | .94 |
| (4,2) | .91 |
| (4,3) | .95 |
| (4,4) | .94 |
| (4,5) | .77 |
| (4,6) | .14 |
| (5,1) | .91 |
| (5,2) | .94 |
| (5,3) | .94 |
| (5,4) | .90 |
| (5,5) | .27 |
| (5,6) | .00 |
| (6,1) | .00 |
| (6,2) | .83 |
| (6,3) | .88 |
| (6,4) | .37 |
| (6,5) | .00 |
| (6,6) | .00 |

TABLE 10. ABSOLUTE DIFFERENCE BETWEEN CALCULATED AND TRUE VELOCITIES (DLS INVERSION OF 36 BLOCK MODEL -- SYNTHETIC DATA)

| BLOCK | ABSOLUTE DIFFERENCE (KM/SEC) | CALCULATED UNCERTAINTY (2S.D.) |
|---|---|---|
| (1,1) | .04 | .11 |
| (1,2) | .21 | .12 |
| (1,3) | .11 | .13 |
| (1,4) | .05 | .13 |
| (1,5) | .10 | .10 |
| (1,6) | .05 | .06 |
| (2,1) | .04 | .13 |
| (2,2) | .01 | .11 |
| (2,3) | .11 | .09 |
| (2,4) | .15 | .12 |
| (2,5) | .07 | .12 |
| (2,6) | .02 | .14 |
| (3,1) | .03 | .13 |
| (3,2) | .03 | .11 |
| (3,3) | .05 | .07 |
| (3,4) | .05 | .09 |
| (3,5) | .05 | .10 |
| (3,6) | .03 | .12 |
| (4,1) | .03 | .07 |
| (4,2) | .01 | .09 |
| (4,3) | .01 | .06 |
| (4,4) | .01 | .07 |
| (4,5) | .00 | .12 |
| (4,6) | .22 | .11 |
| (5,1) | .04 | .09 |
| (5,2) | .00 | .07 |
| (5,3) | .04 | .07 |
| (5,4) | .01 | .09 |
| (5,5) | .10 | .13 |
| (5,6) | .00 | .00 |
| (6,1) | .00 | .00 |
| (6,2) | .03 | .11 |
| (6,3) | .04 | .10 |
| (6,4) | .17 | .15 |
| (6,5) | .00 | .00 |
| (6,6) | .00 | .00 |

When compared with the results of the generalized inversion of the same data, the effect of the increased smoothing and decreased uncertainties of the damped inversion is demonstrated. A possible solution to this problem would be to use the uncertainties associated with the classical least squares as a conservative overestimation of the uncertainties, as these values can be obtained without performing the actual inversion and are the uncertainties of an unsmoothed model.

Forty-Eight Block Model - Generalized Least Squares

The GLS approach was applied to the 262 travel-time residuals associated with the 48 block model. As was the case for the real data, 183 of the 208 eigenvalues and associated eigenvectors were retained. The resulting velocity model, along with the uncertainties, are presented in Fig. 14, with the true velocity model given in Fig. 13. The diagonal elements of the resolution matrix are presented in Table 11. The errors in the calculated velocities, along with the calculated uncertainties, are presented in Table 12. An examination of Table 12 shows that there are three blocks, blocks (1,2,1), (3,1,1) and (5,4,2) which have calculated average velocities that, when viewed in terms of two standard deviations, do not encompass the true values.

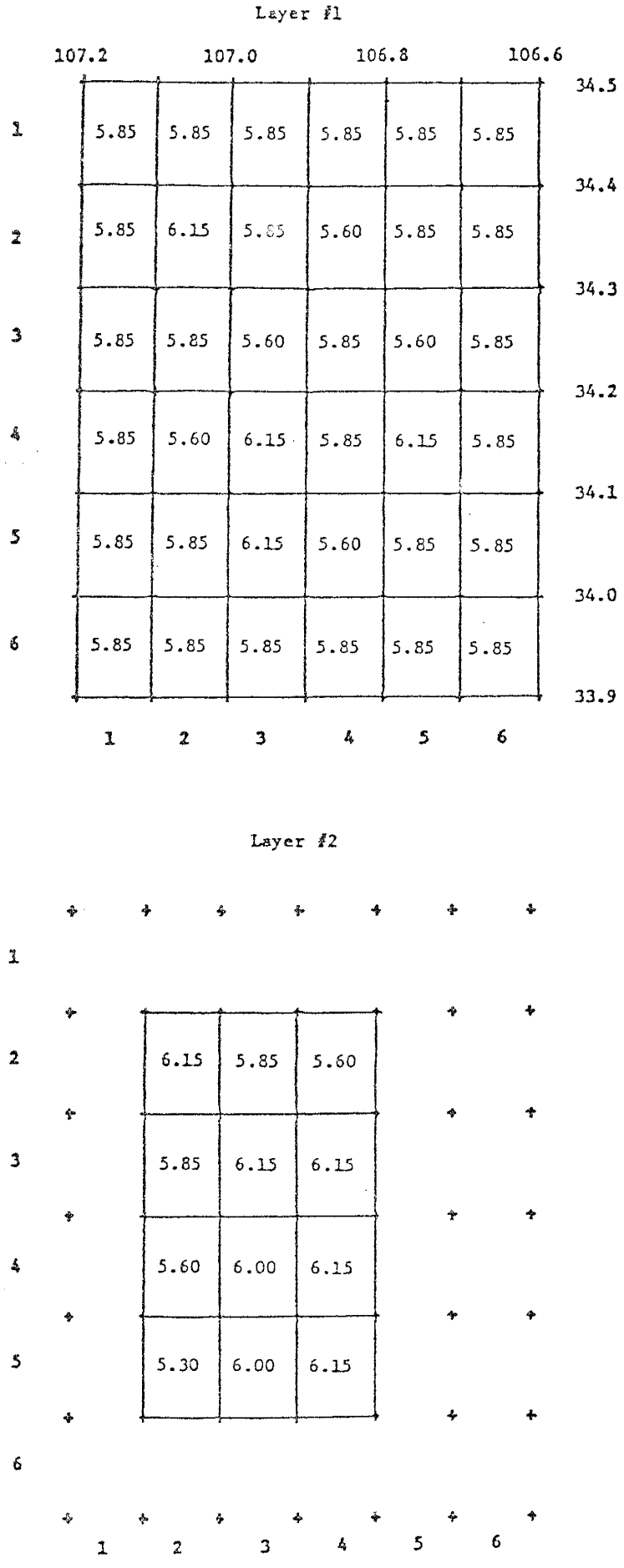
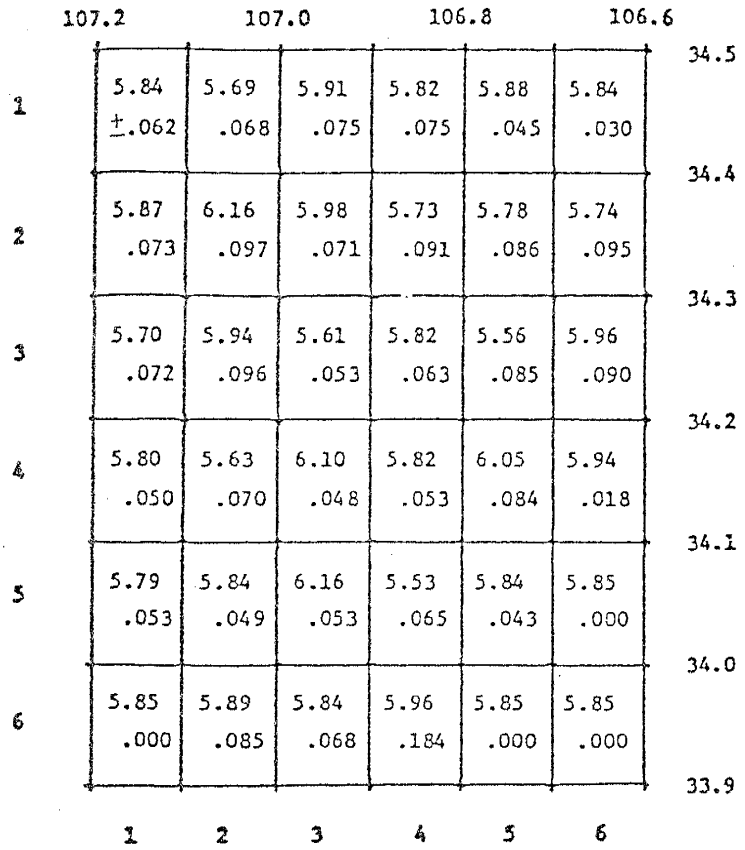



Figure 13. Forty-eight block velocity model used for the generation of synthetic data.

Layer #1




Layer #2

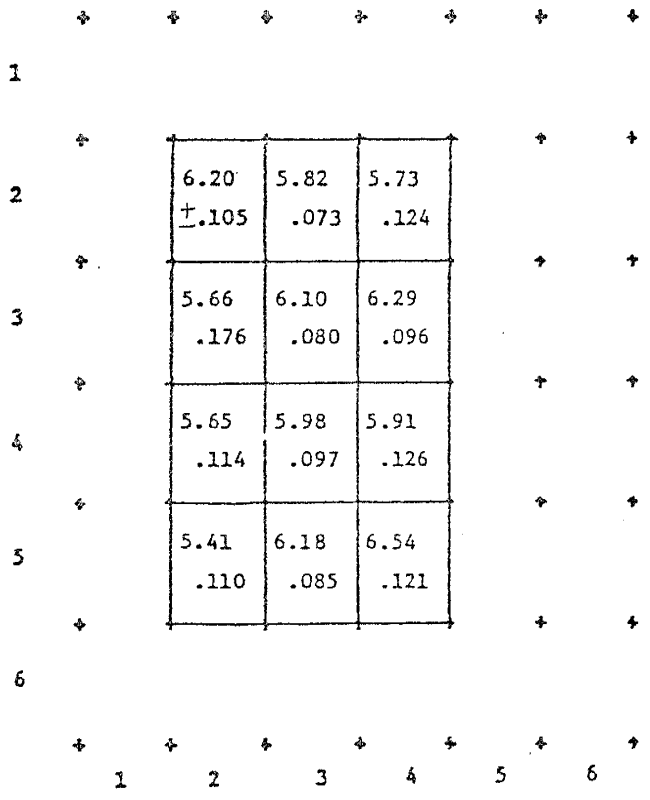



Figure 14. Calculated velocities and uncertainties for the forty-eight block velocity model of the synthetic data --- GLS.

TABLE 11. DIAGONAL ELEMENTS OF RESOLVING KERNELS
(GLS INVERSION OF 48 BLOCK MODEL)

(SYNTHETIC DATA)

| BLOCK | DIAG. ELEMENT |
|---|---|
| (1,1,1) | .50 |
| (1,2,1) | .52 |
| (1,3,1) | .52 |
| (1,4,1) | .30 |
| (1,5,1) | .21 |
| (1,6,1) | .05 |
| (2,1,1) | .65 |
| (2,2,1) | .78 |
| (2,3,1) | .70 |
| (2,4,1) | .46 |
| (2,5,1) | .89 |
| (2,6,1) | .58 |
| (3,1,1) | .59 |
| (3,2,1) | .89 |
| (3,3,1) | .91 |
| (3,4,1) | .91 |
| (3,5,1) | .96 |
| (3,6,1) | .85 |
| (4,1,1) | .95 |
| (4,2,1) | .91 |
| (4,3,1) | .94 |
| (4,4,1) | .92 |
| (4,5,1) | .85 |
| (4,6,1) | .03 |
| (5,1,1) | .97 |
| (5,2,1) | .96 |
| (5,3,1) | .97 |
| (5,4,1) | .97 |
| (5,5,1) | .12 |
| (5,6,1) | .00 |
| (6,1,1) | .00 |
| (6,2,1) | .93 |
| (6,3,1) | .97 |
| (6,4,1) | .78 |
| (6,5,1) | .00 |
| (6,6,1) | .00 |
| (2,2,2) | .76 |
| (2,3,2) | .74 |
| (2,4,2) | .79 |
| (3,2,2) | .84 |
| (3,3,2) | .87 |
| (3,4,2) | .87 |
| (4,2,2) | .89 |
| (4,3,2) | .95 |
| (4,4,2) | .95 |
| (5,2,2) | .97 |
| (5,3,2) | .99 |
| (5,4,2) | .72 |

TABLE 12. ABSOLUTE DIFFERENCE BETWEEN CALCULATED AND TRUE VELOCITIES (GLS INVERSION OF 48 BLOCK MODEL -- SYNTHETIC DATA)

| BLOCK | ABSOLUTE DIFFERENCE (KM/SEC) | CALCULATED UNCERTAINTY (2S.D.) |
|---|---|---|
| (1,1,1) | .01 | .12 |
| (1,2,1) | .16 | .14 |
| (1,3,1) | .06 | .15 |
| (1,4,1) | .03 | .15 |
| (1,5,1) | .03 | .09 |
| (1,6,1) | .01 | .06 |
| (2,1,1) | .02 | .15 |
| (2,2,1) | .01 | .19 |
| (2,3,1) | .13 | .14 |
| (2,4,1) | .13 | .18 |
| (2,5,1) | .07 | .17 |
| (2,6,1) | .11 | .19 |
| (3,1,1) | .15 | .14 |
| (3,2,1) | .09 | .19 |
| (3,3,1) | .01 | .11 |
| (3,4,1) | .03 | .12 |
| (3,5,1) | .04 | .17 |
| (3,6,1) | .11 | .18 |
| (4,1,1) | .05 | .10 |
| (4,2,1) | .03 | .14 |
| (4,3,1) | .05 | .10 |
| (4,4,1) | .03 | .10 |
| (4,5,1) | .10 | .17 |
| (4,6,1) | .09 | .04 |
| (5,1,1) | .06 | .11 |
| (5,2,1) | .01 | .10 |
| (5,3,1) | .01 | .11 |
| (5,4,1) | .07 | .13 |
| (5,5,1) | .01 | .09 |
| (5,6,1) | .00 | .00 |
| (6,1,1) | .00 | .00 |
| (6,2,1) | .04 | .17 |
| (6,3,1) | .01 | .14 |
| (6,4,1) | .11 | .37 |
| (6,5,1) | .00 | .00 |
| (6,6,1) | .00 | .00 |
| (2,2,2) | .05 | .21 |
| (2,3,2) | .03 | .15 |
| (2,4,2) | .13 | .25 |
| (3,2,2) | .19 | .35 |
| (3,3,2) | .05 | .16 |
| (3,4,2) | .14 | .19 |
| (4,2,2) | .05 | .23 |
| (4,3,2) | .02 | .19 |
| (4,4,2) | .24 | .25 |
| (5,2,2) | .11 | .22 |
| (5,3,2) | .18 | .18 |
| (5,4,2) | .36 | .24 |

The diagonal elements of the resolution matrix associated with these average velocities are .52, .59, and .72, respectively. The resulting average of the travel-time residuals had a standard deviation of .014 seconds as compared to a value of .029 seconds for the applied noise, with a portion of the applied noise again being modeled.

## Results of Testing

The damped inversion, relative to the generalized inversion, shows an increase in the number of average velocities which cannot, at two standard deviations, be shown to be equivalent to the true values. Aki and Lee (1976) noted the fact that the uncertainties associated with the DLS approach were sometimes too small to depict the departure of the calculated velocity from the true value for blocks with high velocity resolvability. They claimed that this failure was due to the higher-order terms neglected in the linearization of the basic equations. While this is a possible source of error in all forms of least squares modeling, it should be noted that such errors are greatly reduced if a multi-step iterative procedure is used, as was done here. A more likely explanation is that the uncertainty associated with a smoothed estimate of some parameter is inadequate to define the possible departure of

the estimate from that parameter. It must be noted that this uncertainty is a measure of the possible error in the smoothed estimate and not the possible error in the parameter that the estimate is used to approximate. This is not unexpected, in that the more a given parameter is smoothed, the better it is defined by the data and the smaller its associated uncertainty becomes (e.g., a half-space is a smoothed block model, and is well resolved with low uncertainty). Also, the more a parameter is smoothed the less it represents that parameter which it is meant to estimate. For these reasons, only those smoothed parameters with relatively high resolution should be used to construct a final velocity model.

Repeated trials indicated that if a sufficient number of eigenvalues were to be removed in a generalized inversion to produce resolving kernels comparable to those obtained by a damped inversion, the resulting uncertainties of the associated parameters would also be similar. The reduced ability of the DLS approach, relative to the GLS approach, to reproduce the true velocity model is therefore a function of the reduced resolution and increased smoothing inherent in this approach.

Based on the above results it can be concluded that the generalized least squares approach more accurately reproduced the true model by means of its ability to provide

higher resolution. In addition, the only discrepancies that did occur between the calculated and true models for the generalized inversion were restricted to those velocities with associated diagonal elements of the resolving kernels with values less than .75.

Event Locations

The resulting event locations associated with these velocity models are presented in Appendix 6. A comparison of these locations with the true locations (Appendix 1) shows excellent agreement. The few, small discrepancies that do exist are confined to those events which have a poor azimuthal distribution of stations relative to the event location. It must be noted that this apparent ability to very accurately determine the event locations is a result of choosing the correct parametization of the model. This is not necessarily the case for the real data, as demonstrated by comparing the locations of given events for differing model configurations (see Appendix 5).

## Summary and Conclusions

The inclusion of velocity parameters in the hypocenter location problem provides a powerful technique for the interpretation of arrival times recorded by a local seismograph array. In this study, each event made available independent data (as much as the number of observed arrivals in excess of four) for the refinement of the velocity model. The complete set of arrivals provided sufficient velocity information to resolve, by classical least squares, a representative half-space model as well as an azimuthal velocity model. For models more complex than the azimuthal model it was necessary to use modified forms of the CLS technique, in order to stabilize the inversion. This improved stability allowed an additional number of velocity parameters to be included in the modeling problem. All of the methods used provided both resolution information and error estimates as a part of the complete solution of the problem. In addition, an improved set of hypocenter parameters and a set of station corrections were also obtained.

Initial attempts to model synthetic data demonstrated that the formulations used by other investigators were inadequate, in terms of stability and resolution, to allow for the modeling of the real data. However, the addition of an accurate ray-tracing technique, in conjunction with an

iterative procedure, markedly improved the performance of the inversion process. An additional modification involved the use of eigenvalue/eigenvector decomposition (GLS) to better control the smoothing of the parameters used to model the data, and thereby allowing for greater control of the final resolution obtained. It should be noted that this modification differs from that of Aki et al. (1977), in which decomposition was used to maximize rather than adjust the resolution. The resulting modified formulations (damped and generalized least squares) provided the necessary stability and control of resolution to allow for the inversion of the real data.

Both modified forms of the classical least squares approach (GLS and DLS) act to stabilize the inversion process by suppressing model changes in those parameters poorly defined by the data. The degree of smoothing performed by the resolving kernels is controlled by a damping factor in the case of DLS, and by the number of retained eigenvalues in the case of GLS. A trade-off between resolution and variance is common to both approaches, with the variance decreasing as the resolution becomes poorer. The generalized inverse provides the higher resolution of the two modified approaches, but is computationally more complex, requiring approximately three times the number of numerical calculations per solution.

As formulated, the methods are directly applicable to shear wave data and could be extended to include both P and S wave data. Such modifications could be used in determining a spatial distribution of Poisson's ratio beneath the array as well as providing additional data for the determination of event locations.

A number of test cases have been examined to illustrate various characteristics of the varied methods. Convergence is relatively rapid for the classical least squares approach and is somewhat slower for the modified forms, depending on the amount of smoothing desired. Small negative contributions to the smoothing kernels from using a modified least squares approach can produce distortions in the final model, leading to possible errors in the interpretation of the results. The resolving kernels provide a useful indication of this behavior as they provide information on the degree of smoothing in the final model.

In addition, these test cases demonstrated that the uncertainties associated with some smoothed estimates did not adequately define the departure of these estimates from the values that they were meant to approximate. Since this problem is a direct result of smoothing, it was not unexpected that the generalized least squares approach more accurately reproduced the true model by virtue of its inherent ability to provide higher resolution. This led to

the conclusion that, for the more complex models under investigation, the generalized least squares approach provided the most reliable results.

The initial attempt to model the real data was in terms of a half-space velocity model, the hypocenter parameters, and a set of station corrections. While CLS gave a stable inverse, a GLS approach was used in order to control the depths of certain events. The resulting set of station corrections provided the necessary adjustments to the arrival times to compensate for near-surface effects in this and subsequent models. The resulting hypocenter parameters and the half-space velocity (5.85 km/sec) were used as the initial model in all subsequent inversions.

The data were then analyzed for any possible azimuthal variations in the velocity. However, due to a poor azimuthal distribution of travel paths to peripheral stations of the array, only arrivals at the more centrally located stations could be used. The resulting azimuthal velocity model and uncertainties showed that, at two standard deviations, the resulting azimuthal velocity distribution was not significantly different from the half-space solution found previously. In addition, if an azimuthal velocity distribution does exist, it has a maximum azimuthal variation of less than .08 km/sec.

In order to learn something about possible lateral variations in the velocity, the area under consideration was divided into a 36 block (6x6) array. It was necessary to use modified forms of the CLS approach for this inversion as a classical inversion was no longer stable. The two modified least squares approaches provided statistically equivalent solutions at two standard deviations, with the generalized inversion providing the higher resolution. The resulting model (Fig. 7) obtained by generalized inversion defines two regions of low-velocity relative to adjacent blocks. Block(2,4), with an average velocity of 5.45 $\pm$.069(s.d.) km/sec, defines a region of uniquely low-velocity relative to adjacent blocks. Block(5,4), with an average velocity of 5.60 $\pm$.061(s.d.) km/sec, defines a region of anomalously low-velocity relative to blocks to the west and northwest.

The total number of blocks for which average velocities were determined was then increased from 36 to 48. The additional twelve blocks were constructed by subdividing the twelve well resolved centrally located blocks with an interface at a depth of four kilometers. This increase in the number of blocks provided for the solution of a velocity model with vertical as well as lateral variations in the velocity.

The resulting model (Fig. 9) showed that not one of the upper blocks could be shown to have a velocity that was statistically different (at two standard deviations) from the velocities of adjacent blocks. Of the lower blocks, four could be shown to have velocities that were statistically different (at two standard deviations) from the velocities of their corresponding upper blocks. Three of these velocities, 5.90 $\pm$.12, 6.15 $\pm$.12 and 6.24 $\pm$.11(s.d) km/sec, associated with blocks (2,2,2), (3,4,2) and (4,2,2) respectively, are higher than the velocities of their associated upper blocks. Conversely, the velocity of 5.17 $\pm$.11(s.d.) km/sec associated with block(5,2,2) is significantly lower than the velocity of 5.90 $\pm$.05(s.d.) km/sec associated with its upper block. In addition, the velocity of block(5,2,2) can be shown (at two standard deviations) to be lower than the velocities of adjacent blocks. Therefore, block(5,2,2) defines a region of anomalously low velocity relative to its upper block and all adjacent blocks.

The most outstanding feature of the final velocity structure model is the well resolved, uniquely low velocity of block(5,2,2). The maximum velocity that is possible for this block at three standard deviations (99% confidence level) is 5.51 km/sec. This is lower than the minimum velocity (at three standard deviations) of its corresponding upper block or any of its three adjacent lower blocks.

Several general observations can be made concerning the final velocity model. Most of the events used in this study occur in those blocks with average velocities which are less than the half-space velocity, leading to the conclusion that the cause of the lower-than-normal velocities may somehow be related to the instability causing the events. Notable exceptions are blocks (5,4,1) and (5,4,2) which have low velocities but are virtually aseismic.

While it has been possible to determine that the volume represented by block(5,2,2) has a uniquely low average velocity, it is a far more difficult problem to determine the cause of such a depressed velocity. However, the work of other investigators showed that the volume represented by block(5,2,2) was anomalous in other respects. Johnston (1978) showed that within block(5,2,2) there are four small volumes through which S and sometimes P phases are attenuated. In addition, Fender (1978) found that an anomalously high Poisson's ratio (indicating possible partial melt) exists along the southern boundary of block(5,2,2). It should be noted that the dissimilarity in the degree of resolution implied by these studies and that obtained in this work is due to differences in the parameters modeled (Poisson's ratios and attenuated phases versus P-wave velocities), and therefore not unexpected.

When reviewing the work of these and other investigators, Sanford and Schlue (1980) concluded that the volume represented by block(5,2,2) was a likely site for magmatic intrusion in the form of dikes and sills.

If the decrease in P-wave velocity associated with the formation of a rock melt is assumed to be 40% (Murase and McBirney, 1973), 30% of block(5,2,2) would have to be in the form of a melt in order to explain the observed decrease of approximately 12% in the average velocity of that block. In addition to the possible presence of magma, the fracturing associated with the events that occur within block(5,2,2) could also explain the observed decrease in velocity. It is to be expected that such fracturing, having some preferred orientation due to the existing stress field, would produce azimuthally dependent variations in the velocity. As no such variations were detected for the region as a whole, it must be noted that the determined azimuthal velocity is the average for the region and may not be representative for a given block within the region.

The degree of fracturing necessary to produce the observed decrease in velocity can be determined. O'Connell and Budiansky (1974) define a crack density parameter ($\varepsilon$) as $\varepsilon=N(a^3)$ where "N" is the number of cracks per unit volume and "a" is the radius of a typical circular crack. For a 12% decrease in the velocity, at a depth of four kilometers,

they determined that $\epsilon$ would equal 0.1 for dry cracks and 0.6 for saturated cracks. This corresponds to one dry crack or six saturated cracks of unit radius for every ten unit volumes. Therefore, either a sufficient amount of magma or a sufficient number of cracks could produce the observed decrease in velocity. However, it is more likely that a combination, rather than either one in particular, is the cause of the observed decrease. Consequently, depicting the volume represented by block(5,2,2) as a likely site of magmatic intrusion is supported by its low average velocity, as both the presence of magma and the apparent fracturing associated with its intrusion would depress the average velocity.

It is of interest to note that if a portion of block(5,2,2) were in the form of a melt, a gravity low would result, since igneous rocks generally decrease in density from 6 to 10% upon melting (Murase and McBirney, 1973). However, if 30% of block(5,2,2) were to be assumed to be in the form of a melt, and if the block were modeled in the form of a sphere with a radius of 5 km, the resulting anomaly at the surface directly above the body would be less than four milligals, decreasing to only half the maximum value at a distance of seven kilometers. In addition, if the melt and surrounding material were of differing compositions, the greatest density contrast possible would

increase the anomaly by only a few milligals. Therefore, gravity data could not be used as supportive evidence for such hypothesized magmatic intrusion at these depths.

Other possible sites of magma at high levels within the upper crust discussed in other studies are ESE of station "WT" and SW of station "BG" (Sanford and Schlue, 1980). An examination of Figs. 2 and 9 shows that the average velocities of the blocks encompassing these sites are lower than normal, thus lending possible support to these earlier studies.

The microearthquake activity within the recording array (Figs 15 and 16) is roughly centered on the extensive mid-crustal magma body (Sanford et al., 1979). However, most of this activity correlates with blocks of low average velocity (Fig. 9) and those regions of anomalous upper crust as defined by Sanford and Schlue (1980), with the highest activity occurring within block(5,2,2). Also of interest is the distribution of focal depths within block(5,2,2) which are anomalously deep when compared to the distribution established for the depths of all events occurring within the array (Dan Wieder, personal communication).

It should also be noted that beneath block(5,2,2) (Fig. 17) the mid-crustal magma body (Rinehart et al., 1979) terminates against the transverse shear zone of the northeast-

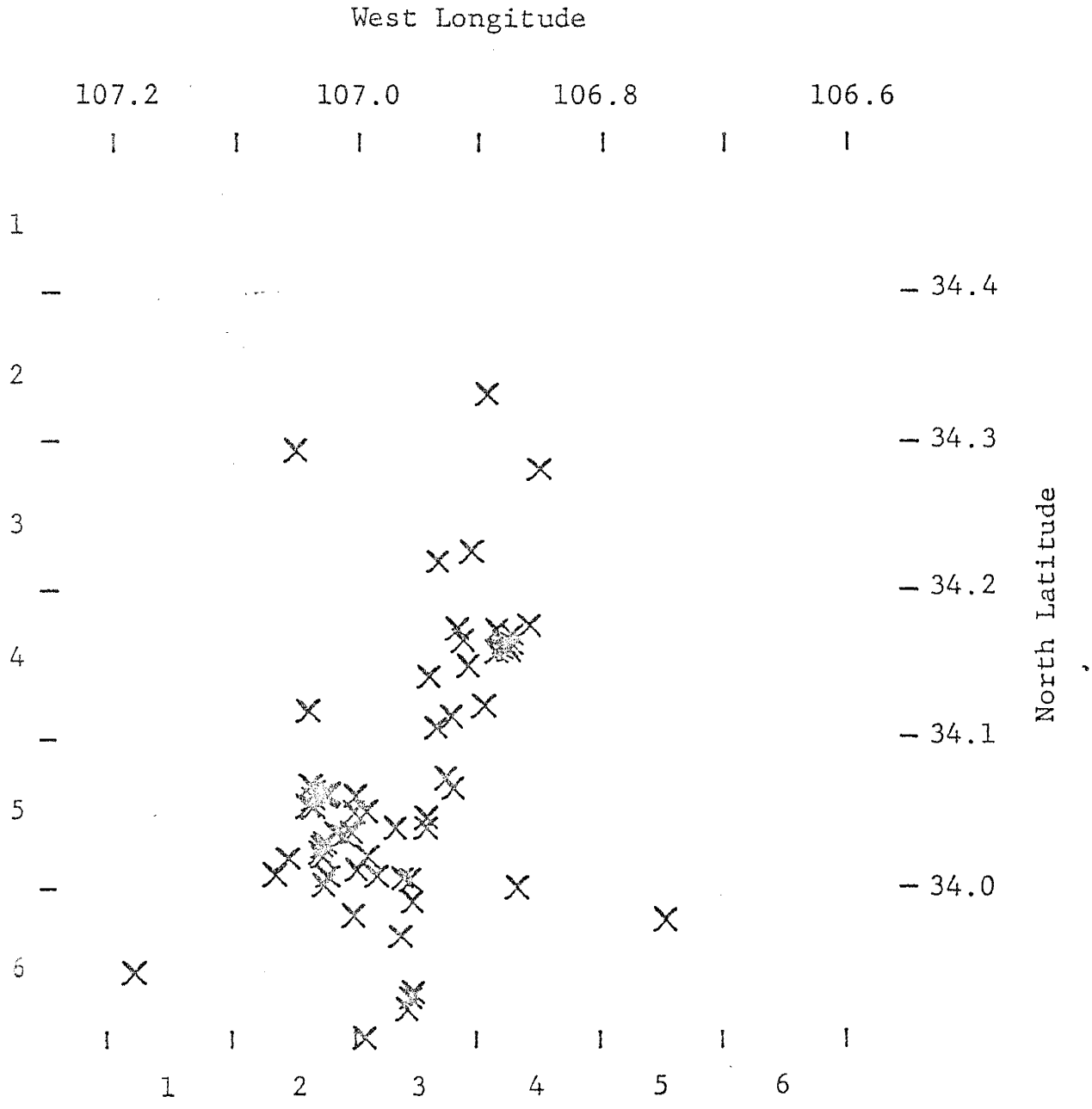



Figure 15. Spatial distribution of all events with depths less than four kilometers recorded by and located within the array.

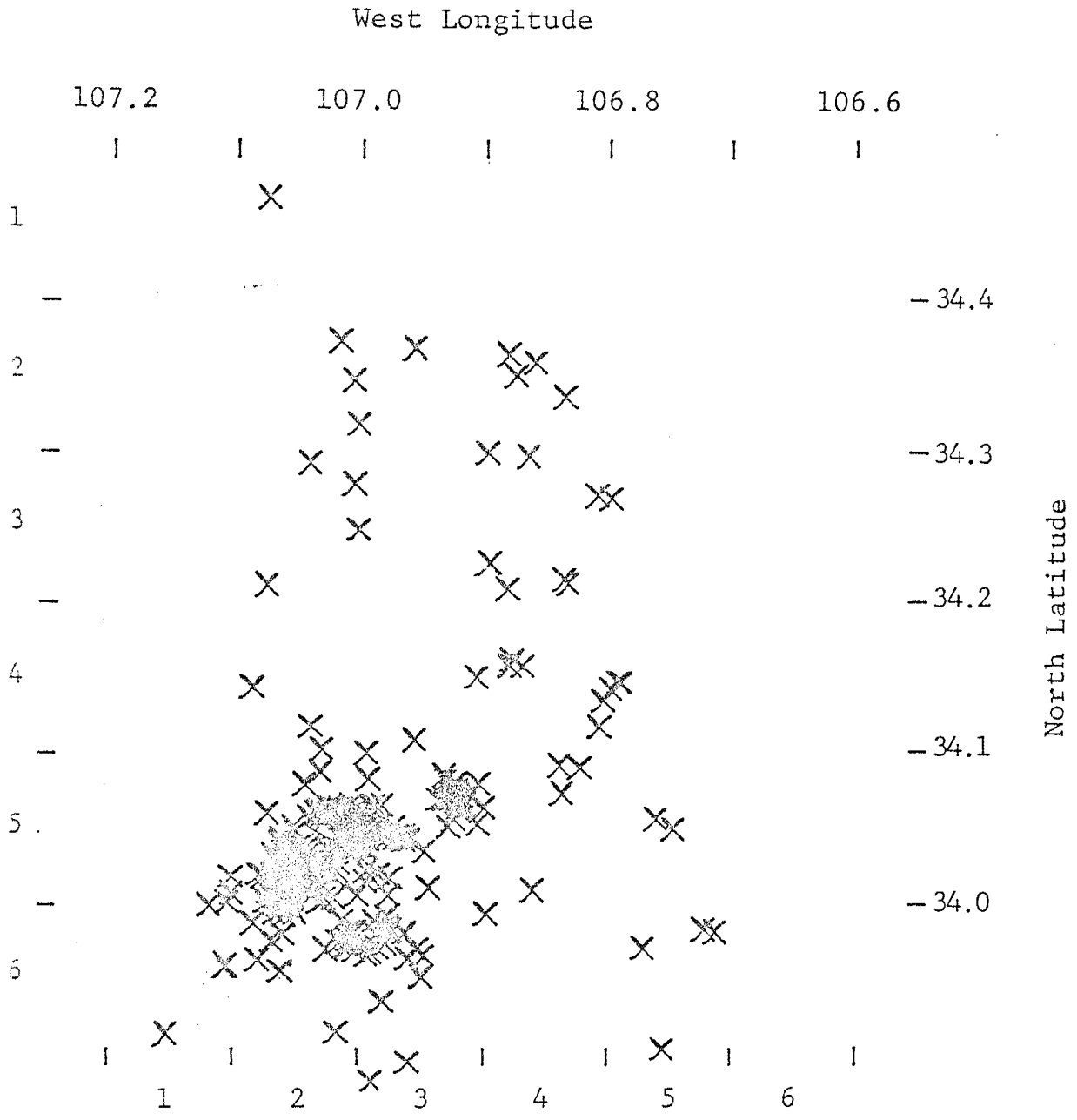



Figure 16. Spatial distribution of all events with depths greater than four kilometers recorded by and located within the array.

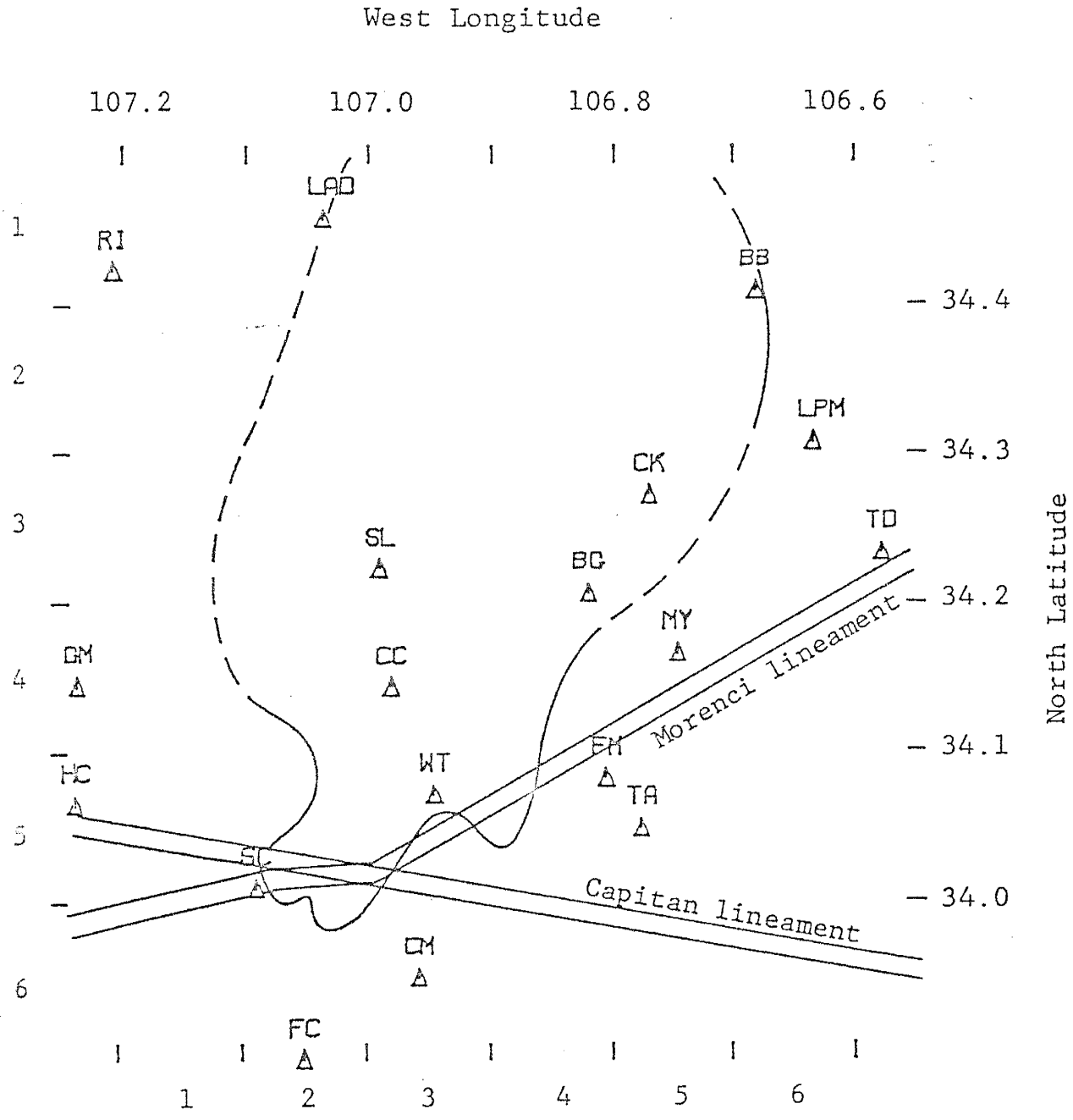



Figure 17. Location of mid-crustal magma body and transverse shear zone relative to block locations. Also shown is the location of the Capitan lineament.

trending Morenci lineament (Chapin, 1979). In addition, block (5,2,2) marks the point of intersection of the Morenci lineament with the west-northwest-trending Capitan lineament, an alignment of Tertiary aged intrusives and other structures (Chapin et al., 1975).

The very low average velocity of block(5,2,2) in conjunction with the observations of other investigators leads to the conclusion that magma is apparently intruding from the mid-crustal magma body into the volume defined by block(5,2,2). Intrusion of magma into the upper crust may have or may be occurring at other localities within the array as suggested by the anomalous characteristics of other blocks. However, based on velocity and event distribution, block(5,2,2) apparently represents the most active region of magmatic intrusion within the array.

Using modified forms of classical least squares, it has been possible to extract a detailed velocity model of the volume of interest from the P-wave arrival time data associated with local events and recorded on the local seismograph array. An immediate application of the resulting velocity information is as supportive evidence in the on-going investigation of possible sites of magmatic intrusion into the upper crust in the vicinity of Socorro, New Mexico. In addition, an improved set of hypocenter parameters and a set of station corrections were also obtained.

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# APPENDIX 1

Appendix 1 contains the event locations associated with a half-space velocity of 5.85 km/sec. These source parameters are used as the initial estimates in subsequent refinements of the velocity model. It should be noted that the depths are relative to a datum 1.5 km above sea level. In addition to source parameters, associated parameter weights are also given within this appendix. It should also be mentioned that the path parameter weights used in this study were .1 km/sec for those velocities associated with upper blocks and .2 km/sec for those associtated with lower blocks.

| | | |
|---|---|---|
| EVENT # 1 | DATE: 8-12-75 | |
| LATITUDE: 34.0180 | | 1.00 (km) |
| LONGITUDE: 106.7900 | | 1.00 (km) |
| DEPTH: 3.00 | | 3.00 (km) |
| ORIGIN TIME: 7: 9:10.76 | | .30 (sec) |
| EVENT # 2 | DATE: 8-12-75 | |
| LATITUDE: 34.0370 | | 1.00 (km) |
| LONGITUDE: 106.9930 | | 1.00 (km) |
| DEPTH: 6.00 | | 3.00 (km) |
| ORIGIN TIME: 15:25:28.63 | | .30 (sec) |
| EVENT # 3 | DATE: 8-13-75 | |
| LATITUDE: 34.2360 | | 1.00 (km) |
| LONGITUDE: 107.0890 | | 1.00 (km) |
| DEPTH:11.00 | | 1.00 (km) |
| ORIGIN TIME: 5:29:49.12 | | .30 (sec) |
| EVENT # 4 | DATE: 8-13-75 | |
| LATITUDE: 34.0680 | | 1.00 (km) |
| LONGITUDE: 106.9200 | | 1.00 (km) |
| DEPTH: 8.50 | | 3.00 (km) |
| ORIGIN TIME: 7:39:18.45 | | .30 (sec) |
| EVENT # 5 | DATE: 8-13-75 | |
| LATITUDE: 34.0020 | | 1.00 (km) |
| LONGITUDE: 106.9740 | | 1.00 (km) |
| DEPTH:10.00 | | 1.00 (km) |
| ORIGIN TIME: 11:22:26.67 | | .30 (sec) |

| | | |
|---|---|---|
| EVENT # 6 | DATE: 1-29-76 | |
| LATITUDE: 33.9690 | | 1.00 (km) |
| LONGITUDE: 106.9810 | | 1.00 (km) |
| DEPTH: 8.70 | | 1.00 (km) |
| ORIGIN TIME: 15: 6:39.94 | | .30 (sec) |
| EVENT # 7 | DATE: 4-13-76 | |
| LATITUDE: 34.0620 | | 1.00 (km) |
| LONGITUDE: 107.0100 | | 1.00 (km) |
| DEPTH: 6.00 | | 1.00 (km) |
| ORIGIN TIME: 9:45:40.70 | | .30 (sec) |
| EVENT # 8 | DATE: 4-13-76 | |
| LATITUDE: 33.9710 | | 1.00 (km) |
| LONGITUDE: 106.9590 | | 1.00 (km) |
| DEPTH: 7.30 | | 1.00 (km) |
| ORIGIN TIME: 11:58:34.43 | | .30 (sec) |
| EVENT # 9 | DATE: 4-16-76 | |
| LATITUDE: 34.0580 | | 1.00 (km) |
| LONGITUDE: 107.0040 | | 1.00 (km) |
| DEPTH: 7.30 | | 1.00 (km) |
| ORIGIN TIME: 14: 7:33.33 | | .30 (sec) |
| EVENT #10 | DATE: 4-20-76 | |
| LATITUDE: 34.0980 | | 1.00 (km) |
| LONGITUDE: 106.8420 | | 1.00 (km) |
| DEPTH: 3.00 | | 3.00 (km) |
| ORIGIN TIME: 8:32:19.35 | | .30 (sec) |

| | | |
|---|---|---|
| EVENT #11 | DATE: 4-21-76 | |
| LATITUDE: 34.2930 | | 1.00 (km) |
| LONGITUDE: 106.8400 | | 1.00 (km) |
| DEPTH: 4.70 | | 1.00 (km) |
| ORIGIN TIME: 11:16:19.92 | | .30 (sec) |
| EVENT #12 | DATE: 7-15-76 | |
| LATITUDE: 34.0260 | | 1.00 (km) |
| LONGITUDE: 107.0610 | | 1.00 (km) |
| DEPTH: 9.00 | | 1.00 (km) |
| ORIGIN TIME: 16:43: 7.83 | | .30 (sec) |
| EVENT #13 | DATE: 8-12-76 | |
| LATITUDE: 34.0390 | | 1.00 (km) |
| LONGITUDE: 106.9960 | | 1.00 (km) |
| DEPTH: 9.00 | | 1.00 (km) |
| ORIGIN TIME: 0:59: 8.07 | | .30 (sec) |
| EVENT #14 | DATE: 9- 3-76 | |
| LATITUDE: 33.9670 | | 1.00 (km) |
| LONGITUDE: 106.9890 | | 1.00 (km) |
| DEPTH: 8.00 | | 3.00 (km) |
| ORIGIN TIME: 6:45:56.34 | | .30 (sec) |
| EVENT #15 | DATE: 9- 3-76 | |
| LATITUDE: 34.1390 | | 1.00 (km) |
| LONGITUDE: 106.8660 | | 1.00 (km) |
| DEPTH: 7.00 | | 3.00 (km) |
| ORIGIN TIME: 9:13: 2.29 | | .30 (sec) |

EVENT #16 DATE: 4-19-77

| | |
|---|---|
| LATITUDE: 33.9930 | 1.00 (km) |
| LONGITUDE: 106.9510 | 1.00 (km) |
| DEPTH: 3.00 | 3.00 (km) |
| ORIGIN TIME: 16:40:20.16 | .30 (sec) |

EVENT #17 DATE: 4-28-77

| | |
|---|---|
| LATITUDE: 34.0420 | 1.00 (km) |
| LONGITUDE: 107.0510 | 1.00 (km) |
| DEPTH: 9.10 | 1.00 (km) |
| ORIGIN TIME: 10:59:10.50 | .30 (sec) |

EVENT #18 DATE: 6- 4-77

| | |
|---|---|
| LATITUDE: 34.2250 | 1.00 (km) |
| LONGITUDE: 106.9010 | 1.00 (km) |
| DEPTH: 3.00 | 3.00 (km) |
| ORIGIN TIME: 6:18:51.78 | .30 (sec) |

EVENT #19 DATE: 7-14-77

| | |
|---|---|
| LATITUDE: 34.1560 | 1.00 (km) |
| LONGITUDE: 106.8650 | 1.00 (km) |
| DEPTH: 7.50 | 3.00 (km) |
| ORIGIN TIME: 10: 0:32.69 | .30 (sec) |

EVENT #20 DATE: 8-17-77

| | |
|---|---|
| LATITUDE: 34.1650 | 1.00 (km) |
| LONGITUDE: 106.8650 | 1.00 (km) |
| DEPTH: 5.80 | 1.00 (km) |
| ORIGIN TIME: 6: 3:20.03 | .30 (sec) |

EVENT #21 DATE: 8-18-77

| | |
|---|---|
| LATITUDE: 34.0220 | 1.00 (km) |
| LONGITUDE: 107.0580 | 1.00 (km) |
| DEPTH: 7.50 | 3.00 (km) |
| ORIGIN TIME: 10:38:14.96 | .30 (sec) |

EVENT #22 DATE: 8-25-77

| | |
|---|---|
| LATITUDE: 33.9640 | 1.00 (km) |
| LONGITUDE: 106.9560 | 1.00 (km) |
| DEPTH: 6.50 | 3.00 (km) |
| ORIGIN TIME: 4:52:32.96 | .30 (sec) |

EVENT #23 DATE: 8-25-77

| | |
|---|---|
| LATITUDE: 34.0040 | 1.00 (km) |
| LONGITUDE: 107.0590 | 1.00 (km) |
| DEPTH:10.50 | 3.00 (km) |
| ORIGIN TIME: 6:26:26.84 | .30 (sec) |

EVENT #24 DATE: 8-26-77

| | |
|---|---|
| LATITUDE: 33.9520 | 1.00 (km) |
| LONGITUDE: 106.9470 | 1.00 (km) |
| DEPTH: 7.50 | 3.00 (km) |
| ORIGIN TIME: 10:35:46.38 | .30 (sec) |

EVENT #25 DATE: 9- 1-77

| | |
|---|---|
| LATITUDE: 34.0560 | 1.00 (km) |
| LONGITUDE: 106.7640 | 1.00 (km) |
| DEPTH: 6.50 | 1.00 (km) |
| ORIGIN TIME: 18:20: 2.48 | .30 (sec) |

EVENT #26 DATE: 9-14-77

| | |
|---|---|
| LATITUDE: 34.5000 | 1.00 (km) |
| LONGITUDE: 106.8950 | 1.00 (km) |
| DEPTH: 8.50 | 3.00 (km) |
| ORIGIN TIME: 13: 9:24.04 | .30 (sec) |

EVENT #27 DATE: 9-15-77

| | |
|---|---|
| LATITUDE: 34.2600 | 1.00 (km) |
| LONGITUDE: 106.9210 | 1.00 (km) |
| DEPTH: 3.00 | 3.00 (km) |
| ORIGIN TIME: 1: 1:34.48 | .30 (sec) |

EVENT #28 DATE: 9-20-77

| | |
|---|---|
| LATITUDE: 34.1550 | 1.00 (km) |
| LONGITUDE: 106.8700 | 1.00 (km) |
| DEPTH: 5.00 | 1.00 (km) |
| ORIGIN TIME: 8:19:23.28 | .30 (sec) |

EVENT #29 DATE: 9-22-77

| | |
|---|---|
| LATITUDE: 34.3350 | 1.00 (km) |
| LONGITUDE: 106.8800 | 1.00 (km) |
| DEPTH: 9.20 | 1.00 (km) |
| ORIGIN TIME: 19:19:16.86 | .30 (sec) |

EVENT #30 DATE: 10-18-77

| | |
|---|---|
| LATITUDE: 34.0200 | 1.00 (km) |
| LONGITUDE: 107.0580 | 1.00 (km) |
| DEPTH: 8.10 | 1.00 (km) |
| ORIGIN TIME: 8:16:32.89 | .30 (sec) |

| | | |
|---|---|---|
| EVENT #31 | DATE: 11-15-77 | |
| LATITUDE: 34.0050 | | 1.00 (km) |
| LONGITUDE: 106.8280 | | 1.00 (km) |
| DEPTH:14.00 | | 3.00 (km) |
| ORIGIN TIME: 0:42:38.74 | | .30 (sec) |
| EVENT #32 | DATE: 11-15-77 | |
| LATITUDE: 34.1410 | | 1.00 (km) |
| LONGITUDE: 106.8870 | | 1.00 (km) |
| DEPTH: 4.25 | | 3.00 (km) |
| ORIGIN TIME: 19: 2:41.85 | | .30 (sec) |
| EVENT #33 | DATE: 11-18-77 | |
| LATITUDE: 34.0620 | | 1.00 (km) |
| LONGITUDE: 106.7770 | | 1.00 (km) |
| DEPTH:10.50 | | 3.00 (km) |
| ORIGIN TIME: 14:22:18.12 | | .30 (sec) |
| EVENT #34 | DATE: 12- 5-77 | |
| LATITUDE: 34.4200 | | 1.00 (km) |
| LONGITUDE: 107.0900 | | 1.00 (km) |
| DEPTH: 7.10 | | 1.00 (km) |
| ORIGIN TIME: 20:57:19.32 | | .30 (sec) |
| EVENT #35 | DATE: 12-15-77 | |
| LATITUDE: 34.3250 | | 1.00 (km) |
| LONGITUDE: 107.0460 | | 1.00 (km) |
| DEPTH:10.00 | | 1.00 (km) |
| ORIGIN TIME: 17:15:40.59 | | .30 (sec) |

| | | |
|---|---|---|
| EVENT #36 | DATE: 12-21-77 | |
| LATITUDE: 34.2700 | | 1.00 (km) |
| LONGITUDE: 106.8640 | | 1.00 (km) |
| DEPTH: 3.50 | | 3.00 (km) |
| ORIGIN TIME: 2:59:39.04 | | .30 (sec) |
| EVENT #37 | DATE: 1- 5-78 | |
| LATITUDE: 34.2720 | | 1.00 (km) |
| LONGITUDE: 106.8900 | | 1.00 (km) |
| DEPTH: 7.00 | | 3.00 (km) |
| ORIGIN TIME: 12: 3:23.32 | | .30 (sec) |
| EVENT #38 | DATE: 1-17-78 | |
| LATITUDE: 34.3120 | | 1.00 (km) |
| LONGITUDE: 106.7250 | | 1.00 (km) |
| DEPTH:11.50 | | 1.00 (km) |
| ORIGIN TIME: 5: 5: 0.98 | | .30 (sec) |
| EVENT #39 | DATE: 1-17-78 | |
| LATITUDE: 34.3500 | | 1.00 (km) |
| LONGITUDE: 106.8710 | | 1.00 (km) |
| DEPTH: 7.00 | | 1.00 (km) |
| ORIGIN TIME: 23:14:21.37 | | .30 (sec) |
| EVENT #40 | DATE: 1-18-78 | |
| LATITUDE: 34.1540 | | 1.00 (km) |
| LONGITUDE: 106.8530 | | 1.00 (km) |
| DEPTH: 7.50 | | 1.00 (km) |
| ORIGIN TIME: 12:24:32.58 | | .30 (sec) |

# APPENDIX 2

Appendix 2 contains the arrival time data used in this study. Observational weights, also presented within this Appendix, are a combination of the assumed reading error and the uncertainty in the associated station corrections. In addition to the data and weights the travel-time residuals associated with each model are also presented.

EVENT # 1 DATE: 08-12-75 ORIGIN TIME: 07:09:10

UNMODELED RESIDUALS (seconds)

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| FM | 09:12.05 | .025 | .014 | .019 | -.010 | .010 | .006 |
| WT | 09:13.16 | .025 | -.064 | -.060 | -.045 | -.057 | -.055 |
| CM | 09:13.78 | .025 | -.003 | .003 | -.011 | -.006 | -.004 |
| MY | 09:13.61 | .030 | -.018 | -.027 | -.004 | -.021 | -.020 |
| CC | 09:14.41 | .025 | .039 | .042 | .025 | .029 | .035 |
| SC | 09:15.58 | .025 | .028 | .015 | .023 | .027 | .020 |

EVENT # 2 DATE: 08-12-75 ORIGIN TIME: 15:25:28

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| WT | 25:29.99 | .025 | .026 | .025 | .017 | .018 | .006 |
| SC | 25:30.78 | .025 | .043 | .041 | .025 | .024 | .011 |
| CM | 25:30.77 | .025 | -.050 | -.051 | -.029 | -.028 | -.013 |
| CC | 25:30.69 | .025 | -.059 | -.056 | -.037 | -.038 | -.017 |
| FM | 25:31.93 | .025 | .038 | .045 | .015 | .008 | .006 |
| MY | 25:33.26 | .030 | .007 | -.005 | .014 | .022 | .009 |

EVENT # 3 DATE: 08-13-75 ORIGIN TIME: 05:29:49

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CC | 29:51.64 | .025 | -.018 | -.027 | -.030 | -.027 | -.018 |
| WT | 29:52.96 | .025 | .048 | .069 | .080 | .081 | .084 |
| SC | 29:53.67 | .025 | .029 | .005 | .006 | .000 | .016 |
| FM | 29:54.47 | .025 | -.007 | -.016 | -.014 | -.017 | -.015 |
| MY | 29:54.70 | .040 | .024 | .011 | .004 | .002 | .018 |
| CM | 29:54.95 | .025 | -.060 | -.036 | -.044 | -.039 | -.065 |

EVENT # 4 DATE: 08-13-75 ORIGIN TIME: 07:39:18

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| WT | 39:19.83 | .025 | -.009 | -.012 | -.003 | .001 | -.001 |
| CC | 39:20.52 | .025 | .027 | .027 | .036 | .034 | .035 |
| FM | 39:20.86 | .025 | -.016 | -.007 | -.037 | -.041 | -.037 |
| CM | 39:21.39 | .025 | .033 | .028 | .054 | .055 | .053 |
| SC | 39:21.78 | .025 | -.034 | -.029 | -.058 | -.061 | -.058 |
| MY | 39:22.04 | .030 | -.000 | -.010 | .012 | .018 | .014 |

EVENT # 5 DATE: 08-13-75 ORIGIN TIME: 11:22:26

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CM | 22:28.83 | .025 | -.030 | -.032 | -.021 | -.019 | .000 |
| WT | 22:28.78 | .025 | .043 | .026 | .026 | .025 | .014 |
| SC | 22:29.44 | .025 | .025 | .029 | .020 | .018 | .003 |
| CC | 22:29.59 | .035 | -.104 | -.091 | -.075 | -.073 | -.023 |
| FM | 22:30.22 | .025 | .019 | .034 | .007 | .001 | -.020 |
| MY | 22:31.65 | .030 | -.006 | -.016 | .009 | .016 | .023 |

EVENT # 6 DATE: 01-29-76 ORIGIN TIME: 15:06:40

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CM | 06:41.65 | .025 | -.042 | -.022 | -.015 | -.014 | -.013 |
| SC | 06:42.59 | .025 | .060 | .028 | .019 | .020 | .017 |
| WT | 06:42.23 | .025 | -.010 | .043 | .030 | .020 | .024 |
| CC | 06:43.25 | .025 | -.081 | -.075 | -.052 | -.047 | -.045 |
| TA | 06:43.90 | .040 | -.002 | -.044 | -.026 | -.039 | -.037 |
| DM | 06:44.02 | .025 | .080 | .043 | .028 | .038 | .032 |

EVENT # 7 DATE: 04-13-76 ORIGIN TIME: 09:45:40

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| WM | 45:42.37 | .030 | .040 | .038 | .036 | .037 | .014 |
| WT | 45:42.06 | .025 | -.045 | -.046 | -.045 | -.045 | -.032 |
| IC | 45:42.68 | .025 | .053 | .063 | .056 | .055 | .045 |
| SC | 45:42.76 | .025 | -.037 | -.037 | -.034 | -.034 | -.021 |
| CC | 45:42:49 | .025 | .026 | .026 | .026 | .026 | .019 |
| CM | 45:43.33 | .025 | -.068 | -.033 | -.029 | -.028 | -.019 |

EVENT # 8 DATE: 04-13-76 ORIGIN TIME: 11:58:34

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CM | 58:36.01 | .025 | .026 | .026 | -.005 | -.005 | -.009 |
| IC | 58:35.94 | .025 | -.008 | -.004 | .031 | .032 | .038 |
| WM | 58:36.02 | .030 | -.071 | -.018 | -.023 | -.024 | -.019 |
| WT | 58:36.56 | .025 | -.009 | -.019 | -.022 | -.024 | -.023 |
| SC | 58:37.16 | .025 | .029 | -.013 | -.016 | -.017 | -.020 |
| CC | 58:37.84 | .035 | .084 | .045 | .054 | .058 | .051 |

EVENT # 9 DATE: 04-16-76 ORIGIN TIME: 14:07:33

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| WM | 07:35.04 | .030 | .027 | .025 | .029 | .030 | .012 |
| WT | 07:34.77 | .025 | -.040 | -.038 | -.040 | -.040 | -.027 |
| IC | 07:35.37 | .025 | .056 | .054 | .051 | .050 | .043 |
| SC | 07:35.55 | .025 | -.035 | -.032 | -.032 | -.032 | -.019 |
| CC | 07:35.31 | .025 | .026 | .024 | .026 | .026 | .016 |
| CM | 07:36.04 | .025 | -.032 | -.026 | -.026 | -.025 | -.019 |

EVENT # 10 DATE: 04-20-76 ORIGIN TIME: 08:32:19

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| DM | 32:20.13 | .025 | .004 | .009 | .006 | .009 | .007 |
| CU | 32:20.80 | .030 | -.022 | -.021 | -.005 | -.003 | .001 |
| WT | 32:21.08 | .025 | .007 | .008 | .003 | .003 | -.001 |
| BG | 32:21.44 | .025 | .007 | -.000 | -.009 | -.013 | -.020 |
| CC | 32:21.58 | .025 | -.023 | -.038 | -.026 | -.028 | -.025 |
| SL | 32:22.64 | .030 | .065 | .051 | .043 | .051 | .055 |

EVENT # 11 DATE: 04-21-76 ORIGIN TIME: 11:16:19

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 16:21.80 | .025 | .041 | .015 | .000 | .006 | -.002 |
| SL | 16:22.64 | .025 | .011 | .016 | .031 | .023 | .017 |
| CU | 16:22.71 | .030 | .013 | -.075 | -.010 | -.002 | .016 |
| LPM | 16:23.00 | .025 | -.071 | | -.013 | -.021 | -.022 |
| DM | 16:23.62 | .025 | .061 | .048 | .041 | .046 | .022 |
| CC | 16:23.34 | .025 | -.102 | -.044 | -.073 | -.079 | -.077 |
| LAD | 16:24.20 | .025 | .052 | | .007 | .014 | .007 |
| WT | 16:24.38 | .035 | -.003 | .031 | .028 | .025 | .017 |

EVENT # 12 DATE: 07-15-76 ORIGIN TIME: 16:43:07

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| SC | 43:09.69 | .025 | .010 | | .008 | .009 | .004 |
| RM | 43:10.09 | .040 | -.002 | | -.028 | -.030 | -.008 |
| NG | 43:10.16 | .025 | -.003 | | -.002 | -.001 | .003 |
| WT | 43:10.33 | .025 | -.002 | | .006 | .006 | -.005 |
| HC | 43:11.29 | .040 | -.036 | | -.035 | -.040 | -.050 |
| GM | 43:11.75 | .025 | .009 | | .012 | .014 | .019 |

EVENT # 13 DATE: 08-12-76 ORIGIN TIME: 00:59:08

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| WT | 59:10.07 | .025 | -.012 | | -.014 | -.015 | -.014 |
| SC | 59:10.62 | .025 | .025 | | .015 | .018 | .014 |
| NG | 59:10.59 | .025 | .004 | | .010 | .009 | .009 |
| FC | 59:11.81 | .040 | -.016 | | -.006 | -.003 | -.003 |
| HC | 59:12.36 | .030 | -.069 | | -.076 | -.083 | -.073 |
| GM | 59:12.63 | .025 | .032 | | .043 | .046 | .042 |

EVENT # 14 DATE: 09-03-76 ORIGIN TIME: 06:45:56

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| NG | 45:57.89 | .025 | .000 | | -.005 | -.005 | -.012 |
| TS | 45:58.90 | .040 | .006 | | .007 | .007 | .003 |
| SC | 45:58.79 | .025 | -.016 | | .007 | .007 | .010 |
| WT | 45:58.76 | .025 | -.001 | | .002 | .001 | .010 |
| HC | 46:01.10 | .030 | .001 | | -.009 | -.014 | .024 |
| GM | 46:01.65 | .025 | .006 | | -.001 | .002 | -.027 |

EVENT # 15 DATE: 09-03-76 ORIGIN TIME: 09:13:02

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| WT | 13:04.37 | .025 | .005 | | .007 | .010 | .003 |
| NG | 13:06.52 | .025 | -.003 | | .005 | .001 | .030 |
| SC | 13:06.84 | .035 | -.103 | | -.069 | -.053 | -.057 |
| TS | 13:08.27 | .040 | .019 | | -.002 | .007 | -.061 |
| GM | 13:08.16 | .025 | -.020 | | -.028 | -.034 | -.045 |
| HC | 13:08.70 | .030 | .096 | | .077 | .078 | .084 |

EVENT # 16 DATE: 04-19-77 ORIGIN TIME: 16:40:20

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CM | 40:21.34 | .025 | .001 | .000 | .010 | .012 | .007 |
| WT | 40:21.61 | .025 | .005 | -.000 | -.009 | -.009 | .004 |
| SC | 40:22.56 | .025 | -.008 | -.000 | -.019 | -.024 | -.023 |
| CC | 40:22.90 | .025 | -.010 | .000 | .024 | .026 | -.001 |
| DM | 40:23.32 | .025 | .001 | -.000 | -.011 | -.013 | -.008 |
| GM | 40:25.41 | .025 | .012 | | .005 | .008 | .019 |

EVENT # 17 DATE: 04-28-77 ORIGIN TIME: 10:59:10

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| SC | 59:12.48 | .025 | -.004 | -.009 | -.018 | -.017 | -.012 |
| WT | 59:12.72 | .025 | .013 | -.002 | .015 | .013 | .013 |
| CC | 59:13.03 | .025 | .020 | .013 | .009 | .010 | -.003 |
| CM | 59:13.58 | .050 | .031 | .052 | .071 | .069 | .030 |
| GM | 59:14.32 | .025 | -.007 | | .005 | .004 | .006 |
| DM | 59:14.86 | .025 | -.032 | -.016 | -.029 | -.028 | -.014 |

EVENT # 18 DATE: 06-04-77 ORIGIN TIME: 06:18:51

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| DM | 18:54.51 | .025 | .016 | | .008 | .004 | -.005 |
| WT | 18:54.68 | .035 | -.034 | | -.023 | -.033 | -.016 |
| LPM | 18:56.07 | .025 | .011 | | .002 | .009 | .016 |
| LAD | 18:56.44 | .025 | -.027 | | -.008 | -.016 | -.022 |
| CM | 18:57.24 | .025 | -.020 | | -.007 | -.006 | -.011 |
| GM | 18:57.27 | .025 | .033 | | .014 | .024 | .028 |

EVENT # 19 DATE: 07-14-77 ORIGIN TIME: 10:00:32

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 00:34.45 | .025 | .028 | .003 | .035 | .040 | .030 |
| DM | 00:34.46 | .025 | -.053 | -.019 | -.052 | -.051 | -.028 |
| CC | 00:34.80 | .025 | .030 | .025 | .019 | .011 | -.007 |
| CM | 00:37:34 | .035 | .135 | .099 | .131 | .131 | .088 |
| SC | 00:37.51 | .025 | -.029 | -.059 | -.038 | -.037 | -.017 |
| LPM | 00:37.31 | .035 | .001 | | -.007 | -.015 | -.031 |
| GM | 00:38.56 | .025 | -.041 | | -.021 | -.015 | -.020 |
| LAD | 00:38.91 | .035 | -.002 | | -.014 | -.015 | .014 |

EVENT # 20 DATE: 08-17-77 ORIGIN TIME: 06:03:20

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 03:21.53 | .025 | .011 | -.013 | .007 | .010 | .001 |
| DM | 03:21.73 | .035 | -.100 | .039 | -.031 | -.033 | -.018 |
| CC | 03:21.91 | .025 | .057 | .025 | .036 | .035 | .036 |
| WT | 03:22.21 | .025 | -.028 | -.035 | -.043 | -.047 | -.041 |
| CM | 03:24.67 | .025 | .039 | .004 | .044 | .046 | .032 |
| GM | 03:25.77 | .025 | -.058 | | -.028 | -.022 | -.033 |
| LAD | 03:26.08 | .035 | -.012 | | -.004 | -.013 | -.014 |

EVENT # 21 DATE: 08-18-77 ORIGIN TIME: 10:38:14

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| SC | 38:16.63 | .025 | .037 | .026 | .032 | .037 | .037 |
| WT | 38:17.24 | .025 | -.015 | .016 | -.004 | -.009 | -.001 |
| CM | 38:17.57 | .025 | -.038 | -.041 | -.028 | -.030 | -.039 |
| CC | 38:17.68 | .025 | -.049 | -.056 | -.049 | -.052 | -.054 |
| GM | 38:18.75 | .025 | -.010 | | -.014 | -.016 | -.013 |
| DM | 38:19.48 | .025 | .042 | .051 | .018 | .016 | .033 |
| BG | 38:20.29 | .025 | .036 | .005 | .036 | .047 | .031 |
| LAD | 38:23.08 | .035 | -.006 | | .016 | .015 | .009 |

EVENT # 22 DATE: 08-25-77 ORIGIN TIME: 04:52:33

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CM | 52:34.31 | .050 | .034 | .076 | .083 | .084 | .088 |
| NG | 52:34.37 | .025 | -.007 | -.023 | -.022 | -.022 | -.032 |
| SC | 52:35.68 | .025 | -.011 | -.000 | -.007 | -.008 | .010 |
| CC | 52:36.47 | .025 | .040 | .021 | .026 | .024 | .019 |
| BG | 52:38.16 | .035 | -.032 | -.033 | -.043 | -.041 | -.026 |
| GM | 52:38.63 | .025 | .006 | | .003 | .004 | -.007 |

EVENT # 23 DATE: 08-25-77 ORIGIN TIME: 06:26:26

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| SC | 26:28.90 | .025 | -.025 | -.012 | -.024 | -.019 | -.014 |
| NG | 26:29.25 | .025 | .004 | -.006 | -.004 | -.005 | -.021 |
| CM | 26:29.66 | .025 | .010 | .018 | .014 | .012 | .019 |
| WT | 26:29.60 | .025 | .003 | -.011 | .013 | .007 | .022 |
| CC | 26:30.18 | .025 | .037 | .035 | .031 | .028 | .006 |
| GM | 26:31.07 | .025 | .014 | | .014 | .012 | .018 |
| BG | 26:32.51 | .025 | -.031 | -.024 | -.032 | -.023 | -.019 |
| LAD | 26:35.38 | .035 | -.045 | | -.023 | -.025 | -.029 |

EVENT # 24 DATE: 08-26-77 ORIGIN TIME: 10:35:46

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CM | 35:47.86 | .025 | -.009 | -.000 | .003 | .004 | -.006 |
| NG | 35:48.07 | .025 | .002 | -.013 | -.013 | -.013 | -.010 |
| WT | 35:48.93 | .025 | .027 | .031 | .027 | .025 | .009 |
| SC | 35:49.40 | .025 | .003 | .013 | .005 | .004 | .024 |
| CC | 35:50.07 | .035 | -.081 | -.059 | -.045 | -.043 | -.022 |
| BG | 35:51.78 | .035 | -.018 | -.001 | -.007 | -.006 | .012 |
| GM | 35:52.32 | .025 | -.000 | | .004 | .005 | -.017 |

EVENT # 25 DATE: 09-01-77 ORIGIN TIME: 18:20:02

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| WT | 20:05.48 | .025 | -.011 | -.007 | -.001 | .009 | .002 |
| BG | 20:05.65 | .025 | -.006 | -.003 | -.005 | -.006 | -.006 |
| CM | 20:06.46 | .025 | .003 | -.002 | .015 | .015 | .024 |
| CC | 20:06.30 | .025 | .014 | .012 | .012 | .011 | .012 |
| NG | 20:06.80 | .025 | .002 | .012 | -.005 | -.007 | -.017 |
| SC | 20:07.91 | .035 | -.039 | -.025 | -.043 | -.047 | -.039 |
| GM | 20:10.06 | .025 | .012 | | .007 | .001 | -.002 |

EVENT # 26 DATE: 09-14-77 ORIGIN TIME: 13:09:24

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| LAD | 09:26.62 | .025 | .006 | | .003 | .004 | .004 |
| RI | 09:29.36 | .030 | -.015 | | .001 | -.006 | -.007 |
| BG | 09:29.99 | .050 | .026 | | -.025 | -.085 | -.019 |
| CC | 09:30.99 | .025 | -.008 | | -.003 | .005 | -.010 |
| TD | 09:31.26 | .030 | -.003 | | .001 | .012 | .005 |
| GM | 09:32.78 | .025 | .020 | | -.005 | -.012 | .010 |
| SC | 09:34.18 | .035 | .015 | | .033 | .031 | .035 |

EVENT # 27 DATE: 09-15-77 ORIGIN TIME: 01:01:34

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 01:36.41 | .025 | -.018 | | -.002 | .001 | -.007 |
| CC | 01:36.78 | .025 | .015 | | .005 | .002 | -.016 |
| LAD | 01:38.44 | .025 | -.037 | | -.006 | -.026 | -.017 |
| GM | 01:39.82 | .025 | -.018 | | -.001 | -.009 | -.024 |
| SC | 01:40.07 | .025 | -.014 | | -.006 | -.010 | -.017 |
| TD | 01:39.90 | .030 | .022 | | .004 | -.001 | -.034 |
| RI | 01:40.06 | .040 | .082 | | .017 | .077 | -.028 |

EVENT # 28 DATE: 09-20-77 ORIGIN TIME: 08:19:23

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 19:24.76 | .025 | .014 | | -.003 | -.004 | -.004 |
| CC | 19:25.07 | .025 | .065 | | .017 | .024 | .017 |
| FM | 19:25.24 | .025 | -.022 | | -.018 | -.019 | -.022 |
| TD | 19:28.26 | .030 | .009 | | .025 | .028 | .034 |
| GM | 19:29.00 | .025 | -.035 | | .005 | -.001 | .013 |
| RI | 19:30.60 | .040 | -.073 | | -.052 | -.055 | -.064 |

EVENT # 29 DATE: 09-22-77 ORIGIN TIME: 19:19:16

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 19:19.97 | .050 | .117 | | .027 | .153 | .072 |
| LAD | 19:20.28 | .025 | -.020 | | -.004 | -.008 | -.017 |
| CC | 19:20.95 | .025 | .005 | | -.003 | -.000 | -.014 |
| FM | 19:21.96 | .025 | -.024 | | -.004 | -.035 | -.000 |
| TD | 19:22.07 | .030 | .009 | | -.001 | -.003 | -.010 |
| RI | 19:22.45 | .040 | .028 | | .014 | .004 | .048 |

EVENT # 30 DATE: 10-18-77 ORIGIN TIME: 08:16:32

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| SC | 16:34.65 | .025 | -.004 | | .008 | .005 | .009 |
| CC | 16:35.65 | .025 | .013 | | -.008 | -.011 | -.016 |
| GM | 16:36.68 | .025 | .001 | | -.015 | -.007 | -.017 |
| BG | 16:38.11 | .025 | -.002 | | .015 | .022 | .020 |
| RI | 16:40.83 | .040 | -.027 | | .025 | .004 | .029 |
| LAD | 16:40.94 | .050 | .012 | | .019 | .025 | .029 |
| TD | 16:41.38 | .040 | -.040 | | -.023 | -.031 | -.052 |
| LPM | 16:41.32 | .050 | .031 | | -.027 | -.018 | .015 |

EVENT # 31 DATE: 11-15-77 ORIGIN TIME: 00:42:38

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| FM | 42:41.62 | .025 | .015 | .015 | .023 | .025 | .028 |
| WT | 42:41.88 | .025 | -.027 | -.031 | -.036 | -.042 | -.045 |
| IC | 42:42.48 | .025 | -.017 | .007 | -.009 | -.006 | -.010 |
| CC | 42:42.96 | .035 | .089 | .078 | .067 | .063 | .079 |
| BG | 42:43.24 | .025 | .006 | -.022 | -.018 | -.013 | -.019 |
| SC | 42:43.75 | .025 | .002 | -.008 | .012 | .012 | .010 |
| LPM | 42:45.44 | .035 | -.061 | | -.008 | -.015 | -.013 |

EVENT # 32 DATE: 11-15-77 ORIGIN TIME: 19:02:41

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CC | 02:43.33 | .025 | -.030 | -.025 | -.033 | -.034 | -.034 |
| WT | 02:43.60 | .025 | .091 | .036 | .085 | .084 | .088 |
| BG | 02:43.57 | .050 | -.046 | .056 | -.008 | -.001 | -.028 |
| FM | 02:43.69 | .025 | -.023 | -.021 | -.027 | -.026 | -.022 |
| IC | 02:45.32 | .035 | -.092 | -.009 | -.078 | -.076 | -.090 |
| LPM | 02:46.80 | .035 | .057 | | .032 | .026 | .028 |
| LAD | 02:48.10 | .050 | .013 | | .001 | .008 | .021 |

EVENT # 33 DATE: 11-18-77 ORIGIN TIME: 14:22:18

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| FM | 22:20.00 | .025 | .006 | -.002 | .013 | .010 | .018 |
| WT | 22:21.22 | .025 | .011 | -.002 | -.025 | -.010 | -.027 |
| BG | 22:21.37 | .025 | -.041 | -.000 | -.021 | -.028 | -.022 |
| CC | 22:21.98 | .025 | .035 | .007 | .033 | .034 | .033 |
| IC | 22:22.36 | .025 | -.005 | .014 | -.002 | -.002 | -.011 |
| SC | 22:23.61 | .025 | -.017 | -.015 | -.001 | -.008 | .012 |
| LPM | 22:23.35 | .025 | .024 | | .004 | .009 | .002 |

EVENT # 34 DATE: 12-05-77 ORIGIN TIME: 20:57:19

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| LAD | 57:20.79 | .025 | -.015 | | -.008 | -.007 | -.010 |
| SL | 57:23.41 | .025 | .058 | | .060 | .042 | .042 |
| CC | 57:24.70 | .025 | -.022 | | -.032 | -.011 | -.030 |
| BG | 57:25.10 | .035 | -.129 | | -.114 | -.123 | -.102 |
| BB | 57:25.82 | .050 | .007 | | .006 | -.030 | .029 |
| LPM | 57:26.70 | .025 | .058 | | .024 | .046 | .026 |

EVENT # 35 DATE: 12-15-77 ORIGIN TIME: 17:15:40

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| SL | 15:43.16 | .025 | -.053 | | -.041 | -.016 | -.003 |
| LAD | 15:43.45 | .025 | -.011 | | .001 | .001 | .003 |
| CC | 15:44.51 | .025 | .065 | | .025 | .004 | .003 |
| BG | 15:45.18 | .035 | -.025 | | .014 | .015 | .010 |
| CK | 15:45.42 | .030 | -.016 | | .056 | .047 | .030 |
| BB | 15:46.95 | .030 | .068 | | .020 | .021 | .029 |
| LPM | 15:47.18 | .025 | -.036 | | -.054 | -.054 | -.046 |

EVENT # 36 DATE: 12-21-77 ORIGIN TIME: 02:59:39

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 59:40.56 | .025 | .031 | | .027 | .029 | .030 |
| CK | 59:40.56 | .030 | -.026 | | -.009 | -.010 | -.015 |
| SL | 59:41.15 | .025 | -.038 | | -.038 | -.040 | -.036 |
| CC | 59:41.97 | .025 | .001 | | .012 | .012 | .009 |
| LPM | 59:42.46 | .050 | -.088 | | -.074 | -.076 | -.066 |
| LAD | 59:43.38 | .035 | .070 | | .047 | .049 | .047 |

EVENT # 37 DATE: 01-05-78 ORIGIN TIME: 12:03:23

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 03:25.34 | .025 | .017 | | .011 | .012 | .001 |
| SL | 03:25.45 | .025 | .036 | | .033 | .034 | .051 |
| CK | 03:25.45 | .030 | -.059 | | -.047 | -.047 | -.056 |
| CC | 03:26.19 | .025 | -.028 | | -.026 | -.028 | -.042 |
| LPM | 03:27.36 | .035 | .021 | | .028 | .029 | .041 |
| BB | 03:27.68 | .030 | .041 | | .021 | .022 | .020 |
| LAD | 03:27.46 | .035 | -.049 | | -.028 | -.030 | -.051 |

EVENT # 38 DATE: 01-17-78 ORIGIN TIME: 05:05:01

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CK | 05:03.12 | .030 | -.021 | | -.023 | -.017 | -.013 |
| LPM | 05:03.12 | .025 | -.017 | | .001 | .000 | .002 |
| BG | 05:04.24 | .025 | .075 | | .031 | .026 | .017 |
| SL | 05:05.89 | .025 | -.015 | | .029 | .032 | .028 |
| CC | 05:06.38 | .025 | -.050 | | -.041 | -.040 | -.032 |
| LAD | 05:06.91 | .025 | .024 | | -.003 | -.004 | -.004 |

EVENT # 39 DATE: 01-17-78 ORIGIN TIME: 23:14:21

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| CK | 14:23.83 | .050 | .038 | | -.003 | .021 | .056 |
| BG | 14:24.38 | .025 | -.021 | | -.029 | -.033 | -.033 |
| SL | 14:24.48 | .025 | -.002 | | .015 | .007 | .028 |
| BB | 14:24.74 | .040 | -.043 | | -.066 | -.083 | -.078 |
| LAD | 14:24.66 | .035 | .010 | | -.001 | -.003 | .000 |
| LPM | 14:25.26 | .035 | .075 | | .084 | .061 | .080 |
| CC | 14:25.62 | .025 | .004 | | -.002 | -.024 | -.019 |

EVENT # 40 DATE: 01-18-78 ORIGIN TIME: 12:24:32

| STATION | ARRIVAL TIME | WEIGHT | H-S (CLS) | AZI (CLS) | 36 (DLS) | 36 (GLS) | 48 (GLS) |
|---|---|---|---|---|---|---|---|
| BG | 24:34.06 | .025 | -.056 | | -.022 | -.021 | -.018 |
| CC | 24:34.82 | .025 | .018 | | .016 | .011 | .014 |
| SL | 24:35.21 | .025 | -.027 | | -.029 | -.024 | -.030 |
| CK | 24:35.53 | .030 | .099 | | .111 | .110 | .105 |
| LPM | 24:37.19 | .025 | .023 | | -.031 | -.020 | -.032 |
| BB | 24:38.26 | .030 | -.045 | | -.030 | -.052 | -.038 |
| LAD | 24:38.99 | .050 | .067 | | .037 | .047 | .038 |

# APPENDIX 3

Appendix 3 contains the intermediate and final results obtained in the determination of the station corrections associated with the real data for both the CLS and GLS approaches. The number of modifications refers to the number of times the station corrections were adjusted within each step.

# DETERMINATION OF STATION CORRECTIONS
by
CLASSICAL LEAST SQUARES

## STEP #1

CONSTANT VELOCITY
(5.84 km/sec)

6 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

| STATION | # OF ARRIVALS | EXPLOSION SC's (sec) | OUPUT SC's (sec) |
|---|---|---|---|
| WT | 26 | .00 | .09 |
| WM | 3 | .32 | .38 |
| IC | 6 | .38 | .33 |
| NG | 8 | .35 | .34 |
| CM | 19 | .42 | .37 |
| SC | 26 | .48 | .36 |
| RM | 1 | .44 | .31 |
| CC | 35 | .11 | .04 |
| SL | 9 | .11 | .13 |
| FM | 10 | .22 | .20 |
| DM | 9 | .11 | .18 |
| BG | 24 | .22 | .19 |
| GM | 18 | .11 | .14 |
| CU | 2 | .17 | .09 |
| RI | 5 | .00 | .20 |
| MY | 5 | .00 | .09 |
| HC | 4 | .00 | .37 |
| FC | 1 | .00 | .43 |
| TS | 2 | .00 | .46 |
| CK | 6 | .00 | .17 |
| BB | 5 | .00 | .12 |
| TA | 1 | .00 | .18 |
| LAD | 18 | .00 | -.05 |
| LPM | 14 | .00 | -.06 |
| TD | 5 | .00 | .12 |

STEP #2
(CLS)

VARIABLE VELOCITY

INITIAL VELOCITY = 5.84 km/sec

4 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

INPUT ADJUSTED by -.20 SECONDS
(TO MORE CLOSELY FIT ORIGIN TIMES)

| STATION | # OF ARRIVALS | INPUT SC's (sec) | FINAL SC's (sec) |
|---|---|---|---|
| WT | 26 | -.11 | -.11 |
| WM | 3 | .18 | .18 |
| IC | 6 | .13 | .12 |
| NG | 8 | .14 | .14 |
| CM | 19 | .17 | .16 |
| SC | 26 | .16 | .15 |
| RM | 1 | .11 | .10 |
| CC | 35 | -.16 | -.17 |
| SL | 9 | -.07 | -.08 |
| FM | 10 | .00 | .00 |
| DM | 9 | -.02 | -.02 |
| BG | 24 | -.01 | -.01 |
| GM | 18 | -.06 | -.06 |
| CU | 2 | -.11 | -.11 |
| RI | 5 | .00 | .00 |
| MY | 5 | -.11 | -.11 |
| HC | 4 | .17 | .16 |
| FC | 1 | .23 | .25 |
| TS | 2 | .26 | .29 |
| CK | 6 | -.03 | -.03 |
| BB | 5 | -.08 | -.08 |
| TA | 1 | -.02 | -.01 |
| LAD | 18 | -.25 | -.24 |
| LPM | 14 | -.26 | -.26 |
| TD | 5 | -.08 | -.05 |

FINAL VELOCITY = 5.84 .027(s.d.) km/sec

STANDARD DEVIATION OF AVERAGE RESIDUAL = .038 SECONDS

DETERMINATION OF STATION CORRECTIONS
by
GENERALIZED LEAST SQUARES

STEP #1

CONSTANT VELOCITY
(5.84 km/sec)

CONSTRAINED Z'S: 6,8,25,34,35,39,40

6 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

| STATION | # OF ARRIVALS | EXPLOSION SC's (sec) | OUPUT SC's (sec) |
|---|---|---|---|
| WT | 26 | .00 | -.11 |
| WM | 3 | .32 | .12 |
| IC | 6 | .38 | .10 |
| NG | 8 | .35 | .14 |
| CM | 19 | .42 | .16 |
| SC | 26 | .48 | .16 |
| RM | 1 | .44 | .11 |
| CC | 35 | .11 | -.15 |
| SL | 9 | .11 | -.11 |
| FM | 10 | .22 | .00 |
| DM | 9 | .11 | .01 |
| BG | 24 | .22 | -.01 |
| GM | 18 | .11 | -.06 |
| CU | 2 | .17 | -.11 |
| RI | 5 | .00 | -.01 |
| MY | 5 | .00 | -.10 |
| HC | 4 | .00 | .16 |
| FC | 1 | .00 | .22 |
| TS | 2 | .00 | .25 |
| CK | 6 | .00 | -.06 |
| BB | 5 | .00 | -.05 |
| TA | 1 | .00 | .13 |
| LAD | 18 | .00 | -.26 |
| LPM | 14 | .00 | -.24 |
| TD | 5 | .00 | -.08 |

STEP #2
(GLS)

VARIABLE VELOCITY

INITIAL VELOCITY = 5.84 km/sec

CONSTRAINED Z'S: 6,8,25,34,35,39,40

6 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

| STATION | # OF ARRIVALS | INPUT SC's (sec) | FINAL SC's (sec) |
|---|---|---|---|
| WT | 26 | -.11 | -.11 |
| WM | 3 | .12 | .12 |
| IC | 6 | .10 | .08 |
| NG | 8 | .14 | .14 |
| CM | 19 | .16 | .13 |
| SC | 26 | .16 | .15 |
| RM | 1 | .11 | .11 |
| CC | 35 | -.15 | -.15 |
| SL | 9 | -.11 | -.11 |
| FM | 10 | .00 | .00 |
| DM | 9 | .01 | -.01 |
| BG | 24 | -.01 | -.01 |
| GM | 18 | -.06 | -.06 |
| CU | 2 | -.11 | -.10 |
| RI | 5 | -.01 | -.01 |
| MY | 5 | -.10 | -.09 |
| HC | 4 | .16 | .16 |
| FC | 1 | .22 | .26 |
| TS | 2 | .25 | .28 |
| CK | 6 | -.06 | -.04 |
| BB | 5 | -.05 | -.04 |
| TA | 1 | .13 | .09 |
| LAD | 18 | -.26 | -.25 |
| LPM | 14 | -.24 | -.24 |
| TD | 5 | -.08 | -.09 |

FINAL VELOCITY = 5.85 .018(s.d.) km/sec

STANDARD DEVIATION OF AVERAGE RESIDUAL = .040 SECONDS

# APPENDIX 4

Appendix 4 contains the intermediate and final results obtained in the determination of the applied station corrections associated with the synthetic data for both the CLS and GLS approaches. The number of modifications refers to the number of times the station corrections were adjusted within each step.

TEST OF CLS APPROACH
with
SYNTHETIC DATA
(5.85 km/sec)

STEP #1

CONSTANT VELOCITY
(5.80 km/sec)

5 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

APPLIED NOISE IS NORMAL(0.,.032)

| STATION | # OF ARRIVALS | APPLIED SC's (sec) | OUPUT SC's (sec) |
|---|---|---|---|
| WT | 26 | -.09 | .02 |
| WM | 3 | -.06 | .04 |
| IC | 6 | .06 | .03 |
| NG | 8 | .01 | .00 |
| CM | 19 | .06 | .01 |
| SC | 26 | .13 | .04 |
| RM | 1 | .14 | .18 |
| CC | 35 | .08 | .03 |
| SL | 9 | .01 | .04 |
| FM | 10 | .02 | -.03 |
| DM | 9 | -.07 | -.02 |
| BG | 24 | .03 | .02 |
| GM | 18 | -.03 | .01 |
| CU | 2 | .08 | .00 |
| RI | 5 | -.20 | -.04 |
| MY | 5 | -.09 | -.02 |
| HC | 4 | -.36 | .00 |
| FC | 1 | -.45 | -.15 |
| TS | 2 | -.44 | -.14 |
| CK | 6 | -.17 | .00 |
| BB | 5 | -.12 | -.03 |
| TA | 1 | -.19 | -.09 |
| LAD | 18 | .04 | -.02 |
| LPM | 14 | .06 | .01 |
| TD | 5 | -.15 | -.08 |

STEP #2
(SYNTHETIC DATA)

VARIABLE VELOCITY

INITIAL VELOCITY = 5.80 km/sec

5 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

APPLIED NOISE IS NORMAL(0.,.032)

| STATION | # OF ARRIVALS | INPUT SC's (sec) | FINAL SC's (sec) |
|---|---|---|---|
| WT | 26 | .02 | .02 |
| WM | 3 | .04 | .05 |
| IC | 6 | .03 | .03 |
| NG | 8 | .00 | .00 |
| CM | 19 | .01 | .00 |
| SC | 26 | .04 | .02 |
| RM | 1 | .18 | .18 |
| CC | 35 | .03 | .02 |
| SL | 9 | .04 | .04 |
| FM | 10 | -.03 | -.03 |
| DM | 9 | -.02 | -.01 |
| BG | 24 | .02 | .02 |
| GM | 18 | .01 | .01 |
| CU | 2 | .00 | .01 |
| RI | 5 | -.04 | -.01 |
| MY | 5 | -.02 | -.04 |
| HC | 4 | .00 | .00 |
| FC | 1 | -.15 | -.11 |
| TS | 2 | -.14 | -.09 |
| CK | 6 | .00 | .00 |
| BB | 5 | -.03 | -.03 |
| TA | 1 | -.09 | -.07 |
| LAD | 18 | -.02 | .00 |
| LPM | 14 | .01 | .01 |
| TD | 5 | -.08 | -.06 |

FINAL VELOCITY = 5.81 .025(s.d.) km/sec

STANDARD DEVIATION OF AVERAGE RESIDUAL = .017 SECONDS

TEST OF GLS APPROACH
with
SYNTHETIC DATA
(5.85 km/sec)

STEP #1

CONSTANT VELOCITY
(5.80 km/sec)

CONSTRAINED Z'S: 1,13,15,18,25,27,29,36

5 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

APPLIED NOISE IS NORMAL(0.,.032)

| STATION | # OF ARRIVALS | APPLIED SC's (sec) | OUPUT SC's (sec) |
|---|---|---|---|
| WT | 26 | -.09 | .02 |
| WM | 3 | -.06 | .04 |
| IC | 6 | .06 | .02 |
| NG | 8 | .01 | .04 |
| CM | 19 | .06 | .01 |
| SC | 26 | .13 | .02 |
| RM | 1 | .14 | .14 |
| CC | 35 | .08 | .02 |
| SL | 9 | .01 | .02 |
| FM | 10 | .02 | -.02 |
| DM | 9 | -.07 | -.02 |
| BG | 24 | .03 | .00 |
| GM | 18 | -.03 | .00 |
| CU | 2 | .08 | .00 |
| RI | 5 | -.20 | -.03 |
| MY | 5 | -.09 | -.01 |
| HC | 4 | -.36 | .02 |
| FC | 1 | -.45 | .00 |
| TS | 2 | -.44 | .02 |
| CK | 6 | -.17 | -.02 |
| BB | 5 | -.12 | -.04 |
| TA | 1 | -.19 | -.08 |
| LAD | 18 | .04 | -.03 |
| LPM | 14 | .06 | .00 |
| TD | 5 | -.15 | -.05 |

STEP #2
(SYNTHETIC DATA)

VARIABLE VELOCITY

INITIAL VELOCITY = 5.80 km/sec

CONSTRAINED Z'S: 1,13,15,18,25,27,29,36

5 MODIFICATIONS
with
3 ITERATIONS/MODIFICATION

APPLIED NOISE IS NORMAL(0.,.032)

| STATION | # OF ARRIVALS | INPUT SC's (sec) | FINAL SC's (sec) |
|---|---|---|---|
| WT | 26 | .02 | .02 |
| WM | 3 | .04 | .04 |
| IC | 6 | .02 | .02 |
| NG | 8 | .04 | .04 |
| CM | 19 | .01 | .01 |
| SC | 26 | .03 | .01 |
| RM | 1 | .14 | .15 |
| CC | 35 | .02 | .01 |
| SL | 9 | .02 | .02 |
| FM | 10 | -.02 | -.02 |
| DM | 9 | -.02 | -.02 |
| BG | 24 | .00 | .00 |
| GM | 18 | .00 | .00 |
| CU | 2 | .00 | .00 |
| RI | 5 | -.03 | -.02 |
| MY | 5 | -.01 | -.03 |
| HC | 4 | .02 | .01 |
| FC | 1 | .00 | -.02 |
| TS | 2 | .02 | .00 |
| CK | 6 | -.02 | -.01 |
| BB | 5 | -.04 | -.04 |
| TA | 1 | -.08 | -.08 |
| LAD | 18 | -.03 | -.02 |
| LPM | 14 | .00 | .00 |
| TD | 5 | -.05 | -.05 |

FINAL VELOCITY = 5.82 .017(s.d.) km/sec

STANDARD DEVIATION OF AVERAGE RESIDUAL = .017 SECONDS

APPENDIX 5

Appendix 5 contains the final source parmaeters and uncertainties associated with each model. The uncertainties (1s.d.) are in terms of degrees for the latitude and longitude, kilometers for the depth, and seconds for the origin time.

LOCATIONS OF THE EVENTS AS DETERMINED BY A DLS INVERSION
OF THE REAL DATA USING A 36 BLOCK MODEL

| EVENT # | N. LATITUDE | W. LONGITUDE | DEPTH (km) | ORIGIN TIME (hr:min:sec) |
|---|---|---|---|---|
| 1 | 34.0217 .0016 | 106.8063 .0022 | 0.95 1.68 | 07:09:10.83 .041 |
| 2 | 34.0377 .0011 | 106.9941 .0014 | 7.19 0.47 | 15:25:28.50 .050 |
| 3 | 34.2177 .0044 | 107.0770 .0038 | 9.74 0.48 | 05:29:49.17 .094 |
| 4 | 34.0714 .0013 | 106.9238 .0014 | 8.98 0.37 | 07:39:18.37 .044 |
| 5 | 34.0025 .0019 | 106.9728 .0018 | 11.03 0.50 | 11:22:26.52 .067 |
| 6 | 33.9785 .0022 | 106.9782 .0016 | 7.66 0.52 | 15:06:40.04 .068 |
| 7 | 34.0639 .0011 | 107.0146 .0018 | 7.43 0.53 | 09:45:40.53 .064 |
| 8 | 33.9823 .0016 | 106.9665 .0019 | 5.57 0.39 | 11:58:34.71 .053 |
| 9 | 34.0596 .0010 | 107.0091 .0017 | 6.30 0.50 | 14:07:33.43 .055 |
| 10 | 34.1006 .0028 | 106.8408 .0026 | 3.72 0.83 | 08:32:19.28 .082 |
| 11 | 34.2954 .0011 | 106.8435 .0012 | 5.98 0.55 | 11:16:19.76 .034 |
| 12 | 34.0178 .0020 | 107.0640 .0014 | 9.45 0.44 | 16:43:07.73 .058 |
| 13 | 34.0406 .0015 | 107.0085 .0020 | 10.02 0.50 | 00:59:08.12 .064 |
| 14 | 33.9679 .0022 | 106.9945 .0024 | 7.91 0.46 | 06:45:56.34 .070 |
| 15 | 34.1294 .0033 | 106.8889 .0058 | 6.82 0.53 | 09:13:02.63 .103 |
| 16 | 33.9924 .0017 | 106.9516 .0015 | 5.06 0.54 | 16:40:19.98 .053 |
| 17 | 34.0472 .0017 | 107.0515 .0012 | 7.92 0.41 | 10:59:10.59 .046 |
| 18 | 34.2278 .0010 | 106.8992 .0013 | 2.17 1.97 | 06:18:51.74 .036 |
| 19 | 34.1575 .0011 | 106.8645 .0014 | 7.89 0.34 | 10:00:32.61 .035 |
| 20 | 34.1662 .0010 | 106.8746 .0015 | 4.97 0.45 | 06:03:20.07 .036 |
| 21 | 34.0226 .0015 | 107.0605 .0013 | 7.89 0.37 | 10:38:14.88 .043 |
| 22 | 33.9526 .0045 | 106.9553 .0025 | 8.08 0.56 | 04:52:32.67 .102 |
| 23 | 34.0041 .0021 | 107.0625 .0016 | 10.56 0.41 | 06:26:26.78 .058 |
| 24 | 33.9425 .0042 | 106.9453 .0027 | 9.36 0.52 | 10:35:46.06 .103 |
| 25 | 34.0559 .0016 | 106.7688 .0037 | 8.68 0.60 | 18:20:02.36 .068 |
| 26 | 34.4893 .0035 | 106.9032 .0024 | 9.02 0.65 | 13:09:24.03 .075 |
| 27 | 34.2592 .0011 | 106.9187 .0014 | 5.15 0.73 | 01:01:34.33 .038 |
| 28 | 34.1577 .0012 | 106.8718 .0011 | 5.09 0.41 | 08:19:23.23 .032 |
| 29 | 34.3408 .0016 | 106.8755 .0020 | 13.43 0.63 | 19:19:16.25 .059 |
| 30 | 34.0196 .0021 | 107.0581 .0016 | 9.67 0.19 | 08:16:32.63 .034 |
| 31 | 34.0091 .0028 | 106.8278 .0027 | 13.75 0.46 | 00:42:38.70 .069 |
| 32 | 34.1430 .0012 | 106.8851 .0012 | 5.01 0.60 | 19:02:41.76 .043 |
| 33 | 34.0627 .0021 | 106.7781 .0025 | 12.21 0.41 | 14:22:17.91 .055 |
| 34 | 34.4051 .0018 | 107.0640 .0033 | 6.04 0.52 | 20:57:19.58 .056 |
| 35 | 34.3265 .0011 | 107.0309 .0022 | 7.71 0.17 | 17:15:40.83 .025 |
| 36 | 34.2720 .0015 | 106.8644 .0014 | 3.72 0.99 | 02:59:38.95 .051 |
| 37 | 34.2718 .0015 | 106.8888 .0013 | 7.38 0.63 | 12:03:23.22 .050 |
| 38 | 34.3187 .0021 | 106.7265 .0024 | 10.99 0.47 | 05:05:00.96 .058 |
| 39 | 34.3474 .0013 | 106.8751 .0013 | 5.82 0.13 | 23:14:21.29 .022 |
| 40 | 34.1643 .0024 | 106.8580 .0014 | 4.44 0.20 | 12:24:32.81 .030 |

LOCATIONS OF THE EVENTS AS DETERMINED BY A GLS INVERSION
OF THE REAL DATA USING A 36 BLOCK MODEL

| EVENT # | N. LATITUDE | W. LONGITUDE | DEPTH (km) | ORIGIN TIME (hr:min:sec) |
|---|---|---|---|---|
| 1 | 34.0215 .0018 | 106.8032 .0025 | 1.18 1.67 | 07:09:10.81 .044 |
| 2 | 34.0376 .0012 | 106.9941 .0017 | 6.96 0.52 | 15:25:28.54 .055 |
| 3 | 34.2161 .0068 | 107.0756 .0052 | 9.17 0.62 | 05:29:49.28 .144 |
| 4 | 34.0714 .0014 | 106.9234 .0015 | 8.77 0.39 | 07:39:18.41 .047 |
| 5 | 34.0025 .0022 | 106.9728 .0020 | 10.88 0.71 | 11:22:26.57 .094 |
| 6 | 33.9770 .0023 | 106.9780 .0018 | 7.94 0.55 | 15:06:40.02 .074 |
| 7 | 34.0639 .0011 | 107.0147 .0019 | 7.23 0.67 | 09:45:40.57 .079 |
| 8 | 33.9823 .0016 | 106.9664 .0019 | 5.42 0.38 | 11:58:34.74 .053 |
| 9 | 34.0596 .0010 | 107.0092 .0018 | 6.11 0.62 | 14:07033.47 .066 |
| 10 | 34.0995 .0034 | 106.8401 .0032 | 3.74 0.99 | 08:32:19.29 .101 |
| 11 | 34.2953 .0012 | 106.8418 .0013 | 5.64 0.69 | 11:16:19.82 .042 |
| 12 | 34.0178 .0023 | 107.0643 .0015 | 9.39 0.53 | 16:43:07.76 .072 |
| 13 | 34.0408 .0016 | 107.0089 .0022 | 9.82 0.65 | 00:59:08:17 .084 |
| 14 | 33.9679 .0024 | 106.9945 .0026 | 7.77 0.50 | 06:45:56.38 .077 |
| 15 | 34.1254 .0060 | 106.8973 .0120 | 6.14 0.71 | 09:13:02.84 .210 |
| 16 | 33.9924 .0018 | 106.9512 .0017 | 4.83 0.62 | 16:40:20.02 .060 |
| 17 | 34.0474 .0018 | 107.0517 .0013 | 7.74 0.49 | 10:59:10.64 .055 |
| 18 | 34.2286 .0010 | 106.8985 .0014 | 0.39 0.28 | 06:18:51.79 .019 |
| 19 | 34.1577 .0012 | 106.8640 .0015 | 7.69 0.38 | 10:00:32.65 .039 |
| 20 | 34.1661 .0011 | 106.8747 .0016 | 4.53 0.58 | 06:03:20.13 .044 |
| 21 | 34.0226 .0016 | 107.0609 .0014 | 7.72 0.40 | 10:38:14.93 .049 |
| 22 | 33.9524 .0060 | 106.9555 .0030 | 7.88 0.74 | 04:52:32.72 .137 |
| 23 | 34.0040 .0023 | 107.0631 .0017 | 10.39 0.46 | 06:26:26.83 .069 |
| 24 | 33.9430 .0052 | 106.9456 .0031 | 9.08 0.66 | 10:35:46.13 .128 |
| 25 | 34.0559 .0017 | 106.7678 .0041 | 7.51 0.75 | 18:20:02.41 .073 |
| 26 | 34.5031 .0047 | 106.8928 .0036 | 8.66 0.70 | 13:09:23.93 .107 |
| 27 | 34.2602 .0012 | 106.9190 .0017 | 4.23 0.99 | 01:01:34.41 .046 |
| 28 | 34.1570 .0012 | 106.8724 .0012 | 4.24 0.55 | 08:19:23.32 .038 |
| 29 | 34.3400 .0016 | 106.8729 .0023 | 9.31 0.72 | 19:19:16.64 .039 |
| 30 | 34.0201 .0035 | 107.0592 .0017 | 9.56 0.54 | 08:16:32.67 .080 |
| 31 | 34.0087 .0033 | 106.8268 .0031 | 13.58 0.50 | 00:42:38.74 .079 |
| 32 | 34.1431 .0012 | 106.8848 .0012 | 4.67 0.68 | 19:02:41.80 .047 |
| 33 | 34.0626 .0023 | 106.7777 .0029 | 11.06 0.40 | 14:22:18.00 .061 |
| 34 | 34.4173 .0019 | 107.0828 .0035 | 8.23 0.32 | 20:57:19.25 .044 |
| 35 | 34.3272 .0014 | 107.0328 .0032 | 6.14 0.75 | 17:15:40.95 .059 |
| 36 | 34.2721 .0015 | 106.8635 .0016 | 3.56 1.12 | 02:59:38.99 .057 |
| 37 | 34.2725 .0016 | 106.8881 .0014 | 7.29 0.68 | 12:03:23.26 .055 |
| 38 | 34.3146 .0026 | 106.7272 .0030 | 10.17 0.53 | 05:05:01.09 .068 |
| 39 | 34.3484 .0013 | 106.8742 .0014 | 3.75 0.57 | 23:14:21.45 .022 |
| 40 | 34.1641 .0024 | 106.8572 .0016 | 4.48 0.41 | 12:24:32.82 .041 |

LOCATIONS OF THE EVENTS AS DETERMINED BY A GLS INVERSION
OF THE REAL DATA USING A 48 BLOCK MODEL

| EVENT # | N. LATITUDE | W. LONGITUDE | DEPTH (km) | ORIGIN TIME (hr:min:sec) |
|---|---|---|---|---|
| 1 | 34.0247 .0018 | 106.8069 .0025 | 1.34 1.60 | 07:09:10.87 .049 |
| 2 | 34.0382 .0012 | 106.9963 .0018 | 7.38 0.52 | 15:25:28.46 .061 |
| 3 | 34.2182 .0053 | 107.0712 .0049 | 8.32 0.69 | 05:29:49.39 .117 |
| 4 | 34.0712 .0015 | 106.9228 .0016 | 8.66 0.39 | 07:39:18.40 .049 |
| 5 | 34.0031 .0025 | 106.9794 .0024 | 11.95 0.79 | 11:22:26.38 .112 |
| 6 | 33.9789 .0028 | 106.9793 .0017 | 7.91 0.65 | 15:06:40.01 .090 |
| 7 | 34.0646 .0011 | 107.0157 .0019 | 7.84 0.67 | 09:45:40.40 .088 |
| 8 | 33.9834 .0016 | 106.9664 .0020 | 5.57 0.38 | 11:58:34.72 .053 |
| 9 | 34.0603 .0010 | 107.0095 .0018 | 6.50 0.61 | 14:07:33.35 .071 |
| 10 | 34.1020 .0032 | 106.8417 .0030 | 3.43 1.00 | 08:32:19.31 .095 |
| 11 | 34.2929 .0015 | 106.8417 .0014 | 5.40 0.80 | 11:16:19.90 .050 |
| 12 | 34.0182 .0022 | 107.0601 .0016 | 9.62 0.51 | 16:43:07.61 .075 |
| 13 | 34.0373 .0018 | 107.0109 .0022 | 10.96 0.64 | 00:59:07.89 .095 |
| 14 | 33.9659 .0026 | 106.9980 .0027 | 9.04 0.58 | 06:45:56.18 .092 |
| 15 | 34.1264 .0068 | 106.8750 .0150 | 7.08 0.75 | 09:13:02.52 .256 |
| 16 | 33.9948 .0018 | 106.9491 .0018 | 4.22 0.69 | 16:40:20.07 .061 |
| 17 | 34.0486 .0017 | 107.0493 .0013 | 7.91 0.43 | 10:59:10.51 .054 |
| 18 | 34.2266 .0012 | 106.8980 .0016 | 0.21 0.26 | 06:18:51.78 .024 |
| 19 | 34.1559 .0012 | 106.8625 .0015 | 7.14 0.43 | 10:00:32.70 .048 |
| 20 | 34.1647 .0011 | 106.8739 .0016 | 4.50 0.60 | 06:03:20.11 .048 |
| 21 | 34.0252 .0016 | 107.0572 .0015 | 7.85 0.39 | 10:38:14.81 .051 |
| 22 | 33.9344 .0084 | 106.9541 .0039 | 11.03 0.97 | 04:52:32.16 .195 |
| 23 | 34.0105 .0022 | 107.0578 .0018 | 9.87 0.43 | 06:26:26.79 .060 |
| 24 | 33.9313 .0069 | 106.9453 .0041 | 11.58 0.89 | 10:35:45.69 .178 |
| 25 | 34.0582 .0018 | 106.7728 .0046 | 8.09 1.04 | 18:20:02.42 .087 |
| 26 | 34.5018 .0050 | 106.8956 .0036 | 8.37 0.79 | 13:09:24.04 .110 |
| 27 | 34.2603 .0012 | 106.9181 .0017 | 4.02 1.08 | 01:01:34.43 .051 |
| 28 | 34.1574 .0013 | 106.8715 .0012 | 4.70 0.54 | 08:19:23.26 .044 |
| 29 | 34.3444 .0028 | 106.8705 .0032 | 11.90 0.85 | 19:19:16.53 .075 |
| 30 | 34.0257 .0033 | 107.0546 .0019 | 8.97 0.55 | 08:16:32.64 .080 |
| 31 | 34.0130 .0037 | 106.8293 .0035 | 13.48 0.55 | 00:42:38.75 .082 |
| 32 | 34.1422 .0013 | 106.8846 .0013 | 4.78 0.71 | 19:02:41.77 .053 |
| 33 | 34.0623 .0029 | 106.7786 .0036 | 11.49 0.49 | 14:22:17.94 .074 |
| 34 | 34.4074 .0021 | 107.0767 .0048 | 5.59 0.39 | 20:57:19.54 .042 |
| 35 | 34.3268 .0014 | 107.0354 .0033 | 5.80 0.75 | 17:15:40.97 .057 |
| 36 | 34.2708 .0016 | 106.8636 .0016 | 3.51 1.11 | 02:59:39.00 .057 |
| 37 | 34.2722 .0016 | 106.8895 .0014 | 6.08 0.84 | 12:03:23.41 .061 |
| 38 | 34.3113 .0033 | 106.7245 .0030 | 9.59 0.55 | 05:05:01.21 .071 |
| 39 | 34.3470 .0013 | 106.8742 .0015 | 2.90 0.46 | 23:14:21.48 .030 |
| 40 | 34.1632 .0026 | 106.8574 .0017 | 4.06 0.48 | 12:24:32.83 .046 |

# APPENDIX 6

Appendix 6 contains the source parameters associated with the synthetic data. It should be noted that the source parameters used to generate the synthetic data are given in Appendix 1.

LOCATIONS OF THE EVENTS AS DETERMINED BY A DLS INVERSION
OF THE SYNTHETIC DATA USING A 36 BLOCK MODEL

| EVENT # | N. LATITUDE | W. LONGITUDE | DEPTH (km) | ORIGIN TIME (hr:min:sec) |
|---|---|---|---|---|
| 1 | 34.0194 .0018 | 106.7878 .0027 | 0.02 1.13 | 07:09:10.82 .040 |
| 2 | 34.0369 .0011 | 106.9938 .0016 | 6.38 0.50 | 15:25:28.61 .047 |
| 3 | 34.2475 .0046 | 107.0960 .0042 | 11.67 0.52 | 05:29:48.89 .099 |
| 4 | 34.0686 .0014 | 106.9202 .0014 | 8.91 0.41 | 07:39:18.40 .045 |
| 5 | 34.0029 .0019 | 106.9738 .0017 | 9.83 0.51 | 11:22:26.69 .063 |
| 6 | 33.9694 .0027 | 106.9796 .0017 | 8.23 0.53 | 15:06:40.00 .074 |
| 7 | 34.0623 .0010 | 107.0104 .0018 | 6.75 0.53 | 09:45:40.62 .058 |
| 8 | 33.9728 .0021 | 106.9632 .0022 | 6.76 0.43 | 11:58:34.51 .065 |
| 9 | 34.0581 .0010 | 107.0039 .0019 | 6.64 0.51 | 14:07:33.41 .056 |
| 10 | 34.1015 .0026 | 106.8434 .0024 | 2.36 1.00 | 08:32:19.41 .069 |
| 11 | 34.2912 .0011 | 106.8399 .0012 | 5.74 0.55 | 11:16:19.89 .033 |
| 12 | 34.0215 .0021 | 107.0636 .0015 | 10.04 0.46 | 16:43:07.70 .059 |
| 13 | 34.0385 .0014 | 106.9958 .0021 | 8.43 0.51 | 00:59:08.12 .060 |
| 14 | 33.9674 .0024 | 106.9873 .0025 | 7.96 0.46 | 06:45:56.33 .071 |
| 15 | 34.1361 .0034 | 106.8788 .0056 | 5.09 0.68 | 09:13:02.56 .097 |
| 16 | 33.9937 .0017 | 106.9494 .0015 | 2.49 0.89 | 16:40:20.19 .050 |
| 17 | 34.0455 .0017 | 107.0495 .0012 | 8.61 0.42 | 10:59:10.57 .048 |
| 18 | 34.2266 .0010 | 106.8989 .0013 | 0.07 0.55 | 06:18:51.82 .016 |
| 19 | 34.1555 .0011 | 106.8640 .0014 | 7.38 0.36 | 10:00:32.70 .035 |
| 20 | 34.1644 .0010 | 106.8667 .0017 | 5.57 0.44 | 06:03:20.14 .039 |
| 21 | 34.0199 .0016 | 107.0606 .0014 | 8.17 0.37 | 10:38:14.88 .044 |
| 22 | 33.9487 .0049 | 106.9495 .0027 | 8.19 0.57 | 04:52:32.62 .106 |
| 23 | 34.0027 .0022 | 107.0627 .0016 | 10.82 0.43 | 06:26:26.79 .060 |
| 24 | 33.9484 .0043 | 106.9464 .0026 | 7.55 0.52 | 10:35:46.31 .098 |
| 25 | 34.0553 .0017 | 106.7570 .0040 | 8.58 0.62 | 18:20:02.28 .072 |
| 26 | 34.5156 .0038 | 106.8906 .0026 | 9.67 0.69 | 13:09:23.82 .079 |
| 27 | 34.2619 .0011 | 106.9199 .0013 | 1.76 1.71 | 01:01:34.51 .033 |
| 28 | 34.1567 .0012 | 106.8699 .0011 | 4.70 0.43 | 08:19:23.29 .031 |
| 29 | 34.3363 .0014 | 106.8801 .0019 | 9.64 0.65 | 19:19:16.84 .047 |
| 30 | 34.0201 .0021 | 107.0597 .0016 | 8.29 0.19 | 08:16:32.88 .033 |
| 31 | 34.0065 .0030 | 106.8279 .0029 | 14.57 0.47 | 00:42:38.67 .072 |
| 32 | 34.1402 .0012 | 106.8855 .0012 | 3.00 0.90 | 19:02:41.93 .041 |
| 33 | 34.0620 .0021 | 106.7762 .0025 | 10.06 0.32 | 14:22:18.15 .047 |
| 34 | 34.4242 .0022 | 107.0970 .0041 | 7.43 0.42 | 20:57:19.20 .065 |
| 35 | 34.3239 .0013 | 107.0464 .0026 | 9.17 0.17 | 17:15:40.67 .029 |
| 36 | 34.2700 .0013 | 106.8662 .0011 | 0.47 1.70 | 02:59:39.15 .021 |
| 37 | 34.2696 .0015 | 106.8900 .0013 | 7.72 0.61 | 12:03:23.29 .051 |
| 38 | 34.3120 .0021 | 106.7255 .0023 | 10.75 0.44 | 05:05:01.07 .055 |
| 39 | 34.3506 .0013 | 106.8710 .0014 | 6.51 0.13 | 23:14:21.43 .022 |
| 40 | 34.1512 .0027 | 106.8514 .0017 | 8.03 0.21 | 12:24:32.51 .037 |

LOCATIONS OF THE EVENTS AS DETERMINED BY A GLS INVERSION
OF THE SYNTHETIC DATA USING A 36 BLOCK MODEL

| EVENT # | N. LATITUDE | W. LONGITUDE | DEPTH (km) | ORIGIN TIME (hr:min:sec) |
|---|---|---|---|---|
| 1 | 34.0201 .0021 | 106.7889 .0029 | 0.12 0.84 | 07:09:10.86 .040 |
| 2 | 34.0370 .0012 | 106.9938 .0016 | 6.33 0.52 | 15:25:28.62 .050 |
| 3 | 34.2481 .0081 | 107.0959 .0065 | 11.59 0.68 | 05:29:48.89 .174 |
| 4 | 34.0688 .0014 | 106.9204 .0015 | 8.89 0.42 | 07:39:18.41 .047 |
| 5 | 34.0031 .0022 | 106.9740 .0019 | 9.80 0.64 | 11:22:26.70 .079 |
| 6 | 33.9705 .0028 | 106.9795 .0018 | 7.99 0.58 | 15:06:40.04 .078 |
| 7 | 34.0625 .0011 | 107.0104 .0019 | 6.72 0.67 | 09:45:40.63 .073 |
| 8 | 33.9730 .0020 | 106.9630 .0022 | 6.72 0.38 | 11:58:34.53 .059 |
| 9 | 34.0583 .0010 | 107.0039 .0020 | 6.60 0.62 | 14:07:33.42 .068 |
| 10 | 34.1020 .0030 | 106.8438 .0028 | 2.21 1.24 | 08:32:19.43 .081 |
| 11 | 34.2916 .0013 | 106.8406 .0013 | 5.69 0.66 | 11:16:19.88 .038 |
| 12 | 34.0217 .0023 | 107.0635 .0015 | 9.95 0.52 | 16:43:07.73 .068 |
| 13 | 34.0386 .0015 | 106.9959 .0024 | 8.29 0.65 | 00:59:08.15 .078 |
| 14 | 33.9674 .0026 | 106.9870 .0028 | 7.91 0.50 | 06:45:56.35 .079 |
| 15 | 34.1364 .0076 | 106.8795 .0014 | 4.95 0.80 | 09:13:02.58 .242 |
| 16 | 33.9940 .0018 | 106.9494 .0016 | 2.22 1.07 | 16:40:20.21 .055 |
| 17 | 34.0457 .0018 | 107.0493 .0013 | 8.50 0.49 | 10:59:10.59 .055 |
| 18 | 34.2269 .0011 | 106.8988 .0014 | 0.37 0.30 | 06:18:51.81 .019 |
| 19 | 34.1559 .0012 | 106.8642 .0015 | 7.35 0.39 | 10:00:32.71 .038 |
| 20 | 34.1647 .0011 | 106.8669 .0018 | 5.55 0.53 | 06:03:20.05 .047 |
| 21 | 34.0202 .0017 | 107.0603 .0015 | 8.06 0.40 | 10:38:14.90 .049 |
| 22 | 33.9490 .0069 | 106.9489 .0033 | 8.11 0.78 | 04:52:32.64 .151 |
| 23 | 34.0032 .0025 | 107.0624 .0017 | 10.71 0.48 | 06:26:26.81 .070 |
| 24 | 33.9496 .0056 | 106.9467 .0031 | 7.34 0.69 | 10:35:46.36 .129 |
| 25 | 34.0559 .0018 | 106.7578 .0043 | 8.47 0.66 | 18:20:02.32 .073 |
| 26 | 34.5034 .0033 | 106.8935 .0035 | 8.52 0.69 | 13:09:24.02 .073 |
| 27 | 34.2617 .0012 | 106.9199 .0016 | 1.51 2.79 | 01:01:34.51 .048 |
| 28 | 34.1568 .0013 | 106.8704 .0012 | 4.61 0.53 | 08:19:23.30 .038 |
| 29 | 34.3356 .0016 | 106.8807 .0022 | 9.25 0.90 | 19:19:16.85 .067 |
| 30 | 34.0197 .0034 | 107.0592 .0017 | 8.26 0.49 | 08:16:32.88 .069 |
| 31 | 34.0075 .0034 | 106.8290 .0033 | 14.39 0.53 | 00:42:38.72 .083 |
| 32 | 34.1404 .0012 | 106.8857 .0012 | 2.98 0.97 | 19:02:41.93 .045 |
| 33 | 34.0626 .0022 | 106.7771 .0029 | 10.07 0.33 | 14:22:18.18 .054 |
| 34 | 34.4237 .0018 | 107.0964 .0035 | 7.84 0.29 | 20:57:19.19 .035 |
| 35 | 34.3238 .0015 | 107.0404 .0032 | 8.61 0.40 | 17:15:40.74 .043 |
| 36 | 34.2703 .0014 | 106.8666 .0012 | 0.60 3.47 | 02:59:39.15 .031 |
| 37 | 34.2694 .0016 | 106.8898 .0013 | 7.69 0.63 | 12:03:23.29 .054 |
| 38 | 34.3130 .0028 | 106.7256 .0032 | 11.01 0.55 | 05:05:01.03 .069 |
| 39 | 34.3500 .0014 | 106.8715 .0014 | 6.01 0.91 | 23:14:21.43 .057 |
| 40 | 34.1519 .0028 | 106.8519 .0017 | 8.04 0.44 | 12:24:32.52 .057 |

LOCATIONS OF THE EVENTS AS DETERMINED BY A GLS INVERSION
OF THE SYNTHETIC DATA USING A 48 BLOCK MODEL

| EVENT # | N. LATITUDE | W. LONGITUDE | DEPTH (km) | ORIGIN TIME (hr:min:sec) |
|---|---|---|---|---|
| 1 | 34.0199 .0024 | 106.7903 .0032 | 0.26 1.50 | 07:09:10.83 .044 |
| 2 | 34.0372 .0012 | 106.9941 .0017 | 6.46 0.54 | 15:25:28.62 .055 |
| 3 | 34.2579 .0093 | 107.0996 .0073 | 11.82 0.74 | 05:29:48.68 .180 |
| 4 | 34.0698 .0016 | 106.9212 .0018 | 9.10 0.43 | 07:39:18.41 .050 |
| 5 | 34.0028 .0021 | 106.9722 .0019 | 9.17 0.60 | 11:22:26.80 .072 |
| 6 | 33.9679 .0035 | 106.9800 .0019 | 8.46 0.69 | 15:06:39.97 .100 |
| 7 | 34.0626 .0011 | 107.0110 .0019 | 6.48 0.67 | 09:45:40.65 .074 |
| 8 | 33.9729 .0020 | 106.9636 .0023 | 6.69 0.41 | 11:58:34.53 .061 |
| 9 | 34.0589 .0010 | 107.0036 .0019 | 6.32 0.63 | 14:07:33.47 .068 |
| 10 | 34.1011 .0030 | 106.8433 .0027 | 2.57 1.08 | 08:32:19.39 .081 |
| 11 | 34.2911 .0012 | 106.8400 .0013 | 5.17 0.69 | 11:16:19.92 .043 |
| 12 | 34.0223 .0023 | 107.0641 .0017 | 9.87 0.52 | 16:43:07.75 .075 |
| 13 | 34.0388 .0015 | 106.9952 .0023 | 8.44 0.65 | 00:59:08.15 .086 |
| 14 | 33.9673 .0026 | 106.9875 .0028 | 7.88 0.54 | 06:45:56.35 .084 |
| 15 | 34.1347 .0056 | 106.8781 .0106 | 4.41 0.79 | 09:13:02.58 .177 |
| 16 | 33.9930 .0020 | 106.9483 .0017 | 3.13 0.90 | 16:40:20.15 .063 |
| 17 | 34.0454 .0018 | 107.0502 .0014 | 8.60 0.50 | 10:59:10.60 .061 |
| 18 | 34.2261 .0012 | 106.8988 .0015 | 0.93 1.18 | 06:18:51.80 .022 |
| 19 | 34.1561 .0012 | 106.8640 .0016 | 7.33 0.42 | 10:00:32.67 .048 |
| 20 | 34.1636 .0012 | 106.8664 .0018 | 5.77 0.55 | 06:03:20.00 .054 |
| 21 | 34.0198 .0018 | 107.0606 .0016 | 8.02 0.40 | 10:38:14.91 .053 |
| 22 | 33.9514 .0073 | 106.9548 .0033 | 7.82 0.88 | 04:52:32.73 .164 |
| 23 | 34.0020 .0031 | 107.0633 .0021 | 10.91 0.52 | 06:26:26.80 .076 |
| 24 | 33.9499 .0051 | 106.9469 .0028 | 7.24 0.64 | 10:35:46.37 .119 |
| 25 | 34.0553 .0022 | 106.7524 .0058 | 6.97 0.80 | 18:20:02.36 .085 |
| 26 | 34.5170 .0057 | 106.8903 .0031 | 10.17 0.82 | 13:09:23.78 .117 |
| 27 | 34.2611 .0013 | 106.9205 .0016 | 2.30 1.78 | 01:01:34.51 .047 |
| 28 | 34.1565 .0013 | 106.8700 .0012 | 4.62 0.55 | 08:19:23.27 .043 |
| 29 | 34.3347 .0017 | 106.8836 .0024 | 8.52 0.84 | 19:19:16.91 .059 |
| 30 | 34.0206 .0035 | 107.0602 .0019 | 8.15 0.55 | 08:16:32.92 .080 |
| 31 | 34.0061 .0049 | 106.8261 .0039 | 14.90 0.73 | 00:42:38.74 .102 |
| 32 | 34.1400 .0013 | 106.8850 .0012 | 3.76 0.81 | 19:02:41.86 .048 |
| 33 | 34.0688 .0025 | 106.7785 .0031 | 9.88 0.35 | 14:22:18.24 .056 |
| 34 | 34.4216 .0027 | 107.0843 .0051 | 6.91 0.48 | 20:57:19.37 .072 |
| 35 | 34.3222 .0021 | 107.0426 .0048 | 9.27 0.97 | 17:15:40.66 .109 |
| 36 | 34.2694 .0016 | 106.8663 .0014 | 1.47 2.40 | 02:59:39.10 .055 |
| 37 | 34.2697 .0016 | 106.8904 .0014 | 6.61 0.73 | 12:03:23.37 .057 |
| 38 | 34.3129 .0027 | 106.7246 .0031 | 10.78 0.61 | 05:05:01.05 .077 |
| 39 | 34.3498 .0015 | 106.8715 .0016 | 6.80 1.26 | 23:14:21.39 .089 |
| 40 | 34.1513 .0028 | 106.8520 .0017 | 7.99 0.49 | 12:24:32.48 .065 |

# APPENDIX 7

Appendix 7 contains the three basic versions of the inversion routines used in this study. Matrix manipulations are performed by routines contained within the IMSL subroutine package maintained by the N. M. Tech Computer Department. A brief description will preceed the listings of each program.

```
C  ************************************************************
C  *                                                          *
C  * AZI.FOR: THIS ROUTINE PROVIDES FOR THE DETERMINATION     *
C  *          OF AN AZIMUTHAL VELOCITY DISTRIBUTION BY        *
C  *          MEANS OF THE CLASSICAL LEAST SQUARES APPROACH.  *
C  *                                                          *
C  ************************************************************



      DIMENSION STA(271),DL(271),R(271),W(271),SZ(271),SX(271)
     $,SY(271),SECO(40),IYR(40),
     $IHR(271),TX(40),TY(40),TZ(40),TOT(40),IHRO(40),IMINO(40)
     $,TOI(40),XH(40),YH(40),ZH(40),TOH(40),IMO(40),IDA(40),
     $STO(271),DLH(271),RH(271),NSTA(40),XI(40),YI(40),ZI(40)
      DIMENSION C(13695),D(165),B(271),A(271,165),H(165,271),
     $VR(165),WP(165),CI(13695),DT(165),CF(165,165)
     $,GI(5),G(5),GH(5),IMIN(271),GGH(5),STAC(2,25)
C       ,RR(165,165),S(271,271)
        EQUIVALENCE (C,CF),(CI,H)
      INTEGER TEST,EVENT,STA,STAC

C  ************************************************************

C     STATION CORRECTIONS . . . . . .


      DATA STAC/'WT',-11,'WM',12,'IC',08,'NG',14,'CM',13
     $,'RM',11,'SC',15,'RI',-01,'BB',-04
     $,'CC',-15,'SL',-11,'FM',00,'DM',-01,'BG',-01,'GM',-06,
     $'CU',-10,'MY',-09,'HC',16,'FC',26,'TS',28,'CK',-04,
     $'TA',09,'LAD',-25,'LPM',-24,'TD',-09/

C  ************************************************************

C     INPUT . . . . . .

C       . . . STATION LOCATIONS - - SX,SY,SZ

C       . . . ARRIVAL TIMES - - IMIN,SEC,W

C       . . . INITIAL ESTIMATES AND WEIGHTS
C                 - - XI,YI,ZI,TOI,VI,WP

C  ************************************************************

        NSC=25

C       NSC = NUMBER OF STATION CORRECTIONS

        TYPE 420
420     FORMAT(/,1X,'THE NUMBER OF EVENTS ?')
        READ(5,*) NUM
```

```
        TYPE 416
416     FORMAT(1X,'INPUT DATA FILE ?')
        READ(5,417) VFN
417     FORMAT(A5)
        IRD=0
        AVR=0.
        SUM=0.
        TYPE 413
413     FORMAT(1X,'REAL DATA ?')
        READ(5,412) TEST
412     FORMAT(A3)
        IF(TEST.EQ.'YES')IRD=1
        IF(IRD.EQ.1)GO TO 414
        TYPE 415
415     FORMAT(1X,'WHAT IS THE DESIRED NOISE LEVEL (1S.D.) ?')
C  ***********************************************************
C                    (SYNTHETIC DATA)
C       TDNL = STANDARD DEVIATION OF MAXIMUM NOISE DESIRED
C       TDNL=1.  WILL BASE THE NOISE ON W(K)  (OBS. WEIGHTS)
C  ***********************************************************
        READ(5,*) TDNL
414     CONTINUE
        TYPE 463
463     FORMAT(1X,'WHAT IS THE DESIRED # OF ITERATIONS ?')
        READ(5,*) IDNI
      NXX = NUM * 4
      NX = NXX + 5
      NSTN = 0
        TYPE 421
421     FORMAT(/,1X,'THE VELOCITY COEFFICIENTS AND WEIGHTS ?')
      READ(5,*) ((GI(I),WP(NXX+I)),I=1,5)
        OPEN(UNIT=22,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
     $  FILE=VFN)
      DO 51 NOQ = 1,NUM
      READ(22,*) NSTA(NOQ),IMO(NOQ),IDA(NOQ),IYR(NOQ)
C  ***********************************************************
C     INITIAL ESTIMATES OF HYPOCENTERS AND ORIGIN TIMES
C                    (XI,YI,ZI,TOI)
C     CAUTION-- DO NOT GUESS EPICENTER COORDS. SAME AS STATION
C  ***********************************************************
      I = 4*(NOQ-1) + 1
      IP1 = I+ 1
```

```
      IP2 = I+ 2
      IP3 = I+ 3
      READ(22,*) X,WP(I),Y,WP(IP1),Z,WP(IP2)
        READ(22,*) IHRO(NOQ),IMINO(NOQ),SECO(NOQ),WP(IP3)
      XI(NOQ) = X
      YI(NOQ) = Y
      ZI(NOQ) = Z
      TOI(NOQ) = SECO(NOQ)
      IF(WP(I).EQ.0.)WP(I)=1.
      IF(WP(IP1).EQ.0.)WP(IP1)=1.
      IF(WP(IP2).EQ.0.)WP(IP2)=3.
      IF(WP(IP3).EQ.0.)WP(IP3)=.3
        IF(IRD.EQ.1)GO TO 424
C  ************************************************************
C                    (SYNTHETIC DATA)
C       . . . ADDITION OF NOISE TO TRUE SOLUTION
C  ************************************************************
        CALL GGNML(1234567.D0,1,RN)
        X=X+RN*.01
        CALL GGNML(1234567.D0,1,RN)
        Y=Y+RN*.01
        CALL GGNML(1234567.D0,1,RN)
        Z=Z+RN*3.
        IF(Z.LT.3.)Z=3.
        CALL GGNML(1234567.D0,1,RN)
        SECO(NOQ)=SECO(NOQ)+RN*.3
        IF(SECO(NOQ).GE.60.)IMINO(NOQ)=IMINO(NOQ)+1
        IF(SECO(NOQ).GE.60.)SECO(NOQ)=SECO(NOQ)-60.
        IF(SECO(NOQ).GT.0.)GO TO 424
        IMINO(NOQ)=IMINO(NOQ)-1
        SECO(NOQ)=SECO(NOQ)+60.
424     CONTINUE
        PRINT 1650,X,Y,Z,SECO(NOQ),XI(NOQ),YI(NOQ),ZI(NOQ)
     $  ,TOI(NOQ)
1650    FORMAT(1X,4F10.4,20X,4F10.4)
      XI(NOQ) = X
      YI(NOQ) = Y
      ZI(NOQ) = Z
      TOI(NOQ) = SECO(NOQ)
C  ************************************************************
C      . . . ARRIVAL TIMES AND WEIGHTS
C  ************************************************************
      NST = NSTA(NOQ)
        OPEN(UNIT=1,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
```

```
     $  FILE='STA')
        DO 49 J=1,NST
        K = NSTN + J
          IFLAG=0
          REWIND 1
          READ(22,425) STA(K),IMIN(K),SEC,W(K)
425       FORMAT(A3,1X,I2,1X,F5.2,1X,F4.3)
426       CONTINUE

C  ************************************************************

C       . . . STATION COORDINATES

C  ************************************************************

          READ(1,427,END=444) TEST,SY(K),SX(K),SZ(K)
427       FORMAT(A3,1X,F7.4,1X,F8.4,2X,F5.3)
          IF(TEST.EQ.STA(K)) GO TO 428
          GO TO 426
444       CONTINUE
          TYPE 429,STA(K)
429       FORMAT(10X,'STATION ',A3,' NOT FOUND',/)
          CLOSE(UNIT=1)
          CLOSE(UNIT=22)
          GO TO 2
428       IF(IMINO(NOQ).GT.IMIN(K))IMIN(K)=IMIN(K)+60
          IF(IRD.EQ.1)GO TO 48

C  ************************************************************

C                     (SYNTHETIC DATA)

C         . . . ADDITION OF NOISE TO DATA

C  ************************************************************

          IF(TDNL.EQ.1.)GO TO 666
          TNL=TDNL
          W(K)=TNL
666       CALL GGNML(1234567.D0,1,RN)
          RESID=RN*W(K)
          AVR=AVR+RESID
          SUM=RESID*RESID+SUM
          SEC=SEC+RESID
          IF(SEC.LT.0.)IMIN(K)=IMIN(K)-1
          IF(SEC.LT.0.)SEC=SEC+60.
          IF(SEC.GE.60.)IMIN(K)=IMIN(K)+1
          IF(SEC.GE.60.)SEC=SEC-60.
48        CONTINUE
        STO(K) = SEC + (IMIN(K) - IMINO(NOQ))*60.
          IF(IRD.EQ.0)GO TO 418
        DO 130 I=1,NSC
        IF(STAC(1,I).NE.STA(K))GO TO 130
```

```
        IFLAG=1
      STO(K) = STO(K) - FLOAT(STAC(2,I))*.01
  130 CONTINUE
        IF(IFLAG.EQ.0)STO(K)=STO(K)+.2
418     CONTINUE
   49 CONTINUE
        CLOSE(UNIT=1)
      NSTN = NSTN + NSTA(NOQ)
   51 CONTINUE
        IF(IRD.EQ.1)GO TO 664
        AVR=AVR/NSTN
        STDR=SQRT(SUM/NSTN-AVR*AVR)
        PRINT665,AVR,STDR
665     FORMAT(1X,//,10X,'AVERAGE RESIDUAL = ',F6.3,10X,
     $  'STANDARD DEVIATION OF AVG. RESIDUAL = ',F6.3,//)
664     CLOSE(UNIT=22)

C  ************************************************************

C    LEAST SQUARES METHOD . . . . . .

C    . . CALCULATION OF DISTANCE BETWEEN STATION AND EPICENTER

C  ************************************************************
        IQF=0
   80 NIT = 0
      DO 169 I=1,NUM
      TX(I) = XI(I)
      TY(I) = YI(I)
      TZ(I) = ZI(I)
  169 TOT(I) = TOI(I)
      DO 810 L=1,5
  810 G(L) = GI(L)
 1000 NIT = NIT + 1
      DO 756 I=1,165
      DO 756 J=1,271
      B(J) = 0.0
      A(J,I) = 0.0
        H(I,J)=0.0
C      DO 756 K=1,271
C      S(J,K) = 0.
  756 CONTINUE
      DO 55 I=1,165
      D(I) = 0.
      DO 55 K=1,165
C      RR(I,K) = 0.
        CF(I,K)=0.
   55 CONTINUE

C  ************************************************************

C     . . . FORMATION OF ARRAY TO BE INVERTED

C  ************************************************************
```

```
933     CONTINUE
        NSTN = 0
        DO 859 NOQ=1,NUM
        X = TX(NOQ)
        Y = TY(NOQ)
        Z = TZ(NOQ)
        NN = 4*(NOQ - 1) + 1
        NNP1 = NN+1
        NNP2 = NN+2
        NNP3 = NN+3
        NST = NSTA(NOQ)
        DO 858 J=1,NST
        K = NSTN + J
        CALL AZ(SX(K),SY(K),X,Y,AZI)
        AZI = AZI/57.2958
        CALL TP(AZI,G,V)
        HPZ = (Z+SZ(K))
          XKDEG=((SY(K)+Y)/2.-34.1)*.018+110.922
          XKC=COS(3.1415927*(SY(K)+Y)/360.)*111.4399
        XX = (X-SX(K))*XKC
        YY = (Y-SY(K))*XKDEG
        DL(K) = SQRT(XX*XX + YY*YY)
        OTT = STO(K) - TOT(NOQ)
        TTT = SQRT(DL(K)*DL(K) + HPZ*HPZ)/V
        R(K) = OTT - TTT
        FF = 1./(V*V*OTT)
        A(K,NN) = XX*FF/W(K)
        A(K,NNP1)= YY*FF/W(K)
        A(K,NNP2) = HPZ*FF/W(K)
        A(K,NNP3) = 1.0/W(K)
        CON = -V*OTT*OTT*FF/W(K)
        A(K,NXX+1)= CON
        A(K,NXX+2)= CON * COS(2.*AZI)
        A(K,NXX+3)= CON * SIN(2.*AZI)
        A(K,NXX+4)= CON * COS(4.*AZI)
        A(K,NXX+5)= CON * SIN(4.*AZI)
        B(K) = R(K)/W(K)
  858 CONTINUE
        NSTN = NSTN + NSTA(NOQ)
  859 CONTINUE
        DO 112 I=1,NSTN
        DO 112 J=1,NX
  112 A(I,J) = WP(J)*A(I,J)
          IF(IQF.EQ.1)GO TO 930
C         . . . FORMATION OF ATA
          CALL VTPROF(A,NSTN,NX,271,C)
        CALL VMULFM(A,B,NSTN,NX,1,271,271,D,165,IER)
  799 CONTINUE
```

```
C  ************************************************************
C     . . CALCULATION OF STANDARD DEVIATION OF AVERAGE RESIDUAL
C     . . . TEST FOR CONVERGENCE
C  ************************************************************
      VARI = 0.
      SUM = 0.
      DO 54 J=1,NSTN
      SUM = SUM + (R(J)*R(J)/(W(J)*W(J)))
      VARI = VARI + R(J)*R(J)
   54 CONTINUE
      VARI = VARI/FLOAT(NSTN-1)
      BIGR = SQRT(SUM/FLOAT(NSTN))
      STDDEV = SQRT(VARI)
      IF(NIT.EQ.1)STDH=STDDEV
      IF(STDH.LT.STDDEV)GO TO 89
      IF(NIT.EQ.1)INF=1
      IF(NIT.GT.1)INF=0
      STDH = STDDEV
      DO 816 L=1,5
  816 GH(L) = G(L)
      DO 609 I=1,NUM
      XH(I) = TX(I)
      YH(I) = TY(I)
      ZH(I) = TZ(I)
  609 TOH(I) = TOT(I)
   89 CONTINUE
        NITM1=NIT-1
        PRINT 1652,NITM1
1652    FORMAT(1X,//,1X,'ITERATION #',I2,/)
        PRINT 1653,((TX(I),TY(I),TZ(I),TOT(I)),I=1,NUM)
1653    FORMAT(1X,4F10.4)
        PRINT 1654,(G(MM),MM=1,5),STDDEV
1654    FORMAT(1X,/,1X,5F9.3,/)
      ITD = 0
      IF(NIT.EQ.1)GO TO 602
      IF(STD.GE.STDDEV)GO TO 602
      ITD = 1
      IF(NIT.GT.IDNI.AND.INF.EQ.1)GO TO 830
      IF(NIT.GT.IDNI)GO TO 2000
  602 STD = STDDEV
      IF(ISITA.EQ.0.AND.NIT.NE.1)ITD=1
      ZIP = STDDEV - 0.005
      IF(ZIP) 2000,2000,512
C  ************************************************************
C     . . SOLVE SIMULTANEOUS EQUATIONS
C     . . INVERSION OF MATRIX AND MATRIX MULTIPLICATION TO GET
C         DX, DY, DZ, DTO, DV
C  ************************************************************
```

```
  512 IF(NIT.GT.IDNI)GO TO 2000
        IDGT=0
        CALL LINV1P(C,NX,CI,IDGT,D11,D22,IER)
        CALL VMULSF(CI,NX,D,1,165,DT,165)
        DO 457 JJJ=1,165
457     D(JJJ)=DT(JJJ)

C  ************************************************************

C     . . . NEW ESTIMATES OF PARAMETERS

C  ************************************************************

      DO 850 I=1,NUM
      X = TX(I)
      Y = TY(I)
  518 YQ = Y
        XKDEG=(Y-34.1)*.018+110.922
      N = 4*(I-1)+ 1
      NP1 = N+1
      NP2 = N+2
      NP3 = N+3
      DT(N) = DT(N)*WP(N)
      DT(NP1) = DT(NP1)*WP(NP1)
      DT(NP2) = DT(NP2)*WP(NP2)
      DT(NP3) = DT(NP3)*WP(NP3)
  519 Y = Y+DT(NP1)/XKDEG
      TY(I) = Y
        XKC=COS(3.1415927*(YQ+Y)/360.)*111.4399
  520 TX(I) = X + DT(N)/XKC
        HLD=TZ(I)
      TZ(I) = TZ(I) + DT(NP2)
        IF(TZ(I).LT.0.)DT(NP3)=DT(NP3)/2.
        IF(TZ(I).LT.0.)TZ(I)=HLD/2.
      TOT(I) = TOT(I) + DT(NP3)
  850 CONTINUE
      DO 811 L=1,5
      GGH(L) = G(L)
      LL = NXX + L
  811 G(L) = G(L) + DT(LL)*WP(LL)
        TYPE 452,(G(I),I=1,5),STDDEV,R(2)
452     FORMAT(1X,7F9.3,/)
      GO TO 1000

C  ************************************************************

C     OUTPUT . . . . . .

C  ************************************************************

 2000 CONTINUE
```

```
      IF(ITD.EQ.0)GO TO 81
      DO 817 L=1,5
  817 G(L) = GH(L)
      DO 611 I=1,NUM
      TX(I) = XH(I)
      TY(I) = YH(I)
      TZ(I) = ZH(I)
  611 TOT(I) = TOH(I)
   81 CONTINUE
        IQF=1
        GO TO 933
930     CONTINUE
        CALL VTPROF(A,NSTN,NX,271,C)
        CALL LINV1P(C,NX,CI,IDGT,D11,D22,IER)
        CALL VCVTSF(CI,NX,CF,165)
        CALL VMULFP(CF,A,NX,NX,NSTN,165,271,H,165,IER)
        CALL VMULFF(H,A,NX,NSTN,NX,165,271,CF,165,IER)
        TYPE 921,(CF(I,I),I=NX-4,NX)
921     FORMAT(1X,5F8.4)
        DO 913 I=161,165
        PRINT 912
912     FORMAT(1X,/)
        PRINT 914,(CF(I,J),J=NX-17,NX)
914     FORMAT(1X,18F7.4)
913     CONTINUE
C      CALL VMULFF(A,H,NSTN,NX,NSTN,271,165,S,271,IER)
      DO 923 I=1,NX
  923 VR(I) = 0.
      DO 796 I=1,NX
      SUM = 0.
      DO 795 J=1,NSTN
  795 SUM = SUM + (H(I,J)*H(I,J))
  796 VR(I) = SUM
      SUM = 0.
      DO 919 I=1,NSTN
  919 SUM = SUM + (R(I)*R(I)/(W(I)*W(I)))
      BIGR = SQRT(SUM/NSTN)
      DO 221 I=1,NX
  221 VR(I) = SQRT(VR(I))*WP(I)
      NIT = NIT - 1
      PRINT 900
  900 FORMAT('1',/)
      DO 812 L=1,5
      LL = NXX + L
        TYPE 352,G(L),VR(LL)
  352 FORMAT(8X,'PG VEL COEF = ',F6.2,17X,'SIGMA = ',F7.3)
      PRINT 351,G(L),VR(LL),WP(LL)
  351 FORMAT(8X,'PG VEL COEF = ',F6.2,17X,'SIGMA = ',F7.3,
     $10X,'WEIGHT = ',F4.2)
  812 CONTINUE
      PRINT 902
      AZI = 0.
      DO 813 L=1,4
```

```
      CALL TP(AZI,G,V)
      AZI = AZI * 57.2958
      PRINT 831,V,AZI
  831 FORMAT (8X,F4.2,' KM/SEC AT',F7.2,' DEGREES')
      AZI = (AZI + 45.)/57.2958
  813 CONTINUE
      PRINT 902
  902 FORMAT(1X,//)
      PRINT 604,NIT
  604 FORMAT(8X,'# OF ITERATIONS = ',I3,//)
      PRINT 902
      PRINT 915, BIGR
  915 FORMAT(8X,'BIG R = ',F7.3,//)
      PRINT 24
   24 FORMAT(8X,'EVENT #',15X,'S.D.(X)',15X,'S.D.(Y)',15X,
     $'S.D.(Z)',15X,'S.D.(OT)',//)
      DO 23 J=1,NUM
      I = 4*(J-1) + 1
      IP1 = I + 1
      IP2 = I + 2
      IP3 = I + 3
      PRINT780,J,VR(I),VR(IP1),VR(IP2),VR(IP3)
  780 FORMAT(16X,I2,11X,4(F6.2,15X),//)
   23 CONTINUE
C       PRINT 900
C       DO 911 I=1,NX
C       SUM = 0.
C       DO 916 J=1,NX
C       IF(J.NE.I)GO TO 935
C       SUM = (RR(I,J)-1.)*(RR(I,J)-1.) + SUM
C       GO TO 916
C   935 SUM = SUM + RR(I,J)*RR(I,J)
C   916 CONTINUE
C       PRINT 910,I,SUM
C   910 FORMAT(10X,'R',I2,' = ',F6.3)
C   911 CONTINUE
      PRINT 900
      NSTN = 0
        VARI=0.
      DO 82 I=1,NUM
      X = TX(I)
      Y = TY(I)
      Z = TZ(I)
      TO = TOT(I)
      IXDEG = IFIX(X)
      IYDEG = IFIX(Y)
      IXMIN = IFIX((X-FLOAT(IXDEG))*60.)
      IYMIN = IFIX((Y-FLOAT(IYDEG))*60.)
      XSEC = ((X-FLOAT(IXDEG))*60.-FLOAT(IXMIN))*60.
      YSEC = ((Y-FLOAT(IYDEG))*60.-FLOAT(IYMIN))*60.
      IXMIN = IABS(IXMIN)
      XSEC = ABS(XSEC)
      IYMIN = IABS(IYMIN)
```

```
      YSEC = ABS(YSEC)
      IHR(I) = IHRO(I)
      IM = IMINO(I)
      IF(TO.GE.0.)GO TO 300
      IM = IMINO(I) - 1
      TO = TO + 60.
  300 CONTINUE
        J=4*(I-1)+1
      PRINT 301, IMO(I),IDA(I),IYR(I),IHR(I),IM,TO,VR(J+3)
  301 FORMAT(40X,'DATE: ',2(I2,'-'),I2,25X,'ORIGIN TIME: ',
     $2(I2,':'),F5.2,3X,F5.3,/////)
      PRINT 302
  302 FORMAT(25X,'LATITUDE',30X,'LONGITUDE',31X,'DEPTH (KM)',/)
      PRINT 202, IYDEG,IYMIN,YSEC,IXDEG,IXMIN,XSEC,Z,VR(J+2)
  202 FORMAT(23X,2(I3,'-',I2,'-',F5.2,26X),F11.3,2X,F6.4,/)
        VR(J)=VR(J)/93.
        VR(J+1)=VR(J+1)/111.
        PRINT 203,Y,VR(J+1),X,VR(J)
203     FORMAT(24X,F7.4,2X,F5.4,23X,F8.4,2X,F5.4,///////)
  205 PRINT 304
  304 FORMAT(2X,'STATION',8X,'WEIGHT',9X,'RESIDUAL (SEC)',12X,
     $'AZIMUTH',
     $12X,'DISTANCE (KM)',7X,'ANGLE OF EMERGENCE',7X,'TIME',/)
      NST = NSTA(I)
      DO 860 J=1,NST
      K = NSTN + J
      CALL AZ(SX(K),SY(K),X,Y,AZI)
      AZI = AZI/57.2958
      CALL TP(AZI,G,V)
      HPZ = (Z+SZ(K))
        XKDEG=((SY(K)+Y)/2.-34.1)*.018+110.922
        XKC=COS(3.1415927*(SY(K)+Y)/360.)*111.4399
      XX = (X-SX(K))*XKC
      YY = (Y-SY(K))*XKDEG
      DL(K) = SQRT(XX*XX + YY*YY)
      OTT = STO(K) - TOT(I)
      TTT = SQRT(DL(K)*DL(K) + HPZ*HPZ)/V
      R(K) = OTT - TTT
  860 CONTINUE
      M = NSTA(I)
      N = NSTA(I) - 1
      DO 401 K=1,N
      DO 400 JJ=2,M
      J = NSTN + JJ
      JM1 = J-1
      IF(DL(J).GT.DL(JM1))GO TO 400
      HDL = DL(JM1)
      DL(JM1) = DL(J)
      DL(J) = HDL
      HDL = STO(JM1)
      STO(JM1) = STO(J)
      STO(J) = HDL
      HDL = W(JM1)
```

```
      W(JM1) = W(J)
      W(J) = HDL
      HDL = R(JM1)
      R(JM1) = R(J)
      R(J) = HDL
      IHDL = STA(JM1)
      STA(JM1) = STA(J)
      STA(J) = IHDL
      HDL = SX(JM1)
      SX(JM1) = SX(J)
      SX(J) = HDL
      HDL = SY(JM1)
      SY(JM1) = SY(J)
      SY(J) = HDL
      HDL = SZ(JM1)
      SZ(JM1) = SZ(J)
      SZ(J) = HDL
  400 CONTINUE
  401 CONTINUE

C       DETERMINE ANGLE OF EMERGENCE MEASURED FROM +Z DIRECTION

      VAR = 0.
      DO 60 J = 1,NST
      K = NSTN + J
        SCR=0.
        IF(IRD.EQ.0)GO TO 419
      SCR = -.2
      DO 131 L=1,NSC
      IF(STAC(1,L).NE.STA(K))GO TO 131
      SCR = FLOAT(STAC(2,L))*.01
  131 CONTINUE
      STO(K) = STO(K) + SCR
419     CONTINUE
      VAR = VAR + R(K)*R(K)
        VARI=VARI+R(K)*R(K)
      CALL AZ(SX(K),SY(K),X,Y,AZI)
      HPZ = Z + SZ(K)
      ANGLE = ATAN2(DL(K),HPZ)*180./3.141593
      SEC = STO(K) - (IMIN(K) - IMINO(I))*60.
      PRINT 805, STA(K),W(K),R(K),AZI,DL(K),ANGLE,IMIN(K),SEC
     $,SCR
  805 FORMAT(4X,A4,9X,F5.3,13X,F6.3,16X,F6.2,15X,F6.2,16X,
     $F6.3,12X,I2,':',F5.2,2X,F4.2,/)
        STO(K)=STO(K)-SCR
   60 CONTINUE
      PRINT 901
  901 FORMAT(1X,////)
      PRINT 608,YI(I),XI(I),ZI(I),IHRO(I),IMINO(I),SECO(I)
  608 FORMAT(8X,'INITIAL ESTIMATE:',3F10.2,5X,2(I2,':'),F5.2,//)
      X = TX(I) - XI(I)
      Y = TY(I) - YI(I)
      Z = TZ(I) - ZI(I)
```

```
      IF(IHR(I).LT.IHRO(I))TOI(I) = TOI(I) + 3600
      T = TOI(I) - TOT(I)
      PRINT 610,Y,X,Z,T
  610 FORMAT(8X,'FINAL DIFFERENCE:',3F10.2,11X,F5.2,//)
      J = 4*(I-1) + 1
      JP1 = J + 1
      JP2 = J + 2
      JP3 = J + 3
        PRINT 612,WP(J),WP(JP1),WP(JP2),WP(JP3)
  612 FORMAT(8X,'WEIGHTING (KMS.):',3F10.2,11X,F5.2,//)
      ST = SQRT(VAR/FLOAT(NST-1))
      PRINT 73,ST
   73 FORMAT(8X,'STDDEV = ',F6.2,//)
      PRINT 900
   82 NSTN = NSTN + NSTA(I)
      GO TO 2
  830 CONTINUE
      PRINT 832,IP
  832 FORMAT('1',20X,'NO IMPROVEMENT OVER THE INITIAL ESTIMATE')
    2 CONTINUE
        VARI=SQRT(VARI/FLOAT(NSTN-1))
        TYPE 4312,VARI
4312    FORMAT(1X,'THE FINAL SIGMA IS =',F6.4)
        PRINT 4312,VARI
      STOP
      END
      SUBROUTINE AZ(SX,SY,X,Y,AZI)

C  ************************************************************

C       DETERMINATION OF AZIMUTH (STATION TO EVENT)

C  ************************************************************

        TAN(A)=SIN(A)/COS(A)
      PI = 3.141592654
      FF = PI/180.
      A = (90.-Y)*FF
      B = (90.-SY)*FF
      C = ABS(SX-X)*FF
      FH =    ATAN(SIN(.5*(A-B))/TAN(.5*C)/SIN(.5*(A+B)))
      SH =    ATAN(COS(.5*(A-B))/TAN(.5*C)/COS(.5*(A+B)))
      AZI = (FH+SH)/FF
      IF(SX.LT.X) AZI=360.-AZI
      RETURN
      END
```

```
      SUBROUTINE TP(AZI,G,V)
C     ************************************************************
C           DETERMINATION OF THE VELOCITY AS A FUNCTION OF AZIMUTH
C           G'S = COEFFICIENTS OF THE VELOCITY FUNCTION
C     ************************************************************
      DIMENSION G(5)
      V = G(1) + G(2)*COS(2.*AZI) + G(3)*SIN(2.*AZI)
     $ + G(4)*COS(4.*AZI) + G(5)*SIN(4.*AZI)
      RETURN
      END
```

```
C    ************************************************************
C    *                                                          *
C    *  DLS.FOR: THIS ROUTINE PROVIDES FOR THE DETERMINATION    *
C    *           OF THE VELOCITY DISTRIBUTION AS A FUNCTION     *
C    *           OF A GIVEN BLOCK CONFIGURATION BY MEANS OF     *
C    *           A DAMPED LEAST SQUARES APPROACH.               *
C    ************************************************************


      DIMENSION STA(262),DL(262),R(262),W(262),SZ(262),SX(262),
     $IHR(262),TX(40),TY(40),TZ(40),TOT(40),IHRO(40),IMINO(40),
     $TOI(40),XH(40),YH(40),ZH(40),TOH(40),IMO(40),IDA(40),
     $IYR(40),STO(262),DLH(262),RH(262),NSTA(40),XI(40),YI(40)
     $,ZI(40)
      DIMENSION C(22791),D(213),B(262),A(262,213),H(213,262),
     $VR(213),WP(213),CI(22791),CF(213,213),BLKT(72),IBLC(53,3),
     $SY(262),SECO(40),DT(213),TDT(6,6,2)
C     $,RR(213,213),S(262,262)
        EQUIVALENCE (CI,H)
      INTEGER TEST,EVENT,STA,STAC

C    ************************************************************

C     STATION CORRECTIONS

      DATA STAC/'WT',-11,'WM',12,'IC',08,'NG',14,'CM',13
     $,'RM',11,'SC',15,'RI',-01,'BB',-04
     $,'CC',-15,'SL',-11,'FM',00,'DM',-01,'BG',-01'GM',-06,
     $'CU',-10,'MY',-09,'HC',16,'FC',26,'TS',28,'CK',-04,
     $'TA',09,'LAD',-25,'LPN',-24,'TD',-09/

C    ************************************************************


C     INPUT . . . . . . . . . . . . . . . . . . . . . .

C       . . . STATION LOCATIONS - - SX,SY,SZ

C       . . . ARRIVAL TIMES - - IMIN,SEC,W

C       . . . INITIAL ESTIMATES AND WEIGHTS
C                 - - XI,YI,ZI,TOI,VI,WP

C    ************************************************************


C       NSC = NUMBER OF STORED STATION CORRECTIONS
        NSC = 25
```

```
C       DF = DAMPING FACTOR
        DF = .50


        OPEN(UNIT=25,DEVICE='TTY')
C
        TYPE 420
420     FORMAT(/,1X,'THE NUMBER OF EVENTS ?')
        READ(5,*) NUM
        TYPE 416
416     FORMAT(1X'INPUT DATA FILE ?')
        READ(5,417) VFN
417     FORMAT(A5)
        IRD=0
        AVR=0.
        SUM=0.
        TYPE 413
413     FORMAT(1X,'REAL DATA ?')
        READ(5,412) TEST
412     FORMAT(A3)
        IF(TEST.EQ.'YES')IRD=1
        IF(IRD.EQ.1)GO TO 414
        TYPE 415
415     FORMAT(1X,'WHAT IS THE DESIRED NOISE LEVEL ?')

C   ************************************************************

C                   (SYNTHETIC DATA)

C       TDNL = STANDARD DEVIATION OF MAXIMUM NOISE DESIRED

C       TDNL=1.  WILL BASE NOISE ON W(K)

C   ************************************************************

        READ(5,*)TDNL
414     CONTINUE
        TYPE 463
463     FORMAT(1X,'WHAT IS THE DESIRED # OF ITERATIONS ?')
        READ(5,*) IDNI
        TYPE 1200
1200    FORMAT(1X,'HOW MANY TOTAL BLOCKS ARE THERE ?')
        ACCEPT *,NBL
        IF(NBL.NE.36)GO TO 903
        DO 904 I=1,NBL
        J=I+NBL
        IBLC(I,1)=2
        IBLC(I,2)=I
904     IBLC(I,3)=J
        GO TO 905
903     CONTINUE

C       BLK.DAT = DATA FILE OF BLOCK CONFIGURATION
```

```
          IF(NBL.LE.36)GO TO 691
          OPEN(UNIT=23,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
        $ FILE='BLK')
          DO 692 I=1,NBL
          READ(23,*) IBL,(IBLC(I,J),J=2,IBL+1)
C         TYPE *,IBL,(IBLC(I,J),J=2,IBL+1)
          IBLC(I,1)=IBL
692       CONTINUE
          CLOSE(UNIT=23)
          GO TO 905
691       CONTINUE
          DO 1225 I=1,NBL
          TYPE 1220,I
1220      FORMAT(1X,'WHICH OLD BLOCKS FORM THE NEW BLOCK #',I2,'?')
C         FIRST NUMBER IS NUMBER OF BLOCKS TO BE COMBINED
          ACCEPT *,IBL,(IBLC(I,J),J=2,IBL+1)
1225      IBLC(I,1)=IBL
905       CONTINUE
        NXX = NUM * 4
        NX = NXX + NBL
          NSYM=NX*(NX+1)/2
        NSTN = 0
          TYPE 1110
1110      FORMAT(1X,'WHAT IS THE INITIAL VELOCITY ?')
          ACCEPT *,VII
          II=0
          DO 863 K=1,NBL
          VI(K)=VII
          II=II+1
          WP(NXX+II)=.02
          IF(II.GT.36)WP(NXX+II)=.03
863       CONTINUE
          OPEN(UNIT=22,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
      $   FILE=VFN)
          DO 51 NOQ=1,NUM
       READ(22,*) NSTA(NOQ),IMO(NOQ),IDA(NOQ),IYR(NOQ)
C     ************************************************************
C       INITIAL ESTIMATES OF HYPOCENTERS AND ORIGIN TIMES
                        (XI,YI,ZI,TOI)
C       CAUTION-- DO NOT GUESS EPICENTER COORDS SAME AS STATION
C     ************************************************************
        I = 4*(NOQ-1) + 1
        IP1 = I+ 1
        IP2 = I+ 2
        IP3 = I+ 3
```

```
      READ(22,*) X,WP(I),Y,WP(IP1),Z,WP(IP2)
        READ(22,*) IHRO(NOQ),IMINO(NOQ),SECO(NOQ),WP(IP3)
      XI(NOQ) = X
      YI(NOQ) = Y
      ZI(NOQ) = Z
        WP(I)=1.
        WP(IP1)=1.
        WP(IP2)=3.0
        WP(IP3)=.3
        ZDIF=Z*100.-FLOAT(IFIX(Z*100.))+.01
        ZDIF=FLOAT(IFIX(ZDIF*10.))
        IF(ZDIF.NE.0.)WP(IP2)=1.
     TOI(NOQ) = SECO(NOQ)
        IF(WP(I).EQ.0.)WP(I)=1.
        IF(WP(IP1).EQ.0.)WP(IP1)=1.
        IF(WP(IP2).EQ.0.)WP(IP2)=3.
        IF(WP(IP3).EQ.0.)WP(IP3)=.3

C    ************************************************************

C                      (SYNTHETIC DATA)

C          . . . ADDITION OF NOISE TO TRUE SOLUTION

C    ************************************************************

        IF(IRD.EQ.1)GO TO 424
        CALL GGNML(1234567.D0,1,RN)
        X=X+RN*.01
        CALL GGNML(1234567.D0,1,RN)
        Y=Y+RN*.01
        CALL GGNML(1234567.D0,1,RN)
        ZMF=3.
        ZDIF=Z*100.-FLOAT(IFIX(Z*100.))+.01
        ZDIF=FLOAT(IFIX(ZDIF*10.))
        IF(ZDIF.NE.0.)ZMF=1.
        Z=Z+RN*ZMF
        IF(Z.LT.3.)Z=3.
        CALL GGNML(1234567.D0,1,RN)
        SECO(NOQ)=SECO(NOQ)+RN*.3
        IF(SECO(NOQ).GE.60.)IMINO(NOQ)=IMINO(NOQ)+1
        IF(SECO(NOQ).GE.60.)SECO(NOQ)=SECO(NOQ)-60.
        IF(SECO(NOQ).GT.0.)GO TO 424
        IMINO(NOQ)=IMINO(NOQ)-1
        SECO(NOQ)=SECO(NOQ)+60.
424     CONTINUE
        PRINT 1650,X,Y,Z,SECO(NOQ),XI(NOQ),YI(NOQ),ZI(NOQ)
     $  TOI(NOQ)
1650    FORMAT(1X,4F10.4,20X,4F10.4)
      XI(NOQ) = X
      YI(NOQ) = Y
      ZI(NOQ) = Z
     TOI(NOQ) = SECO(NOQ)
```

```
      NST = NSTA(NOQ)
C     ***************************************************************
C       . . . ARRIVAL TIMES AND WEIGHTS
C     ***************************************************************
        OPEN(UNIT=1,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
     $  FILE='STA')
       DO 49 J=1,NST
       K = NSTN + J
         IFLAG=0
         REWIND 1
         READ(22,425) STA(K),IMIN(K),SEC,W(K)
425      FORMAT(A3,1X,I2,1X,F5.2,1X,F4.3)
105      CONTINUE
C     ***************************************************************
C         . . . STATION COORDINATES
C     ***************************************************************
         READ(1,427,END=106) TEST,SY(K),SX(K),SZ(K)
427      FORMAT(A3,1X,F7.4,1X,F8.4,2X,F5.3)
         SZ(K)=SZ(K)-1.5
         IF(TEST.EQ.STA(K)) GO TO 428
         GO TO 105
106      CONTINUE
         TYPE 429,STA(K)
429      FORMAT(10X,'STATION ',A3,' NOT FOUND',/)
         CLOSE(UNIT=1)
         CLOSE(UNIT=22)
         GO TO 2
428      IF(IMINO(NOQ).GT.IMIN(K))IMIN(K)=IMIN(K)+60
C     ***************************************************************
C                     (SYNTHETIC DATA)
C         . . . ADDITION OF NOISE TO DATA
C     ***************************************************************
         IF(IRD.EQ.1)GO TO 461
         IF(TDNL.EQ.1.)GO TO 666
         TNL=TDNL
         W(K)=TNL
666      CALL GGNML(1234567.D0,1,RN)
         RESID=RN*W(K)
         AVR=AVR+RESID
         SUM=RESID*RESID+SUM
```

```
          SEC=SEC+RESID
          IF(SEC.LT.0.)IMIN(K)=IMIN(K)-1
          IF(SEC.LT.0.)SEC=SEC+60.
          IF(SEC.GE.60.)IMIN(K)=IMIN(K)+1
          IF(SEC.GE.60.)SEC=SEC-60.
 461      STO(K) = SEC + (IMIN(K) - IMINO(NOQ))*60.
          IF(IRD.EQ.0)GO TO 49
        DO 130 I=1,NSC
        IF(STAC(1,I).NE.STA(K))GO TO 130
          IFLAG=1
        STO(K) = STO(K) - FLOAT(STAC(2,I))*.01
  130 CONTINUE
          IF(IFLAG.EQ.0)STO(K)=STO(K)+.2
   49 CONTINUE
          CLOSE(UNIT=1)
          NSTN=NSTN+NSTA(NOQ)
   51 CONTINUE
          IF(IRD.EQ.1)GO TO 664
          AVR=AVR/NSTN
          STDR=SQRT(SUM/NSTN-AVR*AVR)
          PRINT 665,AVR,STDR
 665      FORMAT(1X,//,10X,'AVERAGE RESIDUAL = ',F6.3,10X,
     $    'STANDARD DEVIATION OF AVG. RESIDUAL = ',F6.3,//)
 664      CLOSE(UNIT=22)

C    ************************************************************

C      LEAST SQUARES METHOD . . . . . .

C      CALCULATION OF DISTANCE BETWEEN STATION AND EPICENTER

C    ************************************************************

          IQF=0
   80 NIT = 0
C           . . . INITIALIZATION
        DO 169 I=1,NUM
        TX(I) = XI(I)
        TY(I) = YI(I)
        TZ(I) = ZI(I)
  169 TOT(I) = TOI(I)
          DO 810 MM=1,NBL
  810     V(MM)=VI(MM)
          ITD=0
          IMP=1
 1000 NIT = NIT + 1
          DO 313 M=1,2
          DO 313 I=1,6
          DO 313 J=1,6
  313     TDT(I,J,M)=0.
        DO 756 I=1,213
        DO 756 J=1,262
        B(J) = 0.0
```

```
      A(J,I) = 0.0
      IF(I.GT.1)GO TO 756
C      DO 756 K=1,262
C      S(J,K) = 0.
  756 CONTINUE
      DO 55 I=1,213
      D(I) = 0.
C      DO 55 K=1,213
C      CF(I,K) = 0.
   55 CONTINUE
        DO 56 I=1,NSYM
        CI(I)=0.
56      C(I)=0.

C   ************************************************************

C     . . . FORMATION OF ARRAY TO BE INVERTED

C   ************************************************************

933     CONTINUE
      NSTN = 0
      DO 859 NOQ=1,NUM
      X = TX(NOQ)
      Y = TY(NOQ)
      Z = TZ(NOQ)
      NN = 4*(NOQ - 1) + 1
      NNP1 = NN+1
      NNP2 = NN+2
      NNP3 = NN+3
      NST = NSTA(NOQ)
      DO 858 J=1,NST
      K = NSTN + J
      HPZ = Z+SZ(K)
        XKDEG=((SY(K)+Y)/2.-34.1)*.018+110.922
      XKC=COS(3.1415927*(SY(K)+Y)/360.)*111.4399
        XP=X
        YP=Y
        DP=HPZ
        CALL TTYM(XP,YP,DP,SX(K),SY(K),SZ(K),TD,TDT)
        CALL BLK(NBL,TD,IBLC,BLKT,V,AVSQ,TTT)
C       TYPE 1230 ,BLKT(1),TTT
1230    FORMAT(1X,2F10.4)
      XX = (X-SX(K))*XKC
      YY = (Y-SY(K))*XKDEG
      DL(K) = SQRT(XX*XX + YY*YY)
      OTT = STO(K) - TOT(NOQ)
      R(K) = OTT - TTT
      FF =1./(AVSQ*OTT)
      A(K,NN) = XX*FF/W(K)
      A(K,NNP1)= YY*FF/W(K)
      A(K,NNP2) = HPZ*FF/W(K)
      A(K,NNP3) = 1.0/W(K)
```

```
          III=0
          DO 862 MM=1,NBL
          III=III+1
          BLKTM=BLKT(III)+R(K)*BLKT(III)/TTT
 862      A(K,NXX+III)=BLKTM/W(K)
        B(K)=R(K)/W(K)
   858 CONTINUE
       NSTN = NSTN + NSTA(NOQ)
   859 CONTINUE
          DO 111 I=1,NSTN
          DO 111 J=1,NX
 111      A(I,J)=WP(J)*A(I,J)

C         . . . FORMATION OF ATA

          CALL VTPROF(A,NSTN,NX,262,C)
          CALL VCVTSF(C,NX,CF,213)
          DO 112 J=1,NX
          DMPF=DF
          IF(J.EQ.119)DMPF=5.
          IF(J.EQ.139)DMPF=5.
          IF(J.EQ.155)DMPF=5.
          IF(J.EQ.159)DMPF=5.
          CF(J,J)=CF(J,J)+DMPF
 112      CONTINUE
          CALL VCVTFS(CF,NX,213,C)
          IF(IQF.EQ.1)GO TO 930

C         . . . . FORMATION OF ATB

       CALL VMULFM(A,B,NSTN,NX,1,262,262,D,213,IER)

C    ************************************************************

C     . . CALCULATION OF STANDARD DEVIATION OF AVERAGE RESIDUAL

C     . . . TEST FOR IMPROVEMENT

C    ************************************************************

       VARI = 0.
       SUM = 0.
       DO 54 J=1,NSTN
       SUM = SUM + (R(J)*R(J)/(W(J)*W(J)))
       VARI = VARI + R(J)*R(J)
    54 CONTINUE
       VARI = VARI/FLOAT(NSTN-1)
       BIGR = SQRT(SUM/FLOAT(NSTN))
       STDDEV = SQRT(VARI)
C        IF(NIT.EQ.1)TYPE *,STDDEV
       IF(NIT.EQ.1)STDH=STDDEV
       IF(STDH.LT.STDDEV)ITD=1
       IF(STDH.LT.STDDEV)GO TO 89
```

```
      IF(NIT.GT.1)IMP=0
      STDH = STDDEV
        DO 816 MM=1,NBL
  816 VH(MM)=V(MM)
      DO 609 I=1,NUM
      XH(I) = TX(I)
      YH(I) = TY(I)
      ZH(I) = TZ(I)
  609 TOH(I) = TOT(I)
   89 CONTINUE
        NITM1=NIT-1
        PRINT 1652,NITM1
1652    FORMAT(1X,//,1X,'ITERATION #',I2,/)
C       TYPE 452,(V(MM),MM=1,NBL),STDDEV,BIGR
452     FORMAT(1X,/,1X,6F9.3,/)
        PRINT 1700,((TX(I),TY(I),TZ(I),TOT(I)),I=1,NUM)
1700    FORMAT(1X,4F10.4)
        PRINT 452,(V(MM),MM=1,NBL),STDDEV,BIGR
      IF(NIT.GT.IDNI.AND.IMP.EQ.1)GO TO 830
      ZIP = STDDEV - 0.001
      IF(ZIP) 2000,2000,512
  512 IF(NIT.GT. IDNI)GO TO 2000

C   ************************************************************

C    . . SOLVE SIMULTANEOUS EQUATIONS
C    . . INVERSION OF MATRIX AND MATRIX MULTIPLICATION TO GET
C          DX, DY, DZ, DTO, DV

C   ************************************************************

        IDGT=0
        CALL LINV1P(C,NX,CI,IDGT,D11,D22,IER)
        IF(IER.EQ.129)TYPE *,IER
        IF(IER.EQ.129)GO TO 2
        CALL VMULSF(CI,NX,D,1,213,DT,213)
C       TYPE 1500,(DT(JJJ),JJJ=1,NX+1)
1500    FORMAT(1X,10F6.3)

C   ************************************************************

C       . . . NEW ESTIMATES OF THE PARAMETERS

C   ************************************************************

      DO 850 I=1,NUM
      X = TX(I)
      Y = TY(I)
  518 YQ = Y
        XKDEG=(Y-34.1)*.018+110.922
      N = 4*(I-1)+ 1
      NP1 = N+1
      NP2 = N+2
```

```
      NP3 = N+3
        DT(N)=DT(N)*WP(N)
        DT(NP1)=DT(NP1)*WP(NP1)
        DT(NP2)=DT(NP2)*WP(NP2)
        DT(NP3)=DT(NP3)*WP(NP3)
  519 Y = Y+DT(NP1)/XKDEG
      TY(I) = Y
        XKC=COS(3.1415927*(YQ+Y)/360.)*111.4399
  520 TX(I) = X + DT(N)/XKC
        HLD=TZ(I)
      TZ(I) = TZ(I) + DT(NP2)
        IF(TZ(I).LT.0.)DT(NP3)=DT(NP3)/2.
        IF(TZ(I).LT.0.)TZ(I)=HLD/2.
      TOT(I) = TOT(I) + DT(NP3)
  850 CONTINUE
        II=0
        DO 811 MM=1,NBL
        II=II+1
        LL=NXX+II
811     V(MM)=V(MM)/(1.+DT(LL)*WP(LL))
      GO TO 1000

C   ************************************************************

C     OUTPUT . . . . . .

C   ************************************************************

 2000 CONTINUE
      IF(ITD.EQ.0)GO TO 81
        DO 817 MM=1,NBL
  817 V(MM)=VH(MM)
      DO 611 I=1,NUM
      TX(I) = XH(I)
      TY(I) = YH(I)
      TZ(I) = ZH(I)
  611 TOT(I) = TOH(I)
   81 CONTINUE
        DO 319 MM=1,2
        DO 319 I=1,6
        DO 319 J=1,6
319     TDT(I,J,MM)=0.
        IQF=1
        GO TO 933
930     CONTINUE
        CALL LINV1P(C,NX,CI,IDGT,D11,D22,IER)
C       TYPE *,IER
        CALL VCVTSF(CI,NX,CF,213)
C       TYPE *,(A(J,159),J=250,262)
C       TYPE *,(A(J,188),J=250,262)
        CALL VMULFP(CF,A,NX,NX,NSTN,213,262,H,213,IER)
        CALL VMULFP(H,H,NX,NSTN,NX,213,213,CF,213,IER)
C       DO 1112 I=161,208
```

```
C        DO 1112 J=161,208
C1112    CF(I,I)=SQRT(CF(I,I))
         DO 2111 I=161,208
         PRINT 912
         PRINT 914,(CF(I,J),J=161,208)
2111     CONTINUE
         CALL VMULFF(H,A,NX,NSTN,NX,213,262,CF,213,IER)
C       CALL VMULFF(A,H,NSTN,NX,NSTN,262,213,S,262,IER)
         PRINT 914,(CF(J,J),J=1,213)
         DO 913 I=161,208
         PRINT 912
912      FORMAT(1X,/)
         PRINT 914,(CF(I,J),J=161,208)
914      FORMAT(1X,18F7.4)
913      CONTINUE
       DO 923 I=1,NX
  923 VR(I) = 0.
       DO 796 I=1,NX
       SUM = 0.
       DO 795 J=1,NSTN
  795 SUM = SUM + (H(I,J)*H(I,J))
  796 VR(I) = SQRT(SUM)*WP(I)
       SUM = 0.
       DO 919 I=1,NSTN
  919 SUM = SUM + (R(I)*R(I)/(W(I)*W(I)))
       BIGR = SQRT(SUM/NSTN)
       NIT = NIT - 1
       PRINT 900
  900 FORMAT('1',/)
         LL=NXX
         DO 812 MM=1,NBL
       LL = LL + 1
         VR(LL)=VR(LL)*5.85
      PRINT 351,MM,V(MM),VR(LL),WP(LL)
 351 FORMAT(8X,'VEL OF BLOCK ',I2,' = ',F6.2,17X,
    $'SIGMA = ',F9.5,8X,'WEIGHT = ',F4.2)
 812 CONTINUE
     PRINT 902
 902 FORMAT(1X,//)
     PRINT 604,NIT
 604 FORMAT(8X,'# OF ITERATIONS = ',I3,//)
     PRINT 902
     PRINT 915, BIGR
915 FORMAT(8X,'BIG R = ',F7.3,//)
    PRINT 24
 24 FORMAT(8X,'EVENT #',15X,'SIG(X)',15X,'SIG(Y)',15X,
   $'SIG(Z)',15X,'SIG(OT)',//)
    DO 23 J=1,NUM
    I = 4*(J-1) + 1
    IP1 = I + 1
    IP2 = I + 2
    IP3 = I + 3
    PRINT780,J,VR(I),VR(IP1),VR(IP2),VR(IP3)
```

```
  780 FORMAT(16X,I2,11X,4(F6.2,15X),//)
   23 CONTINUE
      PRINT 900
      DO 911 I=1,NX
      SUM = 0.
      DO 916 J=1,NX
      IF(J.NE.I)GO TO 935
      SUM = (CF(I,J)-1.)*(CF(I,J)-1.) + SUM
      GO TO 916
  935 SUM = SUM + CF(I,J)*CF(I,J)
  916 CONTINUE
      PRINT 910,I,SUM
  910 FORMAT(10X,'R',I3,' = ',F6.3)
  911 CONTINUE
C
C
      PRINT 900
        DO 318 MM=1,2
        DO 318 I=1,6
        DO 318 J=1,6
318     TDT(I,J,MM)=0.
      NSTN = 0
      DO 82 I=1,NUM
      X = TX(I)
      Y = TY(I)
      Z = TZ(I)
      TO = TOT(I)
      IXDEG = IFIX(X)
      IYDEG = IFIX(Y)
      IXMIN = IFIX((X-FLOAT(IXDEG))*60.)
      IYMIN = IFIX((Y-FLOAT(IYDEG))*60.)
      XSEC = ((X-FLOAT(IXDEG))*60.-FLOAT(IXMIN))*60.
      YSEC = ((Y-FLOAT(IYDEG))*60.-FLOAT(IYMIN))*60.
      IXMIN = IABS(IXMIN)
      XSEC = ABS(XSEC)
      IYMIN = IABS(IYMIN)
      YSEC = ABS(YSEC)
      IHR(I) = IHRO(I)
      IM = IMINO(I)
      IF(TO.GE.0.)GO TO 300
      IM = IMINO(I) - 1
      TO = TO + 60.
300     IF(TO.LT.60.)GO TO 310
        IM=IMINO(I)+1
        TO=TO-60.
  310 CONTINUE
        J=4*(I-1)+1
      PRINT 301, IMO(I),IDA(I),IYR(I),IHR(I),IM,TO,VR(J+3)
  301 FORMAT(40X,'DATE: ',2(I2,'-'),I2,25X,'ORIGIN TIME: ',
     $2(I2,':'),F5.2,3X,F5.3,/////)
      PRINT 302
  302 FORMAT(25X,'LATITUDE',30X,'LONGITUDE',31X,'DEPTH (KM)',/)
      PRINT 202, IYDEG,IYMIN,YSEC,IXDEG,IXMIN,XSEC,Z,VR(J+2)
```

```
  202 FORMAT(23X,2(I3,'-',I2,'-',F5.2,26X),F11.3,2X,F6.4,/)
        VR(J)=VR(J)/93.
        VR(J+1)=VR(J+1)/111.
        PRINT 213,Y,VR(J+1),X,VR(J)
213     FORMAT(24X,F7.4,2X,F5.4,23X,F8.4,2X,F5.4,///////)
  205 PRINT 304
  304 FORMAT(2X,'STATION',8X,'WEIGHT',9X,'RESIDUAL (SEC)',12X,
     $'AZIMUTH',
     $12X,'DISTANCE (KM)',7X,'ANGLE OF EMERGENCE',7X,'TIME',/)
      NST = NSTA(I)
      DO 860 J=1,NST
      K = NSTN + J
      HPZ = Z+SZ(K)
        XKDEG=((SY(K)+Y)/2.-34.1)*.018+110.922
        XKC=COS(3.1415927*(SY(K)+Y)/360.)*111.4399
      XX = (SX(K)-X)*XKC
      YY = (SY(K)-Y)*XKDEG
      DL(K) = SQRT(XX*XX + YY*YY)
      OTT = STO(K) - TOT(I)
        XP=X
        YP=Y
        DP=HPZ
        CALL TTYM(XP,YP,DP,SX(K),SY(K),SZ(K),TD,TDT)
        CALL BLK(NBL,TD,IBLC,BLKT,V,AVSQ,TTT)
      R(K) = OTT - TTT
  860 CONTINUE
      M = NSTA(I)
      N = NSTA(I) - 1
      DO 401 K=1,N
      DO 400 JJ=2,M
      J = NSTN + JJ
      JM1 = J-1
      IF(DL(J).GT.DL(JM1))GO TO 400
      HDL = DL(JM1)
      DL(JM1) = DL(J)
      DL(J) = HDL
        IHDL=IMIN(JM1)
        IMIN(J)=IMIN(J)
        IMIN(J)=IHDL
      HDL = STO(JM1)
      STO(JM1) = STO(J)
      STO(J) = HDL
      HDL = W(JM1)
      W(JM1) = W(J)
      W(J) = HDL
      HDL = R(JM1)
      R(JM1) = R(J)
      R(J) = HDL
      IHDL=STA(JM1)
      STA(JM1) = STA(J)
      STA(J) = IHDL
      HDL = SX(JM1)
      SX(JM1) = SX(J)
```

```
      SX(J) = HDL
      HDL = SY(JM1)
      SY(JM1) = SY(J)
      SY(J) = HDL
      HDL = SZ(JM1)
      SZ(JM1) = SZ(J)
      SZ(J) = HDL
  400 CONTINUE
  401 CONTINUE

C     DETERMINE ANGLE OF EMERGENCE MEASURED FROM +Z DIRECTION

      VAR = 0.
      DO 60 J = 1,NST
      K = NSTN + J
        SCR=0.
        IF(IRD.EQ.0)GO TO 419
      SCR = -.2
      DO 131 II=1,NSC
      IF(STAC(1,II).NE.STA(K))GO TO 131
      SCR = FLOAT(STAC(2,II))*.01
131   CONTINUE
      STO(K) = STO(K) + SCR
419     CONTINUE
      VAR = VAR + R(K)*R(K)
      CALL AZ(SX(K),SY(K),X,Y,AZI)
      HPZ = Z + SZ(K)
      ANGLE = ATAN2(DL(K),HPZ)*180./3.141593
      SEC = STO(K) - (IMIN(K) - IMINO(I))*60.
      PRINT 805, STA(K),W(K),R(K),AZI,DL(K),ANGLE,IMIN(K),SEC,SCR
  805 FORMAT(4X,A4,9X,F5.3,13X,F6.3,16X,F6.2,15X,F6.2,16X,F6.3
     $,12X,I2,':',F5.2,2X,F4.2,/)
        STO(K)=STO(K)-SCR
   60 CONTINUE
      PRINT 901
  901 FORMAT(1X,////)
      PRINT 608,YI(I),XI(I),ZI(I),IHRO(I),IMINO(I),SECO(I)
  608 FORMAT(8X,'INITIAL ESTIMATE:',3F10.2,5X,2(I2,':'),F5.2,//)
      X = TX(I) - XI(I)
      Y = TY(I) - YI(I)
      Z = TZ(I) - ZI(I)
      IF(IHR(I).LT.IHRO(I))TOI(I) = TOI(I) + 3600
      T = TOT(I) - TOI(I)
      PRINT 610,Y,X,Z,T
  610 FORMAT(8X,'FINAL DIFFERENCE:',3F10.2,11X,F5.2,//)
      J = 4*(I-1) + 1
      JP1 = J + 1
      JP2 = J + 2
      JP3 = J + 3
        PRINT 612,WP(J),WP(JP1),WP(JP2),WP(JP3)
  612 FORMAT(8X,'WEIGHTING (KMS.):',3F10.2,11X,F5.2,//)
      ST = SQRT(VAR/FLOAT(NST-1))
      PRINT 73,ST
```

```
   73 FORMAT(8X,'STDDEV = ',F6.2,//)
      PRINT 900
   82 NSTN = NSTN + NSTA(I)
        TTD=0.
        DO 314 M=1,2
        DO 314 I=1,6
        DO 314 J=1,6
314     TTD=TTD+TDT(I,J,M)
        PRINT 317,TTD
317     FORMAT(1X,'TOTAL TRAVEL DISTANCE IN KMS IS ',F7.2)
        DO 315 M=1,2
        DO 315 I=1,6
        DO 315 J=1,6
315     TDT(I,J,M)=TDT(I,J,M)/TTD
        PRINT 316,(((TDT(I,J,M),J=1,6),I=1,6),M=1,2)
316     FORMAT(6(1X,/,1X,6F7.5),///)
      GO TO 2
  830 CONTINUE
      PRINT 832
  832 FORMAT('1',20X,'NO IMPROVEMENT OVER THE INITIAL ESTIMATE ')
    2 CONTINUE
        CLOSE(UNIT=25)
      STOP
      END
      SUBROUTINE AZ(SX,SY,X,Y,AZI)

C     ************************************************************

C        DETERMINATION OF AZIMUTH (STATION TO EVENT)

C     ************************************************************

        TAN(A)=SIN(A)/COS(A)
      PI = 3.141592654
      FF = PI/180.
      A = (90.-Y)*FF
      B = (90.-SY)*FF
      C = ABS(SX-X)*FF
      FH =    ATAN(SIN(.5*(A-B))/TAN(.5*C)/SIN(.5*(A+B)))
      SH =    ATAN(COS(.5*(A-B))/TAN(.5*C)/COS(.5*(A+B)))
      AZI = (FH+SH)/FF
      IF(SX.LT.X) AZI=360.-AZI
      RETURN
      END
        SUBROUTINE TTYM(XP,YP,HPZ,SX,SY,SZ,TD,TDT)

C     ************************************************************

C       DETERMINATION OF THE TRAVEL-DISTANCE WITHIN EACH BLOCK

C     ************************************************************

        DIMENSION TAL(7),GNOL(7),TD(6,6,2),V(72),TDZ(6,6,2)
```

```
     $   ,TDT(6,6,2)
         TAN(A)=SIN(A)/COS(A)
         DO 700 MM=1,2
         DO 700 I=1,6
         DO 700 J=1,6
         TDZ(I,J,MM)=0.
700      TD(I,J,MM)=0.
         STO=0.
         Z=HPZ-SZ
         M=2
         IF(Z.LE.4.0)M=1
         DPP=HPZ
         DTI=4.0
         DGU=Z-DTI
         II=0
         JJ=0
         NTAL=7
         NGNOL=7
         TAL(1)=33.80
         GNOL(1)=107.30
         TAL(2)=34.00
         GNOL(2)=107.10
         TAL(3)=34.10
         GNOL(3)=107.00
         TAL(4)=34.20
         GNOL(4)=106.90
         TAL(5)=34.30
         GNOL(5)=106.80
         TAL(6)=34.40
         GNOL(6)=106.70
         TAL(7)=34.60
         GNOL(7)=106.50
         IF(SY.LT.TAL(1).OR.SY.GT.TAL(NTAL))GO TO 500
         IF(YP.LT.TAL(1).OR.YP.GT.TAL(NTAL))GO TO 500
         IF(SX.GT.GNOL(1).OR.SX.LT.GNOL(NGNOL))GO TO 500
         IF(XP.GT.GNOL(1).OR.XP.LT.GNOL(NGNOL))GO TO 500
         GO TO 520
500      CONTINUE
         TYPE 511,TAL(1),TAL(NTAL),GNOL(1),GNOL(NGNOL)
511      FORMAT(10X,4F10.4)
         TYPE 511,SX,SY,XP,YP
         TYPE 510
510      FORMAT(10X,'INCORRECT ENTRY',/)
         GO TO 90
520      PI=3.1415927
         CF=PI/180.
         XKDEG=((SY+YP)/2.-34.1)*.018+110.922
         XKC=COS(CF*(SY+YP)/2.)*111.4399
         YTN=90.*CF
         OETY=180.*CF
         TSV=270.*CF
         TSX=360.*CF
         XX=ABS(SX-XP)*XKC
```

```
      YY=ABS(SY-YP)*XKDEG
      IF(YY.LE..001)YY=.001
      TH=XX/YY
      AZI=ATAN(TH)
      IF(SY.LT.YP.AND.SX.LT.XP)AZI=OETY-AZI
      IF(SY.LT.YP.AND.SX.GT.XP)AZI=OETY+AZI
      IF(SY.GT.YP.AND.SX.GT.XP)AZI=TSX-AZI
      IF(SY.EQ.YP.AND.SX.GT.XP)AZI=TSV
      IF(SX.EQ.XP.AND.SY.GT.YP)AZI=TSX
      IF(SX.EQ.XP.AND.SY.LT.YP)AZI=OETY
      ANG=ABS(DPP)/SQRT(XX*XX+YY*YY)
      ANG=ATAN(ANG)
      IF(AZI.GT.YTN)GO TO 60
      IF(AZI.LE..0001)AZI=.0001
      DIF=YTN-AZI
      IF(DIF.LE..0001)AZI=AZI-.0001
10    J=0
      I=0
30    I=I+1
      K=I-1
      IF(XP.LT.GNOL(I))GO TO 30
      IF(SX.GE.GNOL(I)) II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/SIN(AZI)
40    J=J+1
      L=NTAL+1-J
      IF(YP.GT.TAL(J))GO TO 40
      IF(SY.LT.TAL(J))JJ=1
      YE=ABS(TAL(J)-YP)
      YD=YE*XKDEG/COS(AZI)
      IPJ=II+JJ
      IF(IPJ.EQ.2)GO TO 70
      IF(YD.GT.XD)GO TO 50
      YP=TAL(J)
      XP=XP-YE*TAN(AZI)*XKDEG/XKC
      TD(L,K,M)=YD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      I=I-1
      GO TO 30
50    CONTINUE
      XP=GNOL(I)
      YP=YP+(XE/TAN(AZI))*XKC/XKDEG
      TD(L,K,M)=XD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      J=J-1
      GO TO 30
70    CONTINUE
      TD(L,K,M)=ABS((SY-YP)*XKDEG/(COS(AZI)*COS(ANG)))
      IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
```

```
      GO TO 90
 60   CONTINUE
      IF(AZI.GT.OETY)GO TO 160
      DIF=AZI-YTN
      IF(DIF.LE..0001)AZI=AZI+.0001
      DIF=OETY-AZI
      IF(DIF.LE..0001)AZI=AZI-.0001
      J=NTAL+1
      I=0
130   I=I+1
      K=I-1
      IF(XP.LT.GNOL(I))GO TO 130
      IF(SX.GE.GNOL(I))II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/COS(AZI-YTN)
140   J=J-1
      L=NTAL-J
      IF(YP.LT.TAL(J))GO TO 140
      IF(SY.GE.TAL(J))JJ=1
      YE=ABS(TAL(J)-YP)
      YD=YE*XKDEG/SIN(AZI-YTN)
      IPJ=II+JJ
      IF(IPJ.EQ.2)GO TO 170
      IF(YD.GT.XD)GO TO 150
      YP=TAL(J)
      XP=XP-YE*TAN(OETY-AZI)*XKDEG/XKC
      TD(L,K,M)=YD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      I=I-1
      GO TO 130
150   CONTINUE
      XP=GNOL(I)
      YP=YP-XE*TAN(AZI-YTN)*XKC/XKDEG
      TD(L,K,M)=XD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      J=J+1
      GO TO 130
170   CONTINUE
      TD(L,K,M)=ABS(SY-YP)*XKDEG/(COS(OETY-AZI)*COS(ANG))
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      GO TO 90
160   CONTINUE
      IF(AZI.GT.TSV)GO TO 260
      DIF=AZI-OETY
      IF(DIF.LE..0001)AZI=AZI+.0001
      DIF=TSV-AZI
      IF(DIF.LE..0001)AZI=AZI-.0001
      J=NTAL+1
      I=NGNOL+1
230   I=I-1
```

```
      K=I
      IF(XP.GT.GNOL(I))GO TO 230
      IF(SX.LE.GNOL(I))II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/SIN(AZI-OETY)
240   J=J-1
      L=NTAL-J
      IF(YP.LT.TAL(J))GO TO 240
      IF(SY.GE.TAL(J))JJ=1
      YE=ABS(TAL(J)-YP)
      YD=YE*XKDEG/COS(AZI-OETY)
      IPJ=II+JJ
      IF(IPJ.EQ.2)GO TO 270
      IF(YD.GT.XD)GO TO 250
      YP=TAL(J)
      XP=XP+YE*TAN(AZI-OETY)*XKDEG/XKC
      TD(L,K,M)=YD/COS(ANG)
      IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      IF(XD.NE.GNOL(I))I=I+1
      GO TO 230
250   CONTINUE
      XP=GNOL(I)
      YP=YP-XE*TAN(TSV-AZI)*XKC/XKDEG
      TD(L,K,M)=XD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      IF(YD.NE.TAL(J))J=J+1
      GO TO 230
270   CONTINUE
      TD(L,K,M)=ABS(SY-YP)*XKDEG/(SIN(TSV-AZI)*COS(ANG))
      IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      GO TO 90
260   CONTINUE
      J=0
      DIF=AZI-TSV
      IF(DIF.LE..0001)AZI=AZI+.0001
      DIF=TSX-AZI
      IF(DIF.LE..0001)AZI=AZI-.0001
      I=NGNOL+1
330   I=I-1
      K=I
      IF(XP.GT.GNOL(I))GO TO 330
      IF(SX.LE.GNOL(I))II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/COS(AZI-TSV)
340   J=J+1
      L=NTAL+1-J
      IF(YP.GT.TAL(J))GO TO 340
      IF(SY.LE.TAL(J))JJ=1
      YE=ABS(TAL(J)-YP)
```

```
      YD=YE*XKDEG/SIN(AZI-TSV)
      IPJ=II+JJ
      IF(IPJ.EQ.2)GO TO 370
      IF(YD.GT.XD)GO TO 350
      YP=TAL(J)
      XP=XP+YE*TAN(TSX-AZI)*XKDEG/XKC
      TD(L,K,M)=YD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      I=I+1
      GO TO 330
350   CONTINUE
      XP=GNOL(I)
      YP=YP+XE*TAN(AZI-TSV)*XKC/XKDEG
      TD(L,K,M)=XD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      J=J-1
      GO TO 330
370   CONTINUE
      TD(L,K,M)=ABS(SY-YP)*XKDEG/(COS(TSX-AZI)*COS(ANG))
      IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
 90   CONTINUE
      TTT=0.
      DO 690 MM=1,2
      DO 690 I=1,6
      DO 690 J=1,6
690   TDT(I,J,MM)=TDT(I,J,MM)+TD(I,J,MM)
      RETURN
      END
      SUBROUTINE BLCHG(TDZ,DGU,TD,L,K,M,ANG)
C     ************************************************************
C          DETERMINATION OF AN INTERFACE INTERSECTION
C     ************************************************************
      DIMENSION TDZ(6,6,2),TD(6,6,2)
      IF(M.EQ.1) RETURN
      STDZ = 0.
      DO 1 LL=1,6
      DO 1 KK=1,6
1     STDZ=STDZ+TDZ(LL,KK,2)
      IF(STDZ.LT.DGU) RETURN
      TZ=TDZ(L,K,2)
      TDZ(L,K,2)=DGU-STDZ+TDZ(L,K,2)
      TD(L,K,2)=TDZ(L,K,2)/SIN(ANG)
      TDZ(L,K,1)=TZ-TDZ(L,K,2)
      TD(L,K,1)=TDZ(L,K,1)/SIN(ANG)
      M=1
      RETURN
      END
```

```
      SUBROUTINE BLK(NBL,TD,IBLC,BLKT,V,AVSQ,TTT)
C     ************************************************************
C
C          DETERMINATION OF THE TOTAL TRAVEL PATH LENGTHS
C                          WITHIN EACH BLOCK
C     ************************************************************
      DIMENSION TD(6,6,2),BLKT(72),IBLC(53,3),V(72)
      DO 2 II=1,NBL
      BLKT(II)=0.
      DO 2 MM=1,IBLC(II,1)
      III=0
      DO 2 M=1,2
      DO 2 I=1,6
      DO 2 J=1,6
      III=III+1
      IF(III.NE.IBLC(II,MM+1))GO TO 2
      BLKT(II)=BLKT(II)+TD(I,J,M)
2     CONTINUE
      TTT=0.
      TTD=0.
      DO 3 I=1,NBL
      TTD=TTD+BLKT(I)
      BLKT(I)=BLKT(I)/V(I)
3     TTT=TTT+BLKT(I)
      AVSQ=(TTD/TTT)**2.
      RETURN
      END
```

```
C     ************************************************************
C     *                                                          *
C     *  GLS.FOR: THIS ROUTINE PROVIDES FOR THE DETERMINATION    *
C     *           OF THE VELOCITY DISTRIBUTION AS A FUNCTION     *
C     *           OF A GIVEN BLOCK CONFIGURATION BY MEANS OF     *
C     *           A GENERALIZED LEAST SQUARES APPROACH.          *
C     *                                                          *
C     ************************************************************


      DIMENSION STA(262),DL(262),R(262),W(262),SZ(262),SX(262)
     $,SY(262),SECO(40),IYR(40),
     $IHR(262),TX(40),TY(40),TZ(40),TOT(40),IHRO(40),IMINO(40),
     $TOI(40),XH(40),YH(40),ZH(40),TOH(40),IMO(40),IDA(40),
     $STO(262),DLH(262),RH(262),NSTA(40),XI(40),YI(40),ZI(40)
      DIMENSION C(22791),D(213),B(262),A(262,213),H(213,262),
     $VR(213),WP(213),IMIN(262),STAC(2,25),BLKT(72),IBLC(53,54),
     $VI(72),V(72),VH(72),TD(6,6,2),RV(213,213),E(213)
      COMMON /C1/A,NSTA/C5/NX,NSTN/C2/H/C3/B/C6/D/C4/C/C9/RV,E
      INTEGER TEST,EVENT,STA,STAC

C     ************************************************************

C       STATION CORRECTIONS . . . . . .

      DATA STAC/'WT',-11,'WM',12,'IC',08,'NG',14,'CM',13
     $,'RM',11,'SC',15,'RI',-01,'BB',-04
     $,'CC',-15,'SL',-11,'FM',00,'DM',-01,'BG',-01,'GM',-06,
     $'CU',-10,'MY',-09,'HC',16,'FC',26,'TS',28,'CK',-04,
     $'TA',09,'LAD',-25,'LPN',-24,'TD',-09/

C     ************************************************************

C      INPUT . . . . . .

C        . . . STATION LOCATIONS - - SX,SY,SZ

C        . . . ARRIVAL TIMES - - IMIN,SEC,W

C        . . . INITIAL ESTIMATES AND WEIGHTS
C                  - - XI,YI,ZI,TOI,VI,WP

C     ************************************************************

C       NSC = NUMBER OF STORED STATION CORRECTIONS
        NSC = 25

C       NRE = NUMBER OF RETAINED EIGENVALUES
        NRE=175
```

```
        TYPE 420
420     FORMAT(/,1X,'THE NUMBER OF EVENTS ?')
        READ(5,*) NUM
        TYPE 416
416     FORMAT(1X'INPUT DATA FILE ?')
        READ(5,417) VFN
417     FORMAT(A5)
        IRD=0
        AVR=0.
        SUM=0.
        TYPE 413
413     FORMAT(1X,'REAL DATA ?')
        READ(5,412) TEST
412     FORMAT(A3)
        IF(TEST.EQ.'YES')IRD=1
        IF(IRD.EQ.1)GO TO 414
        TYPE 415
415     FORMAT(1X,'WHAT IS THE DESIRED NOISE LEVEL ?')
C    ************************************************************
C       TDNL = STANDARD DEVIATION OF MAXIMUM NOISE DESIRED
C       TDNL=1.  WILL BASE NOISE ON W(K)
C    ************************************************************
        READ(5,*)TDNL
414     CONTINUE
        TYPE 463
463     FORMAT(1X,'WHAT IS THE DESIRED # OF ITERATIONS ?')
        READ(5,*) IDNI
        TYPE 1200
1200    FORMAT(1X,'HOW MANY TOTAL BLOCKS ARE THERE ?')
        ACCEPT *,NBL
        IF(NBL.NE.36)GO TO 903
        DO 904 I=1,NBL
        J=I+NBL
        IBLC(I,1)=2
        IBLC(I,2)=I
904     IBLC(I,3)=J
        GO TO 905
903     CONTINUE
        IF(NBL.LE.36)GO TO 691
        OPEN(UNIT=23,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
     $  FILE='BLK')
        DO 692 I=1,NBL
        READ(23,*) IBL,(IBLC(I,J),J=2,IBL+1)
C       TYPE *,IBL,(IBLC(I,J),J=2,IBL+1)
        IBLC(I,1)=IBL
692     CONTINUE
```

```
          CLOSE(UNIT=23)
          GO TO 905
691       CONTINUE
          DO 1225 I=1,NBL
          TYPE 1220,I
1220      FORMAT(1X,'WHICH OLD BLOCKS FORM THE NEW BLOCK #',I2,'?')
          ACCEPT *,IBL,(IBLC(I,J),J=2,IBL+1)
1225      IBLC(I,1)=IBL
905       CONTINUE
        NXX = NUM * 4
        NX = NXX + NBL
          NSYM=NX*(NX+1)/2
        NSTN = 0
          TYPE 1110
1110      FORMAT(1X,'WHAT IS THE INITIAL VELOCITY ?')
          ACCEPT *,VII
          II=0
          DO 863 K=1,NBL
          VI(K)=VII
          II=II+1
          WP(NXX+II)=.02
          IF(II.GT.36)WP(NXX+II)=.03
863       CONTINUE
          OPEN(UNIT=22,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
     $    FILE=VFN)
          DO 51 NOQ=1,NUM
        READ(22,*) NSTA(NOQ),IMO(NOQ),IDA(NOQ),IYR(NOQ)

C     ************************************************************

C       INITIAL ESTIMATES OF HYPOCENTERS AND ORIGIN TIMES
C                       (XI,YI,ZI,TOI)

C       CAUTION-- DO NOT GUESS EPICENTER COORDS SAME AS STATION

C     ************************************************************

        I = 4*(NOQ-1) + 1
        IP1 = I+ 1
        IP2 = I+ 2
        IP3 = I+ 3
        READ(22,*) X,WP(I),Y,WP(IP1),Z,WP(IP2)
          ZDIF=Z*100.-FLOAT(IFIX(Z*100.))+.01
          ZDIF=FLOAT(IFIX(ZDIF*10.))
          IF(ZDIF.NE.0.)WP(IP2)=1.
          READ(22,*) IHRO(NOQ),IMINO(NOQ),SECO(NOQ),WP(IP3)
        XI(NOQ) = X
        YI(NOQ) = Y
        ZI(NOQ) = Z
        TOI(NOQ) = SECO(NOQ)
          IF(WP(I).EQ.0.)WP(I)=1.
          IF(WP(IP1).EQ.0.)WP(IP1)=1.
          IF(WP(IP2).EQ.0.)WP(IP2)=3.
```

```
      IF(WP(IP3).EQ.0.)WP(IP3)=.3
C     ************************************************************
C                              (SYNTHETIC DATA)
C        . . . ADDITION OF NOISE TO TRUE SOLUTION
C     ************************************************************
      IF(IRD.EQ.1)GO TO 424
      WP(I)=1.
      WP(IP1)=1.
      WP(IP2)=3.
      WP(IP3)=.3
      ZDIF=Z*100.-FLOAT(IFIX(Z*100.))+.01
      ZDIF=FLOAT(IFIX(ZDIF*10.))
      IF(ZDIF.NE.0.)WP(IP2)=1.
      CALL GGNML(1234567.D0,1,RN)
      X=X+RN*.01
      CALL GGNML(1234567.D0,1,RN)
      Y=Y+RN*.01
      CALL GGNML(1234567.D0,1,RN)
      ZMF=3.
      IF(ZDIF.NE.0.)ZMF=1.
      Z=Z+RN*ZMF
      IF(Z.LT.3.)Z=3.
      CALL GGNML(1234567.D0,1,RN)
      SECO(NOQ)=SECO(NOQ)+RN*.3
      IF(SECO(NOQ).GE.60.)IMINO(NOQ)=IMINO(NOQ)+1
      IF(SECO(NOQ).GE.60.)SECO(NOQ)=SECO(NOQ)-60.
      IF(SECO(NOQ).GT.0.)GO TO 424
      IMINO(NOQ)=IMINO(NOQ)-1
      SECO(NOQ)=SECO(NOQ)+60.
424   CONTINUE
      PRINT 1650,X,Y,Z,SECO(NOQ),XI(NOQ),YI(NOQ),ZI(NOQ),
     $  TOI(NOQ)
1650  FORMAT(1X,4F10.4,20X,4F10.4)
      XI(NOQ) = X
      YI(NOQ) = Y
      ZI(NOQ) = Z
      TOI(NOQ) = SECO(NOQ)
      NST = NSTA(NOQ)
C     ************************************************************
C        . . . ARRIVAL TIMES AND WEIGHTS
C     ************************************************************
      OPEN(UNIT=1,DEVICE='DSK',MODE='ASCII',ACCESS='SEQIN',
     $  FILE='STA')
```

```
      DO 49 J=1,NST
      K = NSTN + J
        IFLAG=0
        REWIND 1
        READ(22,425) STA(K),IMIN(K),SEC,W(K)
425     FORMAT(A3,1X,I2,1X,F5.2,1X,F4.3)
105     CONTINUE
C     ************************************************************
C        . . . STATION COORDINATES
C     ************************************************************
        READ(1,427,END=106) TEST,SY(K),SX(K),SZ(K)
427     FORMAT(A3,1X,F7.4,1X,F8.4,2X,F5.3)
        SZ(K)=SZ(K)-1.5
        IF(TEST.EQ.STA(K)) GO TO 428
        GO TO 105
106     CONTINUE
        TYPE 429,STA(K)
429     FORMAT(10X,'STATION ',A3,' NOT FOUND',/)
        CLOSE(UNIT=1)
        CLOSE(UNIT=22)
        GO TO 2
428     IF(IMINO(NOQ).GT.IMIN(K))IMIN(K)=IMIN(K)+60
C     ************************************************************
C                (SYNTHETIC DATA)
C        . . . ADDITION OF NOISE TO DATA
C     ************************************************************
        IF(IRD.EQ.1)GO TO 461
        IF(TDNL.EQ.1.)GO TO 666
        TNL=TDNL
        W(K)=TNL
666     CONTINUE
        CALL GGNML(1234567.D0,1,RN)
        RESID=RN*W(K)
        AVR=AVR+RESID
        SUM=RESID*RESID+SUM
        SEC=SEC+RESID
        IF(SEC.LT.0.)IMIN(K)=IMIN(K)-1
        IF(SEC.LT.0.)SEC=SEC+60.
        IF(SEC.GE.60.)IMIN(K)=IMIN(K)+1
        IF(SEC.GE.60.)SEC=SEC-60.
461     STO(K) = SEC + (IMIN(K) - IMINO(NOQ))*60.
        IF(IRD.EQ.0)GO TO 49
      DO 130 I=1,NSC
```

```
      IF(STAC(1,I).NE.STA(K))GO TO 130
        IFLAG=1
      STO(K) = STO(K) - FLOAT(STAC(2,I))*.01
  130 CONTINUE
        IF(IFLAG.EQ.0)STO(K)=STO(K)+.2
   49 CONTINUE
        CLOSE(UNIT=1)
        NSTN=NSTN+NSTA(NOQ)
   51 CONTINUE
        IF(IRD.EQ.1)GO TO 664
        AVR=AVR/NSTN
        STDR=SQRT(SUM/NSTN-AVR*AVR)
        PRINT 665,AVR,STDR
665     FORMAT(1X,//,10X,'AVERAGE RESIDUAL = ',F6.3,10X,
     $  'STANDARD DEVIATION OF AVG. RESIDUAL = ',F6.3,//)
664     CLOSE(UNIT=22)

C     ************************************************************

C      LEAST SQUARES METHOD . . . . . .

C        CALCULATION OF DISTANCE BETWEEN STATION AND EPICENTER

C     ************************************************************

        INLAM=8
        IQF=0
   80 NIT = 0
      DO 169 I=1,NUM
      TX(I) = XI(I)
      TY(I) = YI(I)
      TZ(I) = ZI(I)
  169 TOT(I) = TOI(I)
        DO 810 MM=1,NBL
  810   V(MM)=VI(MM)
        ITD=0
        IMP=1
  999 NIT = NIT + 1
      IF(NIT.EQ.1)GO TO 931
  931 CONTINUE
      DO 756 J=1,262
      B(J) = 0.0
      DO 756 I=1,213
      A(J,I) = 0.0
  756 CONTINUE
      DO 55 I=1,213
      D(I) = 0.
      DO 55 K=1,213
      RV(I,K) = 0.
   55 CONTINUE
```

```
C     ************************************************************
C      . . . FORMATION OF ARRAY TO BE INVERTED
C     ************************************************************
933      CONTINUE
         AVTD=0.
         AVW=0.
       NSTN = 0
       DO 859 NOQ=1,NUM
       X = TX(NOQ)
       Y = TY(NOQ)
       Z = TZ(NOQ)
       NN = 4*(NOQ - 1) + 1
       NNP1 = NN+1
       NNP2 = NN+2
       NNP3 = NN+3
       NST = NSTA(NOQ)
       DO 858 J=1,NST
       K = NSTN + J
       HPZ = (Z+SZ(K))
         XKDEG=((SY(K)+Y)/2.-34.1)*.018+110.922
         XKC=COS(3.1415927*(SY(K)+Y)/360.)*111.4399
         XP=X
         YP=Y
         DP=HPZ
         CALL TTYM(XP,YP,DP,SX(K),SY(K),SZ(K),TD)
         CALL BLK(NBL,TD,IBLC,BLKT,V,AVSQ,TTT)
C        TYPE 1230 ,BLKT(1),TTT
1230     FORMAT(1X,2F10.4)
       XX = (X-SX(K))*XKC
       YY = (Y-SY(K))*XKDEG
       DL(K) = SQRT(XX*XX + YY*YY)
         AVTD=AVTD+SQRT(XX*XX+YY*YY+HPZ*HPZ)
         AVW=AVW+W(K)
       OTT = STO(K) - TOT(NOQ)
       R(K) = OTT - TTT
       FF = 1./(AVSQ*OTT)
       A(K,NN) = XX*FF/W(K)
       A(K,NNP1)= YY*FF/W(K)
       A(K,NNP2) = HPZ*FF/W(K)
       A(K,NNP3) = 1.0/W(K)
         III=0
         DO 862 MM=1,NBL
         III=III+1
         BLKTM=BLKT(III)+R(K)*BLKT(III)/TTT
862      A(K,NXX+III)=BLKTM/W(K)
       B(K)=R(K)/W(K)
 858   CONTINUE
       NSTN = NSTN + NSTA(NOQ)
 859   CONTINUE
         AVTD=AVTD/NSTN
         AVW=AVW/NSTN
         IF(NIT.GT.1)GO TO 934
```

```
 934      CONTINUE
          DO 112 I=1,NSTN
          DO 112 J=1,NX
  112 A(I,J) = WP(J)*A(I,J)
            CALL VTPROF(A,NSTN,NX,262,C)
            IF(IQF.EQ.1)GO TO 930

C     ************************************************************

C     . . CALCULATION OF STANDARD DEVIATION OF AVERAGE RESIDUAL

C     ************************************************************

          VARI = 0.
          SUM = 0.
          DO 54 J=1,NSTN
          VARI = VARI + R(J)*R(J)
          SUM = SUM + (R(J)*R(J)/(W(J)*W(J)))
     54 CONTINUE
          VARI = VARI/FLOAT(NSTN-1)
          STDDEV = SQRT(VARI)
          BIGR = SQRT(SUM/FLOAT(NSTN))
          IF(NIT.EQ.1)STDH=STDDEV
          IF(STDH.LT.STDDEV)ITD=1
          IF(STDH.LT.STDDEV)GO TO 89
          IF(NIT.GT.1)IMP=0
          STDH = STDDEV
            DO 816 MM=1,NBL
  816 VH(MM)=V(MM)
          DO 609 I=1,NUM
          XH(I) = TX(I)
          YH(I) = TY(I)
          ZH(I) = TZ(I)
  609 TOH(I) = TOT(I)
     89 CONTINUE
            NITM1=NIT-1
            PRINT 452,NITM1
 452        FORMAT(1X,//,1X,'ITERATION #',I2,/)
            PRINT 454,((TX(I),TY(I),TZ(I),TOT(I)),I=1,NUM)
 454        FORMAT(1X,4F10.4)
            IF(NIT.GT.1)GO TO 906
 906        CONTINUE
            PRINT 888,(V(MM),MM=1,NBL),STDDEV,BIGR
 888        FORMAT(1X,/,1X,6F9.3,/)
          IF(NIT.GT.IDNI.AND.IMP.EQ.1)GO TO 830
          ZIP = STDDEV - 0.001
          IF(ZIP) 2000,2000,512

C     ************************************************************

C       . . SOLVE SIMULTANEOUS EQUATIONS
C       . . INVERSION OF MATRIX AND MATRIX MULTIPLICATION TO GET
C             DX, DY, DZ, DTO, DV

C     ************************************************************
```

```
  512 IF(NIT.GT.IDNI)GO TO 2000
        NLAM=INLAM
      CALL EIGENS(NLAM)
        IP=NX-NLAM
      CALL SOLVEC(NRE,CO)

C     ************************************************************

C      . . . NEW ESTIMATES OF PARAMETERS

C     ************************************************************

      DO 850 I=1,NUM
      X = TX(I)
      Y = TY(I)
  518 YQ = Y
        XKDEG=(YQ-34.1)*.018+110.922
      N = 4*(I-1)+ 1
      NP1 = N+1
      NP2 = N+2
      NP3 = N+3
      D(N) = D(N)*WP(N)
      D(NP1) = D(NP1)*WP(NP1)
      D(NP2) = D(NP2)*WP(NP2)
      D(NP3) = D(NP3)*WP(NP3)
  519 Y = Y+D(NP1)/XKDEG
      TY(I) = Y
        XKC=COS(3.1415927*(YQ+Y)/360.)*111.4399
  520 TX(I) = X + D(N)/XKC
        HLD=TZ(I)
      TZ(I) = TZ(I) + D(NP2)
        IF(TZ(I).LT.0.)D(NP3)=D(NP3)/2.
        IF(TZ(I).LT.0.)TZ(I)=HLD/2.
      TOT(I) = TOT(I) + D(NP3)
  850 CONTINUE
        II=0
        DO 811 MM=1,NBL
        II=II+1
        LL=NXX+II
  811   V(MM)=V(MM)/(1.+D(LL)*WP(LL))
      GO TO 999

C     ************************************************************

C      OUTPUT . . . . . . . . . . . . . . . . . . . . . . . . .

C     ************************************************************

 2000 CONTINUE
      IF(ITD.EQ.0)GO TO 81
```

```
        DO 817 MM=1,NBL
  817 V(MM)=VH(MM)
      DO 611 I=1,NUM
      TX(I) = XH(I)
      TY(I) = YH(I)
      TZ(I) = ZH(I)
  611 TOT(I) = TOH(I)
   81 CONTINUE
        IQF=1
        GO TO 933
930     CONTINUE
        NLAM=INLAM
      CALL EIGENS(NLAM)
        IP=NX-NLAM
      CALL SOLVEC(NRE,CO)
        JJ=1
        II=0
        DO 571 J=1,213
        DO 571 I=1,262
        II=II+1
        IF(II.LE.213)GO TO 571
        II=1
        JJ=JJ+1
571     H(II,JJ)=A(I,J)
      NSTN = 0
      DO 573 NOQ=1,NUM
      X = TX(NOQ)
      Y = TY(NOQ)
      Z = TZ(NOQ)
      NN = 4*(NOQ - 1) + 1
      NNP1 = NN+1
      NNP2 = NN+2
      NNP3 = NN+3
      NST = NSTA(NOQ)
      DO 572 J=1,NST
      K = NSTN + J
      HPZ = (Z+SZ(K))
        XKDEG=((SY(K)+Y)/2.-34.1)*.018+110.922
        XKC=COS(3.1415927*(SY(K)+Y)/360.)*111.4399
      XX = (X-SX(K))*XKC
      YY = (Y-SY(K))*XKDEG
      DL(K) = SQRT(XX*XX + YY*YY)
      OTT = STO(K) - TOT(NOQ)
        XP=X
        YP=Y
        DP=HPZ
        CALL TTYM(XP,YP,DP,SX(K),SY(K),SZ(K),TD)
        CALL BLK(NBL,TD,IBLC,BLKT,V,AVSQ,TTT)
      R(K) = OTT - TTT
      FF = 1./(AVSQ*OTT)
      A(K,NN) = XX*FF/W(K)
      A(K,NNP1)= YY*FF/W(K)
      A(K,NNP2) = HPZ*FF/W(K)
```

```
          A(K,NNP3) = 1.0/W(K)
            III=0
            DO 887 MM=1,NBL
            III=III+1
            BLKTM=BLKT(III)+R(K)*BLKT(III)/TTT
  887       A(K,NXX+III)=BLKTM/W(K)
    572   CONTINUE
          NSTN = NSTN + NSTA(NOQ)
    573   CONTINUE
          DO 574 I=1,NSTN
          DO 574 J=1,NX
    574   A(I,J) = WP(J)*A(I,J)
            CALL VMULFP(H,H,NX,NSTN,NX,213,213,RV,213,IER)
            DO 1112 I=196,208
            PRINT 2111
  2111      FORMAT(1X,/)
            PRINT 1221,(RV(I,J),J=1,208)
  1221      FORMAT(1X,18F7.4)
  1112      CONTINUE
         CALL VMULFF(H,A,NX,NSTN,NX,213,262,RV,213,IER)
  C       CALL VMULFF(A,H,NSTN,NX,NSTN,262,213,S,262,IER)
           DO 913 I=161,213
           PRINT 912
  912      FORMAT(1X,/)
           PRINT 914,(RV(I,J),J=161,213)
  914      FORMAT(1X,18F7.4)
  913      CONTINUE
        DO 923 I=1,NX
    923 VR(I) = 0.
        DO 796 I=1,NX
        SUM = 0.
        DO 795 J=1,NSTN
    795 SUM = SUM + (H(I,J)*H(I,J))
    796 VR(I) = SUM
        DO 221 I=1,NX
    221 VR(I) = SQRT(VR(I))*WP(I)
        NIT = NIT - 1
        SUM = 0.
        DO 435 I=1,NSTN
    435 SUM = SUM + (R(I)*R(I)/(W(I)*W(I)))
        BIGR = SQRT(SUM/FLOAT(NSTN))
  C      TYPE 439, BIGR
  439   FORMAT(1X,'BIG R = ',F7.3,//)
  C      TYPE 441
  441    FORMAT(1X,'EVENT #',5X,'S.D.(X)',5X,'S.D.(Y)',5X,
       $'S.D.(Z)',5X,'S.D.(OT)',//)
        DO 440 J=1,NUM
        I = 4*(J-1) + 1
        IP1 = I + 1
        IP2 = I + 2
        IP3 = I + 3
  C      TYPE 781,J,VR(I),VR(IP1),VR(IP2),VR(IP3)
  781     FORMAT(2X,I2,9X,4(F6.2,5X),/)
```

```
440      CONTINUE
         PRINT 900
  900 FORMAT('1',/)
         PRINT 21,NRE,NX
   21 FORMAT(40X,'# OF EIGENVALUES RETAINED =',I4,1X,'OF',I4,
        $////)
         PRINT 902
  902 FORMAT(1X,//)
         PRINT 604,NIT
           LL=NXX
           DO 812 MM=1,NBL
         LL = LL + 1
           VR(LL)=VR(LL)*5.85
C         TYPE 882,MM,V(MM),VR(LL)
  882 FORMAT(1X,'VEL OF BLOCK ',I2,' = ',F6.2,4X,
        $'SIGMA = ',F6.3)
         PRINT 889,MM,V(MM),VR(LL),WP(LL)
  889 FORMAT(8X,'VEL OF BLOCK ',I2,' = ',F6.2,17X,
        $'SIGMA = ',F9.5,8X,'WEIGHT = ',F4.2)
  812 CONTINUE
  604 FORMAT(8X,'# OF ITERATIONS = ',I3,//)
         PRINT 902
         SUM = 0.
         DO 919 I=1,NSTN
  919 SUM = SUM + (R(I)*R(I)/(W(I)*W(I)))
         BIGR = SQRT(SUM/FLOAT(NSTN))
         PRINT 915, BIGR
  915 FORMAT(8X,'BIG R = ',F7.3,//)
         PRINT 24
   24 FORMAT(8X,'EVENT #',15X,'S.D.(X)',15X,'S.D.(Y)',15X,
        $'S.D.(Z)',15X,'S.D.(OT)',//)
         DO 23 J=1,NUM
         I = 4*(J-1) + 1
         IP1 = I + 1
         IP2 = I + 2
         IP3 = I + 3
         PRINT780,J,VR(I),VR(IP1),VR(IP2),VR(IP3)
  780 FORMAT(16X,I2,11X,4(F6.2,15X),//)
   23 CONTINUE
         PRINT 900
         DO 911 I=1,NX
         SUM = 0.
         DO 916 J=1,NX
         IF(J.NE.I)GO TO 935
         SUM = (RV(I,J)-1.)*(RV(I,J)-1.) + SUM
         GO TO 916
  935 SUM = SUM + RV(I,J)*RV(I,J)
  916 CONTINUE
         PRINT 910,I,SUM
  910 FORMAT(10X,'R',I3,' = ',F6.3)
  911 CONTINUE
         PRINT 900
         NSTN = 0
```

```
      DO 82 I=1,NUM
      X = TX(I)
      Y = TY(I)
      Z = TZ(I)
      TO = TOT(I)
      IXDEG = IFIX(X)
      IYDEG = IFIX(Y)
      IXMIN = IFIX((X-FLOAT(IXDEG))*60.)
      IYMIN = IFIX((Y-FLOAT(IYDEG))*60.)
      XSEC = ((X-FLOAT(IXDEG))*60.-FLOAT(IXMIN))*60.
      YSEC = ((Y-FLOAT(IYDEG))*60.-FLOAT(IYMIN))*60.
      IXMIN = IABS(IXMIN)
      XSEC = ABS(XSEC)
      IYMIN = IABS(IYMIN)
      YSEC = ABS(YSEC)
      IHR(I) = IHRO(I)
      IM = IMINO(I)
      TO = TO + .004
      IF(TO.GE.0.)GO TO 300
      IM = IMINO(I) - 1
      TO = TO + 60.
  300 CONTINUE
      IF(TO.LT.60.)GO TO 330
      IM = IM + 1
      TO = TO - 60.
  330 CONTINUE
        J=4*(I-1)+1
        PRINT 3030, I
 3030   FORMAT(63X,'EVENT # ',I2,//)
      PRINT 301, IMO(I),IDA(I),IYR(I),IHR(I),IM,TO,VR(J+3)
  301 FORMAT(40X,'DATE: ',2(I2,'-'),I2,25X,'ORIGIN TIME: ',
     $2(I2,':'),F5.2,3X,F5.3,/////)
      PRINT 302
  302 FORMAT(25X,'LATITUDE',30X,'LONGITUDE',31X,'DEPTH (KM)',/)
      PRINT 202, IYDEG,IYMIN,YSEC,IXDEG,IXMIN,XSEC,Z,VR(J+2)
  202 FORMAT(23X,2(I3,'-',I2,'-',F5.2,26X),F11.3,2X,F6.4,/)
        VR(J)=VR(J)/93.
        VR(J+1)=VR(J+1)/111.
        PRINT 213,Y,VR(J+1),X,VR(J)
213     FORMAT(24X,F7.4,2X,F5.4,23X,F8.4,2X,F5.4,///////)
  205 PRINT 304
  304 FORMAT(2X,'STATION',8X,'WEIGHT',9X,'RESIDUAL (SEC)',12X,
     $'AZIMUTH',
     $12X,'DISTANCE (KM)',7X,'ANGLE OF EMERGENCE',7X,'TIME',/)
      NST = NSTA(I)
      M = NSTA(I)
      N = NSTA(I) - 1
      DO 401 K=1,N
      DO 400 JJ=2,M
      J = NSTN + JJ
      JM1 = J-1
      IF(DL(J).GT.DL(JM1))GO TO 400
      HDL = DL(JM1)
```

```
      DL(JM1) = DL(J)
      DL(J) = HDL
      HDL = STO(JM1)
      STO(JM1) = STO(J)
      STO(J) = HDL
      HDL = W(JM1)
      W(JM1) = W(J)
      W(J) = HDL
      HDL = R(JM1)
      R(JM1) = R(J)
      R(J) = HDL
      IHDL = STA(JM1)
      STA(JM1) = STA(J)
      STA(J) = IHDL
      HDL = SX(JM1)
      SX(JM1) = SX(J)
      SX(J) = HDL
      HDL = SY(JM1)
      SY(JM1) = SY(J)
      SY(J) = HDL
      HDL = SZ(JM1)
      SZ(JM1) = SZ(J)
      SZ(J) = HDL
  400 CONTINUE
  401 CONTINUE

C     DETERMINE ANGLE OF EMERGENCE MEASURED FROM +Z DIRECTION

      VAR = 0.
      DO 60 J = 1,NST
      K = NSTN + J
        SCR=0.
        IF(IRD.EQ.0)GO TO 419
      SCR = -.2
        DO 131 II=1,NSC
        IF(STAC(1,II).NE.STA(K))GO TO 131
        SCR=FLOAT(STAC(2,II))*.01
131     CONTINUE
        STO(K)=STO(K)+SCR
419     CONTINUE
      VAR = VAR + R(K)*R(K)
      CALL AZ(SX(K),SY(K),X,Y,AZI)
      HPZ = Z + SZ(K)
      ANGLE = ATAN2(DL(K),HPZ)*180./3.141593
        IMN=IFIX(STO(K)/60.)
        SEC=ABS(STO(K)-FLOAT(IMN)*60.)
        IMN=IMINO(I)
        IF(SEC.LT.TO)IMN=IMN+1
      PRINT 805, STA(K),W(K),R(K),AZI,DL(K),ANGLE,IMN,SEC,SCR
  805 FORMAT(4X,A4,9X,F5.3,13X,F6.3,16X,F6.2,15X,F6.2,16X,F6.3,
     $12X,I2,':',F5.2,2X,F4.2,/)
        STO(K)=STO(K)-SCR
   60 CONTINUE
```

```
      PRINT 901
  901 FORMAT(1X,////)
      PRINT 608,YI(I),XI(I),ZI(I),IHRO(I),IMINO(I),SECO(I)
  608 FORMAT(8X,'INITIAL ESTIMATE:',3F10.2,5X,2(I2,':'),F5.2,//)
      X = TX(I) - XI(I)
      Y = TY(I) - YI(I)
      Z = TZ(I) - ZI(I)
      IF(IHR(I).LT.IHRO(I))TOI(I) = TOI(I) + 3600
      T = TOT(I) - TOI(I)
      PRINT 610,Y,X,Z,T
  610 FORMAT(8X,'FINAL DIFFERENCE:',3F10.2,11X,F5.2,//)
      J = 4*(I-1) + 1
      JP1 = J + 1
      JP2 = J + 2
      JP3 = J + 3
        PRINT 612,WP(J),WP(JP1),WP(JP2),WP(JP3)
  612 FORMAT(8X,'WEIGHTING (KMS.):',3F10.2,11X,F5.2,//)
      ST = SQRT(VAR/FLOAT(NST-1))
      PRINT 73,ST
   73 FORMAT(8X,'STDDEV = ',F6.2,//)
      PRINT 900
   82 NSTN = NSTN + NSTA(I)
        GO TO 2
  830   CONTINUE
        TYPE 884
  884   FORMAT('1',20X,'NO IMPROVEMENT OVER THE INITIAL ESTIMATE')
    2 CONTINUE
      STOP
      END
      SUBROUTINE AZ(SX,SY,X,Y,AZI)

C     ************************************************************

C       DETERMINATION OF AZIMUTH (STATION TO EVENT)

C     ************************************************************

      TAN(A)=SIN(A)/COS(A)
      PI = 3.141593
      FF = PI/180.
      A = (90.-Y)*FF
      B = (90.-SY)*FF
      C = ABS(SX-X)*FF
      FH = ATAN(SIN(.5*(A-B))/TAN(.5*C)/SIN(.5*(A+B)))
      SH = ATAN(COS(.5*(A-B))/TAN(.5*C)/COS(.5*(A+B)))
      AZI = (FH+SH)/FF
      IF(SX.LT.X) AZI=360.-AZI
      RETURN
      END
```

```
      SUBROUTINE TTYM(XP,YP,HPZ,SX,SY,SZ,TD)
C     ************************************************************
C      DETERMINATION OF THE TRAVEL-DISTANCE WITHIN EACH BLOCK
C     ************************************************************
      DIMENSION TAL(7),GNOL(7),TD(6,6,2),V(72),TDZ(6,6,2)
      TAN(A)=SIN(A)/COS(A)
      DO 700 MM=1,2
      DO 700 I=1,6
      DO 700 J=1,6
      TDZ(I,J,MM)=0.
700   TD(I,J,MM)=0.
      STO=0.
      Z=HPZ-SZ
      M=2
      IF(Z.LE.4.)M=1
      DPP=HPZ
      DTI=4.0
      DGU=Z-DTI
      II=0
      JJ=0
      NTAL=7
      NGNOL=7
      TAL(1)=33.80
      GNOL(1)=107.30
      TAL(2)=34.00
      GNOL(2)=107.10
      TAL(3)=34.10
      GNOL(3)=107.00
      TAL(4)=34.20
      GNOL(4)=106.90
      TAL(5)=34.30
      GNOL(5)=106.80
      TAL(6)=34.40
      GNOL(6)=106.70
      TAL(7)=34.56
      GNOL(7)=106.57
      IF(SY.LT.TAL(1).OR.SY.GT.TAL(NTAL))GO TO 500
      IF(YP.LT.TAL(1).OR.YP.GT.TAL(NTAL))GO TO 500
      IF(SX.GT.GNOL(1).OR.SX.LT.GNOL(NGNOL))GO TO 500
      IF(XP.GT.GNOL(1).OR.XP.LT.GNOL(NGNOL))GO TO 500
      GO TO 520
500   CONTINUE
      TYPE 511,TAL(1),TAL(NTAL),GNOL(1),GNOL(NGNOL)
511   FORMAT(10X,4F10.4)
      TYPE 511,SX,SY,XP,YP
      TYPE 510
510   FORMAT(10X,'INCORRECT ENTRY',/)
      GO TO 90
520   PI=3.1415927
      CF=PI/180.
      XKDEG=((SY+YP)/2.-34.1)*.018+110.922
```

```
      XKC=COS(CF*(SY+YP)/2.)*111.4399
      YTN=90.*CF
      OETY=180.*CF
      TSV=270.*CF
      TSX=360.*CF
      XX=ABS(SX-XP)*XKC
      YY=ABS(SY-YP)*XKDEG
      IF(YY.LE..001)YY=.001
      TH=XX/YY
      AZI=ATAN(TH)
      IF(SY.LT.YP.AND.SX.LT.XP)AZI=OETY-AZI
      IF(SY.LT.YP.AND.SX.GT.XP)AZI=OETY+AZI
      IF(SY.GT.YP.AND.SX.GT.XP)AZI=TSX-AZI
      IF(SY.EQ.YP.AND.SX.GT.XP)AZI=TSV
      IF(SX.EQ.XP.AND.SY.GT.YP)AZI=TSX
      IF(SX.EQ.XP.AND.SY.LT.YP)AZI=OETY
      ANG=ABS(DPP)/SQRT(XX*XX+YY*YY)
      ANG=ATAN(ANG)
      IF(AZI.GT.YTN)GO TO 60
      IF(AZI.LE..0001)AZI=.0001
      DIF=YTN-AZI
      IF(DIF.LE..0001)AZI=AZI-.0001
10    J=0
      I=0
30    I=I+1
      K=I-1
      IF(XP.LT.GNOL(I))GO TO 30
      IF(SX.GE.GNOL(I)) II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/SIN(AZI)
40    J=J+1
      L=NTAL+1-J
      IF(YP.GT.TAL(J))GO TO 40
      IF(SY.LT.TAL(J))JJ=1
      YE=ABS(TAL(J)-YP)
      YD=YE*XKDEG/COS(AZI)
      IPJ=II+JJ
      IF(IPJ.EQ.2)GO TO 70
      IF(YD.GT.XD)GO TO 50
      YP=TAL(J)
      XP=XP-YE*TAN(AZI)*XKDEG/XKC
      TD(L,K,M)=YD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      I=I-1
      GO TO 30
50    CONTINUE
      XP=GNOL(I)
      YP=YP+(XE/TAN(AZI))*XKC/XKDEG
      TD(L,K,M)=XD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      J=J-1
      GO TO 30
70    CONTINUE
```

```
      TD(L,K,M)=ABS((SY-YP)*XKDEG/(COS(AZI)*COS(ANG)))
      IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      GO TO 90
   60 CONTINUE
      IF(AZI.GT.OETY)GO TO 160
      DIF=AZI-YTN
      IF(DIF.LE..0001)AZI=AZI+.0001
      DIF=OETY-AZI
      IF(DIF.LE..0001)AZI=AZI-.0001
      J=NTAL+1
      I=0
  130 I=I+1
      K=I-1
      IF(XP.LT.GNOL(I))GO TO 130
      IF(SX.GE.GNOL(I))II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/COS(AZI-YTN)
  140 J=J-1
      L=NTAL-J
      IF(YP.LT.TAL(J))GO TO 140
      IF(SY.GE.TAL(J))JJ=1
      YE=ABS(TAL(J)-YP)
      YD=YE*XKDEG/SIN(AZI-YTN)
      IPJ=II+JJ
      IF(IPJ.EQ.2)GO TO 170
      IF(YD.GT.XD)GO TO 150
      YP=TAL(J)
      XP=XP-YE*TAN(OETY-AZI)*XKDEG/XKC
      TD(L,K,M)=YD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      I=I-1
      GO TO 130
  150 CONTINUE
      XP=GNOL(I)
      YP=YP-XE*TAN(AZI-YTN)*XKC/XKDEG
      TD(L,K,M)=XD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      J=J+1
      GO TO 130
  170 CONTINUE
      TD(L,K,M)=ABS(SY-YP)*XKDEG/(COS(OETY-AZI)*COS(ANG))
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      GO TO 90
  160 CONTINUE
      IF(AZI.GT.TSV)GO TO 260
      DIF=AZI-OETY
      IF(DIF.LE..0001)AZI=AZI+.0001
      DIF=TSV-AZI
```

```
      IF(DIF.LE..0001)AZI=AZI-.0001
      J=NTAL+1
      I=NGNOL+1
230   I=I-1
      K=I
      IF(XP.GT.GNOL(I))GO TO 230
      IF(SX.LE.GNOL(I))II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/SIN(AZI-OETY)
240   J=J-1
      L=NTAL-J
      IF(YP.LT.TAL(J))GO TO 240
      IF(SY.GE.TAL(J))JJ=1
      YE=ABS(TAL(J)-YP)
      YD=YE*XKDEG/COS(AZI-OETY)
      IPJ=II+JJ
      IF(IPJ.EQ.2)GO TO 270
      IF(YD.GT.XD)GO TO 250
      YP=TAL(J)
      XP=XP+YE*TAN(AZI-OETY)*XKDEG/XKC
      TD(L,K,M)=YD/COS(ANG)
      IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      IF(XD.NE.GNOL(I))I=I+1
      GO TO 230
250   CONTINUE
      XP=GNOL(I)
      YP=YP-XE*TAN(TSV-AZI)*XKC/XKDEG
      TD(L,K,M)=XD/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      IF(YD.NE.TAL(J))J=J+1
      GO TO 230
270   CONTINUE
      TD(L,K,M)=ABS(SY-YP)*XKDEG/(SIN(TSV-AZI)*COS(ANG))
      IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
      TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
      CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
      GO TO 90
260   CONTINUE
      J=0
      DIF=AZI-TSV
      IF(DIF.LE..0001)AZI=AZI+.0001
      DIF=TSX-AZI
      IF(DIF.LE..0001)AZI=AZI-.0001
      I=NGNOL+1
330   I=I-1
      K=I
      IF(XP.GT.GNOL(I))GO TO 330
      IF(SX.LE.GNOL(I))II=1
      XE=ABS(GNOL(I)-XP)
      XD=XE*XKC/COS(AZI-TSV)
```

```
340     J=J+1
        L=NTAL+1-J
        IF(YP.GT.TAL(J))GO TO 340
        IF(SY.LE.TAL(J))JJ=1
        YE=ABS(TAL(J)-YP)
        YD=YE*XKDEG/SIN(AZI-TSV)
        IPJ=II+JJ
        IF(IPJ.EQ.2)GO TO 370
        IF(YD.GT.XD)GO TO 350
        YP=TAL(J)
        XP=XP+YE*TAN(TSX-AZI)*XKDEG/XKC
        TD(L,K,M)=YD/COS(ANG)
        TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
        CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
        I=I+1
        GO TO 330
350     CONTINUE
        XP=GNOL(I)
        YP=YP+XE*TAN(AZI-TSV)*XKC/XKDEG
        TD(L,K,M)=XD/COS(ANG)
        TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
        CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
        J=J-1
        GO TO 330
370     CONTINUE
        TD(L,K,M)=ABS(SY-YP)*XKDEG/(COS(TSX-AZI)*COS(ANG))
        IF(YY.LT..01)TD(L,K,M)=ABS(SX-XP)*XKC/COS(ANG)
        TDZ(L,K,M)=TD(L,K,M)*SIN(ANG)
        CALL BLCHG(TDZ,DGU,TD,L,K,M,ANG)
 90     CONTINUE
        TTT=0.
        RETURN
        END
        SUBROUTINE BLCHG(TDZ,DGU,TD,L,K,M,ANG)
C     ********************************************************
C        DETERMINATION OF AN INTERFACE INTERSECTION
C     ********************************************************
        DIMENSION TDZ(6,6,2),TD(6,6,2)
        IF(M.EQ.1) RETURN
        STDZ = 0.
        DO 1 LL=1,6
        DO 1 KK=1,6
1       STDZ=STDZ+TDZ(LL,KK,2)
        IF(STDZ.LT.DGU) RETURN
        TZ=TDZ(L,K,2)
        TDZ(L,K,2)=DGU-STDZ+TDZ(L,K,2)
        TD(L,K,2)=TDZ(L,K,2)/SIN(ANG)
        TDZ(L,K,1)=TZ-TDZ(L,K,2)
        TD(L,K,1)=TDZ(L,K,1)/SIN(ANG)
```

```
      M=1
      RETURN
      END
      SUBROUTINE BLK(NBL,TD,IBLC,BLKT,V,AVSQ,TTT)
C     ************************************************************
C       DETERMINATION OF TOTAL TRAVEL PATH LENGTHS
C                     WITHIN EACH BLOCK
C     ************************************************************
      DIMENSION TD(6,6,2),BLKT(72),IBLC(53,54),V(72)
      DO 2 II=1,NBL
      BLKT(II)=0.
      DO 2 MM=1,IBLC(II,1)
      III=0
      DO 2 M=1,2
      DO 2 I=1,6
      DO 2 J=1,6
      III=III+1
      IF(III.NE.IBLC(II,MM+1))GO TO 2
      BLKT(II)=BLKT(II)+TD(I,J,M)
2     CONTINUE
      TTT=0.
      TTD=0.
      DO 3 I=1,NBL
      TTD=TTD+BLKT(I)
      BLKT(I)=BLKT(I)/V(I)
3     TTT=TTT+BLKT(I)
      AVSQ=(TTD/TTT)**2.
      RETURN
      END
      SUBROUTINE EIGENS(NLAM)
C     ************************************************************
C       DETERMINATION OF EIGENVALUES AND EIGENVECTORS
C     ************************************************************
      DIMENSION E(213),V(213,213),U(262,213),A(262,213),C(22791)
     $,WK(356),NSTA(40)
      COMMON /C1/A,NSTA/C2/U/C5/NX,NSTN/C9/V,E/C4/C
        OPEN(UNIT=25,DEVICE='DSK',MODE='ASCII',ACCESS='SEQOUT',
     $  FILE='PIT')
      DO 3 I=1,262
      DO 3 J=1,213
    3 U(I,J)=0.0
      DO 4 I=1,213
      E(I)=0.0
      DO 4 J=1,213
    4 V(I,J)=0.0
```

```
        CALL EIGRS(C,NX,1,E,V,213,WK,IER)
        CALL SORT(NX,NLAM)
      DO 50 JJJ=1,NX
      IF(ABS(E(JJJ)).LT..00001)E(JJJ)=.00001
      E(JJJ) = SQRT(E(JJJ))
      DO 50 JJ=1,NSTN
      SUM = 0.
      DO 40 J=1,NX
   40 SUM = A(JJ,J)*V(J,JJJ) + SUM
   50 U(JJ,JJJ) = SUM/E(JJJ)
C     V IS TO BE MODIFIED
      DO 60 J=1,NX
      DO 60 I=1,NX
   60 V(I,J) = V(I,J)/E(J)
        CLOSE(UNIT=25)
      RETURN
      END
      SUBROUTINE SOLVEC(N,CO)

C     ***************************************************************

C       FORMATION OF THE INVERTED MATRIX
C       FROM EIGENVALUES AND EIGENVECTORS

C     ***************************************************************

       DIMENSION U(262,213),V(213,213),E(213),A(213,262),B(262)
      $,D(213)
      $   ,NSTA(40)
       COMMON/C2/U/C3/B/C5/NX,NSTN/C6/D/C1/A,NSTA/C9/V,E
       DO 10 I=1,213
       DO 10 J=1,262
   10 A(I,J) = 0.0
      CALL VMULFP(V,U,NX,N,NSTN,213,262,A,213,IER)
      DO 30 I=1,NX
      SUM = 0.
      DO 20 J=1,NSTN
   20 SUM = A(I,J)*B(J) + SUM
   30 D(I) = SUM
      CO = E(1)/E(N)
      RETURN
      END
        SUBROUTINE SORT(NX,NLAM)


C     ***************************************************************

C       SORTS EIGENVALUES FROM LARGEST TO SMALLEST

C     ***************************************************************

        DIMENSION E(213),V(213,213),U(262,213),IREIG(8),IEV(8)
```

```
      COMMON/C2/U/C9/V,E
      DATA IEV/6,8,25,29,34,35,39,40/
      N=NX-1
      DO 1 K=1,N
      DO 1 J=2,NX
      JM1=J-1
      IF(E(J).LT.E(JM1))GO TO 1
      HDL=E(J)
      E(J)=E(JM1)
      E(JM1)=HDL
      DO 2 I=1,NX
      HDL=V(I,J)
      V(I,J)=V(I,JM1)
2     V(I,JM1)=HDL
1     CONTINUE
      PRINT 6969,(IREIG(JJ),JJ=1,8)
6969  FORMAT(1X,10I4)
      CALL SRCH(IREIG,IEV,NLAM)
      PRINT 6969,(IREIG(JJ),JJ=1,8)
C     DO 110 I=1,NX
C     PRINT 150,E(I)
C150  FORMAT(1X,/,1X,F10.4)
C     PRINT 200,(V(J,I),J=1,NX)
C200  FORMAT(1X,10F6.3)
C110  CONTINUE
      DO 111 II=1,NLAM
      NTR=IREIG(II)
      IF(NTR.EQ.NX)GO TO 111
      DO 100 I=NTR,NX-1
      E(I)=E(I+1)
      DO 100 J=1,NX
100   V(J,I)=V(J,I+1)
111   CONTINUE
      PRINT 6968,(E(I),I=1,NX)
6968  FORMAT(1X,6F10.4)
C     DO 10 I=1,NX
C     PRINT 15,E(I)
C15   FORMAT(1X,/,1X,F10.4)
C     PRINT 20,(V(J,I),J=1,NX)
C20   FORMAT(1X,10F6.3)
C10   CONTINUE
      RETURN
      END
      SUBROUTINE SRCH(IREIG,IEV,NLAM)
C     ***************************************************************
C        DETERMINES FOR A GIVEN Z THE ASSOCIATED EIGENVECTOR
C     ***************************************************************
      DIMENSION IRTRN(8),IWK(8,3),IEV(8),E(213),V(213,213)
     $ ,IREIG(8)
```

```
      COMMON /C5/NX,NSTN/C9/V,E
      DO 10 I=1,8
      IREIG(I)=0
      IWK(I,1)=IEV(I)
      DO 10 J=2,3
10    IWK(I,J)=0
      DO 20 I=1,8
      IZ=(IWK(I,1)*4)-1
      DO 20 J=1,NX
      ITN=ABS(IFIX(V(IZ,J)*1000.))
      IF(IWK(I,3).GT.ITN)GO TO 20
      IWK(I,3)=ITN
      IWK(I,2)=J
20    CONTINUE
      DO 600 I=1,8
      DO 600 J=2,8
      IF(I.GE.J)GO TO 600
      IF(IWK(I,2).NE.IWK(J,2))GO TO 600
      NLAM=NLAM-1
600   CONTINUE
      GO TO 601
      DO 500 JJ=1,7
      DO 700 I=1,8
      DO 700 II=1,7
      IF(IWK(II,3).GT.IWK(II+1,3))GO TO 700
      HLD=IWK(II+1,3)
      IWK(II+1,3)=IWK(II,3)
      IWK(II,3)=HLD
      HLD=IWK(II,2)
      IWK(II,2)=IWK(II+1,2)
      IWK(II+1,2)=HLD
      HLD=IWK(II,1)
      IWK(II,1)=IWK(II+1,1)
      IWK(II+1,1)=HLD
700   CONTINUE
      DO 350 I=1,8
      DO 350 II=1,8
      IF(I.LE.II)GO TO 350
      IF(IWK(I,2).NE.IWK(II,2))GO TO 350
      HLD1=IWK(II,2)
      IWK(I,3)=0
      IWK(I,2)=0
      HLD2=I
      IZ=IWK(HLD2,1)*4-1
      DO 400 J=1,NX
      IF(J.EQ.HLD1)GO TO 400
      ITN=ABS(IFIX(V(IZ,J)*1000.))
      IF(IWK(HLD2,3).GT.ITN)GO TO 400
      DO 777 JJJ=1,8
      IF(J.EQ.IWK(JJJ,2).AND.ITN.LT.IWK(JJJ,3))GO TO 400
777   CONTINUE
      IWK(HLD2,3)=ITN
```

```
      IWK(HLD2,2)=J
400   CONTINUE
350   CONTINUE
500   CONTINUE
601   CONTINUE
      DO 50 I=1,8
      PRINT 711,(IWK(I,J),J=1,3)
711   FORMAT(1X,3I10)
50    IRTRN(I)=IWK(I,2)
      DO 60 J=1,8
      DO 60 I=1,7
      IF(IRTRN(I).GT.IRTRN(I+1))GO TO 60
      HDL=IRTRN(I)
      IRTRN(I)=IRTRN(I+1)
      IRTRN(I+1)=HDL
60    CONTINUE
      J=1
      IREIG(1)=IRTRN(1)
      DO 100 I=2,8
      IF(IRTRN(I).EQ.IRTRN(I-1))GO TO 100
      J=J+1
      IREIG(J)=IRTRN(I)
100   CONTINUE
      RETURN
      END
```

This dissertation is accepted on behalf of the faculty of the Institute by the following committee:

Adviser

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August, 1980

Date