Finite-Fault Modeling of the Earthquake Source using Teleseismic Body Waves: A User's Guide

C. Mendoza[1], S. Hartzell[2], and T. Heaton[3]

[1] Centro de Geociencias UNAM, Juriquilla, Queretaro, MEXICO
[2] U.S. Geological Survey, Denver Federal Center, Denver CO 80225 USA
[3] California Institute of Technology, Pasadena CA

1. INTRODUCTION

The widespread availability of digital seismic data has allowed a detailed study of the earthquake rupture history at a global scale. Results from these studies have increased our understanding of the earthquake source and the earthquake generation process. Various seismic waveform-analysis procedures have been used to characterize the extended properties of the earthquake source. One of these schemes is the finite-fault inversion methodology originally developed by Hartzell and Heaton (1983; 1986) that uses a kinematic parameterization of the earthquake fault to identify the simplest distribution of slip that reproduces the seismic waveforms recorded for the earthquake. The method has been used to study numerous large worldwide earthquakes using a variety of data types including local strong ground motions, regional and teleseismic body and surface waves, and geodetic surface displacements. Any time series can be used in the inversion as long as point-source Green’s functions can be accurately calculated at the recording sites. Here, we provide a detailed description of the Hartzell and Heaton (1983) inversion procedure that can be used as a guide for the recovery of the earthquake rupture history using teleseismic body-wave records. We describe the codes and scripts used in the inversion and additionally include a specific test case with sample input and output files. Most of the codes are written in FORTRAN, and the scripts generally invoke C-shell commands in a UNIX operating environment.

2. INVERSION SCHEME

The method uses a rectangular fault with a pre-defined orientation that is based on the source mechanism of the earthquake. The dimensions of the fault are chosen large enough to encompass the expected extent of coseismic slip, and the fault is divided into a specified number of subfaults. The earthquake hypocenter is placed at an appropriate location and depth on the fault, and uniformly-spaced point sources are then distributed across the length and width of each subfault. The response (Green's functions) of each point source is computed at the available recording sites using a prescribed crustal structure and a boxcar source-time function of finite duration. The method can be used to derive the coseismic slip for either a fixed or a variable rake. For a fixed rake, the Green's functions are simply computed for the assumed or known source mechanism of the event. For a variable rake, two separate sets of Green's functions are computed: one each for pure dip-slip and pure strike-slip components of the slip angle. For example, if the slip angle of the earthquake is expected to be around 45°, Green's functions are computed for both a 0° and a 90° rake, and the inversion calculates the amount of slip along the fault corresponding to each component, thus identifying the variability in slip angle along the fault. As will be seen later, this doubles the number of unknowns in the inverse problem to be solved.

The Green's functions for each subfault are then summed to produce synthetic subfault seismograms for each recording site taking into account the time delay due to the propagation of rupture at a specified velocity away from the hypocenter. Figure 1 shows an example of this parametrization for a 255-km by 165-km rectangular fault divided into 187 distinct 15-km by 15-km subfaults. In this example, a rupture velocity of 3 km/s is used to compute the subfault synthetics. By convention, subfaults are numbered consecutively down the dip and across the fault along the strike.

The problem to invert is constructed by joining the subfault seismograms end-to-end for all stations to form the columns of a matrix **A** of subfault synthetics. The observed seismograms are also joined end-to-end in a data vector **b** to form an overdetermined system of linear equations $C_d^{-1}\mathbf{A}\mathbf{x} = C_d^{-1}\mathbf{b}$ where C_d^{-1} is a data covariance matrix that normalizes the observed records to a unit value of 1. The elements of the solution vector **x** correspond to the subfault slips needed to reproduce the normalized observations $C_d^{-1}\mathbf{b}$. In the inversion, a time-window approach is used to discretize the subfault rise time and rupture time. This is accomplished by generating an additional set of seismograms for each subfault, with synthetics delayed in time by the duration of the boxcar source-time function used to calculate the initial Green's functions. The number of times that the subfault synthetics are delayed thus represents the number of time windows to be used in the inversion. This time-window process increases the number of unknowns in the linear problem, and the inversion procedure is used to solve for the contribution of slip for each of the prescribed time windows, thus allowing a variable rise time and relaxing the constraints of a fixed rupture velocity. For example, if a 2-sec boxcar is used to construct the subfault synthetics in Figure 1, and these synthetics are delayed five times by the 2-sec width of the boxcar (corresponding to 5 time windows), then the inversion would allow a rise time of up to 10 sec on each subfault, if required by the observations. Also, the rupture time on any subfault could be delayed by up to 8 sec relative to the time required for a constant rupture propagating at 3 km/sec. In this regard, the rupture velocity used to compute the original Green's functions corresponds to the maximum rupture speed allowed in the inversion. Note also that the number of unknowns increases by a factor corresponding to the number of time windows. In the example shown in Figure 1 the number of unknowns increases from 250 to 1250 when five time windows are used in the inversion.

To stabilize the inverse problem, Hartzell and Heaton (1983) use constraint equations of the form $\lambda \mathbf{F} \mathbf{x} = \lambda \mathbf{d}$, where λ is a scalar weighting factor. Generally, two different constraints are applied: spatial smoothing and moment-minimization, and the λ factors control the tradeoff between applying the constraints and fitting the observations. For spatial smoothing, **F** and **d** are constructed so that the difference in dislocation weights for adjacent subfaults is zero, thus requiring a smooth transition of slip across the fault. In the moment-minimization constraint, **F** is the identity matrix and **d** is the zero vector, effectively reducing the length of **x** and minimizing the total seismic moment. Commonly, both constraints are applied simultaneously using the same λ value, and the solution vector **x** is obtained using the non-negative least-squares (NNLS) inversion scheme of Lawson y Hanson (1974). This scheme limits the inferred subfault slip weights to positive values, eliminating negative slips along the fault that can result in undesirable destructive interference between subfaults.

In typical applications, several runs are conducted in sequence to identify the maximum λ value that allows the observed records to continue to be fit by the predicted waveforms, resulting in the simplest possible solution. This procedure generally involves a visual inspection of the waveform fits after each run to evaluate the goodness of fit and to determine if any additional modification to the value of λ is needed, resulting in a single, empirically-derived λ weight that identifies the slip model inferred for the earthquake. However, the linear system corresponds to a Tikhonov inverse problem whose solution can be derived from a more quantitative L-curve analysis (Hansen, 1998) that identifies the balance between fitting the data and meeting the stabilization constraints. In an examination of this L-curve analysis using teleseismic P waves recorded for several large events, Mendoza and Hartzell (2013) found that a λ weight close to the optimum L-curve value can be estimated from the average of the absolute values of the elements in the coefficient matrix $C_d^{-1}\mathbf{A}$. Thus, the inversion can also be performed using this pre-estimated λ weight to recover the earthquake rupture history in a single step. This is useful, for example, when a relatively rapid application of the procedure is needed such as in the realtime analysis of recorded waveforms. Both inversion options are described here.

3. INVERSION CODES

The finite-fault analysis is conducted by running a series of computer programs that read in the observed data, generate the subfault synthetics, and perform the inversion. An overview of these codes is shown in the flowchart in Figure 2. The programs CADIN and CADLAC are used to generate the subfault synthetics, and TELMOD is used to process both observed and synthetic data records. JULIEW sets up the observations and synthetics for inversion, and the program LISA actually performs the linear inversion. Finally, PLISA is used to recover the resulting distribution of slip across the fault. These and other useful supplementary codes are described in the sections below.

4. WAVEFORM DATA

In order to conduct the teleseismic finite-fault analysis, the raw data recorded for the earthquake to be analyzed is initially obtained from a global earthquake database such as the USGS/NEIC Continuous Waveform Buffer (CWB) or the Incorporated Research Institutions for Seismology (IRIS) data repositories. Data from the CWB database are made available to the scientific community through dedicated USGS client servers shortly after they are recorded at the various worldwide stations. For CWB data-retrieval information, users should consult the USGS/NEIC documentation: ftp://hazards.cr.usgs.gov/CWBQuery/CWBQuery.doc). IRIS data are generally available through the IRIS website (http://www.iris.washington.edu/) using a variety of data-retrieval tools.

Because data acquisition and processing procedures can vary widely from user to user, we refrain from describing specific data retrieval or data preparation procedures here. It is ultimately the responsibility of the user to make sure that the data are retrieved and processed correctly. In our case, we have retrieved raw seismic data in a variety of formats, including the Seismic Analysis Code (SAC) format processed using routines and scripts available through the IRIS website: http://www.iris.washington.edu/ that implement the SAC data-analysis package (Goldstein et al., 2003). Regardless of how the observed data are retrieved or processed, it is important to make sure that they are in the format required by the program TELMOD (Table 1). Also, the inversion codes expect either ground-velocity or ground-displacement amplitudes so that, in addition to reformatting the data records, the response of the instrument must be removed prior to waveform analysis. The data should also be placed in amplitude units consistent with those of the synthetics, as noted later in Section 5.

The data records can begin either at the initial body-wave arrival or at some known fixed time prior to that arrival. This record start time can be numerically adjusted later with program TELMOD (see below). Also, if more than one data type is to be inverted (e.g., P and SH waves), then it is best to prepare a separate data file for each type since synthetics for different data types are constructed separately. Files can be joined later, prior to inversion, using the program CONCAT to create a single file for both observations and synthetics that can then be read in by the inversion codes. Also, the records should be long enough to contain the entire time interval to be inverted.

Program TELMOD

This program is run interactively and can be used to process both observed records and synthetic waveforms. When processing observed data, the code optionally:

1) removes the mean of the data records.

2) filters the records using a Butterworth bandpass filter. Note that any filtering applied to the data records must also be applied to the synthetic waveforms (see Section 5 below).

3) removes the beginning of each record by some prescribed time length to properly align the observed data with the synthetics. This removal is not necessary if the data file already contains records beginning at the body-wave arrival. However, it may be necessary to rerun TELMOD and to conduct the inversion again if adjustments in timing are needed to identify the best-fitting slip model.

4) interpolates the records to a common time step.

5) reverses the polarity of any desired records.

5. SUBFAULT SYNTHETICS

The subfault synthetics for the teleseismic problem are constructed using program CADLAC for a layered crustal structure. It uses the theory of generalized rays (Langston and Helmberger, 1975) to calculate the seismic response for point sources distributed along the length and width of each subfault and then sums the responses to construct synthetic records for each subfault taking into account the propagation of rupture at a prescribed constant velocity. The theory permits the incorporation of internal reflections and mode conversions within a layered crustal structure, thus allowing depth-phase contributions (pP, sP, sS, pS) to the teleseismic response.   CADLAC reads in a series of ray files, with the pathname to these files explicitly hardwired into the code. Thus, the path to these ray files must match their actual location on disk prior to compiling CADLAC. Because the code is relatively cumbersome and complicated, the program CADIN was written to create an input file for CADLAC and simplify its use,, as described below. The subfault synthetics generated by CADLAC correspond to ground displacement in microns. These are then processed using the program TELMOD to prepare them for inversion. If the data records to be inverted are in ground velocity, then the synthetic records must be additionally differentiated in TELMOD to obtain records in microns/sec, as indicated below.

Program CADIN

CADIN is run interactively and requires several input parameters, including the fault dimensions and geometry, the number of subfaults, and the rupture velocity to be used in the inversion. It produces the following files:

1) *cadin.dat*: ASCII file used as input to CADLAC.
2) *weight.dat*: ASCII file read by CADLAC that contains the initial subfault dislocation weights along the strike and dip of the fault. By default, these are set to 1.0 for all subfaults.
3) *arszcad.dat*: ASCII file containing a PARAMETER statement used by CADLAC to define the array dimensions for the particular finite-fault problem to be solved. CADLAC must be compiled separately for each inversion run using the appropriate *arszcad.dat* file.

Program CADLAC

In addition to the *weight.dat* file, CADLAC reads a pre-existing file named either *inlong.dat* or *inshort.dat* that specifies the time length, the number of points and the sampling rate of the synthetics. The file also contains the names, distances, azimuths and ray parameters of the stations to be modeled in addition to the layered crustal structure used to generate the synthetics. Historically, the file *inshort.dat* has been used for short-period data and the file *inlong.dat* has been used for long-period data. However, since most teleseismic data used these days correspond to broadband waveforms, only the file *inlong.dat* is generally used in most applications.

To run CADLAC, first compile the code using the corresponding *arszcad.dat* parameter file and then type:

cadlac < *cadin.dat* to redirect input from the *cadin.dat* file

CADLAC produces the following output files:

1) *cadbin.dat*: Binary file containing the synthetic records calculated for each subfault at each of the stations listed in the *inlong.dat* file, output in the format given in Table 2.
2) *cadout.dat*: ASCII file that prints the details of the CADLAC run. An important parameter listed in this file is the dislocation (in centimeters) per unit weight that

corresponds to the input seismic moment. This value, called the CADLAC scale factor (CSF), is needed later to recover the actual slip on each subfault from the dislocation weights identified in the inversion (see Section 7).

3) *cadarr.dat*: ASCII file listing the earliest arrival (in seconds) after the beginning of the record at each station. That is, these times indicate the length of the zero-amplitude leader of the synthetic record calculated at each station for the subfault containing the hypocenter. Prior to inversion, these times must be cut off from the front end of all the synthetic records to properly align them with the observations. The program TELMOD is used to do this (see below).

Program TELMOD

For the synthetics, TELMOD is used to perform the following tasks:

1) filter the subfault records using a Butterworth bandpass filter, if filtering has previously been applied to the observations. Filter parameters for both data and synthetics must coincide exactly.
2) interpolate to a uniform time step.
3) differentiate to ground velocity, if necessary.
4) remove the *cadarr.dat* times from the front end of the synthetic records at each station to properly align them with the observed waveforms.

It is important to visually inspect the synthetic records before and after running TELMOD to make sure that they are being calculated and cut off correctly since there can be important time shifts (e.g., when velocity synthetics are cut off using *cadarr.dat* times based on CADLAC displacement records). After processing with TELMOD, the start time of the synthetic record computed for the subfault containing the hypocenter should correspond to the body-wave arrival. If not, then the *cadarr.dat* times should be manually adjusted by the appropriate times and TELMOD should be rerun.

The program SYNPLT can be used to view the synthetics calculated for individual subaults or individual stations. The program uses CALCOMP-style plotting calls and must be compiled using an appropriate graphics library. We include a CALCOMP plotting library, although it is the responsibility of the user to properly compile and install the library and/or make the necessary modifications to the existing code. The records could alternatively be viewed using any other user-provided codes or plotting routines adapted to read the *binary* format given in Table 2.

6. WAVEFORM INVERSION

To perform the inversion, the data and synthetics files must first be placed in the proper format using program JULIEW, which also specifies the record lengths and the number of time windows to be used in the inversion. JULIEW prepares two binary files: *juliea.dat* containing the subfault synthetics and *julieb.dat* containing the observed waveforms. These files are read in by program LISA, which is the code that actually performs the inversion using the NNLS routine of Lawson and Hanson (1974), taking into account the desired spatial smoothing and/or moment minimization prescribed by user-defined λ weighting factors. To identify the proper weighting, LISA can be run consecutive times using different λ values and the output examined each time to either confirm the input value or adjust the factor for subsequent runs. In practice, this is done by first running the inversion without any stabilization constraints to identify the best fit to expect between observed and predicted waveforms. The inversion is then run several times, incrementing the λ value each time, until the predicted waveforms no longer fit the observations. This process requires recognizing when the fit has degraded beyond an acceptable form where it no longer identifies the simplest possible solution.

Alternatively, one could plot the residual norms vs. the smoothing norms for many runs to produce an L-curve that would aid in identifying the optimum λ smoothing weight. An example of this L-curve analysis for the finite-fault inverse problem can be found in the study of Mendoza and Hartzell (2013). The inversion can also be performed in a single step using the program LISASS that uses a λ value estimated from the coefficient matrix $C_d^{-1}\mathbf{A}$ using the empirical relation $\lambda = 90\ A_{avg}$ proposed by Mendoza and Hartzell (2013), where A_{avg} is the average of the absolute values of the elements of the coefficient matrix.

Both versions of LISA generate an ASCII file named *lisaout.dat* that contains the subfault dislocation weights (solution vector **x**) required to reproduce the observed records. Both LISA codes must be compiled specifically for the problem being solved, i.e. the problem must be dimensioned exactly. This is done using the parameter file *arszlisa.dat*, where:

M = MDA = Total number of rows in the A matrix
N = Total number of unknowns in the A matrix
N3 = 327 (always)

The total number of rows M in the A matrix is generally given by:

$M = M_{NP} + M_{RS} + M_{RM}$

where M_{NP} is the total number of points for all data records, M_{RS} is the number of rows added for spatial smoothing, and M_{RM} is the number of rows added for moment minimization. Thus, M depends on the stabilization constraints that are placed on the inverse problem. The variables needed to identify the appropriate dimensions are:

$M_{NP} = \text{nrec}\bullet\text{sps}\bullet\text{rlen}$
$M_{RS} = \text{Nm}\bullet\text{Nt}\bullet[\text{Nss}\bullet(\text{Nsd}-1) + \text{Nsd}\bullet(\text{Nss}-1)]$
$M_{RM} = \text{Nm}\bullet\text{Ns}\bullet\text{Nt} = \text{N}$

where:

nrec = number of data records
sps = samples per second in data records
rlen = record length in seconds
Nm = number of mechanisms
Ns = number of subfaults
Nt = number of time windows
Nss = number of subfaults along the fault strike
Nsd = number of subfaults down the dip

7. WAVEFORM FITS AND SLIP MODEL

Program VANGODSH

VANGODSH can be used to view the fits between observed and predicted waveforms. It uses CALCOMP-based plotting calls and thus also requires setting up an appropriate graphics library or modifying the code to use plotting tools available to the user. It reads in the files *juliea.dat*, *julieb.dat* and *lisaout.dat* and also the fault-model information, e.g.

the number of subfaults and the number of time windows, as interactive input. The current version of the program produces a series of postscript files that can be viewed to examine the quality of the fits. The ratio of Synthetic-to-Observed Amplitudes (SOA) is printed to the right of each record pair. If these SOA ratios do not average about 1.0 for all stations, then the resulting seismic moment and subfault slips are either *over*- or *under*-estimated. To identify the proper moment and slip, an amplitude scale factor (ASF) that numerically adjusts the predicted amplitudes is computed in VANGODSH by taking the average of the reciprocals of the original SOA ratios. The original ratios must then be multiplied by this ASF factor to calculate new SOA ratios that are distributed equally above and below 1.0. This ASF factor must also be incorporated into the scaling used by PLISA (below) to calculate the proper seismic moment.

Program PLISA

The subfault slip weights in the *lisaout.dat* file generated by LISA are listed in the following order: slip weights for subfaults 1 through N for time window 1, followed by slip weights for subfaults 1 through N for time window 2, and so on, until all time windows are output to the *lisaout.dat* file. These weights are converted to actual slip using the program PLISA, which also calculates the corresponding seismic moment in units of dyne-cm. To calculate the moment, PLISA requires the shear rigidities (in units of 10^{11} gm/cm-sec^2) for subfaults down the dip. These can be inferred from the input crustal structure by taking the product of the layer density and the square of the shear-wave velocity. To calculate the fault slip, PLISA also requires a dislocation scale factor (DSF) corresponding to the dislocation (in centimeters) per unit weight for the initial input moment used to generate the subfault synthetics. This DSF scale factor generally corresponds to the product of the CSF factor calculated by CADLAC (Section 5) and the ASF factor obtained from an examination of the waveform fits (see previous VANGODSH section). The total slip in centimeters for each subfault is output to the screen as well as the total seismic moment.

PLISA also produces files of the form *contr**.dat*, where ** is a 2-digit number that runs from 01 to the total number of time windows used in the inversion. For example, for three time windows, the files would be named *contr01.dat*, *contr02.dat*, and *contr03.dat*. These files contain either the cumulative sum of the slips (i.e. slip values summed for consecutive time windows) or the slip in each time window for all subfaults. Most commonly, the former option is used such that the final time-window file (e.g., *contr03.dat*. for three time windows) contains the total slip across the fault obtained in the inversion. In the latest version of PLISA, the code actually produces ASCII *xyz* files where the *z* values correspond to GMT (Generic Mapping Tools; Wessel and Smith, 1998) color-palette numerical codes for plotting greyscale squares on a fault grid with the degree of shading based on the amount of slip. An option is provided when running PLISA for producing values as a percentage of the maximum slip in the contr**.dat file or relative to a user-defined input value. The *x* and *y* values give the position along the length and width of the fault.

Shell script PLTSLIP

The values given in any of the *contr**.dat* files can be plotted using the UNIX shell script *pltslip.csh*, which uses GMT commands to produce a greyscale plot of the slip on a rectangular fault. The shell script uses the specific fault parameters used in the inversion to set up the plotting and thus must be modified each time to accommodate different fault dimensions and subfault spacings. If this shell script is used, it is the responsibility of the user to make sure that the changes are made correctly. The shell script requires a command line argument that specifies which *contr**.dat* file to plot. Thus, the command

```
csh pltslip.csh  contr01.dat
```

produces a greyscale plot in *postscript* format (named *grdplt.ps*) that shows the subfault slip values contained in file c*ontr01.dat*.

8. TEST CASE

A finite-fault inversion testcase is included here that documents the inversion of teleseismic P waves recorded at 38 stations for the 9 October 1995 Colima-Jalisco, Mexico, earthquake. Data records have been previously prepared in TELMOD binary format and are in file *telPtpr38.dat*. A second data file named *telPtpr38asc.dat* is also included that contains these same data in ASCII format. This is useful when the *telPtpr38.dat* binary file is not readable or is incompatible with the user's computer system. In this case, it is necessary to run the program JULIEW_ASCII, instead of JULIEW, to read and process the data file.

The test uses a rectangular 200-km by 100-km fault divided into 200 10km-by-10km subfaults. The hypocenter is at a depth of 15 km and is placed 50 km from the left edge and 50 km from the top of the fault. The fault strike and dip are 300° and 15°, respectively. The inversion is conducted for a fixed rake of 90° using a single time window assuming a rupture velocity of 3 km/sec. Two inversion tests are included: one that uses the code LISA without any linear constraints, and a second test that uses the code LISASS to apply an automatically-generated smoothing value for spatial smoothing and moment minimization.

REFERENCES CITED

Goldstein, P., D. Dodge, M. Firpo, and L. Minner (2003). SAC2000: Signal processing and analysis tools for seismologists and engineers, Invited contribution to *The IASPEI International Handbook of Earthquake and Engineering Seismology*, W.H.K. Lee, H. Kanamori, P.C. Jennings, and C. Kisslinger (Editors), Academic Press, London.

Hansen, P. C. (1998). Rank-Deficient And Discrete Ill-Posed Problems, Numerical Aspects of Linear Inversion, *SIAM Monographs on Mathematical Modeling and Computation*, Philadelphia, Pennsylvania.

Hartzell, S. H. and T. H. Heaton (1983). Inversion of strong ground motion and teleseismic waveform data for the fault rupture history of the 1979 Imperial Valley, California, earthquake, *Bull. Seism. Soc. Am.* **73**, 1553-1583.

Hartzell, S. H. and T. H. Heaton (1986). Rupture history of the 1984 Morgan Hill, California, earthquake from the inversion of strong motion records, *Bull. Seism. Soc. Am.* **76**, 649-674.

Langston, C. A. and D. V. Helmberger (1975). A procedure for modeling shallow dislocation sources, *Geophys. J. R. Astr. Soc.* **42**, 117-130.

Lawson, C. L. and R. J. Hanson (1974). Solving Least Squares Problems, Prentice-Hall, Englewood Cliffs, New Jersey.

Wessel. P. and W.H.F. Smith (1998). New, improved version of the Generic Mapping Tools released, *EOS Trans. Am. Geophys. Union* **79**, 579.

TABLES

Table 1. Observed data format (binary) expected by program TELMOD.

VARIABLE	DESCRIPTION
NSTA	(number of stations in the file)
NP1 DT1	(number of points and time step for station-1 record)
A1(I), I=1,NP1	(amplitude values for station-1 record)
NP2 DT2	(number of points and time step for station-2 record)
A2(I), I=1,NP2	(amplitude values for station-2 record)
NP3 DT3	(number of points and time step for station-3 record)
A3(I), I=1,NP3	(amplitude values for station-3 record)
. . . . .	……….
NPN DTN	(number of points and time step for NSTA record)
A(I), I=1,NPN	(amplitude values for NSTA record)

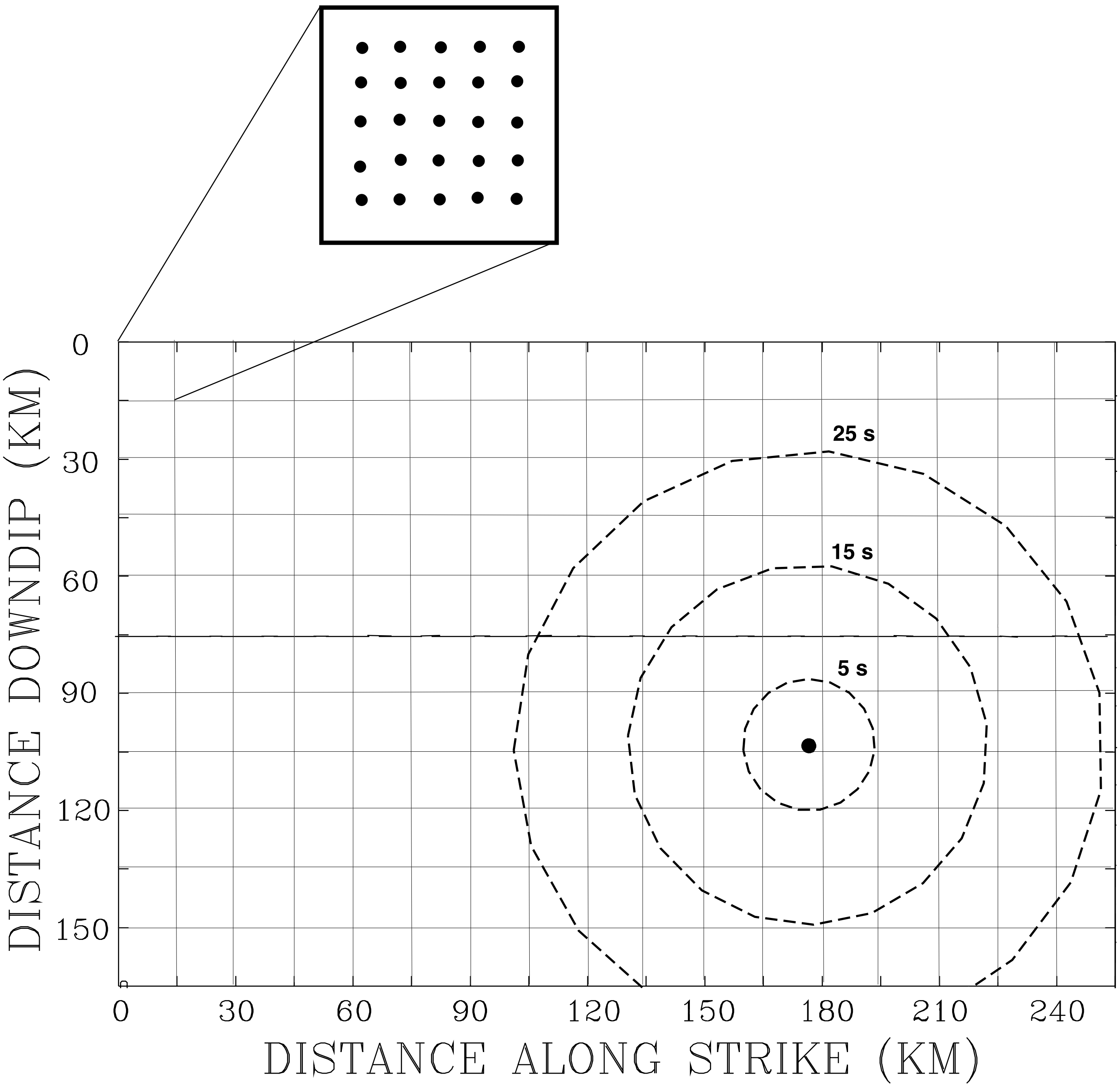
Table 2. Binary format used by CADLAC and TELMOD for the synthetic records.

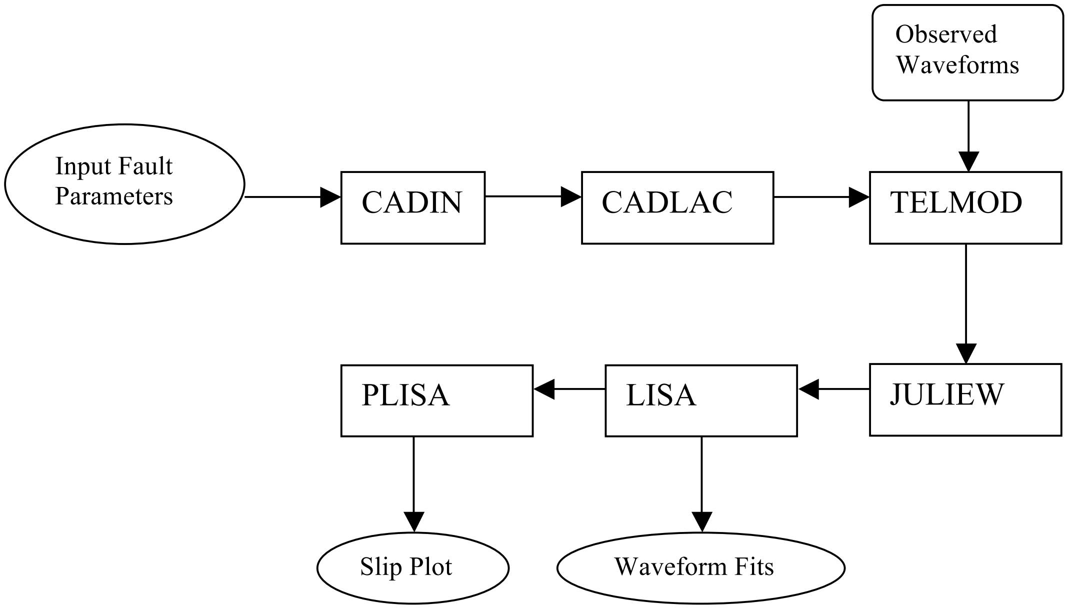
VARIABLE	DESCRIPTION
M	number of stations in the file
NP DT	num of points and time step for subfault-1 synthetic at station 1
A(I), I=1,NP	amplitude values for subfault-1 synthetic
NP DT	num of points and time step for subfault-2 synthetic at station 1
A(I), I=1,NP	amplitude values for subfault-2 synthetic
......	…………
NP DT	(num of points and time step for subfault-N synthetic at station 1)
A(I), I=1,NP	(amplitude values for subfault-N synthetic)
NP DT	(num of points and time step for subfault-1 synthetic at station 2)
A(I), I=1,NP	(amplitude values for subfault-1 synthetic)
NP DT	(num of points and time step for subfault-2 synthetic at station 2)
A(I), I=1,NP	(amplitude values for subfault-2 synthetic)
......	…………
NP DT	(num of points and time step for subfault-N synthetic at station 2)
A(I), I=1,NP	(amplitude values for subfault-N synthetic)
......	
NP DT	(num of points and time step for subfault-1 synthetic at station M)
A(I), I=1,NP	(amplitude values for subfault-1 synthetic)
NP DT	(num of points and time step for subfault-2 synthetic at station M)
A(I), I=1,NP	(amplitude values for subfault-2 synthetic)
......	…………..
NP DT	(num of points and time step for subfault-N synthetic at station M)
A(I), I=1,NP	(amplitude values for subfault-N synthetic)

FIGURE CAPTIONS

Figure 1. Basic parametrization used in the finite-fault analysis. The fault is embedded in the near-source crustal structure at an orientation consistent with the known source geometry and is divided into a fixed number of subfaults with a uniform distribution of point sources. Point-source seismic responses are first computed using a boxcar source-time function of prescribed duration and then summed to construct synthetic waveforms for each subfault at each of the recording sites, taking into account delays due to the propagation of rupture at a constant speed away from the hypocenter (solid circle). In this example, the fault is divided into 187 distinct 15-km by 15-km subfaults, and a rupture velocity of 3 km/sec is used to compute the subfault synthetics. The circles thus represent the rupture front at 5, 15, and 25 sec following rupture initiation.

Figure 2. Computer codes used in the teleseismic finite-fault analysis.


25 s
15 s
5 s
0
30
60
90
120
150
DISTANCE DOWNDIP (KM)
0
30
60
90
120
150
180
210
240
DISTANCE ALONG STRIKE (KM)


Observed Waveforms
Input Fault Parameters
CADIN
CADLAC
TELMOD
JULIEW
LISA
PLISA
Slip Plot
Waveform Fits