

AD-A021 931

IMPROVED PROCEDURES FOR DETERMINING SEISMIC SOURCE  
DEPTH FROM DEPTH PHASE INFORMATION

Edward Page

ENSCO, Incorporated

Prepared for:

Air Force Technical Applications Center

November 1975

DISTRIBUTED BY:

**NTIS**

National Technical Information Service  
U. S. DEPARTMENT OF COMMERCE

083128

ADA021931

IMPROVED PROCEDURES FOR <sup>determining</sup> ~~DETECTING~~  
SEISMIC SOURCE DEPTHS FROM  
DEPTH PHASE INFORMATION

QUARTERLY REPORT

Edward A. Page  
Francis J. Cook

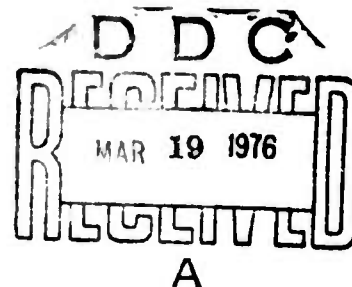
November 1975

Sponsored by:

Advanced Research Project Agency  
ARPA Order No. 2551

APPROVED FOR PUBLIC RELEASE.  
DISTRIBUTION UNLIMITED.

REPRODUCED BY  
NATIONAL TECHNICAL  
INFORMATION SERVICE  
U. S. DEPARTMENT OF COMMERCE  
SPRINGFIELD, VA. 22161





16 April 1973

F234.7

DEPARTMENT OF DEFENSE FORMS

F-200.1473 DD Form 1473: Report Documentation Page

| REPORT DOCUMENTATION PAGE   |                      | READ INSTRUCTIONS<br>BEFORE COMPLETING FORM                 |
|---|----------------------|---|
| 1. REPORT NUMBER  | 2. GOVT ACCESSION NO | 3. RECIPIENT'S CATALOG NUMBER                               |
| 4. TITLE (and Subtitle)<br>Improved Procedures for Determining Seismic Source Depth from Depth Phase Information<br>Edward Page   |                      | 5. TYPE OF REPORT & PERIOD COVERED<br>Quarterly Report      |
| 6. PERFORMING ORGANIZATION NAME AND ADDRESS<br>ENSCO, Inc.<br>8001 Forbes Pl., Springfield, VA. Nov. 1975   |                      | 7. PERFORMING ORG. REPORT NUMBER                            |
| 8. CONTROLLING OFFICE NAME AND ADDRESS<br>DCASD, Baltimore<br>Bldg. 22, Fort Holabird<br>Baltimore, Maryland, 21210   |                      | 8. CONTRACT OR GRANT NUMBER(s)<br>F08606-76-C-0003          |
| 9. DISTRIBUTION STATEMENT (of this Report)<br>APPROVED FOR PUBLIC RELEASE<br>DISTRIBUTION UNLIMITED.  |                      | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 10. SUPPLEMENTARY NOTES   |                      | 11. REPORT DATE<br>Nov. 1975                                |
| 11. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>Seismic Source depth, depth phase, echo detection  |                      | 12. NUMBER OF PAGES<br>18                                   |
| 12. KEY WORDS (Continue on reverse side if necessary and identify by block number)<br>Seismic Source depth determination techniques, developed under two previous contracts, were formulated into an automated analysis procedure. Differential travel time information, for several propagation modes relevant to the analysis, have been made accessible through 3-D curve fitting. |                      | 13. SECURITY CLASS. (of this report)                        |
| 13. SECURITY CLASS. (of this report)  |                      | 14. DECLASSIFICATION/CONTROL SCHEDULE                       |

DD FORM 1473 EDITION OF 1 NOV 68 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ia F-200.1473

ARMED SERVICES PROCUREMENT REGULATION



## Introduction and Summary

During the first quarter of this contract, seismic source depth determination techniques (developed during the two previous contracts), were formulated into an automated analysis procedure. In this procedure, the source depth is determined by the degree to which cepstrum patterns, computed from different portions of multi-station data, agree with those expected for a given source depth. The variation in differential travel times caused by the location of stations and the presence of later propagation modes are both accounted for, and the depth phase information in the entire seismogram is involved in the depth estimate. The analysis procedure involves the computation of the cepstrum, cepstrum match filter outputs, stochastic averaging, and use of the differential travel time for several propagation modes. The travel time data, automatically accessed in the analysis procedure, is stored as coefficients defining a polynomial surface fitted to the three-dimensional data of travel time versus source depth and source to receiver epicenter distance.

In the current procedure, multi-channel seismic data is read in and a plot of the cumulative CMF outputs versus source depth is computed. The Illinois Event of 11/9/68 has been analyzed thus far, and the output indicates a clear detection of a 25 km source depth, correct for this event. We now discuss in more detail the analysis procedure, the computer storage of the travel time information, and the application of the seismic source depth analysis.

## Major Accomplishments

### 1. Seismic Source Depth Analysis Procedure

The seismic source depth analysis procedure is illustrated in the flow chart of Figure 1. The seismic data recorded over a suite of stations are selected to start at the onset of the P wave. Next the data sample length, governing the maximum differential delay time observable, and the length of coda to be analyzed, are selected.

At this point, a set of consecutive data samples covering the selected coda length for each station recording has been determined. A data sample is selected and a cepstrum and cepstrum matched filter output is calculated. The procedure used to calculate the CMF is illustrated in Figure 2. The first of a range of trial source depths are then selected for the analysis. For this trial depth and station epicenter distance, the differential travel times for the following propagation modes are accessed from storage: pP-P, PP-P, pPP-PP, PPP-P, pPPP-PPP, PcP-P, pPcP-PcP. For the start and end time of the data sample, it is decided which modes will contribute to the cepstrum for this particular data sample. The maximum CMF output within a given time window of the expected time delay between the surface reflected arrival and the direct arrival for each of these propagation modes is accumulated in the output amplitude for this trial source depth. For this same sample, the procedure is repeated over the range of trial depths used. This completes the analysis of this data sample and the next data sample is likewise processed. One then plots the cumulative CMF output as a function of depth, and a peak in the distribution will indicate the depth estimate.

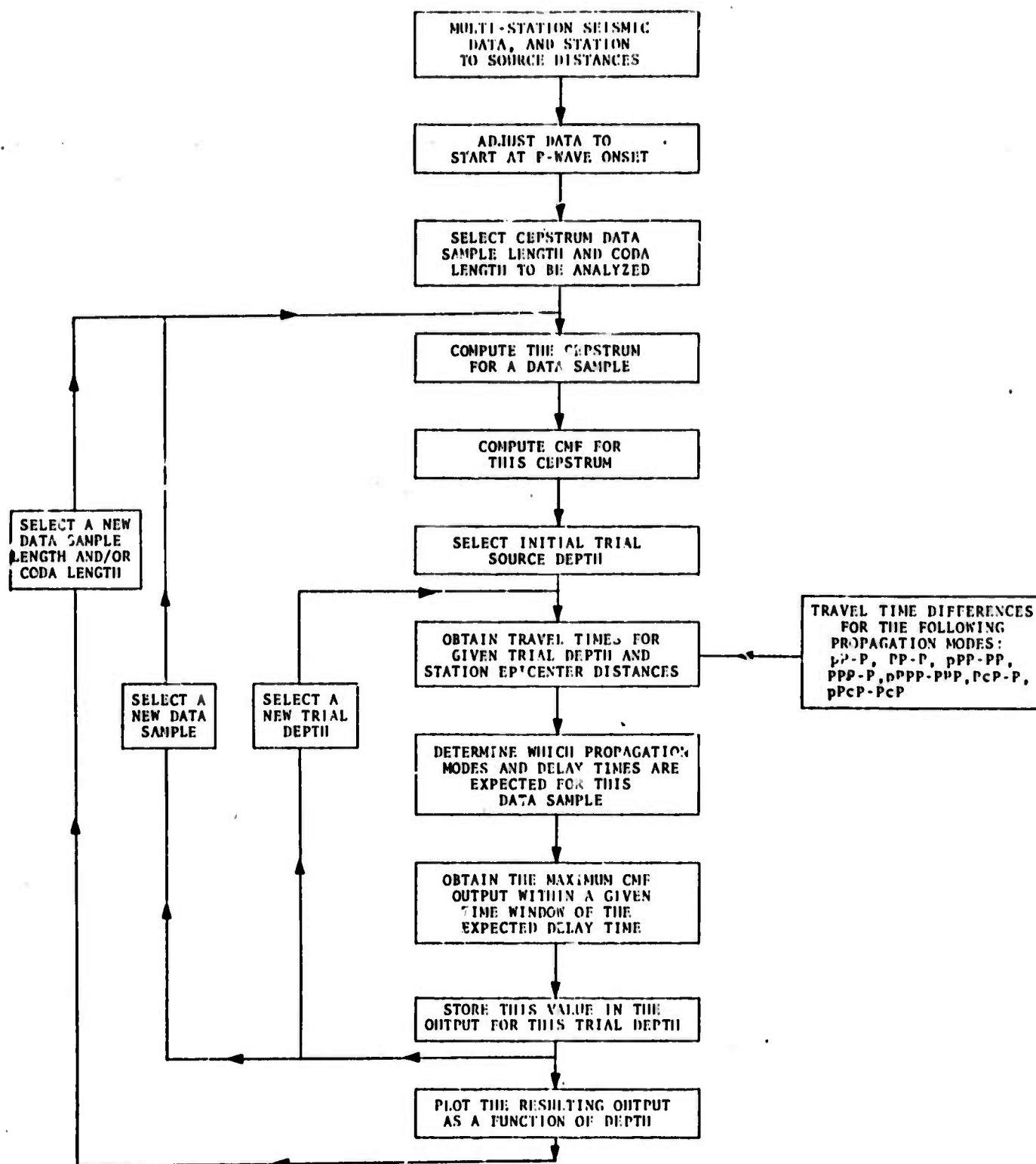


FIGURE 1. SEISMIC SOURCE DEPTH DETERMINATION PROCEDURE

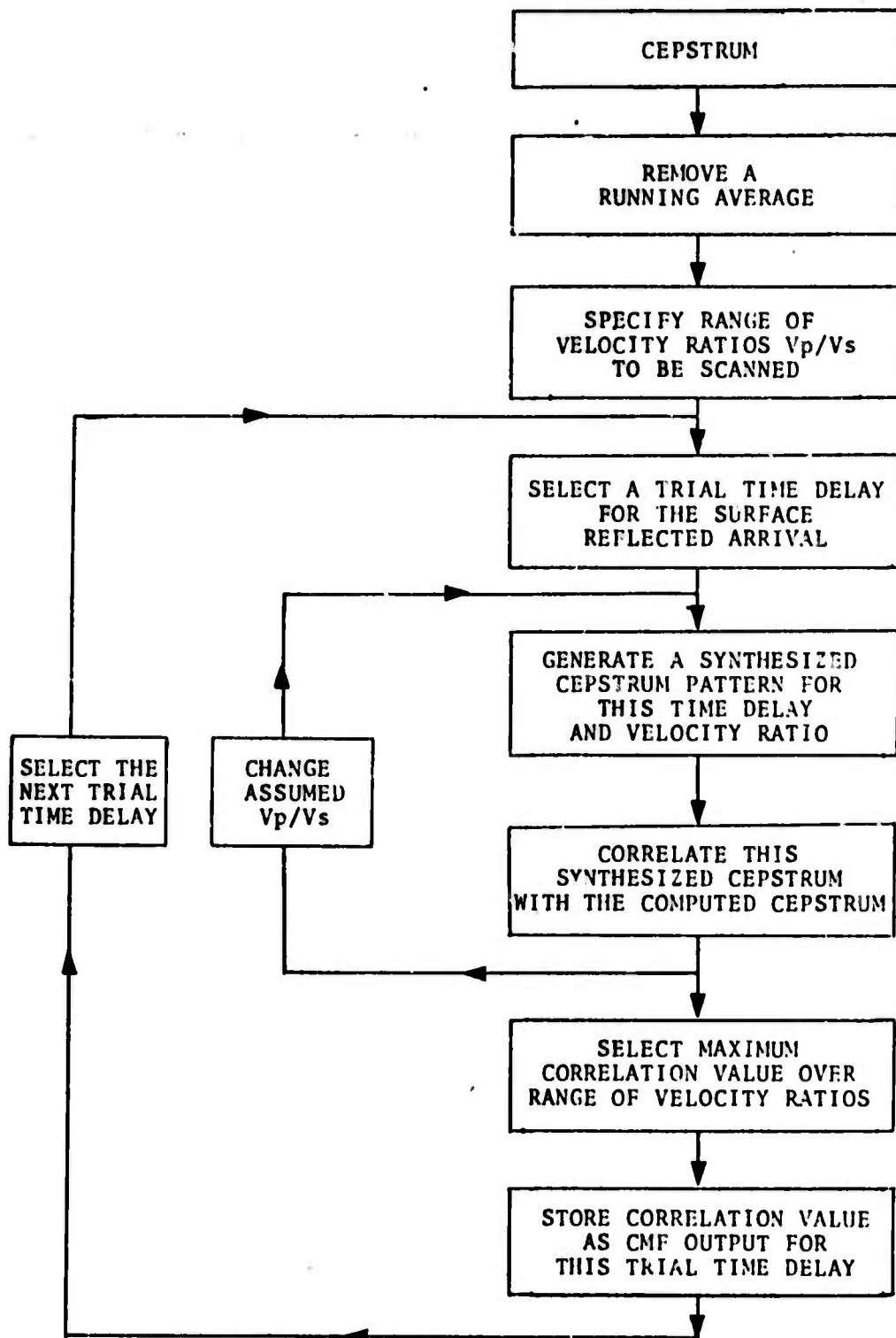


FIGURE 2. CALCULATION OF CEPSTRUM MATCHED FILTER (CMF) OUTPUT

This entire procedure is then repeated for different sample lengths and/or coda lengths.

The procedure was applied to the Illinois Event (11/9/68) using a sample length of 256 points and five consecutive coda samples for each of the six station recordings. The resulting output as a function of depth (in km) is plotted in Figure 3 and a clear detection of the 25 km source depth for the event is evident.

In the next section we discuss the techniques developed to facilitate the storage and accessing of the differential travel times used.

## 2. Polynomial Surface Representation of Differential Travel Times

To account for depth phase delay time variations along seismic coda, one needs access to the differential travel times for various seismic phases. From previous work, these travel time differences were obtained by the application of a ray tracing program based on the spherically symmetric isotropic earth velocity model used for the BSSA seismological tables. For this current work, an analytic three-dimensional representation of these data was developed in order to facilitate computer access and to perform the necessary interpolation of these values. We now describe the procedure for obtaining the representation of these differential travel times as a function of source depth and source to receiver distance for the following seismic propagation modes: pP-P, PP-P, pPP-FP, PPP-P, pPPP-PPP, PcP-P, pPcP-PcP.

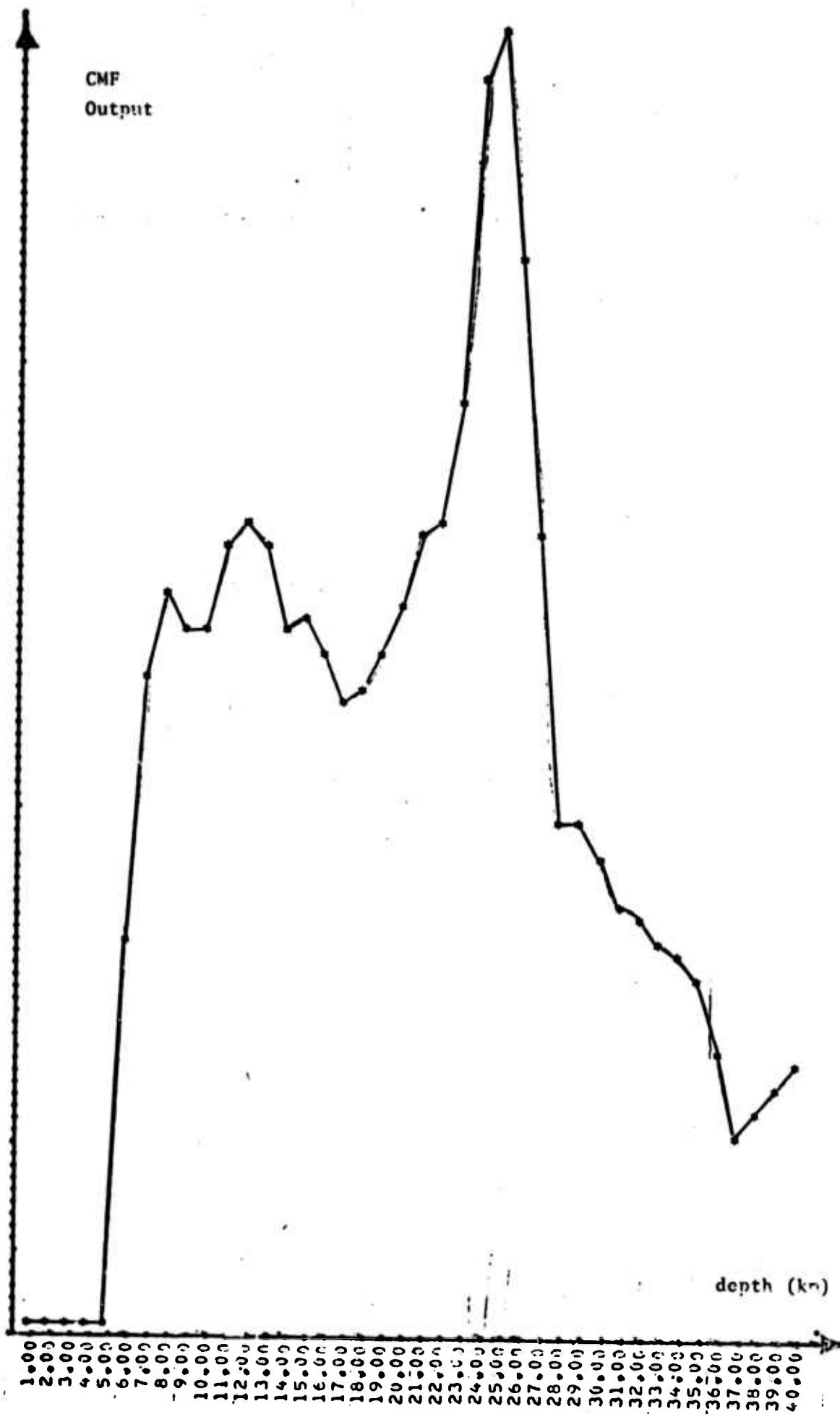


FIGURE 3. RESULTS OF SOURCE DEPTH ANALYSIS FOR ILLINOIS EVENT

Case I: Surface Fits to pP-P, pPPP-PPP, pPP-PP, pPcP-PcP

An examination of Figure 4 suggests we represent these data as a double power series in which the travel time difference  $\tau$  is the dependent variable and the depth  $d$  and epicenter distances  $\Delta$  are the independent variables. The surface of travel time differences is then given by

$$\tau(d, \Delta) = \sum_{ij} \tau_{ij} \Delta^j d^i$$

The coefficients  $\tau_{ij}$  and the number of them needed were determined as follows. Each curve at constant  $\Delta_c$  was found to be adequately represented by a cubic in  $d$ :

$$\tau(d, \Delta_c) = \tau_1(\Delta_c) d + \tau_2(\Delta_c) d^2 + \tau_3(\Delta_c) d^3$$

Here  $\tau$  vanishes at zero depth. The least squares values of  $\tau_i(\Delta)$  were then in turn adjusted to a power series in  $\Delta$ :

$$\tau_i(\Delta) = \sum_{j=0}^N \tau_{ij} \Delta^j, \quad i=1,2,3$$

Reliable input data for  $\Delta$  less than  $10^\circ$  were not available, so no attempt was made to force  $\tau_i(\Delta)$  to vanish at zero epicenter distance. Thus, our representation should be used only for  $\Delta \gg 10^\circ$ . All the data sets of Case I can be represented by  $N=9$ . Examples of the effectiveness of this representation are shown in Figures 5a through 5d for pP-P, pPP-PP, pPPP-PPP, and pPcP-PcP.

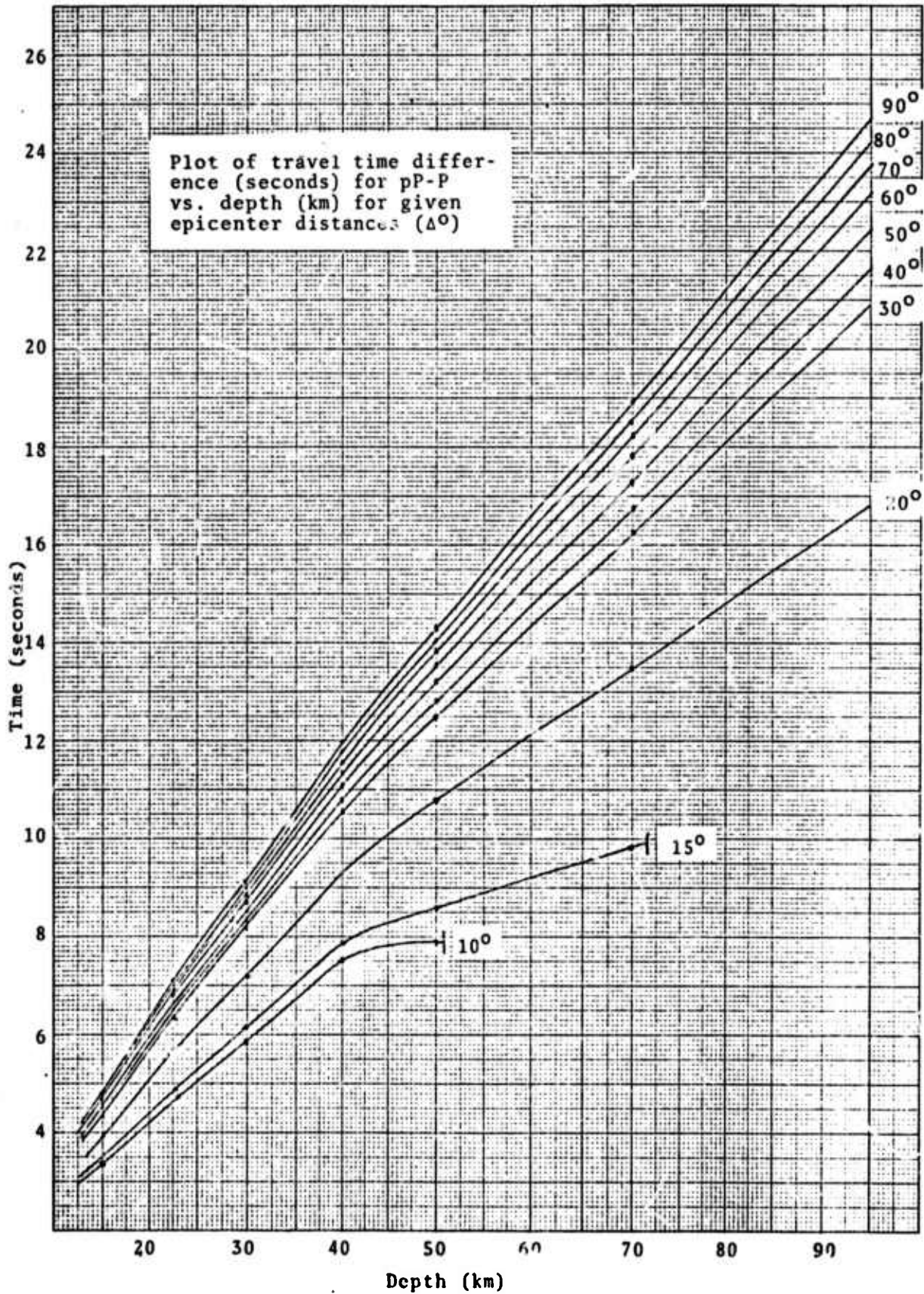


FIGURE 4

(P-P)-P: TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

| J = | TAU SUB 1J     | TAU SUB 2J     | TAU SUB 3J     |
|-----|----------------|----------------|----------------|
| 0   | .70451569E+00  | -.88319599E-03 | -.85335509E-04 |
| 1   | -.15119426E+00 | .18381440E-02  | -.78442494E-05 |
| 2   | .17816886E-01  | -.35701656E-03 | .31772821E-05  |
| 3   | -.10480308E-02 | .27611793E-04  | -.28151927E-06 |
| 4   | .36120111E-04  | -.11502724E-05 | .12401366E-07  |
| 5   | -.77702894E-06 | .28589908E-07  | -.31769065E-09 |
| 6   | .10590388E-07  | -.43734706E-09 | .49528985E-11  |
| 7   | -.89011917E-10 | .40420244E-11  | -.46377519E-13 |
| 8   | .42133363E-12  | -.20718337E-13 | .24000326E-15  |
| 9   | -.85973085E-15 | .45239568E-16  | -.52790138E-18 |

CALCULATED TRAVEL TIME DIFFERENCE TABLE

| DELTA ↑<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | 1.103  | 1.233  | 1.403  | 1.538  | 1.561  | 1.590  | 1.616  | 1.637  | 1.653  | 1.673  |
| 14.900             | 3.249  | 3.474  | 3.923  | 4.360  | 4.439  | 4.528  | 4.614  | 4.677  | 4.734  | 4.793  |
| 23.000             | 4.866  | 5.099  | 5.753  | 6.469  | 6.606  | 6.744  | 6.888  | 6.986  | 7.085  | 7.177  |
| 30.000             | 6.081  | 6.346  | 7.187  | 8.164  | 8.357  | 8.541  | 8.738  | 8.870  | 9.008  | 9.130  |
| 39.900             | 7.382  | 7.850  | 9.015  | 10.387 | 10.671 | 10.924 | 11.198 | 11.382 | 11.578 | 11.744 |
| 50.000             | 8.036  | 9.056  | 10.678 | 12.480 | 12.870 | 13.198 | 13.551 | 13.798 | 14.051 | 14.266 |
| 70.000             | *****  | 10.405 | 13.556 | 16.262 | 16.891 | 17.397 | 17.885 | 18.296 | 18.637 | 18.962 |
| 100.000            | *****  | *****  | 17.527 | 21.622 | 22.670 | 23.533 | 24.102 | 24.906 | 25.245 | 25.784 |

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

| DELTA ↑<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | .040   | -.066  | -.038  | -.083  | -.075  | -.072  | -.071  | -.066  | -.066  | -.061  |
| 14.900             | .125   | .018   | .010   | -.008  | .001   | .002   | -.001  | .008   | .011   | .006   |
| 23.000             | -.141  | -.163  | -.063  | -.090  | -.094  | -.087  | -.091  | -.077  | -.067  | -.075  |
| 30.000             | -.190  | -.184  | -.006  | -.042  | -.053  | -.040  | -.054  | -.044  | -.031  | -.038  |
| 39.900             | .156   | .031   | .305   | .199   | .156   | .183   | .145   | .165   | .173   | .164   |
| 50.000             | -.123  | -.461  | .069   | .014   | -.035  | .002   | -.027  | .012   | .009   | .003   |
| 70.000             | *****  | -.587  | -.046  | -.009  | -.120  | -.083  | -.087  | -.085  | -.027  | -.053  |
| 100.000            | *****  | *****  | .005   | .231   | -.069  | -.082  | .082   | -.114  | .151   | .079   |

FIGURE 5a. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR PP-P

(P+)PP-PP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

| J = | TAU SUB 1J     | TAU SUB 2J     | TAU SUB 3J     |
|-----|----------------|----------------|----------------|
| 0   | .13332966E+01  | -.24582721E-01 | .47856874E-03  |
| 1   | -.28393239E+00 | .33328531E-02  | -.74463907E-04 |
| 2   | .30372292E-01  | -.90408566E-04 | .29860351E-05  |
| 3   | -.18072171E-02 | -.59734377E-05 | .44096374E-07  |
| 4   | .65989127E-04  | .46604204E-06  | -.68787773E-08 |
| 5   | -.15259838E-05 | -.13743890E-07 | .23253861E-09  |
| 6   | .2235513E-07   | .21990505E-09  | -.40304687E-11 |
| 7   | -.20078532E-09 | -.20139218E-11 | .39346127E-13  |
| 8   | .10079121E-11  | .99551033E-14  | -.20598689E-15 |
| 9   | -.21645634E-14 | -.20663571E-16 | .45130638E-18  |

CALCULATED TRAVEL TIME DIFFERENCE TABLE (\*\*\*\*\* MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

| DELTA →<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | 1.193  | 1.070  | 1.104  | 1.216  | 1.406  | 1.518  | 1.535  | 1.559  | 1.558  | 1.572  |
| 14.900             | 3.224  | 3.140  | 3.261  | 3.419  | 3.927  | 4.293  | 4.351  | 4.418  | 4.428  | 4.472  |
| 23.000             | 4.652  | 4.688  | 4.887  | 5.012  | 5.759  | 6.359  | 6.457  | 6.554  | 6.584  | 6.656  |
| 30.000             | 5.789  | 5.844  | 6.105  | 6.229  | 7.196  | 8.013  | 8.152  | 8.271  | 8.326  | 8.424  |
| 39.900             | 7.358  | 7.069  | 7.397  | 7.689  | 9.032  | 10.173 | 10.381 | 10.527 | 10.628 | 10.764 |
| 50.000             | *****  | 7.665  | 8.015  | 8.849  | 10.711 | 12.195 | 12.490 | 12.658 | 12.816 | 12.994 |
| 70.000             | *****  | *****  | *****  | 10.109 | 13.656 | 15.823 | 16.345 | 16.539 | 16.837 | 17.101 |
| 100.000            | *****  | *****  | *****  | *****  | 17.859 | 20.920 | 21.956 | 22.157 | 22.704 | 23.095 |

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

| DELTA →<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | -.083  | .047   | .043   | -.055  | -.077  | -.077  | -.081  | -.078  | -.075  | -.069  |
| 14.900             | .093   | .201   | .115   | .066   | .012   | -.012  | -.007  | -.022  | .014   | .014   |
| 23.000             | .021   | .001   | -.156  | -.097  | -.064  | -.094  | -.066  | -.111  | -.073  | -.067  |
| 30.000             | .031   | .002   | -.201  | -.086  | -.017  | -.048  | -.038  | -.059  | -.024  | -.028  |
| 39.900             | .080   | .404   | .141   | .183   | .301   | .207   | .203   | .170   | .201   | .215   |
| 50.000             | *****  | .102   | -.120  | -.252  | .031   | .027   | .003   | -.004  | .013   | .022   |
| 70.000             | *****  | *****  | *****  | *****  | -.141  | -.004  | -.100  | -.130  | -.069  | -.062  |
| 100.000            | *****  | *****  | *****  | *****  | -.260  | .256   | -.108  | .032   | -.101  | -.052  |

FIGURE 5b. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR PPT-PP.

(P)PPP-PPP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

| J = | TAU SUB 1J     | TAU SUB 2J     | TAU SUB 3J     |
|-----|----------------|----------------|----------------|
| 0   | -.7763389F+00  | .68361173E-01  | -.13622038E-02 |
| 1   | .29864525E+00  | -.20124183E-01 | .38960040E-03  |
| 2   | -.34221106E-01 | .22266622E-02  | -.42768587E-04 |
| 3   | .20635643E-02  | -.12835418E-03 | .24445225E-05  |
| 4   | -.74268357E-04 | .44007204E-05  | -.82830884E-07 |
| 5   | .16826877E-05  | -.95205747E-07 | .17628515E-08  |
| 6   | -.24211801E-07 | .13166893E-08  | -.23880077E-10 |
| 7   | .21451030E-09  | -.11306496E-10 | .20021912E-12  |
| 8   | -.10663313E-11 | .54928750E-13  | -.94807249E-15 |
| 9   | .22742755E-14  | -.11533281E-15 | .19392923E-17  |

CALCULATED TRAVEL TIME DIFFERENCE TABLE

| DELTA →<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | 1.207  | 1.173  | 1.090  | 1.100  | 1.194  | 1.327  | 1.443  | 1.485  | 1.526  | 1.540  |
| 14.900             | 3.252  | 3.242  | 3.210  | 3.257  | 3.343  | 3.639  | 4.012  | 4.203  | 4.321  | 4.354  |
| 23.000             | 4.679  | 4.732  | 4.811  | 4.390  | 4.878  | 5.249  | 5.862  | 6.229  | 6.600  | 6.447  |
| 30.000             | 5.806  | 5.911  | 6.022  | 6.117  | 6.034  | 6.458  | 7.302  | 7.851  | 8.067  | 8.124  |
| 39.900             | 7.345  | 7.465  | 7.342  | 7.423  | 7.384  | 7.913  | 9.125  | 9.965  | 10.248 | 10.319 |
| 50.000             | *****  | *****  | *****  | 4.055  | 8.399  | 9.135  | 10.778 | 11.938 | 12.301 | 12.386 |
| 70.000             | *****  | *****  | *****  | *****  | 9.250  | 10.975 | 13.656 | 15.436 | 16.028 | 16.146 |
| 100.000            | *****  | *****  | *****  | *****  | *****  | 13.039 | 17.815 | 20.191 | 21.429 | 21.635 |

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

| DELTA →<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | -.080  | -.073  | .032   | .052   | -.052  | -.122  | -.118  | -.068  | -.072  | -.088  |
| 14.900             | .027   | .063   | .120   | .119   | .059   | -.027  | .012   | .011   | .010   | -.005  |
| 23.000             | -.003  | -.064  | -.138  | -.155  | -.097  | -.120  | -.052  | -.096  | -.060  | -.074  |
| 30.000             | .012   | -.100  | -.197  | -.215  | -.064  | -.025  | -.078  | -.060  | -.002  | -.018  |
| 39.900             | .069   | -.049  | .113   | .126   | .270   | .351   | .185   | .151   | .251   | .258   |
| 50.000             | *****  | *****  | *****  | -.173  | -.236  | .067   | -.035  | -.059  | .093   | .103   |
| 70.000             | *****  | *****  | *****  | *****  | -.210  | -.002  | -.130  | -.133  | .063   | .019   |
| 100.000            | *****  | *****  | *****  | *****  | *****  | .430   | -.201  | -.144  | .173   | .191   |

FIGURE 5c. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR PPP-PPP

(P)PCP-PCP TRAVEL TIME DIFF (SEC) VS DEPTH (KM) AND EPI-DISTANCE DELTA (DEG)

DOUBLE POWER SERIES COEFFICIENTS FOR CALCULATING TRAVEL TIME DIFFERENCE

| J | TAU SUR 1J     | TAU SUR 2J     | TAU SUR 3J     |
|---|----------------|----------------|----------------|
| 0 | .43430116F+00  | -.39806067E-02 | .26096260E-04  |
| 1 | -.14028699F-01 | .72844103E-03  | -.55860908E-05 |
| 2 | .14257720F-02  | -.78747384E-04 | .59120923E-06  |
| 3 | -.71953567F-04 | .43250873E-05  | -.31612775E-07 |
| 4 | .19617897E-05  | -.13472496E-06 | .94863732E-09  |
| 5 | -.28743273E-07 | .24805786E-08  | -.16505101E-10 |
| 6 | .18608325E-09  | -.26787129E-10 | .16162892E-12  |
| 7 | .25233436E-12  | .15802061E-12  | -.76825728E-15 |
| 8 | -.97609346E-14 | -.40814595E-15 | .70592439E-18  |
| 9 | .36591970E-16  | .12450430E-18  | .45708095E-20  |

CALCULATED TRAVEL TIME DIFFERENCE TABLE (\*\*\*\*\* MEANS UNALLOWED DEPTH FOR GIVEN DELTA)

| DELTA ↓<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | 1.724  | 1.723  | 1.726  | 1.715  | 1.703  | 1.699  | 1.691  | 1.679  | 1.682  | 1.683  |
| 14.900             | 4.953  | 4.947  | 4.948  | 4.921  | 4.887  | 4.870  | 4.848  | 4.819  | 4.821  | 4.823  |
| 23.000             | 7.431  | 7.419  | 7.413  | 7.376  | 7.325  | 7.293  | 7.263  | 7.224  | 7.219  | 7.221  |
| 30.000             | 9.469  | 9.449  | 9.434  | 9.392  | 9.326  | 9.279  | 9.243  | 9.198  | 9.184  | 9.185  |
| 39.900             | 12.210 | 12.179 | 12.148 | 12.099 | 12.013 | 11.942 | 11.900 | 11.846 | 11.817 | 11.817 |
| 50.000             | 14.860 | 14.825 | 14.777 | 14.720 | 14.613 | 14.516 | 14.469 | 14.404 | 14.358 | 14.356 |
| 70.000             | 19.862 | 19.788 | 19.716 | 19.637 | 19.477 | 19.338 | 19.274 | 19.172 | 19.099 | 19.094 |
| 100.000            | 27.187 | 27.073 | 27.028 | 26.864 | 26.583 | 26.432 | 26.306 | 26.075 | 26.012 | 26.007 |

RESIDUALS BETWEEN TRAVEL TIME DIFFERENCE INPUT AND CALCULATED TRAVEL TIME DIFFERENCE

| DELTA ↓<br>DEPTH ↓ | 10.000 | 15.000 | 20.000 | 30.000 | 40.000 | 50.000 | 60.000 | 70.000 | 80.000 | 90.000 |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 5.000              | -.059  | -.058  | -.066  | -.063  | -.057  | -.064  | -.056  | -.049  | -.058  | -.050  |
| 14.900             | .009   | .007   | -.004  | -.001  | .010   | -.000  | .009   | .024   | .019   | .016   |
| 23.000             | -.072  | -.070  | -.080  | -.080  | -.071  | -.077  | -.079  | -.061  | -.071  | -.079  |
| 30.000             | -.038  | -.034  | -.041  | -.048  | -.040  | -.043  | -.049  | -.035  | -.036  | -.048  |
| 39.900             | .149   | .158   | .161   | .144   | .154   | .151   | .145   | .158   | .168   | .165   |
| 50.000             | -.003  | .013   | .021   | -.014  | -.005  | -.002  | -.027  | -.009  | .005   | -.002  |
| 70.000             | -.056  | -.024  | -.047  | -.068  | -.051  | -.076  | -.092  | .005   | -.042  | -.054  |
| 100.000            | .008   | .058   | .019   | -.023  | .038   | -.014  | -.050  | .064   | .058   | .024   |

FIGURE 5d. DIFFERENTIAL TRAVEL TIMES OBTAINED FROM POLYNOMIAL CURVE FIT FOR pCP-PCP

Each differential travel time surface considered in this work, except those representing core reflections, exhibit an unallowed region, i.e., there exists a range of epicenter distances for which below a certain depth the surface reflected mode is not received. The boundary of such a region projected into the  $(d, \Delta)$  plane for pP-P is shown in Figure 6.

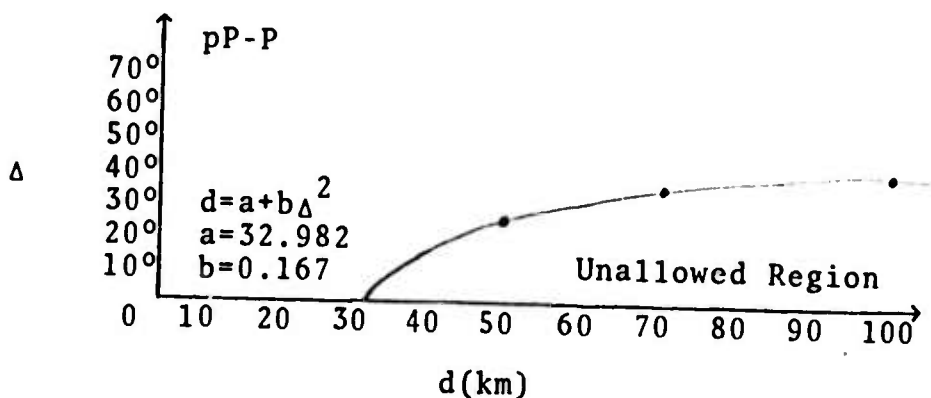


FIGURE 6

These boundaries can be adequately represented by a parabola so that our polynomial model is subject to the constraint that for a given  $\Delta$  we must have  $d < a + b\Delta^2$ , where  $a$  and  $b$  have been determined from least square adjustments to plots like that of Figure 6. In Figure 5, the unallowed region is shown as asterisk table entries.

#### Case II: Line Fits to PP-P, PPP-P, P<sub>c</sub>P-P

These travel time difference plots can be represented as single curves depending on  $\Delta$  only, since between 5 and 100 km, the depth dependence is very weak. Thus we have

$$\tau(d, \Delta) = \tau_o(\Delta) = \sum_{j=0} \tau_{oj} \Delta^j.$$

The PP-P and PPP-P differences appear to vanish as  $\Delta \rightarrow 0$ , so for these curves we set  $\tau_{o0} = 0$  and also find  $N=8$  is sufficient. For PcP-P, the core reflection insures that  $\tau_{o0} \neq 0$ . Here  $N=6$  is sufficient.

This polynomial surface representation of the differential travel times can be stored using a total of 143 coefficients and requires less than .02 seconds to compute these times for eight propagation modes on the CDC 6600 computer.

#### Future Plans

A prototype of the automated seismic source depth analysis procedure has been developed and applied to the first minute of the seismograms recorded for the Illinois Event. During the next quarter we will apply this analysis to succeeding data in which the propagation modes PP, PPP and PcP are present. We will investigate the effectiveness of this analysis in enabling constructive use of the depth phase information and to determine what modifications may be necessary. We will also investigate, through the application of this analysis to additional events, those modifications necessary to enhance the statistical significance and resolution of these source depth estimates. During this period, we will also begin to investigate the usefulness of the Maximum Entropy techniques in extending the applicability of the analysis procedures to shallow events.