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SYN3: A Program for Inversion of Teleseismic  
Body Wave Forms on Microcomputers

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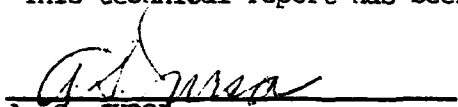
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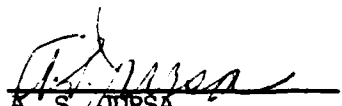
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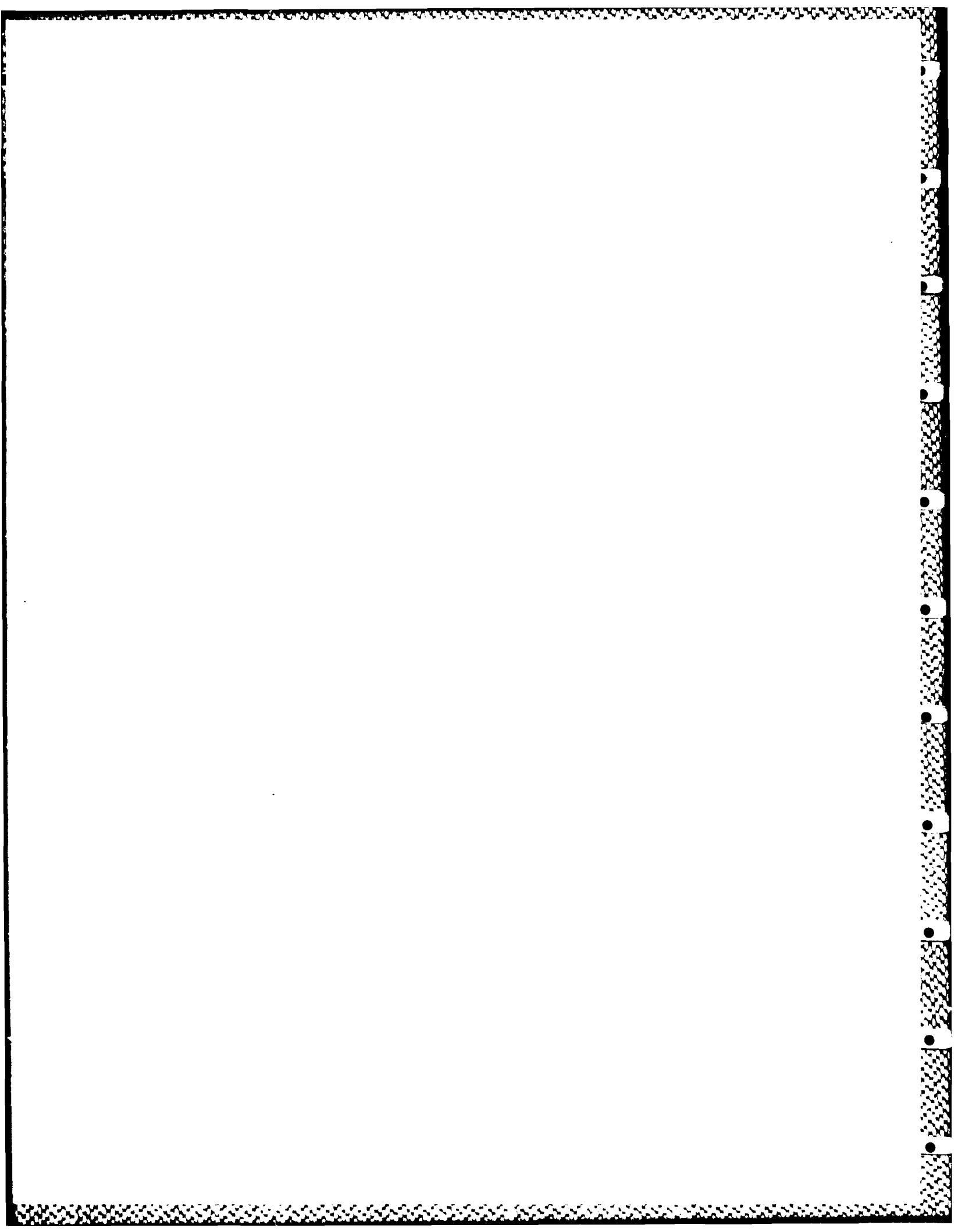
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## SYN3: A PROGRAM FOR INVERSION OF TELESEISMIC BODY WAVEFORMS ON MICROCOMPUTERS

### INTRODUCTION

The analysis of teleseismic body waveforms is by now a standard technique in earthquake source studies. The strength of the method stems from the sensitivity of the waveforms to the depth, duration, and seismic moment as well as to the orientation of the nodal planes. For example, the decrease in the uncertainties in source depth over methods that employ only arrival-time data is roughly an order of magnitude (McCaffrey 1988). Furthermore, waveforms in the epicentral distance range of 30° to 90° can be synthesized quickly because of the simplicity of the correction for propagation through the Earth (HelMBERGER 1974; Langston and HelMBERGER 1975).

This report describes an interactive computer program for the inversion of teleseismic waveforms, written in Microsoft QuickBASIC for PC and AT compatible microcomputers running MS DOS. The technique is based on that of Nabelek (1984) but this implementation incorporates several changes to enable the efficient operation on a small computer. The main advantage of implementing the algorithm on a microcomputer is its portability both in that the program can be run on portable computers and in that it can be run on hundreds of types of computers without modification. The expected disadvantage of slowness is not severe, particularly when compared to the multiple-user environment on some large mainframes. Furthermore, with dynamic arrays supported by the QuickBASIC compiler and by using random access files on fixed or virtual disks, data storage does not pose a problem.

## SUMMARY OF FEATURES

Details of the program can be found in the Appendix and here a brief summary of the features is given. The double-couple earthquake source is parameterized by the strike, dip, and rake (or slip) angles of one of its P-wave nodal planes (using the convention of Aki and Richards, 1980, p. 106), the centroid depth, and the amplitudes of a specified number of overlapping isosceles triangles that represent the source time function (Nabelek 1985). These 'free' parameters are adjusted incrementally by inversion of the digitized observed seismogram amplitudes. Multiple sources can be used, in which case the program will determine the free parameters for each source, plus the position and origin time of the secondary sources relative to those of the first. Horizontal source directivity can be included but is a 'fixed' parameter, meaning that it must be specified by the user and is not adjusted.

The program adjusts the model iteratively to determine the best fit by least-squares of synthetic seismograms to the digitized observed waveform amplitudes. Any parameter can be removed from the inversion or have its adjustment size limited. The time function elements can be forced to remain positive. The program can be used to match either the true amplitudes of the seismograms or their shapes.

Typically the most time-consuming procedure is the computation of the response of the source structure when several layers are used. We do this in the time domain by tracing rays through a plane layered structure which, because of the complexity of the problem for P-waves and for computing considerations, is limited to at most a water layer and one rock layer overlying a halfspace that contains the source. The receiver structures are all assumed to be a halfspace.

The program can invert several data types and sampling intervals simultaneously so that, for example, both long- and short-period data can be used at the same time. WWSSN long-period (15-100 and 30-100 instruments) and WWSSN short-period instrument responses are built-in, and GDSN short-period and long-period instrument responses are calculated from the poles and zeros of their frequency responses supplied by the user. Attenuation in the mantle is represented by a  $t^*$  operator (Futterman 1962) that can be set for each phase type or individually for each seismogram. Individual observed seismograms can be realigned with their synthetic, by either a cross-correlation or interactively on the screen by the user. Also, windowing the seismograms can be done individually so that only selected portions of the waveforms can be included as data. Weights are set for each seismogram and can be set to automatically account for variations among azimuthal distributions, distance, phase, and instrument magnifications.

#### ALGORITHM

##### Elementary Seismograms

Following Nabelek (1984), the synthetic seismograms comprise a combination of elementary seismograms that are summed and delayed by the appropriate amount (see Table 1 for an explanation of symbols used). The elementary seismogram  $E$  is the complete seismogram produced by a particular phase leaving the source ( $P\downarrow$ ,  $P\uparrow$ ,  $SV\uparrow$ ,  $SH\downarrow$ , and  $SH\uparrow$ , where the arrows indicate upgoing or downgoing rays). It is the impulse response of the source structure,  $G^S$ , measured below the source region, convolved with the instrument response,  $I$ , attenuation operator,  $Q$ , and a triangular source time element  $\Lambda$  of half-length  $\tau$ :

$$E(t) = G^S * I * Q * \Lambda. \quad (1)$$



The P wave is made of 3 elementary seismograms ( $P\downarrow$ ,  $P\uparrow$ , and  $SV\uparrow$ ) and SH is made of 2 ( $SH\downarrow$  and  $SH\uparrow$ ). The seismograms are calculated in the time domain and a finite number of rays are used to determine  $G^S$ . Expressions for the reflection coefficients are given in Aki and Richards (1980; Eqn. 5.32 for SH and 5.39 for P-SV). For the reflection coefficients in the following we use the up and down arrows,  $\uparrow$  and  $\downarrow$ , in the sense that Aki and Richards use accent marks.

For the case of the source embedded in a halfspace,  $G^S$  is an impulse with unit amplitude for the direct phases  $P\downarrow$  and  $SH\downarrow$ , and an impulse with amplitude determined from the reflection coefficients from the free surface for the upgoing phases.

For a water layer over the halfspace, the response of NREV reverberations of P waves resulting from a P wave incident at its base as a function of time,  $t$ , is given by the expression

$$G^S_P(t) = P\uparrow P\downarrow \cdot P\downarrow P\uparrow \sum_{n=1}^{NREV} R_0^n \cdot P\downarrow P\uparrow^{n-1} \delta(t - n \cdot t_w). \quad (2)$$

The same expression is used for the incident SV except that  $P\uparrow P\downarrow$  is replaced by  $S\uparrow P\downarrow$ .

For the response of the SH in a single, solid layer over a halfspace containing the source, the calculations are similar to (2) since there are no conversions at interfaces. However, for P, because there are conversions between the P and SV phases, there are  $2^n$  possible ray combinations for the case where  $n$  ray segments make up the entire path (a segment is the ray path between interfaces). In our case the downgoing segment in the lower layer is always a P wave, so that there are in practice only  $2^{n-1}$  rays.

When the phase reverberates in the layer there will be  $2^{2n}$  ray segments for  $n$  reverberations. A similar set of rays will exist for the incident SV wave. The  $2^{2n}$  ray paths will have only  $2n+1$  distinct arrival times. In the program

the user designates  $n$ , the number of reverberations to be calculated in full. Each ray is numbered from 0 to  $2^{2n}-1$  and is uniquely specified by a binary number of  $2n$  digits giving the phase type for each segment (0 for a P-wave and 1 for the SV). For example, the ray paths for a single bounce ( $n=1$ ) are PP, PS, SP, and SS that correspond to 00, 01, 10, and 11 in binary, or 0, 1, 2, and 3 in decimal. The arrival time of each ray path can also be taken from its binary representation by summing the digits; this is the number of segments travelled as an S-wave and the remaining are P-wave segments. For 2 bounces there are  $2^4=16$  rays and for 3 there are  $2^6=256$  rays, each with a different amplitude, so clearly the computer time increases with each bounce (Figure 1).

In the program,  $n$  reverberations are calculated in the above manner and the remaining reverberations out to the end of the seismogram are approximated. The approximation repeats the ray paths of the single bounce; PP, SP, PS, and SS. For example, an approximation for the second bounce consists of the ray paths PPPP, SPSP, PSPS, and SSSS. (The single bounce is always calculated fully and the water reverberations are included only for this first bounce.) In the case of a crustal velocity layer overlying a mantle velocity halfspace, the complete representation of the first bounce and inclusion of the unconverted paths (in particular the pure P path) for additional bounces is a good approximation to the total response because the coefficients for transmission through the Moho without phase conversion and reflection from the free surface are approximately an order of magnitude larger than the rest.

Figure 1 shows synthetic seismograms in which the number,  $n$ , of complete reverberations within a thick, low-velocity layer varies. The most noticeable difference due to increasing the number of rays is later in the seismogram at 30 seconds where a pulse in the multiple-bounce cases is not evident in the single-bounce case. In the case where a water layer is included, a pulse at 20-30 seconds becomes narrower with more rays. Otherwise, the seismograms

change little as the number of rays increase but the increase in computation time is dramatic for more than 3 or 4 reverberations. Also, synthetic seismograms generated by this method were compared to those generated using propagator matrices (Nabelek 1984) and the differences were insignificant compared to the noise level in typical seismograms.

#### Ray Parameters

All rays arriving at a particular station are assumed to have the same horizontal slowness ( $p$ ). This approximation becomes less valid as depth increases but the difference is insignificant for the depth range 0 - 160 km. For example,  $p$  for a P-wave originating at 160 km depth and going a distance of  $50.5^\circ$  is 0.0682 s/km. If the corresponding upgoing ray travels  $0.5^\circ$  (55 km) horizontally then its  $p$  is 0.0688 s/km (i.e.,  $\Delta = 50^\circ$  at depth=0). For a P-wave velocity of 8 km/s at the source this difference in  $p$  results in a difference in the takeoff angle of only  $0.3^\circ$  ( $33.4^\circ - 33.1^\circ$ ) between the upgoing and downgoing rays.

#### Synthetic Seismograms

Synthetic seismograms are produced by summing the elementary seismograms for the number of sources NSOR, the number of source time function elements NTAU, and the number of elementary seismograms NPHS, with the appropriate time shifts for the phase, time function element, and event. These are multiplied by the geometrical spreading, the receiver response, the seismic moment, the amplitude of the time function element, and the radiation pattern.

$$s(t) = G^m G^r \sum_{k=1}^{NSOR} M_k \sum_{m=1}^{NTAU} A_{mk} \sum_{j=1}^{NPHS} E_j(t - \delta_{jk} - (m-1)\tau - \epsilon_k) U_{jk} \quad (3)$$

where  $\delta_{jk}$  is the delay of the  $j^{\text{th}}$  upgoing phase for source  $k$  with respect to its direct phase and

$$\epsilon = \Delta t - p \Delta \Omega \cos(\phi - \Delta \Phi) + (h' - h)\eta \quad (4)$$

is the complete delay of a secondary event relative to the first.

Horizontal directivity is represented by adjusting the length of the triangular source time function element for each seismogram by  $\tau = \tau_0 (1 - p v_r \cos(\phi - \phi_r))$  where  $\tau_0$  is the value entered by the user. Vertical directivity is not included explicitly but can be approximated by using multiple sources at different depths.

### Inversion

Once the synthetic seismograms are calculated, residuals are determined, and the inverse problem can be solved. The function  $f$  that is minimized is either

$$f = \sqrt{\sum_i (o_i - s_i)^2} \quad \text{or} \quad f = \sqrt{\sum_i (o_i / (\sum_j s_j^2)^{1/2} - s_i / (\sum_j s_j^2)^{1/2})^2} \quad (5)$$

where  $o_i$  and  $s_i$  are the observed and calculated seismogram amplitudes, respectively. The summations with respect to  $j$  are made over the data points within the inversion window for a given seismogram. The first function utilizes the amplitude variation among the seismograms while the second is sensitive only to the shapes of the seismograms.

Because a linear approximation to the nonlinear inverse problem is made, the solution is found by iterative adjustments to the model. The adjustments  $|\delta x|$  for NPAR parameters at each iteration are found by the simultaneous solution of linear equations of the form:

$$\sum_{n=1}^{\text{NPAR}} w \frac{\partial s}{\partial x_n} \delta x_n = w(o - s). \quad (6)$$

One equation in the form of (6) is formed for each data point.

The derivatives  $\partial s / \partial x_n$  for strike, dip, and rake are determined by taking partial derivatives of (3):

$$\partial s / \partial x_n = G^m G^r M \sum_{m=1}^{\text{NTAU}} A_m \sum_{j=1}^{\text{NPHS}} E_j(t') \cdot \partial U_j / \partial x_n \quad (7)$$

where  $t'$  is the total delay for an individual point as shown in parentheses in (3). Similarly the partial derivatives for the elements of the source time

function are

$$\partial s / \partial A_m = G^m G^r M \sum_{j=1}^{NPHS} E_j(\tau') U_j. \quad (8)$$

The derivative with respect to depth is

$$\partial s / \partial z = G^m G^r M \sum_{m=1}^{NTAU} A_m \sum_{j=1}^{NPHS} U_j \eta \partial E_j(\tau') / \partial \tau \quad (9)$$

where  $\partial E_j / \partial \tau$  is the slope of the elementary seismogram calculated numerically. The partial derivatives for the time and position of the secondary events are similar to those for the depth except that  $\partial \tau / \partial \Delta t$ ,  $\partial \tau / \partial \Delta \Omega$ , and  $\partial \tau / \partial \Delta \Phi$  derived from (4) replace  $\eta$  in (9).

In matrix form,

$$D_{in} = \left| w_i \frac{\partial s_i}{\partial x_n} \right|, \quad X_n = |\delta x_n|, \quad \text{and} \quad R_i = w_i |o_i - s_i|. \quad (10)$$

The least-squares solution to  $DX = R$  (for  $X$ ) is

$$X = (D^T D + \theta^2 I)^{-1} D^T R \quad (11)$$

where  $\theta$  is the least squares damping term and  $I$  here is the identity matrix.

Positivity for the source time function is enforced by selectively damping those elements of  $D^T D$  that correspond to source-time function elements which have become negative. At each iteration the model parameters  $x_n$  are adjusted by  $x_n = x_n + \delta x_n \cdot \kappa_n$  (12)

and the process is repeated.

#### EXAMPLE

Figure 2 shows an example of an earthquake analysed with SYN3. This example includes both short-period and long-period seismograms from both WWSSN and GDSN instruments. All of the seismograms were inverted simultaneously for the strike, dip, rake, depth, and source time function. The value of  $\tau$  was 0.3s and the data were sampled at 0.1s (WWSSN SP), 0.05s (GDSN SP), 0.5s (WWSSN

LP), and 1s (GDSN LP). The plot shown was generated as is by SYN3 and printed on a laser printer.

Figure 2 shows a typical format for plotting but the program allows significant modification of the format. The positions of the focal spheres, time and amplitude axes, seismograms, and labels are adjustable. Plotting scales are controlled by the user and editors allow moving seismograms on the screen. In addition, a format is available for plotting seismograms in rows to compare the fits of different source models (for example, see Appendix in McCaffrey and Nabelek 1987).

Here the label beneath the date gives the strike/dip/rake/depth/seismic moment where depth is in km and moment is in  $10^{16}$ Newton-meters. P-waves are plotted on the top and SH-waves on the bottom with focal spheres showing their corresponding nodal surfaces. Seismograms are plotted so that their relative amplitudes are preserved and the amplitude axes for each data type are shown to the left of the focal sphere. Amplitudes are labeled in microns and correspond to those that would be observed at a reference distance (here  $40^\circ$ ) on instruments with a reference magnification (here 3000 for the long-period and 25,000 for the short-period). Here observed seismograms are shown by the solid lines and synthetics are dashed but synthetics may also be solid lines and offset from the data. The segment of the seismogram that was used in the inversion is bracketed by the small tic marks on the seismograms. Station codes are written vertically to the left of each seismogram. Capital letters to the right of the station codes show the positions of the stations on the focal spheres but these positions may be shown as dots. Small letters s, x, w, and d to the right and on the amplitude scales denote the data type (see Appendix). Time axes are shown to the long-period (LP), short-period (SP), and the normalized source time function (STF). P and T axes are shown by filled and open circles, respectively.

## SUPPORT PROGRAMS

In addition to SYN3 for the inversion of the waveform data, programs SYN3DIG and SYN3INT are included. SYN3DIG is for the digitization of WSSN seismograms and SYN3INT is used to prepare the digitized WSSN and GDSN data for the SYN3 inversion routine. Details of these programs are found in the User's Manual (Appendix).

Table 1. Symbols.

Symbol	Meaning
$\delta(t)$	impulse at time $t$
$\Delta t$	origin time delay of the secondary event relative to first
$\Delta \Omega$	distance to the secondary event from first event
$\Delta \Phi$	azimuth to the secondary event from to first event
$\epsilon$	total delay for secondary event at a particular station
$\phi$	azimuth to the station from epicenter
$h', h$	depths of the primary and secondary events
$\eta, p$	vertical and horizontal slownesses
$A$	amplitude of the triangular source time function element
$E(t)$	elementary seismogram
$G^m$	geometrical spreading (Langston and HelMBERGER 1975)
$G^r(t)$	receiver response (a constant in the case of a halfspace)
$G^s(t)$	response of source structure
$I(t)$	instrument response
$\kappa$	adjustment limiter
$M$	seismic moment
$Q(t)$	anelastic attenuation
$R_0$	reflection coefficient for P from the air-sea surface (-1)
$s(t)$	synthetic seismogram
$t_w$	two-way travel time for P in the water layer
$r$	half-length of triangular source time element $\Lambda$
$U$	radiation pattern (Aki & Richards Eqn. 4.84 - 4.86)
$v_r, \phi_r$	velocity and azimuth of rupture
$w$	weight for seismogram
$ x $	model parameters



Table 2. Program names and descriptions.

Name	Description
SYN3	Setup, read data, generate elementary seismograms, and set fixed parameters.
SYN3MEN1	Main menus for program flow, adjust models and inversion parameters, look at seismograms and fault plane solution, weighting, realignment, windowing, and parameter file.
SYN3MEN2	Secondary menu to generate synthetic data file, arrival time file, view elementary seismograms, print summary files.
SYN3IT	Generate synthetics and perform inversion.
SYN3PLOT	Generate graphic plot file.

Support programs:

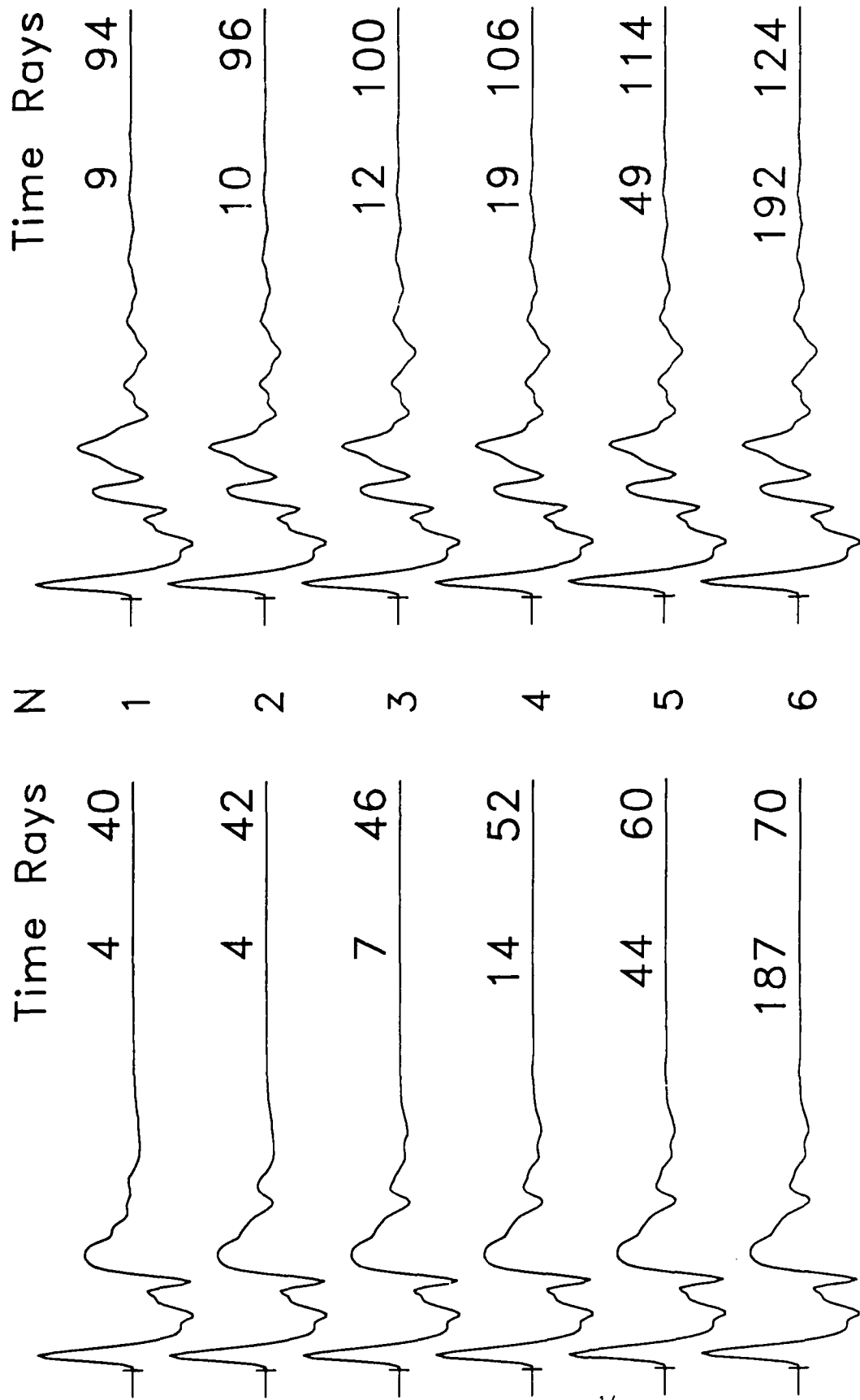
SYN3DIG	Digitize paper copies of analog seismograms
SYN3INT	Interpolate digitized data, rotate horizontal components, detrend, output data for SYN3

External subroutines:

S3AUXPL	Calculate auxiliary plane
S3COMFUN	Complex functions
S3COMMON	Common blocks, array dimensions, and constants
S3DELAZ	Get delta and azimuth of station
S3FFT	Fourier transform routines
S3FUNCTN	Functions and subroutines
S3GJINV	Perform Gauss-Jordan elimination
S3IRESP	Calculate instrument responses
S3PTBAX	Calculate P, T and B axes
S3RAPARS	Get ray parameter from table
S3RDPAR1	Read and write parameter file
S3STF	Normalize source time function and calculate duration
S3SYNIO	Input-output of data and synthetics
S3TTIMES	Calculates travel-times from Jeffreys-Bullen tables
S3WIGINT	Wiggins interpolator, remove linear trend from data

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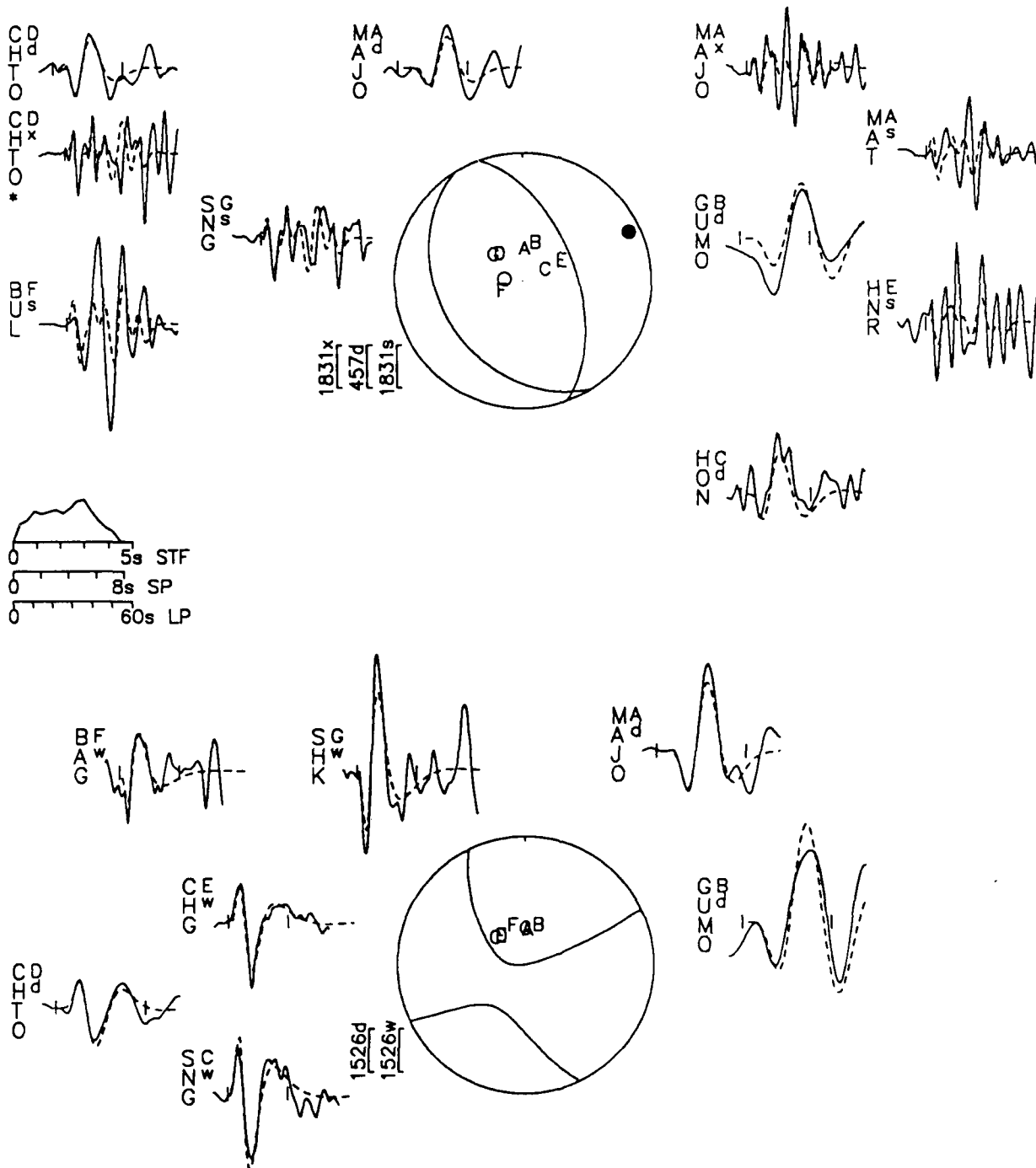
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P waveforms calculated for different numbers (N) of reverberations in a thick (10 km), low velocity layer ( $v_p=3.5$  km/s,  $v_s=2.0$  km/s,  $\rho=2400$  kg/m<sup>3</sup>) over a halfspace ( $v_p=6.5$  km/s,  $v_s=3.7$  km/s,  $\rho=2800$  kg/m<sup>3</sup>). The set on the right-hand side include a 4 km thick water layer. Time is the computer time in seconds (on IBM-AT computer) to calculate the elementary seismograms and Rays is the number of arrivals that comprise each elementary seismogram. This seismogram is calculated for a station at  $\delta=46^\circ$  and  $\alpha=0^\circ$ , using a mechanism of  $\text{strike}=10^\circ$ ,  $\text{dip}=45^\circ$ ,  $\text{rake}=90^\circ$ , and  $\text{depth}=40$  km.

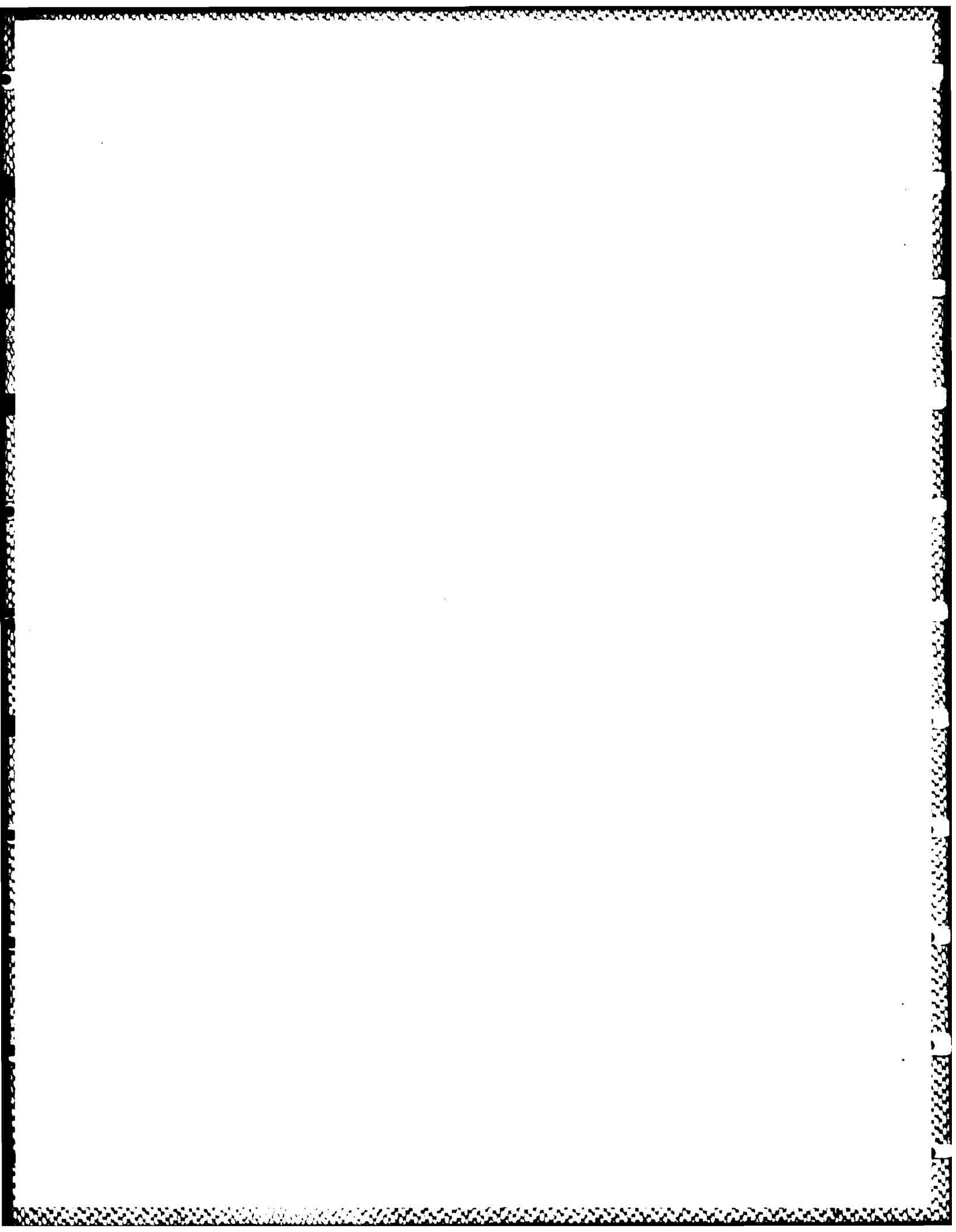
FIGURE 1

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Example of waveform solution: the central Australia Marrayat Creek earthquake of 30 March 1986 (Fredrich et al., 1988).

FIGURE 2



APPENDIX  
USER'S MANUAL

## SYN3 USER'S MANUAL

This manual describes a set of programs for digitizing, preparing, and modeling of teleseismic body waveforms. SYN3DIG is for digitizing WWSSN seismograms and SYN3INT prepares the digitized WWSSN and GDSN data for SYN3, the waveform inversion program. SYN3 consists of 5 main programs that are chained together so that to the user they appear to be a single program. The programs are menu driven and designed for interactive use.

This manual explains the use of all programs but we recommend in addition that you look at the following publications for background information: Aki and Richards (1980; chaps. 4 & 5), Langston and Helmberger (1975), Nabelek (1984 chaps. 2 and 3), Nabelek (1985), and McCaffrey and Nabelek (1984 and 1987). You should also look through the program code for additional information. The end of this manual contains a section on FORMATS of all input and output files.

### GENERAL

**PROGRAMMING LANGUAGE:** The SYN3 programs are all written using the Microsoft QuickBASIC 3.0 compiler. Common statements, functions, and subroutines are attached to the main routines via \$INCLUDE statements which act during compilation. No special commands are required for compilation. The .OBJ files should be linked with the BRUN30.LIB. For example:

```
C> QB [filename] /d /q /w;          QB is the QuickBASIC compiler
C> LINK [filename],,nul,BRUN30;
```

In addition the BRUN30.EXE runtime module must be accessible in the PATH when the program is run.

**UNITS:** In this manual and in the programs, times are in seconds, seismogram amplitudes in microns, variances are in microns<sup>2</sup> (except when normalized), velocities in km/s, densities in g/cm<sup>3</sup>, epicentral distances and angles in degrees, distances in km, and seismic moment in Nm. SYN3, however, performs its calculations using seismogram amplitudes in centimeters (for computational stability) which are then converted to microns in all input and output.

**ABBREVIATIONS** used in the manual and in the programs:

- \* - after the station code indicates that the seismogram was not used in the solution
- CR - carriage return or Enter key
- LP - long period
- SP - short period
- GDSN - Global Digital Seismograph Network
- WWSSN - World Wide Standardized Seismograph Network
- PDT - phase-data type
- STF - source time function
- RAF - random access file (cannot be edited)
- ASCII - ASCII file (text file)

**PHASE-DATA TYPES:** 6 combinations of phases (P and SH) and data (LP and SP WWSSN and GDSN) are used. A single earthquake may include data from any or all of these types.

Number	Inst.	Phase	Phase-data Type	Abbreviation	Symbol
1	1,2	1	WWSSN LP P	WWLP	w
2	1,2	2	WWSSN LP SH	WWLS	w
3	3	1	WWSSN SP P	WWSP	s
4	4	1	GDSN LP P	GDLP	d
5	4	2	GDSN LP SH	GDLS	d
6	5	1	GDSN SP P	GDSP	x

INSTRUMENTS: 1-WWSSN 15-100, 2-WWSSN 30-100, 3-WWSSN SP, 4-GDSN LP, 5-GDSN SP.  
 PHASES: 1-P, 2-SH.

MENUS: Items in Menus are generally selected by typing in the first letter of the item descriptor. Where a cursor is to be moved, again the first letter of the function (e.g. l for left, r for right) can be used or the arrow keys can be used with the NumLock on. The programs read either letters or numbers; they will not respond to the arrow keys if NumLock is off. The programs deal with lower case letters and will convert upper case to lower case in most menus. To avoid unseen problems, use lower case letters. Also, where the character '#' is the item descriptor, the appropriate number can be typed directly.

SHELL: Each program contains a shell escape that allows you to run DOS commands without ending the program. It is invoked with the X option in menus. After running the DOS commands, type EXIT at the DOS prompt to reenter the program. Keep in mind that the SYN3 program is still resident and the memory may be effected if you try to run a program that is too large.

INTERRUPTS: To interrupt a particular action in the programs, hit the 'q' key. While running, all programs intermittently check the keyboard buffer for the letter 'q'. This will stop whatever is happening and take you back to the appropriate menu. In some instances the response will be delayed because the programs look for keyboard input only at certain times. The 'q' key is also used to switch between many of the menus. When you quit from the program, you will be asked for verification.

INPUT AND OUTPUT FILE NAMES: Files have default extensions and can be designated by their prefixes only (defaults can be overridden by entering file names). For example, for a prefix of EARTHQK1 the following filenames are used (all are ASCII files):

- EARTHQK1.DIG - digitized WWSSN waveform data, input for SYN3INT
- EARTHQK1.DSN - GDSN waveform data, input for SYN3INT
- EARTHQK1.INV - interpolated waveform data file that is the input for SYN3
- EARTHQK1.PRM - parameter file for SYN3
- EARTHQK1.PLT - Golden Software plot file generated by SYN3
- EARTHQK1.SUM - summary file generated by SYN3
- EARTHQK1.ATD - travel time data file generated by SYN3

In addition several temporary files (.TMP) are created:

DIGIT.TMP - ASCII file generated when digitizing. This file is in the format of an input file for SYN3DIG and can be read back in to reproduce the .DIG file. Also a file of this format can be created on another system and used as input for SYN3DIG to create the .DIG file (SYN3DIG).



DATA.TMP - RAF of digitized data (SYN3INT)  
INST.TMP - RAF of instrument responses (SYN3)  
GFXI.TMP - RAF of Green's functions convolved with the instruments (SYN3)  
AMPS.TMP - ASCII listing of times and amplitudes for rays making up the  
crustal response function (SYN3)  
PLOT.TMP - ASCII temporary plot file used in plotting Format 3 (SYN3)  
Other .TMP files contain overflow of some arrays in the SYN3 program.

**HYPOCENTER HEADER:** The first line in .INV file is one which gives the hypocentral data. This information is either put in the file by you (the format is shown in the FORMATS section) or SYN3INT will request it. The hypocenter information is used by SYN3INT to predict the arrival times of the phases on the seismograms. It is recommended that the parameters from an earthquake location program, such as the ISC location, be used so that the depth and origin time are consistent in the sense that they provide the correct arrival times with the Jeffreys-Bullen tables.

**TRAVEL-TIME TABLES, RAY PARAMETERS, and GEOMETRICAL SPREADING:** The travel-times and ray parameters are based on the Jeffreys-Bullen P and S tables (in file JEF-BUL.PS). The ray parameters were calculated from the travel-time tables at 0 and 160 km depth and from 25° to 100° every 0.5° with smoothing applied (ray parameters are in S3RAPARS). SYN3 interpolates the ray parameter table between 0 and 160 km depth for the appropriate source depth. Geometrical spreading is taken from the curve of Langston and Helmberger (1975).

#### PROGRAM ENVIRONMENT

**CONFIGURATION SETUP FILE '\SYN3.SET':** This file tells the SYN3 programs about the computer being used. It contains the directory with the SYN3 programs, a directory or drive for storing .TMP files, the graphics card type and the color codes. This file must reside in the ROOT (directory \) of the disk drive where the programs are being run. \SYN3.SET consists of 3 lines:

Line 1. SYNDIR\$ - the directory containing the SYN3 programs.

Line 2. DRIVES\$ - the drive or directory for .TMP file storage (preferably a virtual or RAM drive). All files generated with the .TMP extension (except DIGIT.TMP) reside in this drive or directory.

Line 3. 3 numbers separated by commas to denote the type of screen graphics, the color of the observed seismogram, and the color of the synthetic seismograms. The screen graphics type is designated by the following:  
1=standard IBM Color Graphics Adapter (CGA), 640x200 pixels, no color; 2=IBM CGA, 320x200 pixels with color; 3=IBM Enhanced Graphics (EGA), 640x350 with color.

Examples: A computer with the IBM CGA, a hard disk C: with the SYN3 programs in the directory \SEISMO, and a RAM drive D: will have the following contents of \SYN3.SET:

```
"C:\SEISMO\  
"D:\"  
1, 1, 1
```

\SYN3.SET for a system with an EGA, a hard disk C: with the programs in \SYN, and no RAM drive may be

```
"C:\SYN\  
"C:\JUNK\  
3, 12, 14
```

In this case the .TMP files are stored on the hard disk in directory \JUNK. You may have to experiment with the color codes as they will vary among displays depending on the amount of screen memory available (warning - if you use the background color the seismograms will not appear).

To be able to run the programs from any directory, place the name of the SYNDIR\$ directory in your PATH statement. The path names for SYNDIR\$ and DRIVE\$ in \SYN3.SET should end with a \ (back-slash).

### SYN3DIG (Waveform Digitizing)

SYN3DIG is for digitizing paper copies of seismograms. Default parameters for WWSSN seismograms are provided but any seismogram can be digitized, even those with pivoting pens. Its output is a .DIG file in the format for the SYN3INT interpolation routine. Note that if you have a digitizer attached to another computer or cannot get SYN3DIG to work with your tablet, you can make a file of digitized data points (in digitizer units) with a program of your own and this file can be read and processed by SYN3DIG (see DIGITIZER DATA FILE below). Accordingly, when you start SYN3DIG you will be asked if you are using a digitizer or input file.

The subroutines DIGINIT and DIGITXY within SYN3DIG control the interaction of the program with the digitizing tablet. These will likely have to be modified for your setup.

#### MAIN MENU

The main menu allows you to change station and seismogram information. If you are using the file input mode (instead of the digitizer), this menu will automatically read the station information from the file each time you start a new seismogram. You need change only that information that is different for the different seismograms.

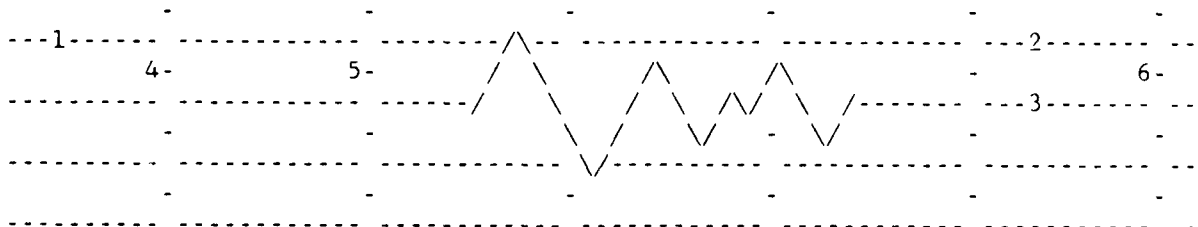
- F - The output file will be the .DIG file. This file is always opened in the APPEND mode.
- H - A header to identify the seismogram (up to 12 characters). This header is entered on the station line in the .DIG file for each seismogram but is not used.
- O - If this option is on, the program checks each point to see if its time is after that of the previous point. If this test fails, that is, if you start digitizing backwards in time, a beep will sound and you will be asked if this point should be kept. A negative response will ignore the point. If points go backward in time it is probably an indication that the reference trace being used is not parallel to the trace containing the earthquake. In this case, start over using a different trace for reference. If digitizing short-period data you may turn off the order-checking and digitize all the peaks, then all the troughs. When you finish digitizing all points are sorted chronologically.
- S - WWSSN or other station code (up to 4 letters).
- M - instrument magnification (negative number for reversed polarity). Some defaults are listed and can be chosen by entering the index number.
- C - component, enter the number of the component.
- I - the time of the initial point to be digitized in Hours, Minutes, and Seconds. This is used as a reference time and its position on the seismogram is digitized just before digitizing the waveform. All subsequent times are measured from this time. For LP WWSSN seismograms this time is usually the

minute mark before the onset of the phase and the initial time is taken as this minute plus 1 second. In this way the middle of the 2s long minute mark, which is less distorted than the edges, can be digitized to improve accuracy. The reference time may be a point within the part of the seismogram to be digitized.

- P - the radius in mm of the pen that drew the seismogram. The program will remove the arc of the pen. Enter 0 if no pen was used.
- A - clock correction in milliseconds. This correction is added to the initial time.
- R - the type of instrument for this seismogram. This number is used by SYN3 to calculate the appropriate response.
- T - The seismogram type is used to calculate the scaling of the paper seismogram, so that the amplitudes can be recovered, and to calculate the correction for the non-orthogonality of the time and amplitude axes. If you choose type 1, 2, or 3 (standard WWSSN formats) the program uses known values for the number of minutes per trace, the drum speed, and the angle between the time and amplitude axes. If you use type 4, the program will later ask for the first two of these values and will calculate the third from points that you digitize. WARNING: Using the wrong seismogram type causes the calculated times and amplitudes to be wrong. If you finish digitizing and have used the wrong seismogram type, rather than re-digitizing you can recover the raw data from the DIGIT.TMP file, correct the seismogram type, and re-analyse the seismogram.
- D - this option starts reading from the input file or digitizer.

#### DIGITIZING

When you start digitizing, the six (6) initial points digitized orient the seismogram on the tablet and determine the scaling factors. Imagine the following is a seismogram. The minute marks are the raised tics and the signal to be digitized is shown by the slanted lines. The numbers show locations of the 6 points to be digitized. Points 1 and 2 are at either end of a single trace and tell the program how the time axis is oriented on the tablet. Try to find a representative trace and place these points at either end. Point 3 is anywhere on the trace below the one containing points 1 and 2. This tells the program the spacing between the traces from which the angle between the time and amplitude axes is calculated (if a WWSSN seismogram is being digitized this point is ignored). Points 4 and 5 are minute marks on the same trace and one minute apart. Point 6 is a later minute mark on the same trace. These points provide time and amplitude scaling. On the screen, the program tells you which point it is expecting.



After digitizing these 6 points, digitize the Initial Point at the time entered in the menu. You may use the minute mark rather than the trace itself for this point - the resulting DC shift will be removed. When this point is digitized the bell sounds to let you know you are in the correct sequence. You are then ready to digitize the waveform.

The first point for the digitized waveform need not be directly after the Initial Point, but once you have started digitizing, be sure to sample the

waveform completely. The waveform is sampled unevenly while digitizing but later a weighted-average-slope interpolator is used to produce an evenly sampled curve (see Wiggins, 1976, for a description of the interpolator's behavior). Digitize peaks, troughs, and points where the slope changes.

While digitizing, the time of the current point and its amplitude in microns will appear on the screen. You may also encounter one of three warning messages, each of which is accompanied by a bell.

(1) 'Time is going backward': see above

(2) 'Maximum number of data points reached': the arrays are set to 1000 points. The program will go to the next Menu.

(3) 'Exceeded previous record length': this message appears if you are digitizing a LPE seismogram and you have digitized beyond the maximum time of the previously digitized LPN seismogram. Because rotation requires both horizontal components, any data not digitized for both components will be discarded. For this message to work, you should digitize LPN just before LPE for the same station. Note, however, that if only one of the horizontal components is digitized, the SYN3INT program will assign all zeros to the component not digitized.

When you finish digitizing, a menu appears that allows Storing, Plotting, Adding to, Rotating, and Editing the digitized data (for the file input mode, some options are not available). You can see the seismogram as it will appear interpolated by choosing a non-zero value for DT and plotting. For DT=0, plotted points will be connected by lines. You can remove a slant from the seismogram by rotating it with the R option. This option can help correct the seismogram if its trace was not parallel to the reference trace used in digitizing (points 1 and 2 above), but you have to do this correction by eye.

The Edit mode allows you to move the cursor on the screen to a particular point on the seismogram and either remove it or redigitize it. Use the number keys or the capitalized letters on the bottom lines to select options. To redigitize a point hit key '7' or 'd' and then digitize the new position of the point on the tablet.

If you choose to Add points and start redigitizing at a time before the final point that you had already digitized, the 'Time is going backward' warning will appear. The program compares the newly digitized point to the last point kept so this warning will continue for each point until you either keep one or exceed the time of the last point kept. The data points are sorted chronologically each time you finish digitizing.

#### DIGITIZER

The present version of SYN3DIG is set up for the Summagraphics MM series digitizers attached to a serial port, but any tablet can be used by modifying the subroutines DIGINIT and DIGITXY.

SUB DIGINIT opens the appropriate input port, initializes the digitizer, and allows testing of the digitizer.

SUB DIGITXY (X, Y, NPT, IEND) reads the X and Y value in digitizer units for point number NPT from the digitizer, and allows an end of input (IEND) flag to be set. For the present setup, hitting button 4 on the digitizing cursor ends input (sets IEND to True). DIGITXY also prints the values of X, Y, and NPT to the file DIGIT.TMP.

#### DIGITIZER DATA FILE

As you digitize, the station information, the digitized data points (in digitizer units), and the data point number are written to the file DIGIT.TMP. This file can be used as input to SYN3DIG to allow some corrections to the data without having to redigitize. It is important to note that any file of

the same format (see FORMATS section) can be used instead of the digitizer for input to SYN3DIG. This allows you to digitize the seismogram on any system, create a data file in the DIGIT.TMP format, and then run it through SYN3DIG to reduce the raw digitizer data to waveform data and create the .DIG file.

### SYN3INT (Waveform Data Processing)

The purpose of this program is to prepare the digitized WWSSN and the GDSN data for SYN3 and create the .INV file. It can also be used to plot .DIG, .DSN, or .INV files on the screen as explained below. SYN3INT interpolates the WWSSN data, gets the delta and azimuth for all stations, allows filtering of the data, rotates the North and East horizontal components to obtain the transverse SH, and marks the predicted arrival times of the P and S phase based on Jeffreys-Bullen travel time tables (in JEF-BUL.PS) and the ISC hypocenter.

#### STARTUP MENU

SYN3INT can either process digitized data (.DIG and .DSN files) to produce an .INV file (option 1), or plot seismograms from either an .INV file (option 2) or .DIG and .DSN files (option 3) on the screen.

If either option 2 or 3 is selected, the interpolated seismograms are plotted in succession on the screen, with the station name and phase on the left and the delta/azimuth beneath. Amplitudes are all normalized to the maximum of the individual seismogram. Dots are 5s apart and a vertical bar shows the predicted arrival time of the phase. When the screen is full, hit CR to get the next set of seismograms or hit 'q' at any time to return to the startup menu.

#### PARAMETER SETUP MENU

When you select Option 1 a second menu will appear. As in all menus in these programs, select the first letter on the line to change the item.

**INPUT FILE:** The input file will be your .DIG or .DSN file or both. Enter the default prefix name and .DIG and .DSN extensions will be assumed for the input if you have the particular data file. At this point a default .INV output file name will be assigned if you have not already provided a name. When the input file is entered, the program will read the file immediately and will write it to a random-access file DATA.TMP in directory DRIVE\$. The seismograms are sorted by phase in the order: LP P, LP North, LP East, and SP P. For each phase LP P, LP SH, and SP P, the stations are sorted by azimuth. If there is no Hypocentral Header line in either the .DIG or .DSN file, you will be asked to provide this information.

**OUTPUT FILE:** The output file is an .INV file which will be the input file for the SYN3 program. This file contains both the WWSSN and GDSN data. Here it can be opened either as a NEW file, in which case the contents of an existing file of the same name will be lost, or in APPEND mode where the new seismograms are added to the existing file. You may wish to use the APPEND option if you have to restart the program after interpolating several seismograms or wish to reinterpolate one seismogram, in which case you can edit the .INV file to rearrange the data.

**PARAMETER / DATA TYPE:** For each PDT, these parameters control the length of the seismogram written to the .INV file, the amount of data saved before the onset of the phase (Lead time), the sampling interval (DT), and the filter.

The segment of the seismogram written to the .INV file should be long enough so that you include the reflected phases and allow for some realignment of the seismogram. The length of data to be kept prior to the picked onset of the

direct phase should be long enough to allow for re-alignment. The amplitude of the waveform is sampled every DT seconds and these amplitudes are the data for the inversion. DT should be large enough so that there are not too many data points (more points increase the computer time needed for the inversion) but small enough to avoid aliasing the waveforms; typically we use 0.5s for LP and 0.1s for SP data. The DT's entered for the GDSN data have no function as the digital data come with their own DT specified. The Filter cutoff period is the period in seconds corresponding to the cutoff frequency for a 3-pole Butterworth high-pass filter. The seismograms are automatically detrended and the filter can be used at your discretion to remove additional long-period noise. When the data are filtered the filter period is saved in the .INV file and the corresponding synthetic seismograms are filtered in the same way in SYN3.

#### SEISMOGRAM MENU

This part of the program allows station-by-station data preparation. You have the options of analysing the seismograms in order or of designating a particular station and phase. Option L shows a list of the seismograms in order and their status - 'w' means it has been written to the .INV file, 's' indicates it has been skipped, and ' ' (blank) means it has not yet been looked at. M returns you to the Parameter Setup menu.

To designate a particular station and phase, enter them with 4 letters for the station name (left-justified) followed by the phase number and data type. For example, 'mat 11' gets the MAT WSSN LP P-wave, 'SHK 21' for SHK WSSN LP SH, or 'chto22' for CHTO GDSN LP SH. Case does not matter for the station name.

N and R OPTIONS: To analyse the seismograms sequentially in the order shown in the list (L option), use the N option. N will analyse the seismogram indicated by the value of the counter (the seismograms are numbered in the list), and repeatedly using N will take you through the remaining seismograms. As each seismogram is analysed, the counter value increases.

The R option allows you to reset the counter and indicate the next seismogram to be analysed with the N option. Note, however, that with the N option any seismogram that has a 'w' or 's' status will be skipped over, so be careful about resetting the counter to a lower value. In most cases, you will use only the N option to step through all the seismograms in order. You may occasionally set the counter ahead to start in the middle of the seismograms if, for examples, you are restarting the program or wish to re-interpolate only the SH phases.

After a station, phase, and data type is designated by either method, the program looks for the station in the station list (file S3STATS.DAT) and the phase and data type in the data list. If either are not found you will be informed. If found the delta, azimuth, back-azimuth, and the theoretical travel-time (from J-B tables) with ellipticity corrections are printed. If the phase is a P, the seismogram is then plotted for the windowing process.

If the phase is S, the horizontal components are plotted and rotated to isolate the transverse component (SH). The LPN and LPE time series are truncated to include only their common segments. If their magnifications are different their amplitudes are corrected accordingly and the larger magnification is used. (If the two components have different instrument responses, you're out of luck.) The LPN, LPE, and rotated SH will next be plotted on the screen. If the station is naturally rotated, you may have only one of the horizontal components, in which case the program will ignore the other component.

WINDOWING: At this step you decide what segment of the seismogram to write to the .INV file and where the phase starts. Each item has a default that normally suffices and only on occasion must you do anything other than save the seismogram here. The default start of phase is the theoretical arrival time and the window segment is designated in the Parameter Menu.

At the top of the screen is the station name and phase, delta, azimuth, the time of the start of the seismogram (Tmin), and its maximum amplitude in microns (Amax). The seismogram is plotted and dots mark .5s intervals. Normally 4 vertical bars and a small circle will appear on the seismogram; the 2 smaller bars extending up from the waveform enclose the segment of the seismogram to be saved (the window), the larger bar and circle mark the onset of the phase (the theoretical arrival time), and at the far left is the cursor bar. If all these bars do not show up then either the timing is incorrect or the digitized seismogram is shorter than the window. The positions of these markers can be changed by moving the cursor to a point on the seismogram and moving the marker to it. At the bottom of the screen are your options:

- 1 Filt - this invokes the detrend or Butterworth filter. When the data are filtered, the filtered seismogram is plotted over the present one with dots (hit CR to replot filtered seismogram).
  - 2 New - return to the Seismogram Menu without saving seismogram in .INV file. Assigns an 's' status to the seismogram.
  - 3 Save - write seismogram to .INV file. Assigns a 'w' status to the seismogram and returns to the Seismogram Menu.
  - 4 L - move cursor left by number of points equal to Inc.
  - 5 Inc. - increase number of points for each cursor move. This number will increase to 10 and then return to 1.
  - 6 R - move cursor right by number of points equal to Inc.
  - 7 Cut - cut the seismogram window at the cursor position
  - 8 Phase - pick the cursor position as the phase arrival time
  - 9 DC - add a DC shift to the entire seismogram amplitude (amount entered in microns). To shift a particular point to the baseline, move the cursor to the point and read the amplitude from the screen, then apply a DC shift of negative this amount.
- B Begin - the next Cut is the beginning of the seismogram.  
E End - the next Cut is the end of the seismogram. For example, to cut the right side of the seismogram, hit 'e', move the cursor left with 'l' or '4' to the desired position, then use the Cut (7) option.

When the seismogram first appears the cursor is at the beginning of the seismogram. When the cursor is moved the time and amplitude at its position are shown. This allows picking the phase arrival time by some other criteria, such as the short-period arrival time. If you move the arrival time of the phase with 'p' option (8), the bar will move but the circle stays at the theoretical arrival time. The point written to the file as the phase arrival time is shown by the bar, not the circle. Also note that the Phase arrival point must be contained within the window. Any Cut that would place the Phase outside the window will be ignored and a warning given. To clear the extraneous marks that may appear, use the DC option with a 0 shift.

If using the N option, you will be informed when you have reached the end of the list of seismograms. At this point you should use 'q' to return to the startup menu where you can see the seismograms plotted on the screen with Option 2.

## SYN3 (Waveform Inversion)

SYN3 consists of five programs (SYN3, SYN3IT, SYN3MEN1, SYN3MEN2, and SYN3PLOT) that work together for the manipulation and inversion of waveform data to solve for the double-couple fault plane solution, the centroid depth, the shape of the source time function, and the seismic moment. Simply put, the program generates synthetic seismograms for the current model, compares them to the observed seismograms read from the .INV file, and then computes adjustments to the model in order to make the synthetics look more like the observed seismograms. Because the relationship between the waveform amplitudes and the model parameters is not linear, this process is done iteratively. Each sample of the amplitude of the observed seismogram within the part of the seismogram that is being inverted (the 'inversion window') is a data point for which a theoretical amplitude is calculated. An equation which equates the difference between the observed and calculated amplitudes (the 'residual') to the sum of the products of the parameter adjustment and the derivative of the amplitude with respect to the parameter is generated. The many equations, one for each amplitude sample, are solved simultaneously for the adjustments of each free parameter. If you have no data but wish to generate synthetic seismograms then enter 0 for the number of data points on the Seismogram Header Line in the .INV file (see FORMATS).

You designate the values of fixed parameters, such as the source structure, attenuation, rupture velocity and azimuth (optional) and the length of a source time function element (TAU), and initial values for the free parameters (the 'starting model'). While running the program you can adjust features of the data such as the relative weighting on the seismograms and adjust the size and position of the inversion windows (i.e. windowing and realigning). Also the type of inversion can be modified so that the only shapes of the seismograms are used, the source time function elements always have positive values (i.e. 'positivity'), or to limit the adjustments for or remove individual parameters from the inversion altogether. Also the starting model can be changed. Plots of seismograms, response functions, and fault plane solutions can be shown on the screen. A fairly versatile routine (SYN3PLOT) makes plots for hard-copy and a summary sheet can be printed to a file. The program can also generate an .INV file of the synthetic seismograms or residuals. You are advised to read through the following menu descriptions to see what options are available.

### SETUP MENU

The setup menu sets the values for parameters that control input and output files, source structure, the response functions, plotting on the screen, TAU, and defaults. The values of the defaults are set in the SETUP routine of SYN3.BAS

- I - I/O FILE HEADER: Default input and output files use this prefix and assume suffixes which denote particular files (see INPUT AND OUTPUT FILE NAMES above).
- R - PARAMETER FILE: The parameter file (.PRM) is written by a command in the MAIN MENU and contains information about current the model, alignments, plotting configuration, source structure, and several controls. This option allows you to read in the .PRM file at startup time.
- F - SETUP FILE: This option reads the \SYN3.SET file. This file is read automatically at startup time, but you may change the environment (for example, change colors) by exiting via the SHELL, editing the \SYN3.SET file, returning to the program with the EXIT command, and then read the \SYN3.SET setup file.



- N - SEISMOGRAMS PER SCREEN: Seismograms are plotted in two rows and N columns; this number is 2N.
- P - PLOT TIME SCALE: Time scale for plotting seismograms on screen in pixels per second (for LP; SP scale is expanded by factor of 5).
- T - TAU (s): the half-width of the triangular elements used to represent the source time function (see Nabelek 1985).
- V - RUPTURE VELOCITY AND AZIMUTH: The velocity (in km/s) and azimuth (degrees clockwise from North) of the horizontal component of rupture propagation. This acts to compress and expand the apparent source time function.
- H - SOURCE DEPTH FOR RAY PARAMETERS (km): Ray parameters depend on the epicentral distance for each seismogram and the source depth. Ray parameters for this depth are used in the calculation of the source structure response functions.
- W - WATER DEPTH (km): The depth of the ocean layer above the earthquake source.
- L - SOURCE STRUCTURE: The plane-layered structure of the earth at the source. The structure can consist of at most 2 layers and the earthquake source must be in the lowest layer. Each layer is described by the depth below sea level to its top (Ztop), its P-wave velocity (Vp), S-wave velocity (Vs), and density (RHO).
- C - COMPLETE REVERBERATIONS FOR TOP LAYER: The response of the upper layer of the 2-layer structure is calculated by summing rays. This number tells how many complete bounces should be calculated (2 or 3 is typically a good compromise between speed and accuracy).
- G - GREEN'S FUNCTIONS TO BE GENERATED: If the file GFXI.TMP exists for the current model it can be read in rather than recomputed. This file contains the Green's functions convolved with the instrument. It can be reused if the program bombs and is restarted with the same structure, seismograms, and lengths of seismograms. This will go to YES when a change is made to any parameter that will cause the crustal response to change.

(For each of the PDTs, the following provides default values. These can be changed and are saved in the .PRM file.)

- S - SEISMOGRAM LENGTH (s): The length of the seismogram to be calculated.
- A - ATTENUATION  $t^*$  (s): The value of  $t^*$  for each PDT. After the data has been read in the values of  $t^*$  may be changed individually by station.
- M - MAGNIFICATION REFERENCE: The magnification of the instrument used for calculation of the synthetics. The data are also corrected to this magnification. All amplitudes are scaled by this magnification.

OTHER DEFAULTS IN SETUP PROGRAM (SYN3.BAS):

Reference distance (all seismograms are corrected to this distance) [DELO=40°]  
 Receiver structure: halfspace, Vp [ALPHR=6.0], Vs [BETAR=3.4], density [RHOR=2.7]  
 Free surface: Vp [ALPHF=0.335], Vs [BETAF=0.001], density [RHOF=0.001]  
 Water: Vp [ALPHW=1.50], Vs [BETAW=0.001], density [RHOW=1.03]  
 Data sampling increments (used if DT not specified in .INV file): [PHDT] for PDTs, WWLP:0.5s WWLS:0.5s WWSP:0.1 GDLP:1.0 GDLS:1.0 GDSP:0.1

When you 'q' from this menu the program will:

- (1) Read the data file and print the station header lines on the screen.
- (2) Calculate the instrument response for each seismogram. If a previous seismogram has the same response, it will be copied rather than re-calculated.
- (3) Calculate the crustal response functions for each seismogram. If 2 or more

layers are in the structure and a previous seismogram of the same phase is within DELMIN degrees (1° in SYN3.BAS), the Green's functions will be taken from the previous seismogram rather than being re-calculated.

- (4) Convolve each elementary seismogram with the appropriate triangular source time function element (TAU).
- (5) Bring up the Model Menu, then the Inversion Parameter Menu.

#### MODEL MENU:

- # - Source number - display the model values for this source #
- E - Number of sources - the number of separate sources to be used (now up to 6)
- S - strike - |
- D - dip - | using the convention of Aki & Richards 1980
- R - rake angle - |
- H - depth of source - below sea level
- O - origin time offset - the delay time between this source and the first source
- X - distance offset - the distance in km from this source to the first source
- Y - azimuth of offset - the azimuth from the first source to this source
- M - moment (N-m) - seismic moment in Newton-meters
- N - # of STF elements - number of triangular elements used for the source-time function
- A - amplitudes of STF elements - the relative amplitudes of the elements to make up the source-time function, these are listed in % of total. You may enter the numbers relative to each other and the program will normalize them to 100%. For example, a STF with TAU=1.0s and NTAU=4 each with an amplitude of 25 is a 5s long trapezoid of 1s rise time, 3s plateau, and 1s fall time (see Nabelek, 1985; Fig. 6).

#### INVERSION PARAMETER MENU:

- # - display the values for this source #
- DAMPING FACTOR: (enter first letter of parameter to change) This number is multiplied by the adjustment to the parameter at each iteration. These are not least-squares dampers. If the factor is 0, the parameter is taken out of the equations (i.e. fixed).
- M - minimum percent decrease in variance: If the percent decrease in variance from one iteration to the next is below this number, iteration ceases.
- P - positivity of STF: If YES the elements of the source time function are forced to remain positive. Enforcement is performed by increasing the damping on any element that goes negative, setting it to 0, and re-inverting the entire matrix. This is done until either some maximum damping is reached or the element stays positive. %TOLERANCE is the minimum value the element can have before it is considered negative (this should be about negative the error in the STF amplitudes). DAMPING INCREMENT is the increase in damping applied when the STF element goes negative.
- I - The inversion can be run while trying to match either the AMPLITUDE or SHAPE of the observed seismograms. Using AMPLITUDE the seismograms reflect the true variations in amplitude around the focal sphere due to the radiation pattern and these variations are used to constrain the solution. With the SHAPE option the amplitudes of each seismogram are normalized by  $\sqrt{\Sigma a^2}$ , where the sum is over all the amplitudes a within the inversion window, and only the shape of the seismogram will constrain the solution. When the SHAPE option is on, the variances are also normalized.
- T - station t statistics: If YES then t-statistics (see Huang et al. 1985) can be used to compare models. If this is turned on then the next option is available.
- C - change reference station RMS values. This stores the station variance

aside for comparison to subsequent models in the t-test.

- K - if YES then statistics will be calculated when a single iteration is run.
- L - least squares damper: this number is squared and added to the diagonal of the inner product matrix.
- W - change weights by seismogram with the following options:
  - 1 - Reset all weights to 1.0
  - 2 - Store current weights
  - 3 - Reset weights to stored values
  - 4 - Multiply all seismograms of same PDT by same weight factor
  - 5 - Scale weights proportional to MAG, DELTA: weight according to predicted S/N ratio as a function of the instrument magnification and epicentral distance to account for geometrical spreading.  
Weight is proportional to:  $SQR(MAG/3000 * (1.3 - 0.01 * DELTA))$
  - 6 - Scale weights to station azimuthal density: set weights according to density of stations at azimuth so stations clumped at near azimuths will not be over represented. Weight is proportional to:  
 $SQR(1/\text{sum over all stations of } EXP(-((\text{difference in azimuth}/20)^2))$
  - 7 - Normalize all weights so their average is 1.0

#### MAIN MENU

DESCRIPTION: The main menu provides information on the current model and statistics. NTAU is the number of source time function elements and TAU is their half-width. The relative values of the STF elements are given in percent of the total and their standard errors are in parentheses. The model parameters, their standard errors, and dampers are given in the next 3 lines. Dur. (duration) is the time for 95% of the seismic moment to occur as determined from the source time function. dTo is the shift in s of the origin time for this event relative to the first or relative to the alignment of the seismograms. Dist and Az are the distance and azimuth of this event relative to the first. VAR:Unwtd and Wtd are the unweighted and weighted variances of the amplitude residuals for the entire set of data. These are in microns<sup>2</sup> unless normalized.

Under VARIANCE the variance of the data ('Data') and the ratio of the weighted residual variance to the weighted data variance ('Res/Dat') are given for all the data (under 'Total') and for each PDT. These numbers can be used to decide on relative weighting between PDTs. If you are running a SHAPE inversion these variances are normalized as noted above.

If the t-statistics are being calculated the following information is furnished: DOF = number of degrees of freedom (Number of seismograms -1); Mean Dif = mean difference in seismogram variances between the current model and the reference model; SD Dif = the standard deviation of the differences between the current model and the reference model; and t = t-value. A t-test table should be consulted to determine the significance of the difference between the two models. See the Inversion Parameter Menu to change the reference model and see Huang et al. (1986) for details on the t-test.

#### OPTIONS:

- A - Print details of the solution to file or printer. Also print solution summary lines in 2 formats to the file SYN3FPS.HDR in the current directory (see FORMATS).
- B - Generate data file of the travel times for each phase based on the new alignments
- C - Change parameters that control the inversion (see above)

- D - Generate file of synthetics or residuals in the .INV format
- F - Plot P, SH, or SV (upgoing for SV) radiation patterns on focal spheres for the current model, the source time function is also shown. Three sources are shown per screen.
- H - provides a help menu
- I - Perform the inversion; enter the number of iterations or 0 to return to Menu. For N iterations, the program will adjust the model N-1 times (using 1 iteration only generates the synthetic seismograms). Hit q to return to the main menu at any time. If there is more than 1 source, hit the source number and its parameters will be shown on the screen (see below).
- L - List station data on the screen and allow adjustment of the flag, alignment, polarity, inversion window, and weights (see below).
- M - Adjust the starting model (see above)
- P - Make a Golden Software plot file (see below)
- Q - Quit program
- R - Realign and window seismograms (see below)
- S - Observed and calculated seismograms are plotted on the screen at the same scales for comparison. You control whether the synthetics are plotted directly on top of the data, which seismograms are plotted, whether or not they are normalized, and scaling factors for each of the PDTs. After each screenful hit CR or hit q at any time to return to the main menu.
- V - Plot on the screen the elementary seismograms for each seismogram and the corresponding structure response functions. The stations are viewed sequentially. Hit CR to see next set.
- W - Write or read .PRM file containing information about the current model, alignments, weights, plot controls, etc. In this menu only certain model parameters are read (station data, alignments, source model, flags, plotting controls; see FORMATS section).
- Z - (return to STARTUP MENU) This allows you to change the structure, etc. Any changes that effect the elementary seismograms are flagged and the appropriate calculations are redone.
- # - Any of the sources can be displayed on the MAIN MENU screen. Just type in the source number you want displayed. This source number is then carried over to the MODEL MENU and INVERSION PARAMETER MENU.

#### REALIGNING and WINDOWING (Option R):

This routine permits realignment and windowing of the data either automatically or manually on the screen by you. The inversion window is the section of the observed seismogram that is used as data in the inversion. Realignment is the process by which the point that marks the beginning of the arriving phase in the data is adjusted. This is the beginning of the inversion window. Windowing is changing the length of the inversion window. In short, realignment determines the beginning of the inversion window and windowing determines the end of the inversion window.

AUTOMATIC REALIGNMENT performs a cross-correlation between the data and the synthetic seismogram to determine the beginning of the phase. You designate the TIME WINDOW, which is the length of the seismograms that will be correlated (starting at the beginning of the phase), and the TOLERANCE, which is the maximum time in seconds that the new realigned position can move from the initial pick. The program stores the alignments in the form of the data point number that corresponds to the initial pick (Po1) and the realigned point (Po2; see below).

AUTOMATIC WINDOWING allows you to designate by PDT how many seconds of data will be inverted. A negative number skips the particular PDT.

**REALIGN/WINDOW BY HAND** This option allows you to realign and window while viewing the data and synthetic seismograms on the screen. You can choose the starting station number and whether the seismograms are normalized or are scaled to the seismic moment. At the top of the screen you see the station and phase information and both the amplitude residual variance and the arrival-time residual for the current alignment. The synthetic seismogram can be moved with respect to the data or the right side of the inversion window can be moved. Movement is Left, Right, Fast, and Slow with the keys in parentheses or with the number/arrow keys, 'c' swaps between realigning and windowing, 'n' and 'p' get the next or previous seismogram, and the N shows the number of points for each incremental move. Hit 'q' to return to the menu.

**STATION DATA MENU** (option L) permits the changing of the flag, polarity, alignment, window, and weight for each seismogram. Move the arrow with the letter keys or use the number/arrow keys on the number pad (NumLock must be on). Hit 'c' to change the value where the arrow is pointing or 'q' to return to the menu. 'n' and 'p' produce the next and previous pages.

Del - epicentral distance in degrees  
Az - azimuth from epicenter to station  
TOA - take-off angle of direct phase  
Var - unweighted variance of amplitude residuals in micron<sup>2</sup>

The following may be changed:

Flag -1 station is being used, =0 station is ignored  
+/- polarity correction applied to data, enter -1 to flip polarity  
Pol the data point which was picked originally as the start of the phase  
Po2 the data point currently being used as the first in the inversion window  
Tinv the inversion window in seconds  
Wt the weight applied to this seismogram

#### ITERATION SCREEN:

While iterating, information about the model and statistics are printed on the screen. If there are multiple sources, one screen in memory is printed for each source. You can view the screen for a particular source by hitting the source number at the keyboard (it may take some time to respond). You can quit iterating by hitting 'q'.

**Important Note:** the full synthetics are generated only during the final iteration. If you interrupt the iterating or if it stops due to one of the error messages listed below, the synthetic seismograms may not correspond to the current model. If ever in doubt, you can generate them by running a single iteration.

At the top of the screen are printed the source number being displayed, the number of iterations, and the number of free parameters being adjusted. As the program loops through the seismograms the station and PDT are printed in the lower right and the elapsed time in seconds is at the left (on the screen for source 1 only). After the first iteration the elapsed time for the previous iteration also appears after the '/' on the time line to help in planning coffee breaks. When iterating is through the message 'Finished' appears at the lower right (hit CR to continue or the source number to see iteration information).

For each iteration the model, standard errors, and variances are printed on the screen. This is similar to the Main Menu screen in its contents.

**MESSAGES:** While iterating some messages appear in the bottom lines:

'Variance reduction x%' gives the % reduction in variance from the previous iteration.  $x = [\text{var}(i) - \text{var}(i-1)] / \text{var}(i-1) \times 100\%$  for the i-th iteration

'Variance reduction below cutoff' indicates that the reduction in variance is below the minimum designated in the Inversion Parameter Menu. When this occurs the synthetics will be generated and iteration will stop.

'STF elements negative: ( I, J)' appears when STF positivity is enforced and the STF element I for source number J has become less than the critical value assigned in the Inversion Parameter Menu. This element will be forced to become positive.

'STF negative, max damping reached' appears when too much damping has been applied to the STF element.

'\*\*\* Singular Matrix \*\*\*' indicates that either two parameters are completely coupled or that a column of the derivative matrix is zero. Hint: the latter happens when the source time function is longer than the inversion window.

'\*\*\* Invalid number of parameters' means there are either too few (i.e. 0) free parameters or too many (>NPARMAX).

'\*\*\* Phase arrival time is negative' indicates that some phase is arriving before the start of the seismogram. This can happen when a second source arrives at a particular station before the first due to their spatial offset. To get around this problem, realign all seismograms so that they start prior to the first event and add an origin time offset (dTo) to the first event.

#### PLOTTING

SYN3 includes a program to plot seismograms for hard-copy output. The graphics commands used are those of the Golden Software PLOTCALL program. This consists of 5 simple commands; move, draw, change the origin, select a character set, and print a character string. Obviously the PLOTCALL driver cannot be included with the SYN3 disk, so you can either purchase it or write a program to convert the PLOTCALL format into one that drives your particular plotter or printer. Alternatively, you can change the plotting subroutines at the end of SYN3PLOT.BAS that handle the plotting output (all these subroutines start with GS).

Plots are made on a page 250mm in the x-direction by 200mm in the y-direction (if the P and SH are on the same page then the plot area is multiplied by 0.706). All coordinates and distances are measured in mm. The positions of the seismograms, focal spheres and time scale axes are normally assigned a number which designates a box within a grid. The plot positions assign x and y values that provide the center of the focal sphere or the lower left corner of the box for the seismogram. To make a plot you designate a page layout either by using the default (Format 1), by designing your own (Format 2), or by using the special format (3) which plots seismograms in a line for comparing seismograms for different models. Formats 1 and 2 are used to plot seismograms around a central focal sphere and can be modified. The formats can be seen with the 'v' option in the menu. The positions of the seismograms are determined by you either with a screen text editor in which you designate the box number for the seismogram or a graphics editor that allows you to move the seismograms around. You also designate amplitude and time plot scales or use the default values.

#### PLOTTING MENU:

- 1 - if NO the P-waves are not plotted
- 2 - if NO the SH-waves are not plotted
- 3 - the P and SH can either be plotted on the same page (1 plot file) or on separate pages. In the latter case 2 plot files are generated, one xxxP.plt and the other xxxSH.plt, where the xxx is the name you supply. The 2-page

- mode produces a larger plot.
- A - if YES the seismogram amplitudes are normalized, otherwise amplitudes are scaled to the seismic moment.
  - B - if YES each seismogram is labeled with a letter which is also plotted in the focal sphere. If NO small circles are plotted in the focal sphere and seismograms are not labeled.
  - C - allows you to change plot positions for seismograms either through a screen editor or interactively while plotting (see below).
  - D - synthetics can be dashed, dotted, or solid. The DS increment in mm is the length of the dashes or distance between dots.
  - E - the location and size of the P and SH focal spheres are determined by designating their X, Y and radius. If the default is used, for Formats 1 and 2 they are centered with a 30mm radius; for Format 3 they are in box 1 with a radius half the box height. The focal spheres can be turned off completely.
  - G - Golden Software format plot file (.plt) for the plot output, a .PLT extension is added. If Format 3 is used, APPEND mode signals that the current plot can be added to the previous one.
  - H - plot time scale in mm/min for LP and SP data. Default values that fill the available space are determined but can be changed. A warning is given when the scale exceeds the default.
  - J - the page label plotted along the side of the page gives the event file name, date & time, scaling factors, and the mechanism (see option U for mechanism label).
  - L - the title is contained in the brackets < >. If its position is 0 then it is centered at the top of the page.
  - M - magnification factors for each PDT. Note that the amplitudes on the page are scaled to the maximum amplitude of the data so that adding or removing seismograms from the plot may cause the scaling to be changed.
  - N - plot position format (see below).
  - O - synthetics can either overlap the observed seismograms or they can be offset vertically from one another.
  - P - position of the source time function and amplitude scale. The position of the amplitude scale defaults to the lower left of the focal sphere and a separate scale is plotted for each PDT present.
  - S - for each PDT, the length of the seismogram to be plotted.
  - T - if YES time scale and amplitude scales are included on plot. If the seismograms are normalized, an amplitude scale will not be given.
  - U - where to plot the label giving the solution as STRIKE/DIP/RAKE/DEPTH/MOMENT where strike, dip, and rake are in degrees, depth in km below sea level or the free surface, and moment is in  $10^{16}$  Nm.
  - V - allows you to see the layout of plotting positions and where each station will be plotted.
  - W - occasional pauses occur to allow you to view the plots on the screen.

PLOTTING FORMATS: (Option N) Three formats are available for plotting the seismograms on paper. The first 2 formats allow a centered focal sphere surrounded by seismograms. The third format plots seismograms in a line and allows an offset between lines of seismograms, for use when comparing fits for different models. The positions of the seismograms are determined by a rectangular grid of numbered boxes. Each seismogram is assigned to a box (or 0 to not plot) by either editing the numbers with a spreadsheet type screen editor or moving the boxes with a graphics plot editor. The seismogram is plotted within the box but may extend beyond it if you use a scale factor >1 or a time scale larger than the default. In the program the box is referenced

by the coordinates in mm of its lower left corner. The default plot time scales will fill up the length of the box while allowing room for the station labels. Time and amplitude axes are controlled in the main plot menu. The .PRM file saves all plot information.

FORMAT 1: The positions of the 40x20mm boxes are fixed but their locations can be fine-tuned by moving them 1mm steps with the graphics plot editor. The focal sphere can be moved but in default it is at the center of the plot. In this format the boxes are numbered clockwise around the focal sphere.

FORMAT 2: The grid used in this format is specified by you. You enter the box size (X and Y in mm) and the plot area is then divided into as many boxes as possible up to the limit of 60. Each box is numbered starting with 1 in the upper left corner and can be viewed with the V option. The focal sphere can be given a box number and it will be centered on the center of the box or the default will place it in the center of the page. In Format 2 the plot editor allows you to move the seismogram positions by box position only (there is no fine-tuning as in Format 1).

FORMAT 3: In this format you designate the number of boxes across the page and only one line of boxes is used. The positions of the seismograms, time scale, and focal spheres can be adjusted as in Format 2. Amplitude scales are not plotted. When using this format each complete plot is shifted down by an amount you designate (30 mm default). When an individual plot is finished you are asked whether or not to append it to the composite plot file. While using Format 3, the first plot opens a new file, includes all time scales, and prints the station names at the top. Subsequent plots to be appended include only the seismograms and the source time function. The append mode can be stopped (i.e. a new file opened) with the G option.

EDITORS: The plot positions can be edited by a screen editor similar to earlier editors or a graphics editor that moves the boxes on the screen. For the screen editor use the designated letter keys or number/arrow keys to move the pointer to a value and the 'c' key to change the value. You can move the pointer sideways among the Formats. Hit 'q' to leave editor.

Positions can also be edited graphically while plotting. To turn on this graphics editor use the 'c' option. While plotting with the edit mode on, the position of each seismogram is shown by a box on the screen (if its position is 0, it is shown in position 1). Move the box with the letter or number/arrow keys or hit 'c' to enter a new box number (0 to not plot). Hitting 'p' will fix the plot location at the present location and the seismogram will be plotted. CR will perform the same function unless the plot position is 0, in which case the seismogram will not be plotted. 'q' will return you to the menu. All changes are saved when you write the .PRM file.

The amplitude scaling is such that the largest amplitude in the observed seismograms to be plotted corresponds to the height of a box. If all the seismograms have a 0 plot position, such as at the start, the scaling is arbitrary and should be re-adjusted after all desired seismograms have been assigned a position. Also when you add or remove seismograms from the plot the plot scale may change.

PLOT: In the Golden Software plot solid circles are the P axes and the large open circles are T axes (the T axis is a circle with an X when option B is NO). Time axes are shown for both LP and SP seismograms as needed. The normalized source time function is shown on its own time axis. Dot and dashed lines show the mechanisms and source time functions for subevents. The amplitude axes are labeled in microns and are corrected for a distance of 40° [DELO] and the reference instrument magnification. The values also reflect the factors used in the 'm' option. Observed seismograms are shown with solid lines and the synthetics can either be dashed or solid as you designate. The



vertical tic marks on the seismograms enclose the inversion window. An asterisk below the station code indicates that the seismogram was not used in the inversion. The small letters correlate the seismogram with its position in the focal sphere and provide the data type (see above).

PLOT COMMANDS: Plot commands in the .PLT file are in the Golden Software Plotcall format. This consists of 5 commands:

1. X,Y,1 - shift the origin by X and Y
2. X,Y,2 - draw from the current pen position to X,Y
3. X,Y,3 - move to X,Y
4. X,Y,4,S,A,"TEXT" - print TEXT at X,Y with a size S (inches) and at an angle A (degrees)
5. 0,0,5,"setX.sym" to select character set X or  
0,0,5,"centered.sym" to select the set of symbols to be used in the next print command

All X and Y values are in inches and correspond to a coordinate system in which the X-axis (0 to 8) is along the short edge of a 8 1/2'' x 11'' sheet of paper and the Y-axis (0 to 10) is along the 11'' side. The SYN3 programs use only 3 of the PLOTCALL character sets; SET1, SET7, and the CENTERED set.

## INPUT/OUTPUT FILE FORMATS

Formats are given both by the field (columns) for the number on the left side followed by a letter-number format (a-alphanumeric; i-integer; f-floating point; d-exponential). For floating point and integer formats the number can fall anywhere within the field. For 'free' formats the values must be separated by a space or a comma, but there can be any number of values per line.

### EVENT HEADER

Hypocentral information (first line in .DIG and .INV files)

1-2 i2 Year  
3-4 i2 Month  
5-6 i2 Day  
7-8 i2 Hour  
9-10 i2 Minute  
11-13 i3 Seconds \*10  
14-18 i5 Latitude \*100 (positive North)  
19-24 i6 Longitude \*100 (positive East)  
25-27 i3 Depth, km  
28-29 i2 Magnitude \*10  
30-32 i3 Number of Stations in location

### DIGIT.TMP FILE

This file is generated by SYN3DIG as you digitize but can be generated in other ways depending on your system. A file of this format (instead of the digitizer) can be used as input for SYN3DIG to produce the .DIG file.

Line 1. Station/instrument/seismogram information

1-4 a4 Station code  
5-7 a3 Component (lpz,lpn,lpe, or spz)  
8 i1 Instrument type (WWSSN 15-100 =1, WWSSN 30-100 =2, WWSSN SP =3, other =4)  
9 i1 Seismogram type (WWSSN 15mm/min =1, 30 mm/min =2, 60 mm/min =3, other =4)  
10-11 i2 Hour |  
12-13 i2 Minute | Initial time: actual time of first point digitized  
14-19 f6 Second |  
20-29 f10 Magnification of instrument  
30-39 f10 Clock correction in milliseconds (added to initial time)  
40-49 f10 Radius of pen in mm (0 if no pen)  
50-59 f10 Number of minutes per trace on original seismogram  
60-69 f10 Original seismogram time scale in mm/minute

Line 2. For digitized data points

1-8 i8 X-value from digitizer in tablet units  
9-16 i8 Y-value from digitizer in tablet units  
17-21 i5 Point number

(the first 6 points are for seismogram orientation as discussed above, the seventh is at the reference time, and the rest are the waveform points. Except for the initial 7 points, the point number is the index for that data point in the storage array so that they should be numbered sequentially starting with 1. If two points have the same point number, the second one encountered will replace the first. The point number should not be zero.)

\*\*\*\* A blank line separates digitized seismograms \*\*\*\*

## DIGITIZED DATA FILES (.DIG and .DSN)

These files are the input for SYN3INT, the program that prepares the waveform data for the inversion. SYN3INT assumes the .DIG and .DSN extensions for the WWSSN and GDSN data, respectively, but either file may contain data of either type. The separate extensions are used only for the convenience of keeping the data separate, if desired, but both data types may be placed in a single file with any extension. The data formats for the WWSSN and GDSN data differ, specifically because the GDSN data comes already sampled evenly and requires that the instrument constants be supplied. The program SYN3DIG supplies the .DIG file in the correct format.

The amplitudes of the WWSSN seismograms in the .DIG and .INV files are those that are observed on the original seismogram (in microns). Corrections for instrument magnification are done in the SYN3 program. The data points of the WWSSN seismograms are designated by the time (in seconds multiplied by 100 and relative to an initial time) and amplitude in microns relative to an arbitrary baseline (SYN3INT will detrend the data to remove this baseline). From the initial time and the time of each point SYN3INT picks the predicted arrival of the phase with the hypocentral information supplied.

For the GDSN data, the amplitudes are in microns (not counts) and the values can be scaled arbitrarily by a magnification factor that is then entered in the input field for magnification (otherwise use magnification=1, do not use 0.0). The initial time for the GDSN data is the time of the first data point in the list and the real times of subsequent points are found by adding the point number times the sampling interval to initial time.

Line 1. First line is EVENT HEADER line (above)

Line 2. Seismogram header line

```
1-4  a4  Station code
      5   i1  Instrument type
          (1-WWSSN 15-100, 2-WWSSN 30-100, 3-WWSSN SP, 4-GDSN LP, 5-GDSN SP)
6-8  a3  Component name (spz, lpz, lpn, or lpe)
9-18 f10 Magnification of instrument (negative for reversed polarity)
19-30 a12 Event label
31-32 i2  Hour   | Initial time: Time to which the times in the data list are
33-34 i2  Minute | referenced. For GDSN this is the time of the first point
35-39 f5  Second  | in the list.
40-44 f5  sampling interval dt (for GDSN only)
45-51 f7  Station latitude +N (optional) | if not given the station coordinates
52-58 f7  Station longitude +E (optional)| are found in file S3STATS.DAT
```

Line 3. Number of data points (and instrument constants for GDSN)

```
1-5  i5  Number of data points
6-10 i5  Number of zeros in instrument response (for GDSN only)
11-15 i5  Number of poles in instrument response (for GDSN only)
16-25 d10 Calibration constant (for GDSN only)
```

Line 4. Instrument ZEROS and POLES (for GDSN only)

```
*** free Real and imaginary ZEROS (alternate Real and Imaginary parts)
*** free Real and imaginary POLES (alternate Real and Imaginary parts)
```

Line 5. Data points

For WWSSN:

\*\*\* free Time and amplitude pairs, time in seconds\*100, amplitudes in microns

For GDSN:

\*\*\* free Amplitudes in microns

#### INTERPOLATED DATA FILE FORMAT (.INV)

This the input file for the SYN3 inversion routine. Its default extension is .INV and contains the evenly sampled seismograms for both the WWSSN and GDSN data. Each seismogram consists of a station header line, instrument constants (for GDSN only), and the waveform amplitudes in microns. The event header line must be the first line in the file.

Line 1. EVENT HEADER line (above)

Line 2. Station Header Line

1-4 a4 Station code (left-justified)  
5 i1 Phase (1=P, 2=SH)  
6-7 i2 Instrument type (see above)  
8-15 f8 Delta in degrees  
16-23 f8 Azimuth in degrees  
24-31 f8 Magnification or GDSN scale factor  
32-39 f8 Time from origin time to first point in seismogram  
40-44 f5 Weight  
45-49 i5 Data point number which marks beginning of phase  
50-54 i5 Number of data points (0 if no data, synthetics generated)  
55-62 i8 Maximum amplitude of waveform in microns  
63-68 f6 Data sampling increment DT  
69-74 f6 Time from beginning of seismogram to phase arrival  
74-80 f6 Period of high-pass (frequency) filter

Line 3. Poles and Zeros (for GDSN only)

\*\*\* free Number of zeros, Number of poles, Calibration constant  
\*\*\* free Real and imaginary zeros (alternate Real and Imaginary)  
\*\*\* free Real and imaginary poles (alternate Real and Imaginary)

Line 4. Amplitude data

\*\*\* free Amplitudes of original seismogram in microns every DT seconds

#### PARAMETER FILE (.PRM)

The .PRM file stores the model and input parameters. It is generated by SYN3 and can be read in when the program is run again for the same .INV file. It can also be partly read in to change model parameters, alignments, plotting parameters, and weights (those values read for such a partial read are marked below by a \*). Most changes made while running SYN3 are saved in the .PRM file and these can be adjusted also by editing it. If you adjust flags, note that in BASIC, True=-1 and False=0 (functions listed below for T or F).

Line 1:

1-8 i8 Number of seismograms plotted per screen, an even number  
9-16 i8 Number of pixels per second, screen plotting scale  
17-24 not used  
25-32 i8\* Number of sources  
33-40 not used

41-48 i8 Number of layers in structure  
49-56 i8 Plot format number  
57-64 i8 Number of Phase types (must be 6)

Line 2:

1-8 f8 TAU in s  
9-16 f8 Source depth in km  
17-24 f8 Water depth in km

Line 3:

1-8 f8\* Least-squares damper

Line 4: Flags

1-8 i8\* T = time function positivity ON, F = OFF  
9-16 i8\* T = invert amplitudes, F = invert shapes  
17-24 i8\* T = t-statistics ON, F = OFF  
25-40 not used  
41-48 i8 Number of reverberation for top layer

Line 5:

1-8 f8 Rupture velocity, km/s  
9-16 f8 Rupture azimuth

Line 6 (1 line for each phase-data type):

1-5 a5 Phase-data type label (WWLP, WWLS, etc.)  
6-13 f8 Plotting amplitude multiplier  
14-21 f8 Length of calculated seismogram in seconds  
22-29 f8 Length of seismogram to be plotted  
30-37 f8 Default DT for this Phase-data type  
38-45 f8 Default t-star for this Phase-data type  
46-53 i8 Default magnification for this Phase-data type

Line 7 (1 line for each layer):

1-8 f8 Top of layer, km  
9-16 f8 P-wave velocity, km/s  
17-24 f8 S-wave velocity, km/s  
25-32 f8 Density, g/cm<sup>3</sup>

Line 8:

1-5 i5\* Number of stations

Line 9 Station parameters (1 line for each station):

1-4 a4 Station code  
5-8 i4\* Flag (F = station ignored)  
9-13 i5 Original phase point index  
14-18 i5\* Realigned phase point index  
19-23 i5\* Number of data points in inversion window  
24-28 i5\* Plot position for format 1  
29-33 i5\* Polarity of seismogram  
34-40 f7\* Current weight  
41-47 f7 t-star  
54-60 f7\* Stored weight  
61-65 i5\* Plot position for format 2  
66-70 i5\* Plot position for format 3  
71-75 i5\* X-offset for plot format 1, in mm  
76-80 i5\* Y-offset for plot format 1, in mm

Lines 10-13 (4 lines for each source):

Line 10:

1-10 f10\* Strike  
11-20 f10\* Dip  
21-30 f10\* Rake  
31-40 f10\* Depth in km  
41-50 f10\* Origin time offset relative to event 1  
51-60 f10\* Distance offset relative to event 1  
61-70 f10\* Azimuth of event relative to event 1  
71-120 not used  
121-131 dll\* Seismic moment in Nm

Line 11:

\*\*\* free\* Number of source time function elements

Line 12:

\*\*\* free\* Relative amplitudes of source time function elements

Line 13:

1-6 f6\* Strike damper  
7-12 f6\* Dip damper  
13-18 f6\* Rake damper  
19-24 f6\* Depth damper  
25-30 f6\* Origin time offset damper  
31-36 f6\* Distance offset damper.  
37-42 f6\* Azimuth damper  
43-48 f6\* Damper for source time function

Lines 14-16: Plotting controls

Line 14:

\* Title for plot

Line 15: Flags and plot controllers

1-3 i3\* T=put letters in focal sphere, F=use dots  
4-6 i3\* T=plot label on side of plot, F=don't  
7-9 i3\* Position of title on plot  
10-12 i3\* Controller for mechanism label  
13-15 i3\* Plot position for source time function  
16-18 i3\* Plot position for amplitude scale  
19-21 i3\* Plot position for P-wave focal sphere  
22-24 i3\* T=plot P-wave focal sphere, F=don't  
25-27 i3\* Plot position for S-wave focal sphere  
28-30 i3\* T=plot S-wave focal sphere, F=don't  
31-33 i3\* T=plot station codes beside seismograms, F=plot them above (for Format 3)

Line 16:

1-4 i4\* X-position of P-wave focal sphere (in mm)  
5-8 i4\* Y-position of P-wave focal sphere (in mm)  
9-12 i4\* Radius of P-wave focal sphere (in mm)  
13-15 i4\* X-position of S-wave focal sphere (in mm)  
16-18 i4\* Y-position of S-wave focal sphere (in mm)

19-21 i4\* Radius of S-wave focal sphere (in mm)  
22-29 f8\* Short-period plot scale (mm/min)  
30-37 f8\* Long-period plot scale (mm/min)  
38-45 f8\* Length of plotting box for format 2 (in mm)  
46-53 f8\* Height of plotting box for format 2 (in mm)  
54-61 f8\* Length of plotting box for format 3 (in mm)

#### SUMMARY OUTPUT (.SUM)

EARTHQUAKE FILE: filename, date, and time

HYPOCENTER HEADER: Hypocentral information in format above.

SOURCE STRUCTURE: ZTOP is the depth in km of the top of the layer; Vp, Vs are in km/s; RHO is density in g/cm<sup>3</sup>. A water layer is noted by a w and the number of complete reverberations calculated for the upper layer is given.

#### STATION DATA

F - flag, 1 if station used, 0 if not  
P - phase, 1=P, 2=SH  
I - instrument, 1=WWSSN 15-100, 2=WWSSN 30-100, 3=WWSSN SP, 4=GDSN LP, 5=GDSN SP  
Phs - phase-data type  
Pol - point of theoretical arrival time of phase in units of DT  
Po2 - new arrival time of phase determined by realignment  
+/- polarity correction  
Win - seconds in inversion window  
Del - epicentral distance in degrees  
Az - azimuth from epicenter to station  
TOA - take-off angle at source  
Res - travel time residual of phase based on new alignment  
Wt - weight of seismogram  
Var - unweighted variance of residuals for this seismogram, in microns<sup>2</sup>  
DT - sampling interval in s  
t\* - t-star used to calculate attenuation  
Filter - cutoff period for 3-pole high frequency pass Butterworth filter applied to data; the same filter is applied to synthetic seismograms.

#### PHASE-DATA INFORMATION

Num - the number of weighted seismograms of this P-D type  
Mag. - the reference magnification used  
Time - the length of calculated seismograms, in s  
t\* - default t\*  
ResVar - variance of residuals for this P-D type, in microns<sup>2</sup>  
DataVar - variance of data for this P-D type, in microns<sup>2</sup>  
Res/Data - ratio of residual to data variance for this P-D type  
Total - gives values for all phase-data types

#### SOURCE DESCRIPTION: (2 standard errors given in parentheses)

TIME, LATITUDE, LONGITUDE: new origin time and epicenter based on determined values of dTo, Dist and Az.

SOURCE FUNCTION ELEMENTS: TAU is the half-length of the triangular element and NTAU is the number of these used; the next line gives the normalized values of these. Half- and 95% duration are the times for this fraction of the seismic moment to be released.

SOLUTION: Strike, dip, and rake are as defined in Aki&Richards. Depth is relative to the free surface. Seismic moment is in N-m. Or. Time is the origin time difference between this subevent and the first event. Distance is the

distance from this subevent to the first event. Azimuth is the azimuth to this subevent from the first event. Aux Pl Str, Dip are the strike and dip of the second nodal plane. Ppl, Paz, Tpl, Taz, Bpl, Baz are the plunges and azimuths of the P, T and B axes.

Option A also prints 3 summary lines in file SYN3FPS.HDR

Line 1 gives the event file name, and the current date and time

Line 2 Brief summary line:

1-6 Year Month Day  
7-10 Hour Minute  
11-13 Seconds \*10  
14-18 Latitude \*100  
19-24 Longitude \*100  
25-27 Depth, km  
28-29 Magnitude \*10  
30-32 Number of stations in location  
33-35 Moment mantissa in Nm \*100  
36-37 Exponent of moment | i.e. 12318 =  $1.23 \times 10^{18}$  Nm  
38-41 Strike  
42-44 Dip  
45-48 Rake

Line 3 Expanded summary line:

1-6 Year Month Day  
7-9 Hour  
10-12 Minute  
13-17 Seconds  
18-25 Latitude  
26-33 Longitude  
34-39 Depth, km  
40-45 2 standard errors in depth  
46-49 Magnitude  
50-53 Number of stations in locations  
54-58 Moment in  $10^{16}$  Nm  
59-63 2 standard errors in moment ( $\times 10^{16}$  Nm)  
64-68 Duration in s  
69-72 Strike  
73-76 2 standard errors in strike  
77-79 Dip  
80-82 2 standard errors in dip  
83-86 Rake  
87-90 2 standard errors in rake  
91-94 Strike nodal plane 2  
95-98 Dip nodal plane 2  
99-102 P-axis azimuth  
103-106 P-axis plunge  
107-110 T-axis azimuth  
111-114 T-axis plunge  
115-118 B-axis azimuth  
119-122 B-axis plunge  
123-125 # weighted WWLP  
126-128 # weighted WWLS  
129-131 # weighted WWSP



132-134 # weighted GDLP  
135-137 # weighted GDLS  
138-140 # weighted GDSP  
141-144 water depth  
145-153 Variance of residual in microns<sup>2</sup>  
154-160 Ratio of residual to data variance

TRAVEL TIME DATA FILE (.ATD)

This file consists of adjusted travel times resulting from the realignment of the observed seismograms with the synthetics.

Line 1. Event header line (as above)

Line 2. Station-phase and travel time data

1-4 a4 Station code (left-justified)  
5 i1 Phase (1-P, 2-SH)  
6-13 f8 Travel time of phase in seconds