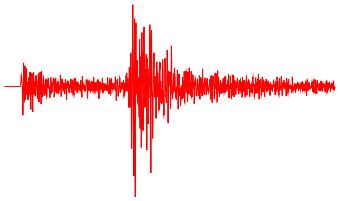
COMPUTER PROGRAMS IN SEISMOLOGY



SOURCE INVERSION

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Version 3.30
2002

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CHAPTER 1
SEISMIC SOURCE ANALYSIS

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1. Introduction

Seismic source investigations date from the 1920's when seismologists noted different patterns of P-wave first motion polarities associated with the earthquake. Different combinations of point forces were proposed to describe the observed aptterns - these were the couple and double-couple representations. Observational studies in the early 1960's, by Stauder and others, and theoretical studies of dislocations by Maruyama and later Burridge and Knopoff, demonstrated the appropriateness of describing the elastic wave field generated by slip motion on a fault in terms of the double-couple source. As seismology matured the moment tensor representation of the seismic source was proposed as a generalization of the double-couple source.

Regional waveforms recorded by modern seismographs contain much information about the seismic source and the Earth between the source and each receiver. When low-pass filtered, the waveforms appear simple enough to be modeled using synthetic seismograms, such as generated using the programs distributed in *Computer Programs in Seismology*. This volume described a set of tools built upon the synthetic seismogram codes, to analyze source properties.

2. Organization

The key to performing data inversion is organization. This is especially important if inversion is not performed routinely. For this purpose this tutorial discusses an organization of Green's functions for a give earth model, digital data preparation, and two techniques for soruce parameter inversion - analysis of surface-wave amplitude radiation patterns and actual waveform fitting. The waveform fit programs are conceptually simple. Other investigators use programs that attempt to fit waveform segments. Perhaps these other tools will be added in the future.

CHAPTER 2
GREEN'S FUNCTIONS

---

1. Introduction

Regional earthquake studies.
Small earthquake - no source time function unless built into Green's functions
note keep surface wave general to permit TI media

2. Green's Functions Organization

Two types of files must be created to implement the inversion techniques described in this tutorial. For a given regional Earth model, one consists of depth dependent files used for the surface-wave fundamental mode spectral amplitude studies and the other consists of SAC formatted time-series of basic Green's functions for a given source depth and epicentral distance. To provide general support for these techniques, these files are precomputed and stored using the heirarchical organization of the file system.

```
HamModel/
    |----sregn96.der       (surface wave excitation)
    |----slegn96.der       (surface wave excitation)
    |
    |----0005/            (Waveform   0.5 km depth)
    |       |
    |       |           (  0.5 km epicentral distance)
    |       |---000050005.ZDD  (these are Green's))
    |       |---000050005.RDD
    |       |---000050005.ZDS
    |       |---000050005.RDS
    |       |---000050005.TDS
    |       |---000050005.ZSS
    |       |---000050005.RSS
    |       |---000050005.TSS
    |       |---000050005.ZEX
    |       |---000050005.REX
    |       |
    |       |           (105.0 km epicentral distance)
    |       |---01050005.ZDD
    |       |         ...
    |       |----W.CTL    (Waveform wave control file for depth
    |
```

```
|----0010/          (Waveform   1.0 km depth)
|       |
|      ...
|----0400/          (Waveform  40.0 km depth)
|       |
|      ...
```

This structure highlights regional design constraints as well as internal aspects of the inversion techniques:

1) The first important point is that the inversion results are governed by a particular Earth model. One may use different earth models in a region for research, or one may be interested in earthquake source parameters in different regions.
2) The organization of information required for surface information depends solely upon source depth since the epicentral distance component is by the inversion program itself. The directory structure and eigenfunction file name, e.g., *dddd.srf* is a function of source depth. The naming convention is that a directory 1234.S with corresponding eigenfunction file 1234.srf is associated with a depth of 123.4 km in the model.
3) A general inversion of a three-component seismogram for source moment-tensor elements, requires just ten Green's functions. These can be generated by any of the synthetic seismogram techniques described in the overview. Each Green's function, stored as a SAC binary file (in the binary format of the local computer architecture), is a function of source depth and epicentral distance. This requires an organization that incorporated source depth and epicentral distance. The naming of the files is of the form *xxxxxdddd.grn* where *xxxxx* denotes the epicentral distance, *dddd* denotes the source depth, and *grn* denotes one of the ten Green's functions. The convention used is this tutorial is to assume that the last digit of each description indicates tenth's. The use *123456789.ZSS* is the vertical component Green's function at a distance of 1234.5 km and a source depth of 678.9 km. The reason for this precision is to permit waveform modeling of aftershock data.

3. Green's Functions Computation

To compute all Green's functions and to create the organization described above, the following script is run:

```
#!/bin/sh

set -x


#####
#     shell script for creating the eigenfunction
#     Green s function files for source inversion
#####

#####
#     define the DESTINATION DIRECTORY
#
#     PATH is high level path which must exist
#     MODEL is the model directory which will be created if required
#     PMIN, PMAX are the periods for which eigenfunctions are
#     to be created
```

```
#
#####

DEST=/home/rbh/PROGRAMS.310t
MODEL=CUS
PMIN=4.0
PMAX=100.0
Mname=cusq.mod

if [ ! -d ${DEST}/${MODEL} ]
then
       echo Creating the Directory ${DEST}/${MODEL}
       mkdir ${DEST}/${MODEL}
fi

#####
#      create the model subdirectory
#####

if [ ! -d ${DEST}/${MODEL}/Model ]
then
       echo Creating the Directory ${DEST}/${MODEL}/Model
       mkdir ${DEST}/${MODEL}/Model
fi

#####
#      create the surface-wave control directory
#####

if [ ! -d ${DEST}/${MODEL}/SW ]
then
       echo Creating the Directory ${DEST}/${MODEL}/SW
       mkdir ${DEST}/${MODEL}/SW
fi

#####
#      define the earth model here - the many layers permit the
#      specification of eigenfunctions with depth - should
#      rewrite slegn96 and regn96 to permit layer insertion
#      this way the simple model can be used to get disperion curves
#
#      cusq.mod is the simple model for for wavenumber integration
#      dcusq.mod is the detailed model for eigenfunctions
#
#      Note the the models are in MODEL96 format and can be created
#      using the program mkmod96
#####

cat > ${DEST}/${MODEL}/Model/cusq.mod << EOF
MODEL.01
CUS Model with Q from simple gamma values
ISOTROPIC
KGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11
  H(KM) VP(KM/S) VS(KM/S) RHO(GM/CC)   QP   QS  ETAP  ETAS  FREFP  FREFS
  1.0000  5.0000  2.8900  2.5000 0.172E-02 0.387E-02 0.00  0.00  1.00  1.00
  9.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
 10.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
 20.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  0.0000  8.1500  4.7000  3.3640 0.194E-02 0.431E-02 0.00  0.00  1.00  1.00
EOF

cat > ${DEST}/${MODEL}/Model/dcusq.mod << EOF
MODEL.01
CUS Model with Q from simple gamma values
ISOTROPIC
KGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11
  H(KM) VP(KM/S) VS(KM/S) RHO(GM/CC)   QP   QS  ETAP  ETAS  FREFP  FREFS
```

```
  1.0000  5.0000  2.8900  2.5000 0.172E-02 0.387E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  1.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  0.0000  8.1500  4.7000  3.3640 0.194E-02 0.431E-02 0.00  0.00  1.00  1.00
EOF


#####
#      go to the workind directory
#####

cd ${DEST}/${MODEL}/SW

#####
#      create the surface wave data sets
#####

sprep96 -PMIN ${PMIN} -PMAX ${PMAX} -M ../Model/d${Mname} -L -R -NMOD 1
sdisp96
sregn96 -DER
slegn96 -DER
######
#      Uncomment this if you want to see the eigenfunctions
#####
sdpder96 -L -TXT
sdpder96 -R -TXT

#####
#      now systematically create the wavenumber integration Green s functions
#####

#####
#      return to the main directory
#####
cd ${DEST}/${MODEL}

#####
#      Now begin the wavenumber integration run
#      remove the W.CTL file
#####
rm -f W.CTL


for HS in 0.5 01 02 03 04 05 06 07 08 09 10 \
```

```
      11 12 13 14 15 16 17 18 19 20 \
      21 22 23 24 25 26 27 28 29 30 \
      31 32 33 34 35 36 37 38 39 40
do

#####
#     define the directory name
#####

case $HS in
      0.5) DIRNAME=0005 ;;
      *)   DIRNAME=0${HS}0;;
esac

if [ ! -d  ${DIRNAME} ]
then
      echo creating the Green s Function depth directory
      echo $DIRNAME for depth $HS
      mkdir ${DIRNAME}
fi

cd $DIRNAME
#####
#     compute the Green's functions for different distances
#     To save computational time, the number of data points will
#     be controlled by the distance
#
#     ALSO CANNOT HAVE MORE THAN 500 RECEIVERS SO BE CAREFUL OF THE
#     number of distances in the DFILE TABULATION
#####

DT=0.25
VRED=8
NPTS=512
T0=-5
rm -f dfile

for DIST in \
          001 002 003 004 005 006 007 008 009  \
      010 011 012 013 014 015 016 017 018 019  \
      020 021 022 023 024 025 026 027 028 029  \
      030 031 032 033 034 035 036 037 038 039  \
      040 041 042 043 044 045 046 047 048 049  \
      040 051 052 053 054 055 056 057 058 059  \
      050 062 064 066 068 \
      070 072 074 076 078 \
      080 082 084 086 088 \
      090 092 094 096 098 \
      100 105 110 115 120 125 130 135 140 145 \
      150 155 160 165 170 175 180 185 190 195 \
      200 205 210 215 220 225 230 235 240 245 \
      250 255 260 265 270 275 280 285 290 295
do
cat >> dfile << EOF
$DIST $DT $NPTS $T0 $VRED
EOF
echo $DIST $DT $NPTS $T0 $VRED ${DIRNAME} 0${DIST}0${DIRNAME} >> ${DEST}/${MODEL}/${DIRNAME}/W.CTL

done
wc dfile
#####
#     do the wavenumber integration
#####
rm -fr hspec96.*
hprep96 -M ../Model/${Mname} -d dfile -HS ${HS} -HR 0.0 -EQEX
hspec96
hpulse96 -V -p -l 1 | f96tosac -G

#####
#     now do the greater distances
#####

DT=0.25
VRED=8
NPTS=1024
T0=-5
rm -f dfile

for DIST in \
      300 305 310 315 320 325 330 335 340 345 \
      350 355 360 365 370 375 380 385 390 395 \
```

```
        400 405 410 415 420 425 430 435 440 445 \
        450 455 460 465 470 475 480 485 490 495 \
        500 505 510 515 520 525 530 535 540 545 \
        550 555 560 565 570 575 580 585 590 595
do
cat >> dfile << EOF
$DIST $DT $NPTS $T0 $VRED
EOF
echo $DIST $DT $NPTS $T0 $VRED ${DIRNAME} 0${DIST}0${DIRNAME} >> ${DEST}/${MODEL}/${DIRNAME}/W.CTL

done
wc dfile
#####
#      do the wavenumber integration
#####
rm -fr hspec96.*
hprep96 -M ../Model/${Mname} -d dfile -HS ${HS} -HR 0.0 -EQEX
hspec96
hpulse96 -V -p -l 1 | f96tosac -G

#####
#      return to upper level directory
#####

cd ..

done
```

Note that in this script that a different number of points were used for distances less than or greater than 300 km. This is because at larger distances the signals have a longer duraation.

As mentioned, creation of the entire data set requires significant computational effort. If only one earthquake is being analyzed, then only the few distances need be computed - however the computational time for the wavenumber integration code depends both upon the frequency content and the desired distances - so that the difference between computing the Green’s function for one distance versus many distances many not be a simple multiple of the number of distances.

CHAPTER 3
DATA PREPARATION

---

1. Introduction

Seismic data are just an imperfect representation of ground motions because of the filtering effect of the instruments and internal noise. The ground motion signal is a composite of the signal of interest and noise. Our ability to retrieve information about the earthquake source is affected by the degree that the desired signal is significantly above noise.

For quantitative studies of the earthquake source one may either compared observed to predicted seismograms by passing ground motion synthetics through a mathematical model of the seismic data acquisition system, or, comparing predicted ground motions to data derived estimates. The first approach requires a convolution, while the second, a deconvolution. This chapter addresses the first technique and describes the steps required to process the data obtained from different sources.

2. SEED

SEED is a documented Standard for the Exchange of Earthquake Data. It is the archival format of the IRIS DMC. The advantage of SEED is that the instrument response file is well documented and that the program *evalresp* can be used to define the response for a given data channel.

2.1 Making a Data Request

Data can be requested from the IRIS DMC

`http://www.iris.washington.edu`

and the Canadian National Waveform Archive

`http://www.seismo.nrcan.gc.ca/nwfa/index_e.html`

After a request is made, the data will be available in a SEED volume, which includes both the data and the instrument responses. If the data file is called *Evansville.seed*, run the

IRIS command **`rdseed`** as

```
rdseed -f Evansville.seed -o 1 -R  -d
```

This command will unpack the archive and create the waveform files in a SAC format as well as the SEED response files. For example, this data set provides the following for the IRIS station *WCI* in southern Indiana (UNIX command ls -l *WCI*):

```
-rw-rw-r--   1 rbh      rbh        23100 Aug 21 13:24 RESP.IU.WCI..BHE
-rw-rw-r--   1 rbh      rbh        23100 Aug 21 13:24 RESP.IU.WCI..BHN
-rw-rw-r--   1 rbh      rbh        23100 Aug 21 13:24 RESP.IU.WCI..BHZ
-rw-rw-r--   1 rbh      rbh       132860 Aug 21 13:24 2002.169.17.32.42.1481.IU.WCI..BHN.SAC
-rw-rw-r--   1 rbh      rbh       125056 Aug 21 13:24 2002.169.17.33.35.2481.IU.WCI..BHZ.SAC
-rw-rw-r--   1 rbh      rbh       119072 Aug 21 13:24 2002.169.17.35.16.5981.IU.WCI..BHE.SAC
```

2.2 Waveform manipulation

Before being able to analyze the wave form data, several essential processing steps are required:

- **`DOEVT`** - Place the event information in the SAC headers of all `.SAC` files. This is the only modification made to the original files.
- **`DORESP`** - Deconvolve the instrument response from the `.SAC` files. Rename the output files to something with a shorter name. For example the station WCI BHZ component will be names `WCIBHZ.Sac`. The Original trace file will be saved in a subdirectory. The traces will now have the physical units of *m/sec*.

  Since this is a convenient place to process all traces, a list is made of station names, and all components are read in and the traces time synchronized. This means that the same reference time will be used for all traces from that station. One trace will start at this reference time and the others before this time. In terms of the SAC header, one B will be 0.0 and the others negative.
- **`DOCUT`** - Using the synchronized traces, ensure that all traces for a station have the same absolute start and end times by cutting the waveforms. All components will have the same number of sample points. This step is required to rotate the horizontal components into radial and transverse directions. Implementation requires the specification of the name of the local C compiler.
- **`DOROT`** - Actually rotate the two horizontal components. The rotated components will have the component names BHR and BHT, respectively, for the radial and transverse components. For the data set above, the files `WCIBHZ.Sac`, `WCIBHN.Sac`, `WCIBHE.Sac`, `WCIBHR.Sac` and `WCIBHT.Sac` will exist in the current directory.
- **`DODIST`** - Create a data file, `dist.sort`, listing the station name and epicentral distance in order of increasing distance. This provides an easy reference on station distances to assist in selecting traces to process.

- Quality control - this cannot be formalized in a script because it requires the user to examine individual traces. The resultant ground velocity traces may not be useful for many reasons.

  † The desired signal may not be in the trace time window.
  † There may be no resolvable signal at this station because of distance or instrument failure.
  † The waveform may not look appropriate because of an incorrect instrument response used for deconvolution.

The following sections present and describe the shell scripts. The shell scripts must be executed in the order presented. The scripts could be combined into one large one, but it is easier to discuss the steps individually.

2.2.1 - DOEVT

This script invokes the programs **`sac2000f1 to set the event coordinates. Two flags are set to permit sac2000`** to use the coordinates to calculate the station distances and azimuths and place them also in the trace header. Note that we rely on the fact the **`rdseed`** places the station orientation and location coordinates into the trace header.

```
#!/bin/sh
#####
#              set the event coordinates
#####
for i in *.SAC
do

sac2000 << EOF
r $i
ch EVLA 37.97 EVLO -87.79 EVDP 5.0
ch O GMT 2002 169 17 37 16 000
ch lovrok true
ch lcalda true
wh
quit
EOF

done
```

2.2.2 - DORESP

This is a long script, but easy to understand. First some subdirectories are created to store files. After we use the 8.SAC files they will be placed in the subdirectory *Raw* in case the original data must be reused. Another subdirectory, *AmpPhase*, is created to place the instrument response information.

The next step is to process each `*.SAC` file individually. The IRIS program **`evalresp`** is used to convert the detailed response description into two tables, AMP.IU.WCI..BHZ and PHASE.IU.WCI..BHZ, which give the amplitude (in units of counts/m/sec) and phase (in degrees) as a function of frequency (first column), respectively. These tables are used by the program **`sacevalr`** to deconvolve the instrument response. Deconvolution is tricky, since very low and very high frequency noise will be amplified.

Because these traces will be used for low frequency studies, the traces are automatically decimated by a factor of 5 using the **`sac2000f1 command`** *decimate 5*. This means that 20 sample per second data will become 5 samples per second. The reason for this is that the higher frequencies are not of interest and that later processing is faster if a longer sampling interval, and corresponding smaller number of points, are used.

The final step is to synchronize traces. *Since subsequent analysis of the sample earthquake will focus on periods less than 100 seconds, the trace is zero-phase, highpass filtered at 0.005 Hz to eliminate any deconvolution noise. The user may wish to carefully use some other filter*.

```
#!/bin/sh

#####
#               test for the Raw data directory
#####

if test -d Raw
then
                echo raw Data Directory Exists
else
                mkdir Raw
fi

if test -d AmpPhase
then
                echo AmpPhase Data Directory Exists
else
                mkdir AmpPhase
fi

DIRRESP=.
NET='*'
LOC='*'

#####
#               clean up
#####
                rm -f stalist

#####
#               now systematically
#               get the instrument response
#####

for i in *.SAC
do

KSTNM=`saclhdr -KSTNM $i`
KCMPNM=`saclhdr -KCMPNM $i`
NZYEAR=`saclhdr -NZYEAR $i`
NZJDAY=`saclhdr -NZJDAY $i`
```

```
echo ${KSTNM} ${KCMPNM} ${NZYEAR} ${NZJDAY} 0.001 10.0 1000 \
              ${DIRRESP}/RESP.${NET}.${KSTNM}.${LOC}.${KCMPNM}
evalresp  ${KSTNM} ${KCMPNM} ${NZYEAR} ${NZJDAY} 0.001 10.0 1000 -u 'vel' -f \
              ${DIRRESP}/RESP.${NET}.${KSTNM}.${LOC}.${KCMPNM}
#####
#       deconvolve the trace
#####
cp $i Raw
mv $i ${KSTNM}${KCMPNM}.sac
sac2000 << EOF
r ${KSTNM}${KCMPNM}.sac
rtr
taper
w ${KSTNM}${KCMPNM}.sac
quit
EOF

mv RESP.${NET}.${KSTNM}.${LOC}.${KCMPNM} Raw

sacevalr -R -AMP AMP.${NET}.${KSTNM}.${LOC}.${KCMPNM} -PHA PHASE.${NET}.${KSTNM}.${LOC}.${KCMPNM} \
              -SACIN ${KSTNM}${KCMPNM}.sac -SACOUT ${KSTNM}${KCMPNM}.Sac
mv PHASE* AMP* AmpPhase
sac2000 << EOF
r ${KSTNM}${KCMPNM}.Sac
decimate 5
w over ${KSTNM}${KCMPNM}.Sac
quit
EOF

echo ${KSTNM} >> stalist
done

#####
#             Now make a list of all stations
#             read in all traces for this station, synchronize,
#             hp c 0.005 np 2 p 2  to remove long period trend
#             write over all *.Sac
#####


cat stalist | sort | uniq > stalist.uniq

for i in 'cat stalist.uniq'
do
echo $i
sac2000 << EOF
r ${i}*.Sac
synchronize
hp c 0.005 np 2 p 2
rtr
taper
w over
quit
EOF

done
```

2.2.3 - DOCUT

In order to successfully rotate the traces, the horizontal traces must have the same number of points and the same absolute begin and end time. This is done using the **sac2000** *cut* command.

```
#!/bin/sh

#####
#              program to set cut limits for data stream
#              Note that the *.Sac files are considered here
#              these files have had instrument removed by DORESP
#              and have been time synchronized and high pass filtered at 0.005 Hz
#              by DORESP
#
#              Prior to rotating the horizontal components, is is necessary to ensure
#              that the horizontal traces have the same begin and end times
#####

for STA in ‘cat stalist.uniq‘
do
sac2000 << EOF
cuterr fillz
cut 0 ${E}
r ${STA}*.Sac
w over
quit
EOF


done
```

2.2.4 - DOROT

The final step is simple. Just tell this program the name of one of the horizontal components. The program will determine the other. Usually these are called BHE or BHN, but sometimes there will be BH1 and BH2. For convenience the rotated traces are given the internal component names BHR, for radial away from the source, and BHT, for transverse components.

```
#####
#              now systematically create the transverse and radial component
#              since some stations have components 1 2 for the horizontal
#              do this carefully
#####

for i in $*
do


KSTNM=’saclhdr -KSTNM $i’
KCMPNM=’saclhdr -KCMPNM $i’
case ${KCMPNM} in
               BHN) OTHER=BHE;;
               BHE) OTHER=BHN;;
               BH2) OTHER=BH1;;
               BH1) OTHER=BH2;;
```

```
esac

sac2000 << EOF
qdp off
r ${KSTNM}${KCMPNM}.Sac ${KSTNM}${OTHER}.Sac
rtr
taper
rotate to gc
w ${KSTNM}BHR.Sac ${KSTNM}BHT.Sac
r ${KSTNM}BHR.Sac
ch KCMPNM BHR
wh
r ${KSTNM}BHT.Sac
ch KCMPNM BHT
wh
q
EOF

done
```

Note that significant modifications have been made to the recorded waveforms. It is important to be aware of these changes and their consequences for later data processing. For example, do long look for surface wave dispersion data at periods greater than 100 seconds since those data have been filtered out by the hig pass filter step. Remember the original data are in the subdirectory *Raw.*.

2.2.5 - DODIST

This simple script is useful for providing some information about the data set. A list of data in order of increasing distance cat be used to quickly focus on

```
#!/bin/sh

rm -f dist

for i in *Z.SAC
do
echo ‘saclhdr -DIST $i ‘ $i >> dist
done

sort -n dist > dist.sort
```

3. AutoDRM

The Automatic Data Request Manager operates worldwide and permits rapid access to digital seismic data. The reference URL is

http://seismo.ethz.ch/waves4u/

As of August 28, 2002, there are 1236 stations, providing 4990 channels through Auto-DRMs worldwide. Access to these data is through Email. The simplest operation is to send an Email to an AutoDRM site with the word *HELP* in the text. To run in a UNIX shell script, do the following

```
Mail autodrm@gldfs.cr.usgs.gov << EOF
HELP
EOF
```

You will then obtain an Email in return which tells you how to use the service. You will then use a program that you compile to read the Email message and convert the encoded waveform into a format that you can use. A list of available programs can be found in the ORFEUS Seismological Software Library

`http://orfeus.knmi.nl/other.services/conversion.shtml`

The programs *gsesac* and *codeco* may be useful.

If you use the conversion program **`codeco`** and if you save the return Email message as 33, then you would execute the following commands (The executable path is explicitly given in this example. The programs **`uico.csh`** provides an interactive session. In the example here, user input is in bold.

```
rbh> /rx/BBAND/CODECO/bin/uico.csh
Enter the name of the file to be converted.
Input file: 3
Enter input format.  The following choices are possible:
auto     automatic detection of input format (may fail)
gse      any GSE1/2 format
sac      SAC-binary or SAC-ascii format
saca     SAC-binary or SAC-ascii format
seed     MiniSEED (4096-blocks) format
css      CSS (2.8/3.0) format
Input format: auto
Enter name of output file where the results of the conversion will go.
Output file: lunk
Enter output format.  The following choices are possible:
intv-0   GSE1.0 uncompressed integer, no differences (printable)
intv-1   GSE1.0 uncompressed integer, first differences (printable)
intv-2   GSE1.0 uncompressed integer, second differences (printable)
cmp6-0   GSE1.0 6-bit compressed, no differences (printable)
cmp6-1   GSE1.0 6-bit compressed, first differences (printable)
cmp6-2   GSE1.0 6-bit compressed, second differences (printable)
cmp7-0   GSE1.0 7-bit compressed, no differences (binary)
cmp7-1   GSE1.0 7-bit compressed, first differences (binary)
cmp7-2   GSE1.0 7-bit compressed, second differences (binary)
cmp8-0   GSE1.0 8-bit compressed, no differences (binary)
cmp8-1   GSE1.0 8-bit compressed, first differences (binary)
cmp8-2   GSE1.0 8-bit compressed, second differences (binary)
int      GSE2.0 uncompressed integer, no differences (printable)
cm6      GSE2.0 6-bit compressed, second differences (printable)
cm7      GSE2.0 7-bit compressed, second differences (binary)
cm8      GSE2.0 8-bit compressed, second differences (binary)
sac      SAC format (binary)
saca     SAC ASCII format (printable)
seed     Mini-SEED, Steim1-compressed (binary)
```

```
css2    'CSS-2.8' format
css3    'CSS-3.0' format
Output format: sac
rbh>ls
33      34      lunk.001   lunk.002   lunk.003   lunk.004   lunk.005
```

The last line indicates that the files *lunk.???* were created. These can be renamed using the following shell script:

```
#!/bin/sh

for i in lunk.???
do
                KSTNM=,saclhdr -KSTNM $i,
                KCMPNM=,saclhdr -KCMPNM $i,
                mv $i ${KSTNM}${KCNMNM}.SAC
done
```

After running this script one would see the following files:

```
WCIBHESTS-1.SAC WCIBHNSTS-1.SAC WCIBHZSTS-1.SAC WVTBHNSTS-1.SAC WVTBHZSTS-1.SAC
```

The program **codeco** creates a component name by concatenating the channel, e.g., *BHZ*, with the sensor name *STS-1*. This must be accounted for in adapting the processing scripts introduced for the SEED data set,

There is no easy way to create data files with the instrument response. The GSE documentation for the data format is found at

http://seismo.ethz.ch/autodrm/autodrm_doc.html

Consider the WVT BHN Channel. If one examines the Email files, one will see an entry like this for the waveform

```
WID2 2000/03/06 15:02:00.000 WVT   BHN US   CM6    12001   40.000000   1.93E-01 1.000 STS-1    0.0 90.0
DAT2
mhCWg37WBMmIUMVJkMkFUJBkOkQUNUROkPLUMUNkNkTUQUSQl9-VAKkMGBUJTkQUFCkJAULMkPkMV45k
K+2V1HlCJV1Dl+kKUTV0l1l6V6V6l9kSVL3lT3VI4lAOV6LQDkK+V7PlGUSV7m60WEl6lKVFV9lBkTV6
```

The WID2 line describes the data and the DAT2 is the encoded data. The entries on the WID2 line are as follow:

Column	Name	Fortran Format	Description
1-4	"WID2"	a4	Must be "WID2"
6-15	Date	i4,a1,i2,a1,i2	Date of the first sample (yyyy/mm/dd)
17-28	Time	i2,a1,i2,a1,f6.3	Time of the first sample (hh:mm:ss.sss)
30-34	Station	a5	Station code
36-38	Channel	a3	FDSN channel code
40-43	Auxid	a4	Auxiliary identification code
45-47	Sub_format	a3	"INT", "CMn", or "AUx" INT is free format integers as ASCII characters; "CM" denotes compressed data, and n is either 6 (6-bit compression), or 8 (8-bit binary compression) "AU" signifies authentication andd x is T (uncompressed or binary integers), 6 (6-bit compression), or 8 (8-bit binary compression)
49-56	Samps	i8	Number of samples
58-68	Samprate	f11.6	Data sampling rate (Hz)
70-79	Calib	e10.2	Calibration factor; i.e., the ground motion in nanometers per digital count at calibration period (calper)
81-87	Calper	f7.3	Calibration reference period; i.e., the period in seconds at which calib is valid. calper should b bear the flat part of the response curve. (in most cases, 1 sec).
89-94	Instype	a6	Instrument type (From Table 8)
95-100	Hang	f5.1	Horizontal orientation of sensor, measured in positive degrees clockwise from North (-1 if vertical)
102-105	Vang	f4.1	Vertical orientation of sensor, measured in positive degrees from vertical (90.0 if horizontal)

Note for vertical sensor, Vang = 0 must be up (RBH)

The GSE format recognizes that modern data acquisitions have Finite Impulse Response (FIR) digical filters and documents their them. However, the FIR filters usually do not affect the instrument response in the range of seismic frequencies. The pole-zero formulation contains the necessary information.

If the instrument response is requested with the *CALIB* query of AutoDRM, one would find the following somewhere within the Email message.

```
DATA_TYPE LOG
```

```
   Channels selected (RESPONSE):
 WCI:  BHZ, BHN, BHE
 WVT:  BHZ, BHN, BHE

DATA_TYPE RESPONSE GSE2.0

CAL2 WVT   BHN US   STS-1    1.93E-01   1.000   40.00000 1996/11/17 00:00
PAZ2  1 C  3.25435791E+03                 4   3 STS-1
 -1.23399999E-02  1.23399999E-02
 -1.23399999E-02 -1.23399999E-02
 -3.91800003E+01  4.91199989E+01
 -3.91800003E+01 -4.91199989E+01
  0.00000000E+00  0.00000000E+00
  0.00000000E+00  0.00000000E+00
  0.00000000E+00  0.00000000E+00

STOP
```

The documentation of the *CAL2* field is

Column	Name	Fortran Format	Description
1-4	"CAL2"a4	must be "CAL2"	
6-10	Sta	a5	station code
12-14	a3	FDSN channel code	
15-19	Auxid	a4	auxiliary identification code
21-26	Instype	a6	instrument type (see Table 7)
28-42	Calib	e10.2	system sensitivity (nm/count) at reference period
44-50	Calper	f7.3	calibration reference period (seconds)
52-62	Samprat	f11.5	system output sample rate (Hz)
64-73	Ondata	i4,a1,i2,a1,i2	effective start data (yyyy/mm/dd)
75-79	Ontime	i2,a1,i2	effective start time (hh:mm)
81-90	Offdata	i4,a1,i2,a1,i2	effective end data (yyyy/mm/dd)
92-96	Offtime	i2,a1,i2	effective end time (hh:mm)

Calibration, cal period and sample rate should be the same as in the WID2 header..br The start/end date-times specify the timer period for which the response is valid. If the response is still valid, the off date-time should be left blank.

The documentation of the PAZ2 line and subsequent lines is

Column	Name	Fortran Format	Description
Header			
1-4	"PAZ2"	a4	must be "PAZ2"
5-7	Snum	i2	stage sequence number
9	Ounits	a1	output units (V-volts,A=amps,C=counts)
11-25	Sfactor	e15.8	scale factor
27-30	Deci	i4	decimation factor (blank if analog)
32-39	Corr	f8.3	group correction if applied (seconds)
41-43	Npole	i3	number of poles
45-47	Nzero	i3	number of zeros
49-73	Descip	a25	description
Data			
2-16	Rroot	e15.8	real part of pole or zero
18-32	Iroot	e15.8	imaginary part of pole or zero

The scale factor is in output units per input units. If this is the first stage, (seismometer) section the input units are nm. Otherwise, the input units are the output units of the previous section.
the decimation factor and group correction must be blank for an analog filter and non-blank for a digital filter.
For an analog filter, the poles and zero specify the Laplace transform. For an IIR filter, they specify the Z-transform.

To use this pole-zero representation with the Computer Program in Seismology codes, we express them in a SAC pole-zero format with the major exception that the units will be forced to be output *counts* for input *meters/sec*.The desired velocity sensitivity is obtained by dropping one zero. The conversion from nm to m is accomplished by adding 9 to the scale factor exponent. The desired file, called *WVTBHZ.pz*, is

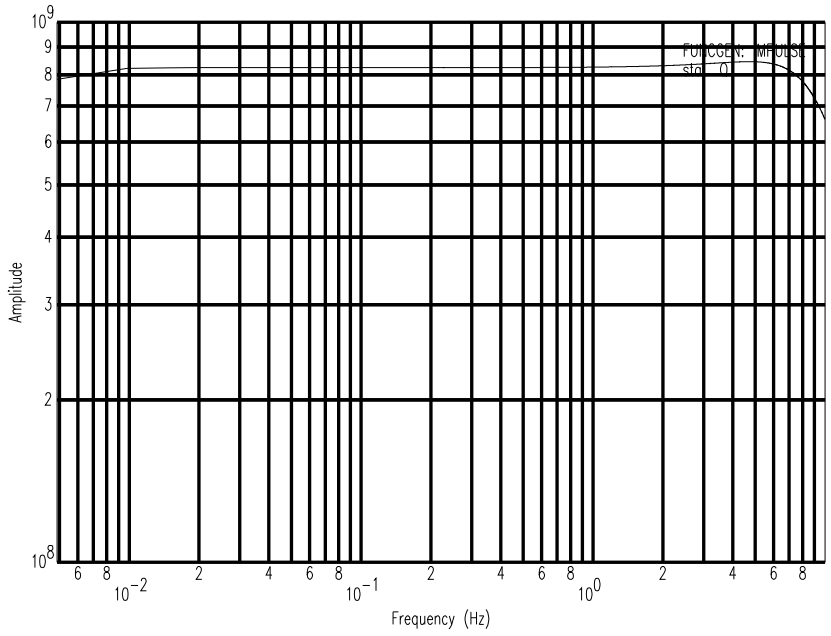
```
ZEROS   2
  0.  0.
  0.  0.
POLES   4
   -1.23400E-02    1.23400E-02
   -1.23400E-02   -1.23400E-02
   -39.1800    49.1200
   -39.1800   -49.1200
CONSTANT     3.25436E+12
```

You can quickly see the correspondence between the numbers in this file and those in the PAZ2 description. To see the response, we can use the **sac2000** *funcgen* and *transfer*

commands:

```
#!/bin/sh

#####
#       program to test the instrument response
#       by convolving the response with the pole zero response
#       Here we test the response in the range from 0.01 - 10 Hz
#       The initial impulse has a height of 1.0 To create
#       one with unit are, divide by the sample rate
#####

sac2000 << EOF
qdp off
funcgen impulse delta 0.05 npts 4096 begin -102.4
div 0.05
transfer from none to polezero subtype WVTBHN.pz
w WVTBHZ.PZ
fft
xgrid on
ygrid on
bg sgf
plotsp am loglog
sgftoai f001.sgf AM.eps 1 t
quit
EOF
```

I did not attempt to plot the phase spectra, since the *funcgen* places the impulse at the center of the trace and this introduces linear phase shift in addition to the instrument phase. The velocity sensitivity plot is



Note that the STS-1 response is essentially flat to velocity in the bad of 100 sec to 6 Hz. To validate the gains stated in the WID2 and CAL2 headers, note that the sensitivity at

1.0 Hz (1.0 second) is about $\mathbf{8.3 \times 10^8}$ counts/meter/second, or equivalently **0.83** counts/nanometer/sec. At a frequency of 1.0 Hz, $\omega = 2\pi$ radians/sec. To obtain the displacement sensitivity return the dropped zero and multiply the velocity sensitivity by ω to give the sensitivity of **5.2** counts/nm. Inverting this gives the constant **0.192** nm/count which is the same as the value **0.193** nm/count in the CAL2 and WID2 headers, given the fact that the **8.3** was obtained from the figure.

3.1 Trace processing

The processing of AutoDRM data follows the same steps described above for processing SEED files. The only difference is the user must manually rename the SAC files to be of the form StionComponent.SAC and manually create the response files. Only the script **`DORESP`** must be modified to become **`DORESPDRM`** because of the different form of the instrument response. Repeating, the steps and scripts are

- **`DOEVT`** - Place the event information in the SAC headers of all `.SAC` files. This is the only modification made to the original files.
- **`DORESPDRM`** - Deconvolve the instrument response from the `.SAC` files. Rename the output files to something with a shorter name. For example the station WCI BHZ component will be names `WCIBHZ.Sac`. The Original trace file will be saved in a subdirectory. The traces will now have the physical units of *m/sec*.

  Since this is a convenient place to process all traces, a list is made of station names, and all components are read in and the traces time synchronized. This means that the same reference time will be used for all traces from that station. One trace will start at this reference time and the others before this time. In terms of the SAC header, one B will be 0.0 and the others negative.
- **`DOCUT`** - Using the synchronized traces, ensure that all traces for a station have the same absolute start and end times by cutting the waveforms. All components will have the same number of sample points. This step is required to rotate the horizontal components into radial and transverse directions. Implementation requires the specification of the name of the local C compiler.
- **`DOROT`** - Actually rotate the two horizontal components. The rotated components will have the component names BHR and BHT, respectively, for the radial and transverse components. For the data set above, the files `WCIBHZ.Sac`, `WCIBHN.Sac`, `WCIBHE.Sac`, `WCIBHR.Sac` and `WCIBHT.Sac` will exist in the current directory.
- **`DODIST`** - Create a data file, `dist.sort`, listing the station name and epicentral distance in order of increasing distance. This provides an easy reference on station distances to assist in selecting traces to process.

- Quality control - this cannot be formalized in a script because it requires the user to examine individual traces. The resultant ground velocity traces may not be useful for many reasons.

  † The desired signal may not be in the trace time window.
  † There may be no resolvable signal at this station because of distance or instrument failure.
  † The waveform may not look appropriate because of an incorrect instrument response used for deconvolution.

3.2 - DORESPDRM

Given the pole-zero response file giving the instrument response in units of counts/meter/sec, one can use the *transfer* command of **sac2000** or the Computer Program in Seismology command **sacfilt** to do this. In the **DORESPDRM** script the *transfer* technique will be used and the **sacfilt** method will be correctly written, but commented out. The script assumes that the pole-zero file has the name *StationComponent.pz*.

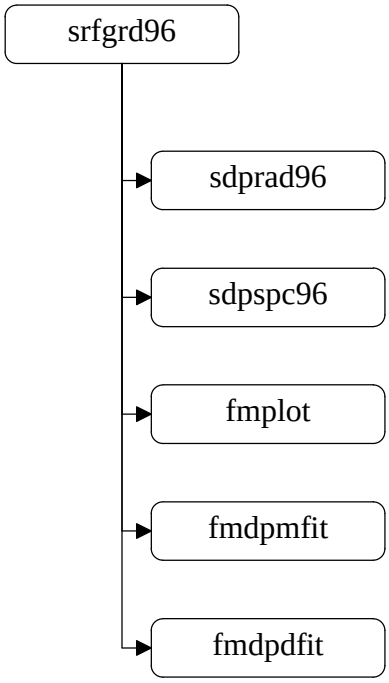
```
#!/bin/sh

#####
#               test for the Raw data directory
#####

if test -d Raw
then
               echo raw Data Directory Exists
else
               mkdir Raw
fi



#####
#               clean up
#####
               rm -f stalist

#####
#               now systematically
#               get the instrument response
#####

for i in *.SAC
do

KSTNM=‘saclhdr -KSTNM $i‘
KCMPNM=‘saclhdr -KCMPNM $i‘
NZYEAR=‘saclhdr -NZYEAR $i‘
NZJDAY=‘saclhdr -NZJDAY $i‘
#####
#       deconvolve the trace
#####
cp $i Raw
mv $i ${KSTNM}${KCMPNM}.sac
```

```
sac2000 << EOF
r ${KSTNM}${KCMPNM}.sac
rtr
taper
w ${KSTNM}${KCMPNM}.sac
quit
EOF


sac2000 << EOF
r ${KSTNM}${KCMPNM}.sac
transfer from polezero subtype ${KSTNM}${KCMPNM}.pz to none freqlimits 0.003 0.002 5 10
decimate 5
w over ${KSTNM}${KCMPNM}.Sac
quit
EOF

#####
#              or
#sacfilt -TAPER -PZ ${KSTNM}${KCMPNM}.pz -R -SACIN ${KSTNM}${KCMPNM}.sac -SACOUT ${KSTNM}${KCMPNM}.Sac
#sac2000 << EOF
#r ${KSTNM}${KCMPNM}.Sac
#decimate 5
#w over ${KSTNM}${KCMPNM}.Sac
#quit
#EOF
#####

echo ${KSTNM} >> stalist
done

#####
#              Now make a list of all stations
#              read in all traces for this station, synchronize,
#              hp c 0.005 np 2 p 2  to remove long period trend
#              write over all *.Sac
#####


cat stalist | sort | uniq > stalist.uniq

for i in ‘cat stalist.uniq‘
do
echo $i
sac2000 << EOF
r ${i}*.Sac
synchronize
hp c 0.005 np 2 p 2
rtr
taper
w over
quit
EOF

done
```

CHAPTER 4
SURFACE-WAVE RADIATION PATTERNS

1. Introduction

This chapter describes the a technique for estimating possible focal mechanisms from fundamental-mode surface-wave radiation patterns from Love- and Rayleigh-wave spectral amplitudes. Because of the combination of spectral amplitudes and a single mode, the theory of surface-wave excitation from earthquake dislocation sources shows that the focal mechanism obtained is not unique. The mechanism can be rotated 180° and/or the P- and T-axes interchanged without affecting the fit to the radiation pattern. The actual mechanism must be selected on the basis of other information such as P-wave first motions.



There are several reasons related to distance for using the spectral amplitude approach. Time-domain waveform modeling, which will be introduced in Chapter 5, requires a well calibrated earth model to use to create the required Green's functions at all distances. At a given frequency, this task becomes increasingly difficult as distance increases because more precision is required in the eacth model velocities. The effect of the earth model upon the surface-wave spectral amplitudes is not as direct as on the phase velocities. Successful time-domain modeling requires a usable signal, even when filtered. A spectral amplitude study can still use the few good spectral amplitudes from the same waveform. If the source depth and focal mechanism are already known, then the output of the program **`sdprad96`** can be used to refine regional estimates

of the anelastic attenuation coefficient, γ.

Spectral amplitudes are obtained from the use of **sacmft96** and **do_mft** to create the data set for the grid search program **srfgrd96**. The output of the grid search is a set of tables of possible focal mechanisms in terms of strike, dip and rake angles with corresponding seismic moment. The program **fmplot** plots the mechanism with optional first motion data. **fmdpmfit** plots the goodness of fit as a vector in the dip-strike space, with the angle of the vector indicating rake and the length the goodness of fit, while the program **fmdpdfot** plots the quality of fit value as a function of depth so that the sensitivity to depth can be determined. The program **sdprad96** plots the observed spectral amplitudes and the predicted radiation patterns. For one station and one wave type, **sdpspc96** plots the theoretical displacement spectrum as a function of period and overlays the spectral amplitudes observed at one station.

2. srfgrd96

The theory of surface-wave spectral amplitudes shows that the complex spectrum for a point source with a step source time function of an observation at a distance, r and and frequency f is given by

$$U_z(r,f) = \frac{M_0}{i\omega}\frac{e^{-\gamma r}}{\sqrt{r}}\left[A(f,h) + iB(f,h)\cos\phi + iC(f,h)\sin\phi + D(f,h)\cos 2\phi + E(f,h)\sin 2\phi\right]$$

$$U_t(r,f) = \frac{M_0}{i\omega}\frac{e^{-\gamma r}}{\sqrt{r}}\left[iF(f,h)\cos\phi + iG(f,h)\sin\phi + H(f,h)\cos 2\phi + I(f,h)\sin 2\phi\right]$$

where M_0 is the seismic moment, h is the source depth, γ is the anelastic attenuation coefficient, and ϕ is the source - receiver azimuth. U_z is the vertical-component Rayleigh-wave spectral amplitude and U_t is the transverse-component Love-wave spectral amplitude. The functions A(), B(), C(), D(), E(), F(), G(), H() and I() are functions of frequency, source depth and the event focal mechanism.

the objective of the program **srfgrd96** is to determine the combination of strike, dip and rake angles and source depth that provides the *best* fit between observed and predicted surface-wave amplitude spectra. For simplicity let O be the observed spectral amplitude at a distance r. T is the theoretically predicted spectral amplitude at a reference distance, r_{ref}, in a medium with no anelastic attenuation and a source with unit seismic moment. γ is the anelastic attenuation coeficient for the medium. The method of separation of the anelastic attenuation effect is apparent.

The search for goodness of fit involved comparing two vectors, x and y, which are defined using the flags **-N1** or **-N2**:

Norm	**y**	x
-N1	$O\,(r/r_{ref})^{1/2}e^{\gamma r}$	T

-N2	$O\,(r/r_{ref})^{1/2}$	$Te^{-\gamma r}$

Both methods require the observed data to be corrected for geometrical spreading. Method 1 removes the effect of anelastic attenuation from the observed data. This weights distant data, especially the short period data, more. Method 2 attempts to match observed to predicted at distance by applying the anelastic attenuation to the prediction. This will actually weigh less the more distant, perhaps noisier data.

The model for the observations is that $y = M_0 x$, where M_0 is the seismic moment. A least squares estimate of the seismic moment is given by

$$M_0 = \frac{x \cdot y}{x \cdot x}$$

which requires vector dot products between the vector of observations. A goodness of fit parameter is defined as

$$R = \frac{x \cdot y}{\sqrt{x \cdot x}\sqrt{y \cdot y}}$$

The quantity R, the normalized vector dot product, is the same as the correlation coefficient if the mean values of x and y are zero. It is easy to show the relation of R to the reduction of variance:

$$\mathrm{RedVar} = 1 - \frac{(y - M_0 x) \cdot (y - M_0 x)}{y \cdot y} = \frac{(x \cdot y)^2}{(x \cdot x)(y \cdot y)} \equiv R^2$$

Since the Love- and Rayleigh-wave amplitude spectra differ in level because of focal mechanism and depth, and because there may be different numbers of observations in each data set, the goodness of fit criteria used attempts to find the solution which reduces the variance of each of the two data sets separately. A R_L and M_{0L} are computed from the Love-wave and R_R and M_{0R} from the Rayleigh-wave data. The *best* solution is defined as that which maximizes R_L and R_R and simultaneously brings the two seismic moment estimates into agreement:

$$BEST = R_L R_R \frac{M_{0L}}{M_{0R}} \quad if \quad M_{0R} > M_{0L}$$

$$\mathrm{BEST} = R_L R_R \frac{M_{0R}}{M_{0L}} \quad \text{if} \quad M_{0R} < M_{0L}$$

Note that dimensionally BEST is similar to the reduction of variance, but can take on values in the range [–1,1]. Other criteria are possible, but this preserves, in some sense, the idea of finding the best fit to each data set individually without the criteria being controlled by one of the two data types.

Figure 1 shows the processing flow for this program. The program requires access to the files *slegn96.der* and *sregn96.der* created using **`slegn96 -DER`** and **`sregn96 -DER`**, respectively. In addition the program requires access to multiple filter analysis spectral amplitudes in the format of **`sacmft96`** or **`do_mft`**. The output files are *FMFIT.sh*, *fmdpfit.dat* and *fmfit001.dat*, *fmfit002.dat*, etc.

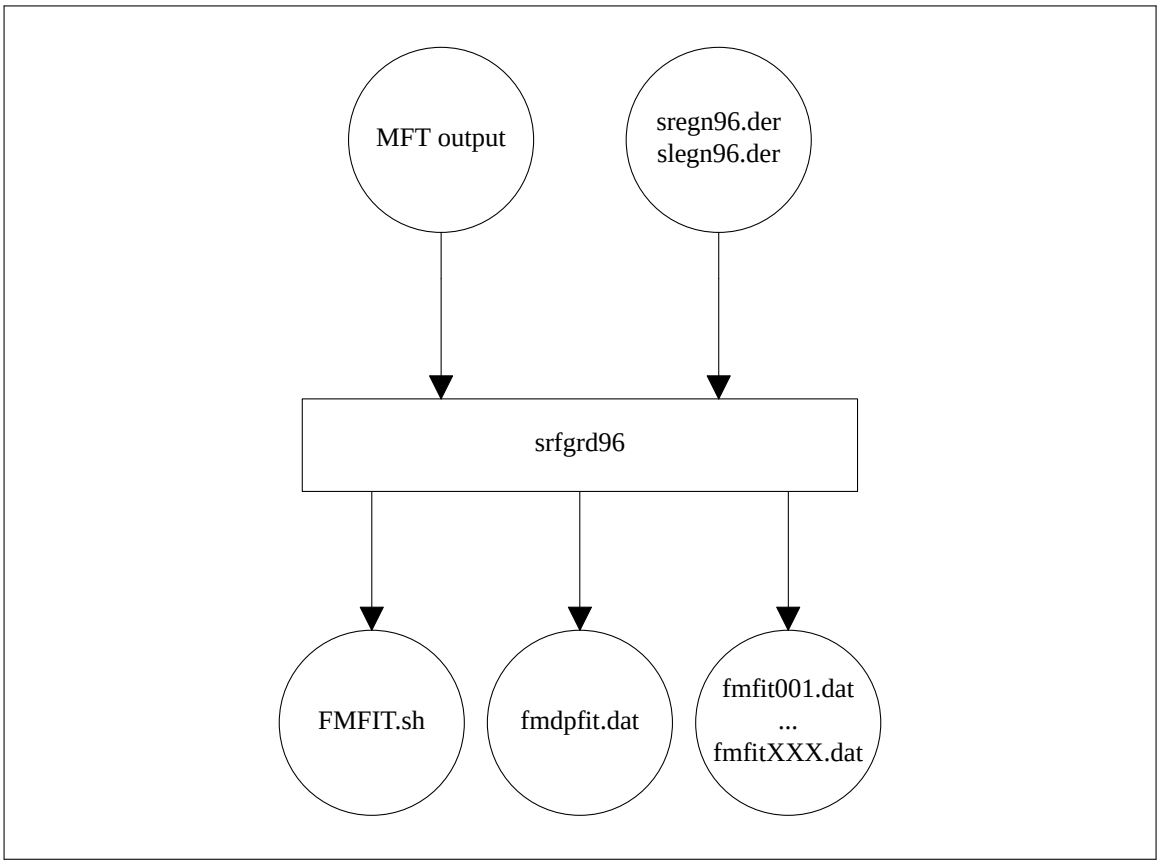


Fig. 1. Processing flow for **srfgrd96**

Program control is through the command line:

srfgrd96 *[flags]*, where the command flags are
- **-DMN dipmn** (default 30) Minimum dip
- **-DMX dipmx** (default 90) Maximum dip
- **-DD ddip** (default 15) Dip increment
- **-RMN dipmn** (default -180) Minimum rake
- **-RMX dipmx** (default 180) Maximum rake
- **-DR ddip** (default 15) Rake increment
- **-SMN stkmn** (default 0) Minimum strike
- **-SMX stkmx** (default 350) Maximum strike
- **-DS dstk** (default 10) Strike increment
- **-HMN dpmin** (default 1) Minimum strike
- **-HMX dpmax** (default 30) Maximum strike
- **-DH ddepth** (default 2) Strike increment
- **-DMIN dmin** (default 0 km) minimum for distance sieve
- **-DMAX dmax** (default 100000 km) maximum for distance sieve
- **-FMAX fitmin** (default 0.5) Goodness of fit output threshold
- **-O observed_data** File with observations
- **-PATH path** (default ./) path to slegn96.der sregn96.der
- **-PMN permn** (default 0) Minimum period to use

-PMX permx (default 2000) Maximum period to use
-N1 Obs*exp(gamma r) vs Theo
-N2 (default) Obs vs Theo*exp(-gamma r)
-? This online help
-h This online help

The terms *Maximum, Minimum and Increment control the search range and the fineness of the search. The computational time depends upon the maximum number of mechanisms considered. The default parameters search through 6 values of dip (90-30)/15 + 1, 25 values of rake and 35 values of strike.*

This program creates several output files: *FMFIT.sh, fmdpfit.dat, fmfit001.dat, fmfit002.fit, ...* The search results are given in the files *fmfit001.dat*, etc., where the index 001, 002 indicates the sequence of search depths. An example of a *fmfit006.dat* is

```
SRGRID96     6.  110.   65.    0. 0.876 0.897   4.36   4.48 0.5055
SRGRID96     6.  110.   65.    5. 0.875 0.888   4.36   4.48 0.5061
SRGRID96     6.  115.   65.   -5. 0.876 0.932   4.36   4.49 0.5132
 ...
```

Where the first word is the name of the search program (used by the programs **fmdpdfit** and **fmdpmfit**). The second entry is the source depth, the third is strike, the fourth is the dip, the fifth is the rake, the sixth is $\mathbf{R_R}$, the seventh is $\mathbf{R_L}$, the eighth and ninth are $\mathbf{M_{0R}}$ and $\mathbf{M_{0L}}$, and the tenth entry is the *Best* value.

The other data file created is *fmdpfit.dat*, which is exactly the same format, but with the largest value of *Best* for each depth:

```
SRGRID96    16.  120.   80.   10. 0.910 0.952   4.55   4.55 0.8646
SRGRID96    17.   30.   80.    5. 0.911 0.952   4.56   4.55 0.8644
SRGRID96    18.   30.   85.   10. 0.929 0.953   4.57   4.56 0.8692
SRGRID96    19.  210.   85.   10. 0.929 0.953   4.57   4.57 0.8792
SRGRID96    20.  120.   80.   10. 0.919 0.952   4.58   4.59 0.8731
SRGRID96    21.  210.   85.   10. 0.920 0.952   4.59   4.59 0.8695
SRGRID96    22.  210.   85.  -10. 0.905 0.951   4.60   4.60 0.8591
SRGRID96    23.  210.   85.    5. 0.894 0.950   4.61   4.61 0.8327
SRGRID96    24.  210.   85.   -5. 0.881 0.950   4.61   4.62 0.8288
SRGRID96    25.  125.   85.    0. 0.855 0.940   4.62   4.62 0.7974
```

The last file, *FMFIT.sh* is a UNIX shell script which uses the data output to create some plots:

```
#!/bin/sh

#####
#     Output of srgrid96
#     For use with fmmfit
#     For use with fmdpdfit and fmdpmfit
#####
fmdpdfit -HMN   1. -HMX  25. < fmdpfit.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 001 < fmfit001.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 002 < fmfit002.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 003 < fmfit003.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 004 < fmfit004.dat
```

```
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 005 < fmfit005.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 006 < fmfit006.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 007 < fmfit007.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 008 < fmfit008.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 009 < fmfit009.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 010 < fmfit010.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 011 < fmfit011.dat
fmdpmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 012 < fmfit012.dat
 ...
```

The use of these files and the auxiliary programs in the analysis of actual earthquake observations is given in Chapter 7 of this tutorial.

3. sdprad96

This program plots theoretical surface wave radiation patterns for selected periods. If optional data are provided, these are placed on the plot. Its use is described in *An Overview of Synthetic Seismogram Computation* in this package. There are two uses of this program. The first, conveniently invoked with the **`-A`** automatic flag plot all radiation patterns so that the fit can be visually inspected. The second permits an overlay of several plots to form a figure for publication.

Figure 2 shows the processing flow for this program. The program requires access to the files *slegn96.der* and *sregn96.der* created using **`slegn96 -DER`** and **`sregn96 -DER`**, respectively. In addition the program requires access to multiple filter analysis spectral amplitudes in the format of **`sacmft96`** or **`do_mft`**. The output files are CALPLOT graphics files *SRADL.PLT* or *SRADR.PLT* and the text files *SRADL.TXT* or *SRADR.TXT*, for Love or Rayleigh wave output, respectively.

Program control is through the command line:

`sdprad96` *[flags]*, where the command flags are

`-DIP dip` dip of fault plane
`-STK Strike` strike of fault plane
`-RAKE Rake` slip angle on fault plane
`-M0 Moment` (def=1.0) Seismic moment in units of dyne-cm
`-MW mw` Moment Magnitude
`-E` Explosion
`-DIST dist` Normalization distance (km)
`-HS hs` Source depth km
`-fx FX -fy Fy -fZ fz` Point force amplitudes (N,E,down) in dynes
`-XX Mxx -YY Myy -ZZ Mzz` Moment tensor elements in units of
`-XY Mxy -XZ Mxz -YZ Myz` dyne-cm
`-X0 x0` (default=1.5) x-coordinate of center of plot
`-Y0 y0` (default=1.75) y-coordinate of center of plot
`-O observed_data` File with observations single period and mode data
`-PER period` (default 20.0 sec) desired period

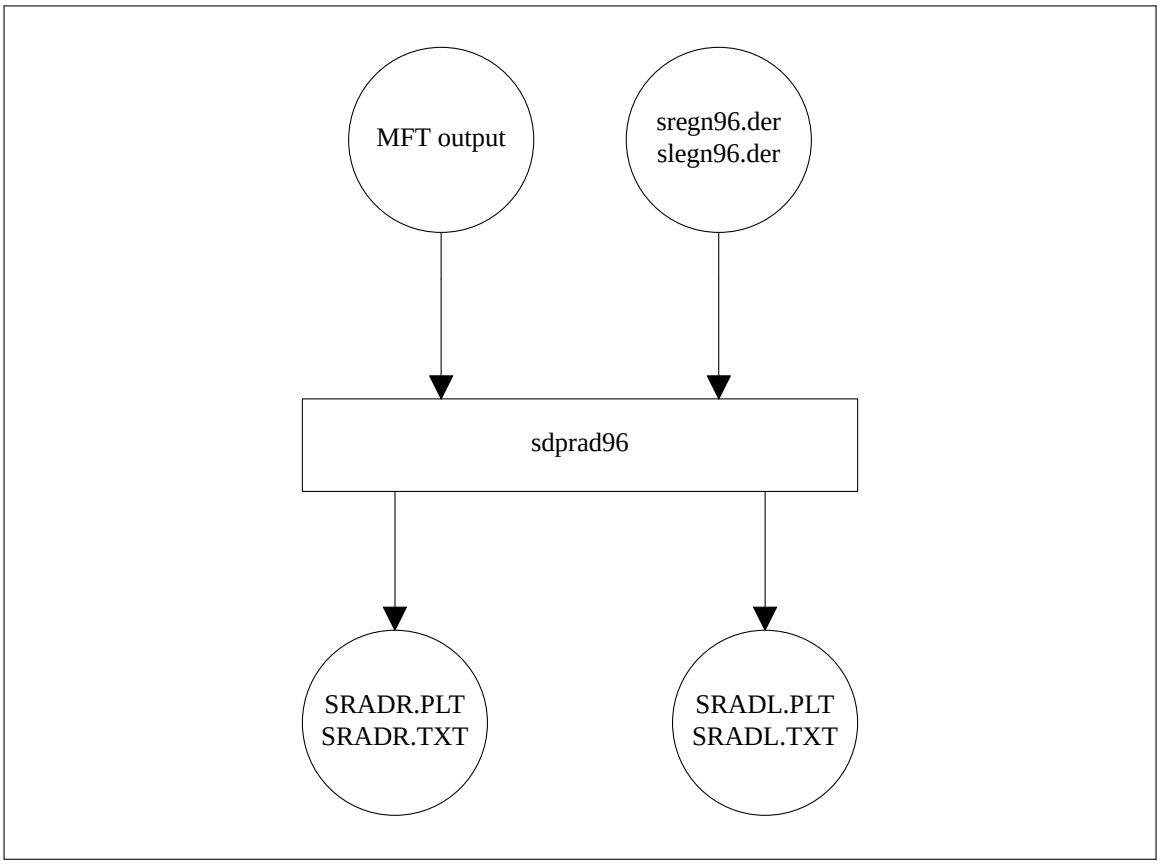


Fig. 2. Processing flow for **sdprad96**

-M mode (default 0) desired mode (0-Fund)
-L (default Rayl) Plot Love wave radiation
-R (default) Plot Rayleigh wave radiation
-DMIN dmin (default 0 km) minimum for distance sieve
-DMAX dmax (default 100000 km) maximum for distance sieve
-A (default false) Plot all periods in one plot
-PATH path (default ./) path to slegn96.der sregn96.der
-? This online help
-h This online help

The output of the program is contained in the plot files *SRADL.PLT* or *SRADR.PLT* and in the text files *SRADL.TXT* or *SRADR.TXT* for Love and Rayleigh plots, respectively. These plots and text files are discussed further in Chapter 7.

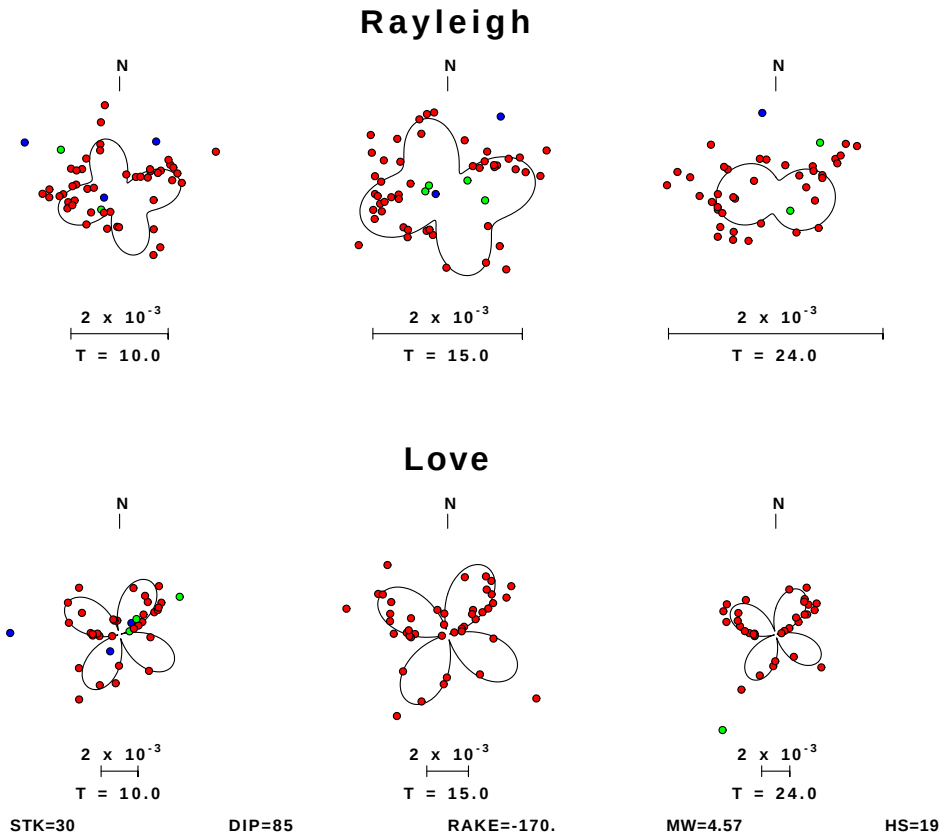
A shell script to overlay the information for several periods is

```
#!/bin/sh
#####
#             define the mechanism, seismic moment and source depth
#####
DMIN=100
DMAX=3000

for HS in 19
do
```

```
case $HS in
               19) STK=30; DIP=85; RAKE=-170.; MW=4.57;;
esac
#####
#              define reference distance and mode
#####
DIST=1000
MODE=0
#####
#              Loop over Rayleigh Wave Data
#####
for FIG in 01 02 03
do
case ${FIG} in
               01) PER=10 ; X0=2.0 ; Y0=6.0;;
               02) PER=15 ; X0=5.0 ; Y0=6.0;;
               03) PER=24 ; X0=8.0 ; Y0=6.0;;
esac
sdprad96 -PATH /home/rbh/PROGRAMS.310t/QST/ -R -DIP ${DIP} -RAKE ${RAKE} \
    -STK ${STK} -DIST ${DIST} -PER ${PER} -HS ${HS} -M ${MODE} \
    -MW ${MW} -O ALL.DSP.nopp -X0 ${X0} -Y0 ${Y0} -DMIN ${DMIN} -DMAX ${DMAX}
mv SRADR.PLT R${FIG}.PLT
done
#####
#              Loop over Love Wave Data
#####
for FIG in 04 05 06
do
case ${FIG} in
               04) PER=10 ; X0=2.0 ; Y0=2.0;;
               05) PER=15 ; X0=5.0 ; Y0=2.0;;
               06) PER=24 ; X0=8.0 ; Y0=2.0;;
esac
sdprad96 -PATH /home/rbh/PROGRAMS.310t/QST/ -L -DIP ${DIP} -RAKE ${RAKE} \
    -STK ${STK} -DIST ${DIST} -PER ${PER} -HS ${HS} -M ${MODE} \
    -MW ${MW} -O ALL.DSP.nopp -X0 ${X0} -Y0 ${Y0} -DMIN ${DMIN} -DMAX ${DMAX}
mv SRADL.PLT L${FIG}.PLT
done
#####
#              use calplt to annotate the final figure
#####
calplt  << EOF
NEWPEN
1
CENTER
5.0 3.5 0.20 'Love' 0.0
CENTER
5.0 7.5 0.20 'Rayleigh' 0.0
LEFT
1.0 0.2 0.1 'STK=${STK}' 0.0
LEFT
3.0 0.2 0.1 'DIP=${DIP}' 0.0
LEFT
5.0 0.2 0.1 'RAKE=${RAKE}' 0.0
LEFT
7.0 0.2 0.1 'MW=${MW}' 0.0
LEFT
9.0 0.2 0.1 'HS=${HS}' 0.0
PEND
EOF
#####
#              concatenate all invividual figures to make
#              final display figure
#####
cat L??.PLT R??.PLT CALPLT.PLT > SRAD${HS}.PLT
```

```
plotnps -F7 -W10 -EPS -K < SRAD${HS}.PLT > SRAD${HS}.eps
#####
#              clean up
#####
rm -f CALPLT.PLT CALPLT.cmd L??.PLT R??.PLT
done
```

The plot resulting is



Each figure provides a scale which gives the displacement spectra in *cm-sec* and the period. The red color indicates that the observed and predicted amplitudes are within a factor of 2, the green within a factor of 3 and the blue that they differ by more than a factor of 3.

4. sdpspc96

This program provides a different way to visualize the fit to the data - a plot of observed and predicted spectral as a function of period.

Figure 3 shows the processing flow for this program. The program requires access to the files *slegn96.der* and *sregn96.der* created using **`slegn96 -DER`** and **`sregn96 -DER`**, respectively. In addition the program requires access to multiple filter analysis spectral

amplitudes in the format of **sacmft96** or **do_mft**. The output files are CALPLOT graphics files *SSPCL.PLT* or *SSPCR.PLT* for Love or Rayleigh wave output, respectively.

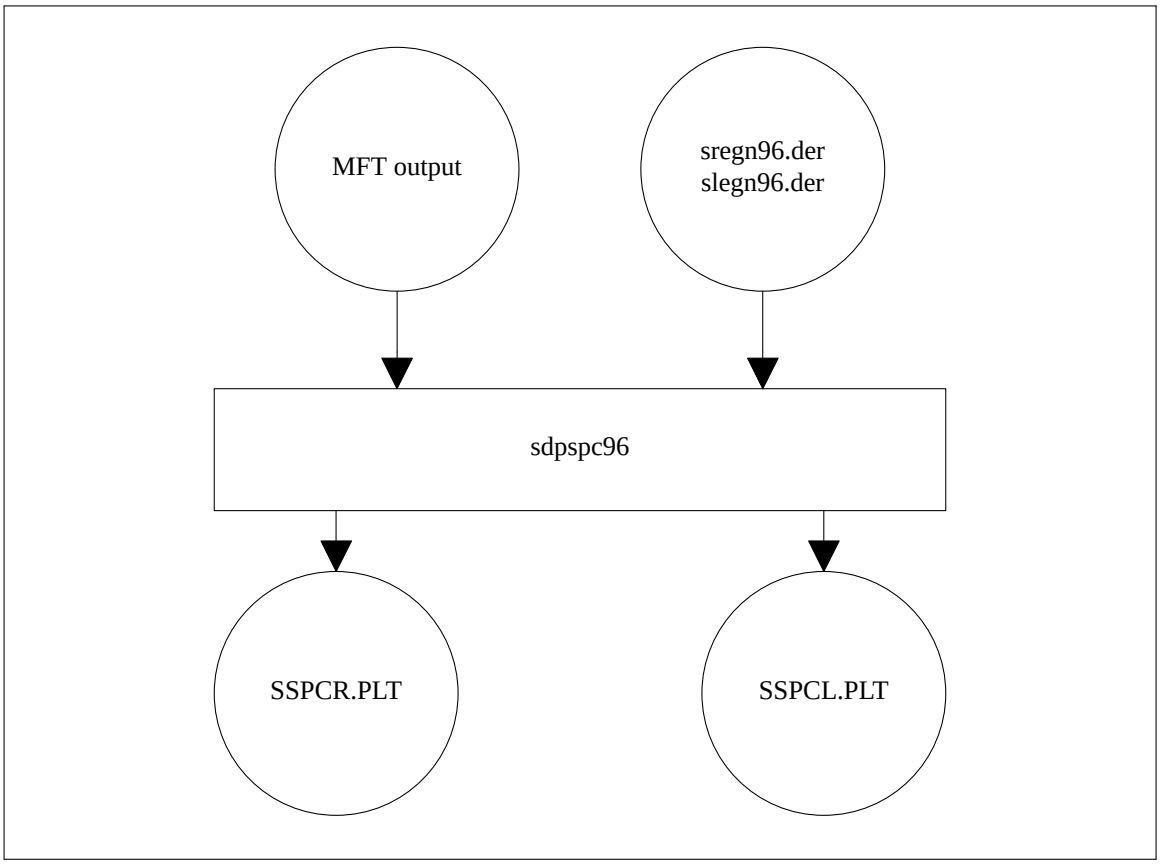


Fig. 3. Processing flow for **sdpspc96**

Program control is through the command line:

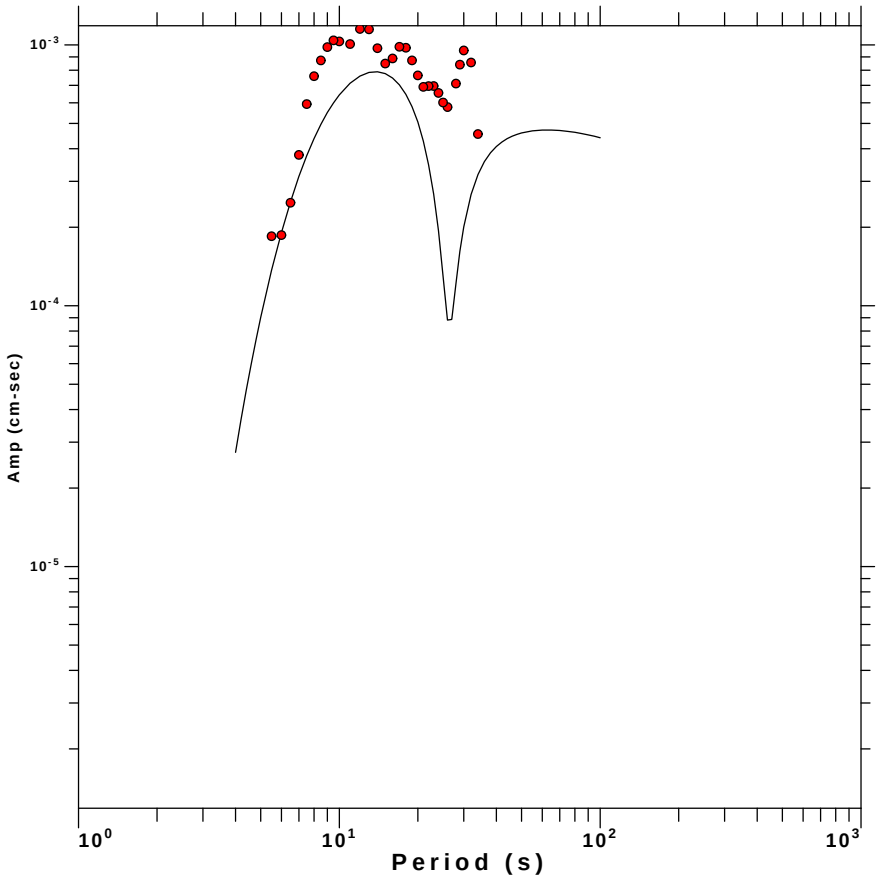
sdpspc96 *[flags]*, where the command flags are
- **-DIP dip** dip of fault plane
- **-STK Strike** strike of fault plane
- **-RAKE Rake** slip angle on fault plane
- **-M0 Moment** (def=1.0) Seismic moment in units of dyne-cm
- **-MW mw** Moment Magnitude
- **-E** Explosion
- **-DIST dist** Normalization distance (km)
- **-HS hs** Source depth km
- **-fx FX -fy Fy -fZ fz** Point force amplitudes (N,E,down) in dynes
- **-XX Mxx -YY Myy -ZZ Mzz** Moment tensor elements in units of
- **-XY Mxy -XZ Mxz -YZ Myz** dyne-cm
- **-FREQ** (default false) X-Axis is frequency
- **-PER** (default true)X-Axis is period
- **-XMIN xmin** (default 0.0) minimum value of X-Axis
- **-XMAX xmax** (default) maximum value of X-Axis

-YMIN ymin (default 0.0) minimum value of Y-Axis
-YMAX ymax (default 0.0) maximum value of Y-Axis
-X0 x0 (default 2.0) lower left corner of plot
-Y0 y0 (default 1.0) bottom left corner of plot
-XLEN xlen (default 6.0) length of X-Axis
-YLEN ylen (default 6.0) length of Y-Axis
-P kolor (default 1) color for curves
-NOBOX (default false) do not plot axes
-XLOG (default linear) X axis is logarithmic
-YLOG (default linear) Y axis is logarithmic
-O observed_data File with observations single period and mode data
-PER period (default 20.0 sec) desired period
-M mode (default 0) desired mode (0-Fund)
-L (default Rayl) Plot Love wave radiation
-R (default) Plot Rayleigh wave radiation
-STA stanam (Required) station name
-COMP cmpnam (Required) component name
-PATH path (default ./) path to slegn96.der sregn96.der
-? This online help
-h This online help

The output of this program is the plotfile *SSPCL.PLT* if the **-L** flag is used, and *SSPCR.PLT* if the **-R** flag is used. An example run is given in this shell script:

```
#!/bin/sh
STA=$1
for HS in 19
do
case $HS in
        19) STK=30; DIP=85; RAKE=-170; MW=4.57;;

esac
#####
#       define reference distance and mode
#####
DIST=1000
MODE=0
sdpspc96 -X0 6 -Y0 1 -XLEN 6 -YLEN 6 -PATH /home/rbh/PROGRAMS.310t/QST/ -R \
   -DIP ${DIP} -RAKE ${RAKE} -STK ${STK} -DIST ${DIST} -PER ${PER} -HS ${HS} -M \
   ${MODE} -MW ${MW} -O ALL.DSP.nopp  -STA  ${STA} -COMP BHZ
```

Invoking this script, named **SDPSPC**, as **SDPSPC FCC**, creates the following plot:



Rayleigh FCC BHZ Dist= 2356.08 Az= 351. Rnorm= 1000.00

CHAPTER 5
WAVEFORM INVERSION

---

1. Introduction

This chapter presents several programs for inverting waveforms for source depth, focal mechanism or moment tensor. Successful inversion requires a good estimate of local structure so that appropriate Green's functions can be generated for the medium. When applying these techniques to real data, it will be necessary to filter both the Green's functions and observed data with the same filters to focus on the signal and not the noise in the observed data.

The requirements are precomputed Green's functions, as discussed in Chapter 2, and instrument corrected data, as discussed in Chapter 3. Further, the P-wave first arrival must be indicated in the SAC headers of the observed data. This time is automatically included in the headers of the synthetics.

2. Waveform Organization

Data need P, copy from

Green save type

3. Data Format

The programs **wvfgrd96**, **wvfmtd96** and **wvfmt96** require only a simple ASCII file to specify the traces. Each line of the input file consists of 4 columns. The second and third columns contain strings which must be delimited by single quotes - ' - because the FORTRAN programs use list directed IO. An example data set is

```
1 'SIUCZ' '013000005' 2.000000
2 'SIUCR' '013000005' 2.000000
3 'SIUCT' '013000005' 2.000000
```

```
1 'MPHZ' '037000005' 0.250000
2 'MPHR' '037000005' 0.250000
3 'MPHT' '037000005' 0.250000
```

The field separators can be blanks or tabs. The column entries have the following meaning:

Column 1: *Integer* Number to indicate the component of motion. 1 = vertical with positive ground motion up, 2 = radial with positive ground motion away from the source, and 3 = transverse with motion to the right when looking away from the source in a radial direction.

Column 2: *String* File name of observed data. This must be delimited by ''s

Column 3: *String* Base of filenames for Green's functions. If the base is *013000005*, then the Green's functions *013000005.ZDD*, *013000005.RDD*, *013000005.ZDS*, *013000005.RDS*, *013000005.TDS*, *013000005.ZSS*, *013000005.RSS*, *013000005.TSS*, *013000005.ZEX*, *013000005.REX* must exist in the working directory. The Green's functions and observed data file names can also have the absolute of relative path included, but it is simpler to run the program in the directory with all files present.

Column 4: *Float* This is a numerical weight applied to the trace. This weight can be anywhere in the range $[0, \infty]$, but a user defined criteria is acceptable, e.g., $[0, 1]$. In the example above the nearest station, which happens to be on a hard rock site 130 km from the source, is weighted 8 times more than the distance data at 370 km of on deep sediment site.

4. wvfgrd96

This program is based on *srcgrd* by Ammon (1994). The program interactively requests the name of the file which contains the waveforms to be used for inversion, and then the name of an output file for search results.

Program control is through standard input and the command line:

wvfgrd96 *[flags]*, where the command flags are

-N *nshift* (default 0) permit waveform shift of ±*nshift* time samples.

-h

-? Online help

If the list of data files is called *ww* and the output file is to be called *oout.0190*, then the program is run as:

```
rbh> wvfgrd96
What is the input file name?
ww
What is the output file name?
oout.0190
rbh>
```

The output consists of the search result file, *oout.0190*, the summary file *fmdfit.dat*, and a predicted waveform for each trace used, e.g., a *SIUCZ.pre* corresponding to *SIUCZ*.

The output file *fmdfit.dat* contains a single line corresponding to the best fitting solution of the weighted data. An example of the output is

```
WVFGRD96  19.0  30  85  170  4.42 0.2985
```

The first entry defines the program used. this is followed by the source depth, strike, dip and rake angles, the moment magnitude, and the goodness of fit parameter. The goodness of fit parameter is the reduction of weighted variance and takes values in the range of $[0,1]$.

The other file, *oout.0190*, in this example, is a large file which presents information about the data set and which gives the result of each strike-dip-rake triplet. The information about the data set indicates whether a waveform is rejected because of different sample rates between the observed data and the Green's functions, and whether an adjustment is made for different numbers of samples. The results for the test focal mechanism look like the following:

```
WVFGRD96  19.0  35  85  165  4.42 0.2835 0.5559 0.6715 0.5044
WVFGRD96  19.0  35  85  170  4.42 0.2845 0.5508 0.6726 0.5055
WVFGRD96  19.0  35  85  175  4.42 0.2772 0.5209 0.6524 0.5059
WVFGRD96  19.0  35  85 -180  4.41 0.2622 0.4607 0.6080 0.5054
```

The first 7 columns have the same meaning as in the file *fmdfit.dat*. The remaining three columns are the normalized vector dot products between the observed and predicted, vertical, radial and transverse components, respectively. Ideally the best solution is the one with values closest to 1.0 for each component.

To visualize the goodness of fit, one can use the program **`fmmfit`** discussed in Chapter 4 as follows:

```
grep WVFGRD96 oout.0190 | fmmfit
```

The output contained in *fmdfit.dat* can be concatenated for each trial depth, and the depth sensitivity seen by using the program **`fmdfit`**.

As of Version 3.30, the predicted waveform can be permitted to shift in order to provide a better fit to the observed traces. This may be necessary because of a slightly imperfect velocity model used to generate the Green's functions or because the Green's functions are not at the exact epicentral distance. The permitted shift is $\pm nshift\ dt$ seconds, where *dt* is the sampling interval. The time shift used is written in the *USER9* header value. A positive value indicates that the synthetic is too early and should be delayed by the indicated number of seconds to ensure a better fit. A negative value indicates that the predicted trace is too slow and should be shifted to an earlier time.

5. wvfmtd96

This program is based on *mtinv* by Ammon (1994). The program performs a least-squares inversion of the waveform for the deviatoric moment tensor. This is accomplished by not using the isotropic Green's functions in the linear inversion. Even though the trace of the deviatoric moment tensor is guaranteed to be zero, the resultant moment tensor will not be that of a double couple source since the non-linear constraint that the eigenvalues of the moment tensor be ($\lambda, 0, -\lambda$) is not applied.

```
rbh> wvfmtd96
What is the input file name?
ww
What is the output file name?
oout.0190
rbh>
```

The output file *fmdfit.dat* contains a single line corresponding to the best fitting solution of the weighted data. An example of the output is

```
WVFMTD96 19.0 300. 89. -12. 4.45 0.101 0.158E-05 0.295 0.130E-05 5.5
```

The first entry defines the program used. this is followed by the source depth, strike, dip and rake angles, the moment magnitude of the major-double couple. Next are the reduction of variance and variance of the unweighted data set, followed by the reduction of variance and variance using the weights. The weighted reduction of variance is used by the programs **`fmdfit`**. The last entry is the percent of the deviatoric moment tensor that is represented as a CLVD. A value of zero indicates that the source is a pure double couple.

The other file, *oout.0190*, in this example, is a large file which presents information about the data set and which gives the moment tensor and its many decompositions. The initial information indicates whether a data set is rejected because of different sample rates between the observed data and the Green's functions, and whether an adjustment is made for different numbers of samples.

The program also provide a predicted waveform file in SAC binary format for each trace used. The name of the file has a *.pre* appended. Thus the data file *SLMZ* will have a prediction *SLMZ.pre*.

Note that the prediction uses the moment tensor. If you wish to see the prediction for the major double couple, run the program **`wvfmch96`**.

6. wvfmt96

This program a simple modification of based on **`wvfmtd96`** which permits an unconstrained data inversion for moment tensor.

```
rbh> wvfmt96
What is the input file name?
ww
What is the output file name?
```

```
oout.0190
rbh>
```

The output consists of the search result file, *oout.0190*, the summary file *fmdfit.dat*, and a predicted waveform for each trace used, e.g., a *SIUCZ.pre* corresponding to *SIUCZ*.

The output file *fmdfit.dat* contains a single line corresponding to the best fitting solution of the weighted data. An example of the output is

```
WVFMT96 19.0 257. 46. -88. 4.88 0.103 0.158E-05 0.296 0.130E-05 56.2
```

The other file, *oout.0190*, in this example, is a large file which presents information about the data set and which gives the moment tensor and its many decompositions. The initial information indicates whether a data set is rejected because of different sample rates between the observed data and the Green's functions, and whether an adjustment is made for different numbers of samples.

The program also provide a predicted waveform file in SAC binary format for each trace used. The name of the file has a *.pre* appended. Thus the data file *SLMZ* will have a prediction *SLMZ.pre*.

Note that the prediction uses the moment tensor. If you wish to see the prediction for the major double couple, run the program **wvfmch96**.

7. wvfmch96

This program reads the control file and creates predicted seismograms for a focal mechanism solution specified on the command line.

Program control is through the command line:

wvfmch96 *[flags]*, where the command flags are

-D dip dip of fault plane
-S Strike strike of fault plane
-R Rake slip angle on fault plane
-M0 Moment (def=1.0) Seismic moment in units of dyne-cm
-MW mw Moment Magnitude
-? This online help
-h This online help

This program a simple modification of based on **wvfmtd96** which permits an unconstrained data inversion for moment tensor.

```
rbh> wvfmt96
What is the input file name?
ww
What is the output file name?
Oout.0190
```

```
rbh>
```

The output consists of the file, *out.0190* and a predicted waveform for each trace used, e.g., a *SIUCZ.prd* corresponding to *SIUCZ.* The string *.prd* appended to the data file name is different that the *.pre* produced by **`wvfgrd96`**, **`wvfmtd96`** or **`wvfmt96`**, so that one compare the synthetics from this user specified focal mechanism to the original data and to the best estimate from the other programs.

8. Summary

The waveform inversion programs presented are simple in the sense that data preparation is done prior to the inversion. This was done to make the programs simpler and hopefully easier to understand. Many things can be done on a trace by trace basis. Traces and corresponding Green's functions can be filtered differently. Green's functions can be time shifted slightly with respect to the observed trace for better signal correlation. Finally the Green's functions can be convolved with an appropriate source time function.

CHAPTER 6
DISPLAY PROGRAMS

---

1. Introduction

This chapter presents some useful utility programs for source mechanism studies. **fmplot** plot the focal mechanism and radiation patterns on the focal sphere, **fmdfit** plots goodness of fit parameter from programs such as **srfgrd96** as a function of depth, and **fmmfit** plots the goodness of fit from programs such as **srfgrd96** for a given depth in terms of strike, dip and rake.

2. fmplot

This program plots radiation pattern information for a general moment-tensor and point force sources on equal area or stereographic upper or lower hemisphere projections. The program is general enough to make some interesting plots.

Program control is from the command line and an optional P-wave first motion data file. Output consists of a CALPLOT graphics file *FMPLOT.PLT*, screen output.

The first motion data file consists of a single line for each observation of the format

```
Azimuth Takeoff_angle polarity
```

Since list direction FORTRAN IO is used, an optional string placed at the end will be ignored. The following would be an acceptable data set:

```
289 48 -1 'SLM'
257 66 -1 'SIUC'
 39 48 +2 'BLO'
271 48 -1 'CCM'
179 48 +1 'WVT'
 77 66 -1 'WCI'
```

Program control is through the command line:

fmplot *[flags]*, where the command flags are

-eq	Equal area projection (default)
-st	Stereographic projection

-XX Mxx (1,1) component of moment tensor
-XY Mxy (1,2) component of moment tensor
-XZ Mxz (1,3) component of moment tensor
-YY Myy (2,2) component of moment tensor
-YZ Myz (2,3) component of moment tensor
-ZZ Mzz (3,3) component of moment tensor
-P P-wave display
-SV SV-wave display
-SH SH-wave display
-pol S-wave polarization angle
-RAD rad Radius of circle (default 2.0 in)
-X0 x0 x-coordinate of center of circle (default 4.0 in)
-Y0 y0 y-coordinate of center of circle (default 4.0 in)
-S Strike of fault plane
-D Dip of fault plane
-R Rake or rake angle on plane
-MOM Mom Seismic moment in dyne-cm)default 1.0)
-MW Mw Moment Magnitude
-FMFILL Solid Fill region of positive amplitude (default = .false.)
-FMPLMN Fill region with +- signs related to amplitude (default = false)
-FMAMP Display amplitude contour (default = .false.)
-F file file contains P-wave first motion data
Trend Takeoff-angle ID
where ID =+-1 > Circle/triangle, +-2 -> + or - sign
-ANN Annotate plot with type: P, SV, SH, S or pol
-Z Clears background - useful for Overlays (default=false)
-TT title Title above plot
-TB subtitle Title below plot
-TS titlesize (inches. Default=0.28*rad)
-NM No mechanism only circle and first motion data
-K For amplitude plots use red for zero line
-UP Upper hemisphere projection (default lower)
-F1 f1 -F2 f2 -F3 f3 (default 0.0) point force
-? Usage query, but no execution
-h Usage query, but no execution

An example of how to use this program and the resultant plot follows. The test program illustrate the use of many options available.

```
#!/bin/sh
#####
#             create first motion data file
#####
cat > dfile << EOF
45 10 -1
45 80 1
0 110 -1
0 170 1
EOF
#####
#             define focal mechanism
```

```
#####
DIP=70
STK=0
RAKE=25
#####
#              create plot annotations
#####

calplt << EOF
CENTER
2.5 7.5 0.10 'P' 0.0
CENTER
2.5 5.0 0.10 'SH' 0.0
CENTER
2.5 2.5 0.10 'SV' 0.0
CENTER
7.5 7.5 0.10 'POL' 0.0
CENTER
7.5 5.0 0.10 'Observed P' 0.0
CENTER
7.5 2.5 0.10 'P' 0.0
PEND
EOF
cat CALPLT.PLT > MECH.PLT
rm CALPLT.PLT CALPLT.cmd

fmplot -RAD 1.0 -X0 1.25 -Y0 6.5  -P -D ${DIP} -R ${RAKE} -S ${STK} -FMPLMN -FMPLMN
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 3.75 -Y0 6.5  -P -D ${DIP} -R ${RAKE} -S ${STK} -FMPLMN -FMPLMN -UP
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 1.25 -Y0 4.0  -SH -D ${DIP} -R ${RAKE} -S ${STK} -FMPLMN -FMPLMN
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 3.75 -Y0 4.0  -SH -D ${DIP} -R ${RAKE} -S ${STK} -FMPLMN -FMPLMN -UP
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 1.25 -Y0 1.5  -SV -D ${DIP} -R ${RAKE} -S ${STK} -FMPLMN -FMPLMN
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 3.75 -Y0 1.5  -SV -D ${DIP} -R ${RAKE} -S ${STK} -FMPLMN -FMPLMN -UP
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 6.25 -Y0 6.5  -pol -D ${DIP} -R ${RAKE} -S ${STK}
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 8.75 -Y0 6.5  -pol -D ${DIP} -R ${RAKE} -S ${STK}  -UP
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 6.25 -Y0 4.0  -P -D ${DIP} -R ${RAKE} -S ${STK} -F dfile
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 8.75 -Y0 4.0  -P -D ${DIP} -R ${RAKE} -S ${STK} -F dfile -UP
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 6.25 -Y0 1.5  -P -D ${DIP} -R ${RAKE} -S ${STK} -FMFILL
cat FMPLOT.PLT >> MECH.PLT
fmplot -RAD 1.0 -X0 8.75 -Y0 1.5  -P -D ${DIP} -R ${RAKE} -S ${STK} -FMFILL -UP
cat FMPLOT.PLT >> MECH.PLT

cat FMPLOT.PLT >> MECH.PLT
#####
#              clean up
#####
plotnps -F7 -W10 -EPS -K < MECH.PLT > mech.eps
rm MECH.PLT
rm FMPLOT.PLT
rm dfile
```

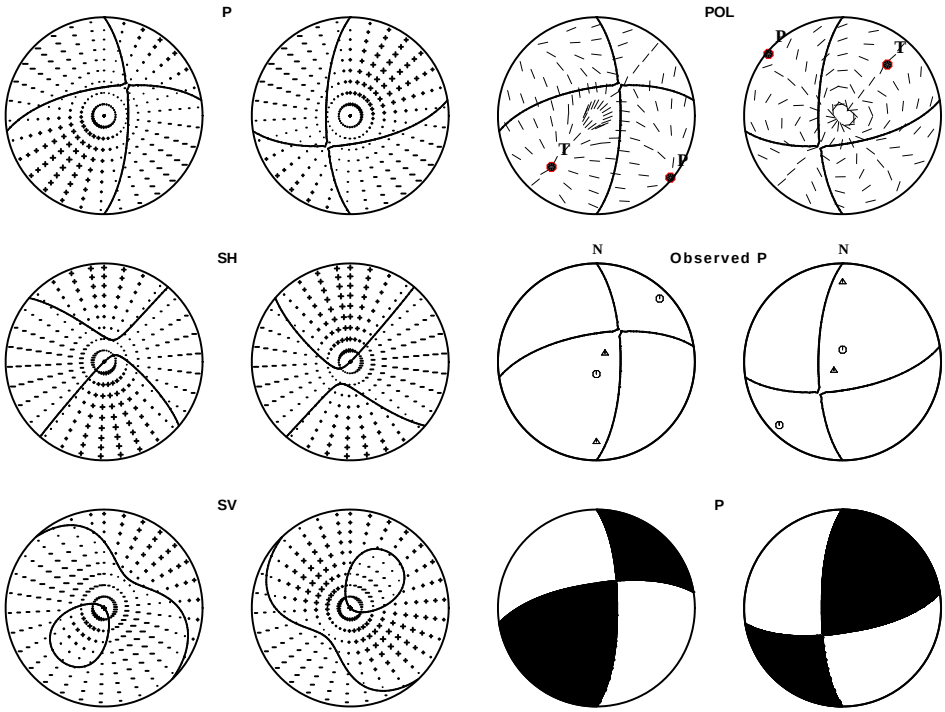


Fig. 1. Output of **fmplot** test script. The output consists of focal mechanism amplitude plots for P, SH, SV and S motions, first motion and S-wave polarization. For each type of plot there are two figures - the left is the projection of the amplitudes on the lower hemisphere, and the right onto the upper. The shear dislocation source has a strike of 0°, a dip of 70° and a rake of 25 °.

In addition to the CALPLOT file *FMPLOT.PLT*, the program outputs some text. Consider the command

```
fmplot -MW 6 -RAD 1.0 -X0 6.25 -Y0 4.0  -P -D 70 -S 0 -R 25 -F dfile
```

which gives the following text:

```
 DIP       =  70.
 RAKE      =  25.
 STRIKE    =  0.
 MOMENT    =  1.12201652E+25
 Equivalent Moment Tensor
  M(1,1)    =  0.
  M(1,2)    =  9.55566188E+24
  M(1,3)    = -3.47797651E+24
  M(2,1)    =  9.55566188E+24
  M(2,2)    = -3.04800049E+24
  M(2,3)    = -3.6324654E+24
  M(3,1)    = -3.47797651E+24
  M(3,2)    = -3.6324654E+24
  M(3,3)    =  3.04800049E+24
 EIGENVALUE, AND EIGENVECTOR OF M(i,j)
-0.1122E+26  ( 0.6409E+00,-0.7667E+00,-0.3897E-01)
 0.6001E+17  (-0.4226E+00,-0.3100E+00,-0.8517E+00)
 0.1122E+26  (-0.6409E+00,-0.5623E+00, 0.5227E+00)
P-WAVE FIRST MOTION DATA
 TR   PL   AZ   Io   Pol    Amp
 45.  80.  45.  10.   -1 0.148E+25 Inconsistent
 45.  10.  45.  80.    1 0.616E+25
180.  20.   0. 110.   -1 0.259E+25 Inconsistent
```

```
    180.  80.   0. 170.    1 0.415E+25
```

This output lists the source parameters given on the command line, the correponding moment tensor. The eigenvectors of the moment tensor provide the orientations of the pressure, null and tension axes. The P-wave first motion output gives the trend and plunge of the observation for plotting onto the focal sphere, the azimuth, takeoff angle and polarity of the first motion, the predicted P-wave amplitude, and an indication whether the observed polarity is or is not consistent with the predicted first motion. The first inconsistency has a low, perhaps nodal, predicted amplitude which may explain the inconsistency.

3. fmmfit

This program attempts to visually represent the goodness of fit of a grid search for a focal mechanism. For each strike, dip and rake value there is a corresponding goodness of fit parameter in the range [0,1]. This goodness of fit value is used to define the length of a vector and the rake the orientation of the vector. This is plotted on a dip-strike grid. The program recognizes the output of the programs **`srfgrd96`** and **`wvfgrd91`**. The output is a CALPLOT graphcis file names *FMMFIT.PLT*, or optionally, *FMMFITxx.PLT* where *xx* is an integer specified by the **`-ID`** flag. Examples of these plots are seen in §2 of Chapter 7.

Program control is through the command line:

`fmmfit` *[flags]*, where the command flags are
- **`-DMN dipmn`** (default 30) Minimum dip
- **`-DMX dipmx`** (default 90) Maximum dip
- **`-DD ddip`** (default 15) dip increment
- **`-SMN stkmn`** (default 0) Minimum strike
- **`-SMX stkmx`** (default 350) Maximum strike
- **`-DS dstk`** (default 10) strike increment
- **`-ID jid`** (default 0) Integer ID for naming plot
- **`-?`** This online help
- **`-h`** This online help

4. fmdfit

This program plots the goodness of fit parameter from the programs **`srfgrd96`**, **`wvfgrd96`**, **`wvfmtd96`** or **`wvfmt96`** as a function of depth. See the exmaples in Chapter 7 on how to invoke **`fmdfit`**. Presumably the depth with the largest value is the correct one.

Program control is through the command line:

`fmdfit` *[flags]*, where the command flags are

-HMN hmn (default 0) Minimum depth
-HMX hmx (default 40) Maximum depth
-M (default no) plot mechanism
-? This online help
-h This online help

5. fmtp

This is not a graphical display program but a utility that permits one to convert between a strike, dip and rake description of a fault plane solution to the tension- and pressure-axis description. It can also be used to obtain the other nodal plane from a given nodal plane.

Program control is through the command line:

fmtp *[flags]*, where the command flags are
-D dip dip of fault plane
-S strike strike of fault plane
-R rake rake angle on fault plane
-PTR ptrend P-axis trend, 0 = N
-PPL pplunge P-axis plunge, 90 = down
-TTR ttrend T-axis trend, 0 = N
-TPL tplunge T-axis plunge, 90 = down
-? This online help
-h This online help

As an example consider focal mechanism in §2, e.g., one with a dip of 70°, a rake of 25° and a strike of 0°. The output below indicates that the other fault plane can be charactrized by a strike of 261°, a rake of 158° and a dip of 67°.

```
fmtp -D 70 -R 25 -S 0
  NODAL PLANES

  STK=     360.00
  DIP=      70.00
 SLIP=      24.99

            OR

  STK=     260.94
  DIP=      66.61
 SLIP=     158.12

         X-DIR     Y-DIR     Z-DIR

 X:(     -0.91,      0.14,      0.40 )
 Y:(      0.00,     -0.94,      0.34 )
 Z:(      0.42,      0.31,      0.85 )
 T:(     -0.64,     -0.56,      0.52 )
 P:(     -0.64,      0.77,      0.04 )

         TREND     PLUNGE
```

```
X:(    170.92,     23.39 )
Y:(    269.99,     20.01 )
Z:(     36.27,     58.38 )
T:(    221.25,     31.51 )
P:(    129.88,      2.22 )
```

which gives the same results as the command

```
fmtp -PPL 2.22 -PTR 129.88 -TPL 31.51 -TTR 221.25
```

CHAPTER 7
CASE STUDY

1. Introduction

In this chapter, we will discuss the June 18, 2002 Evansville, Indiana earthquake. Moderate to small earthquakes affect this region of the central United States, with a magnitude 5 earthquake occurring every ten years. Because of this level of seismicity, the region has been monitored by seismograph stations for almost one hundred years. Recently, the region has seen the installation of broadband digital instruments. Even with these instruments, there are never enough stations for good depth location.

The initial location was incorrect by at least 100 km because of the few automatic observations used in the location. About 20 minutes after the location, the USGS provided a reviewed location. The locations for this event are

Date	Time (UT)	Lat (°N)	Lon (°W)	Dep (km)	Mag (Lg)	Authority
02/06/18	17:37:15.2	37.985	87.778	5.0	4.4	USGS
02/06/18	17:37:16	38.01	87.80	3.8	4.9	SLU - regional stations
02/06/18	17:37:16	37.97	87.79	6.2	4.9	SLU - with Indiana PEPP stations
02/06/18	17:37:16.8	37.97	87.78	15.76	4.9	SLU, Indiana PEPP and New Harmony

PEPP, Princeton Earth Physics Project, has vertical component broadband sensors installed in schools in Indiana. The USGS did not have access to these readings for rapid determination. The PEPP stations were installed by Indiana University and Purdue University.

A short period instrument was installed at New Harmony, Indiana, in a State Museum. These data were available to Indiana University through an Earthworm system forwarding data to a Kinemetrics Antelope acquisition and analysis system. These data were not available for the initial location.

The arrival times used in the SLU final location using their *Upland* velocity model is presented next. We will use the P-wave takeoff angles to plot first motions on the focal mechanism.

```
 STA   DIST   AZM  AIN  P-SEC  TPCAL  P-RES  WT  S-SEC  S-RES WT
*NHIN   23.4  321  124  21.70   4.64   0.25  2   25.00   0.15 3
 PPCH   47.7   20  108  25.05   8.26  -0.02  3   30.90  -0.22 3
 PPCC  104.0   81   66  33.68  17.16  -0.29  2   46.44  -0.09 3
 SIUC  130.1  257   66  37.17  21.04  -0.69  1   52.62  -0.64 2
 WCI   133.5   77   66  37.98  21.55  -0.38  2   54.43   0.29 2
```

```
 PEGH  150.1   37   66  40.52  24.03  -0.33  2   58.28  -0.16 3
 PBNL  154.1   48   66  41.24  24.63  -0.20  3   61.30   1.83 3
*CGM2  159.4  241   66  42.07  25.43  -0.17  2    0.00   0.00 0
*CGM1  172.3  248   48  43.89  27.14  -0.06  2    0.00   0.00 0
 BLO   172.9   39   48  43.85  27.20  -0.16  2   64.54   0.61 2
 PNVW  180.3   17   48  44.79  28.11  -0.13  3   66.77   1.27 3
*CGM4  185.6  241   48  45.86  28.76   0.29  1    0.00   0.00 0
*CGM3  194.7  248   48  47.17  29.88   0.48  1    0.00   0.00 0
 UTMT  204.6  208   48  48.85  31.08   0.96  2   75.08   0.64 8
 WVT   206.4  179   48  48.86  31.30   0.75  3   73.67  -1.27 8
 SLM   227.8  289   48  50.79  33.91   0.06  2   78.12  -2.85 7
 TYS   252.1  284   48  54.24  36.89   0.53  3    0.00   0.00 0
 CCM   304.8  271   48  60.79  43.33   0.47  3  100.95  -1.73 8
 PMUN  322.9   39   48  61.74  45.55  -0.62  3    0.00   0.00 0
 PLAL  332.8  184   48  63.80  46.75   0.23  3  110.81   0.25 8
 MPH   369.8  211   48  68.40  51.28   0.31  3  121.00   0.02 8
```

STA is the station name, DIST is the epicentral distacne in kn, AZM is the soruce-to-receiver azimuth, **AIN** is the P-wave takeoff angle, P-SEC is the P-wave arrival time, TPCAL is the predicted P-wave travel time, P-RES is the P-wave residual in sec, WT is a quality weight, with similar meaning for the S arrivals. The asterisk indicates stations with a short period sensor. All station data are digital. The weighting scheme is based on HYPO71, for which a 0 is maximum weight and a 4 is zero weight. The weights 5-8 indicate that the S arrival is Lg and not direct S and that a 5 has maximum weight and an 8 zero weight. Arrival times are with respect to reference time of 17:37:00.0.

The importance of this exercise is that depth control was possible only by adding the data from the station NHIN which has an epicentral distance of about 1.5 source depths. Thus we again realize that adequate depth determination requires other information, available only from regional waveforms.

This may be possible directly from the waveform if the the P- and svP-phases from the source have adequate amplitudes. The svP is the SV component of the S-wave from the source which refracts along the free-surface as a P-wave. For a simple halfspace, travel times of the P and sP phases are

$$T_P = \frac{\sqrt{r^2 + h^2}}{V_P}$$

$$T_{sP} = \frac{h \cos i_c}{V_S} + \frac{r}{V_P}$$

where $\sin i_c = V_S/V_P$, h is the source depth, and r is the epicentral distance. At large distance, $r \gg h$, $T_P \approx r/V_P$ and the time difference between these two arrivals is

$$T_{sP} - T_P = \frac{h \cos i_c}{V_S}$$

If we assume that $V_P/V_S = \sqrt{3}$, and that $V_S = 3.5$ km/sec, then $T_{sP}(\text{sec}) - T_P(\text{sec}) = h(\text{km})/4.38$. If these phases can be identified, then the depth can be determined.

Fortunately, these phases are seen at the IRIS station WCI, 133 km ENE of the earthquake. To see the phases, the wave forms are detrended, and end tapered, and passed through a 2-pole Butterworth highpass filter at 0.01 Hz and a 2-pole lowpass filter at 0.15 Hz. Figure 1 presents these filtered traces. The $T_{sP} - T_P = 4.98$ sec, which implies a depth of 21.8 km. This depth is a maximum since the S-wave velocity may be slightly greater than the assumed 3.5 km/sec.

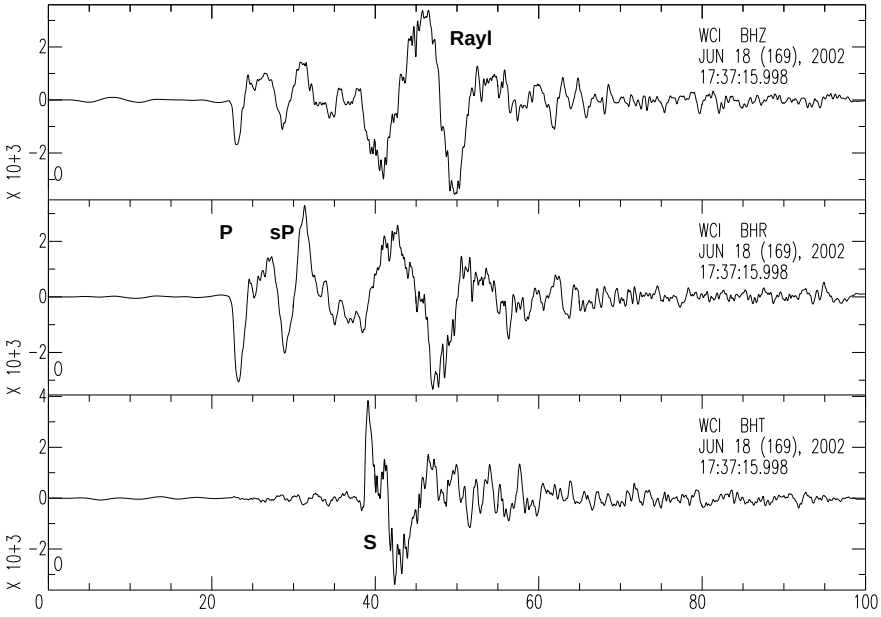


Fig. 1. Bandpass filtered waveforms at WCI. The P, sP and S arrivals are noted. The first point on each trace is the origin time. The sense of motion on the three components is that positive is up on BHZ, radially away form the source in BHR and in a horizontal direction to the right when viewed from the source on the BHT component.

The WCI waveform has good signal-to-noise, and well developed phases: P, sP and Rayleigh on the vertical and radial components and the SH on the transverse component. This single station's three-component waveforms may be adequate for a single station determination of source parameters by waveform modeling.

This earthquake was well recorded by broadband stations in North America. Figure 2 shows the stations used on a continental scale map while Figure 3 shows the stations closer to the source.

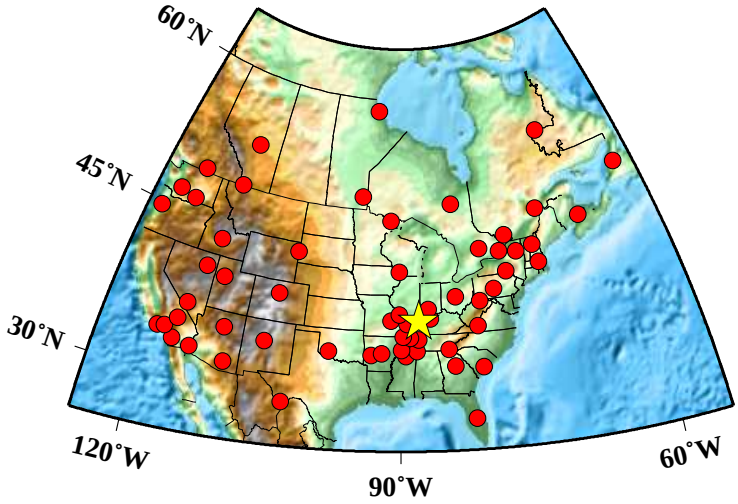


Fig. 2. Broadband stations used in the analysis of this earthquake.

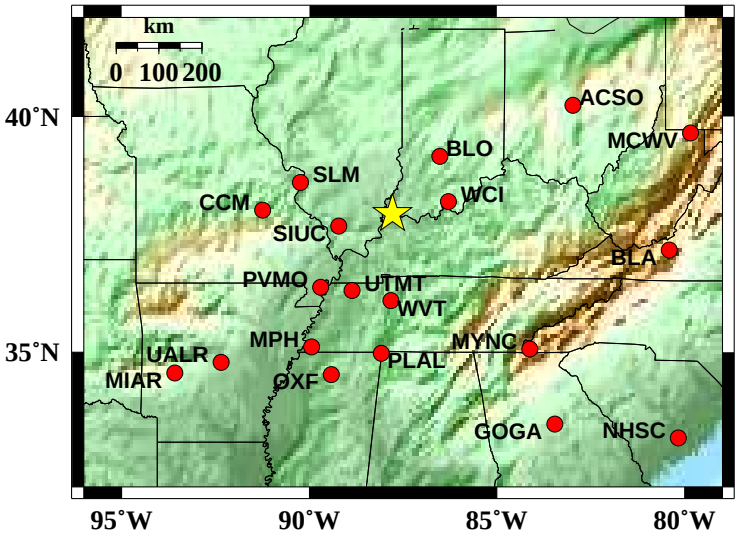


Fig. 3. Broadband stations used which were nearer to the epicenter.

2. Surface-Wave Spectral Amplitudes

Surface-wave spectral amplitudes were prepared by obtaining the digital data from IRIS and SLU, deconvolving to ground velocity in *m/sec* using the IRIS program **`evalresp`** and the program **`sacevalr`**. Radial and transverse components were formed from the horizontal components. The waveforms were decimated to 0.25 sec, which is adequate for the surface-wave studies. The spectral amplitudes were estimated using the program **`do_mft`**, with the α filter parameter chosen to be 100 for distances > 2000 km and 50 at shorter distances. The spectral amplitude data were selected on the basis of expected group velocities and spectral amplitude shapes.

The data set consisted of 1046 Love-wave and 1362 vertical component Rayleigh-wave spectral amplitude points. The focal mechanism search was performed in two ways

by using the *-N1* and *-N2* command line flags to **srfgrd96**. In both runs a fine search was performed. Normally a crude search with rake, dip and strike increments of 15° is performed. The initial results are scanned and the search is repeated with finer increments over a limited range of strike, dip and rake angles. Since the best fit to surface-wave spectral amplitudes is desired, one need only search over 180° in rake instead of the 360° required for fit waveforms.

The Central U. S. (Herrmann and Ammon, 1997) earth model used to generate the surface-wave eigenfunctions is as follows:

```
MODEL.01
CUS Model with Q from simple gamma values
ISOTROPIC
KGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11
  H(KM) VP(KM/S) VS(KM/S) RHO(GM/CC)   QP   QS  ETAP  ETAS  FREFP  FREFS
  1.0000  5.0000  2.8900  2.5000 0.172E-02 0.387E-02 0.00  0.00  1.00  1.00
  9.0000  6.1000  3.5200  2.7300 0.160E-02 0.363E-02 0.00  0.00  1.00  1.00
 10.0000  6.4000  3.7000  2.8200 0.149E-02 0.336E-02 0.00  0.00  1.00  1.00
 20.0000  6.7000  3.8700  2.9020 0.000E-04 0.000E-04 0.00  0.00  1.00  1.00
  0.0000  8.1500  4.7000  3.3640 0.194E-02 0.431E-02 0.00  0.00  1.00  1.00
```

The Q model is chosen to fit previously observed spectral amplitude decay with distance for this part of North America.

2.1 Search using -N1 Weighting

This scheme removes the effect of anelastic attenuation from all observations and then compares them with theoretical predictions for an non-attenauting earth. The shell script for performing the grid search is:

```
#!/bin/sh

#####
#              clean up
#####
rm -f fmfit*
#####
#              do a complete search - normally one would use larger values of
#              DD DH DS and DR
#
#              note that since amplitude spectra are being fit, the search over
#              rake need only cover 180 degrees since strike is varied over 360 degrees
#              - hence the restriction to positive values here
#####
srfgrd96 -N1 -PATH . -O ALL.DSP.nopp -DMIN 100 -DMAX 3000 -DMN 30 -DMX 90 -DD 5 \
     -RMN -90 -RMX 90 -DR 5 -SMN 0 -SMX 355 -DS 5 -FMIN 0.5 -HMN 1 -HMX 25 -DH 1
```

Computations took about 5 minutes per depth on a 1.6GHz Pentium IV PC running LINUX, because each depth search examined 13 dip, 37 rake and 72 strike angles for a total of 34632 focal mechanisms.

Output consists of the files `FMFIT.sh`, `fmfit.dat`, and `fmfit001.dat` through `fmfit025.dat`. The file `fmfit.dat` summarizes the mechanism that provided the best fit for each depth:

```
SRFGRD96     1.   30.   75.   20. 0.848 0.929   4.21   4.47 0.3205
SRFGRD96     2.   35.   75.   20. 0.870 0.930   4.30   4.47 0.4485
SRFGRD96     3.  130.   80.   -5. 0.844 0.891   4.35   4.44 0.5615
SRFGRD96     4.  310.   80.   -5. 0.828 0.893   4.40   4.44 0.6451
SRFGRD96     5.  130.   80.   -5. 0.815 0.894   4.43   4.44 0.6940
SRFGRD96     6.  310.   80.   -5. 0.814 0.896   4.45   4.45 0.7286
SRFGRD96     7.  305.   80.   -5. 0.823 0.929   4.46   4.47 0.7446
SRFGRD96     8.  125.   80.   -5. 0.834 0.931   4.47   4.47 0.7731
SRFGRD96     9.  300.   80.   -5. 0.850 0.945   4.49   4.49 0.7973
SRFGRD96    10.  125.   80.  -10. 0.865 0.933   4.49   4.49 0.8047
SRFGRD96    11.  125.   80.  -10. 0.875 0.934   4.50   4.50 0.8166
SRFGRD96    12.  125.   80.  -10. 0.885 0.935   4.51   4.51 0.8238
SRFGRD96    13.  125.   80.  -10. 0.894 0.937   4.51   4.52 0.8303
SRFGRD96    14.  305.   80.  -10. 0.901 0.938   4.52   4.52 0.8350
SRFGRD96    15.  305.   80.  -10. 0.906 0.939   4.53   4.53 0.8372
SRFGRD96    16.  120.   80.   10. 0.902 0.952   4.55   4.55 0.8429
SRFGRD96    17.  300.   80.   10. 0.906 0.952   4.56   4.56 0.8499
SRFGRD96    18.  120.   80.   10. 0.907 0.952   4.57   4.57 0.8535
SRFGRD96    19.  120.   80.   10. 0.907 0.952   4.58   4.58 0.8529
SRFGRD96    20.  120.   80.  -10. 0.903 0.952   4.58   4.59 0.8581
SRFGRD96    21.  125.   80.  -10. 0.892 0.940   4.59   4.59 0.8353
SRFGRD96    22.   30.   80.  -10. 0.885 0.951   4.60   4.60 0.8352
SRFGRD96    23.  210.   85.   10. 0.879 0.950   4.61   4.61 0.8346
SRFGRD96    24.   30.   90.   10. 0.860 0.950   4.62   4.62 0.8159
SRFGRD96    25.   30.   85.    5. 0.842 0.948   4.63   4.63 0.7878
```

The best solution corresponds to one with a source depth of 20 km, a strike of 120°, a dip of 80°, rake angle of -10° and a moment magnitude of 4.59.

The file `FMFIT.sh` is a prototype for plotting the results:

```
#!/bin/sh

#####
#     Output of srfgrd96
#     For use with fmmfit
#     For use with fmdfit and fmmfit
#####
fmdfit -HMN   1. -HMX  25. < fmfit.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 001 < fmfit001.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 002 < fmfit002.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 003 < fmfit003.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 004 < fmfit004.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 005 < fmfit005.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 006 < fmfit006.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 007 < fmfit007.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 008 < fmfit008.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 009 < fmfit009.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 010 < fmfit010.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 011 < fmfit011.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 012 < fmfit012.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 013 < fmfit013.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 014 < fmfit014.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 015 < fmfit015.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 016 < fmfit016.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 017 < fmfit017.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 018 < fmfit018.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 019 < fmfit019.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 020 < fmfit020.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 021 < fmfit021.dat
```

```
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 022 < fmfit022.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 023 < fmfit023.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 024 < fmfit024.dat
fmmfit -SMN    0. -SMX  355. -DMN  30. -DMX  90. -ID 025 < fmfit025.dat
```

On UNIX/LINUX, this script is run by doing either `chmod +x FMFIT.sh ; FMFIT.sh` or `sh FMFIT.sh`. The resultant plot for the value of `BEST` as a function of depth is shown in Figure 4:

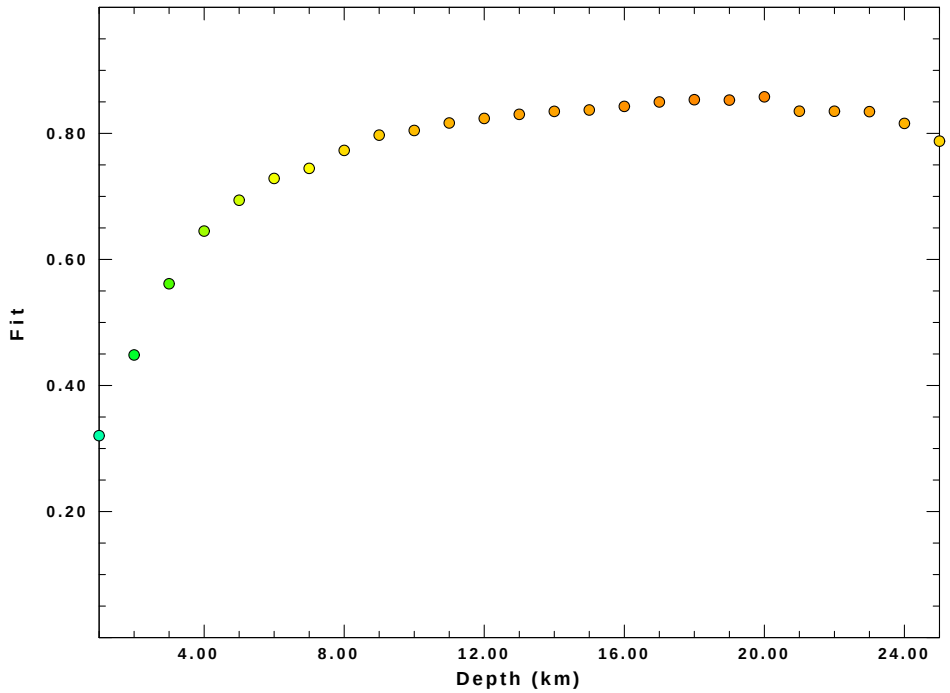


Fig. 4. Goodness of fit as a function of source depth. The best fit is a value of 1.0.

Selecting the 20 km depth, running the command from the prototype listed above,

```
fmmfit -SMN 0. -SMX 355. -DMN 30. -DMX 90. -ID 020 < fmfit020.dat
```

leads to the following plot of the entire search:

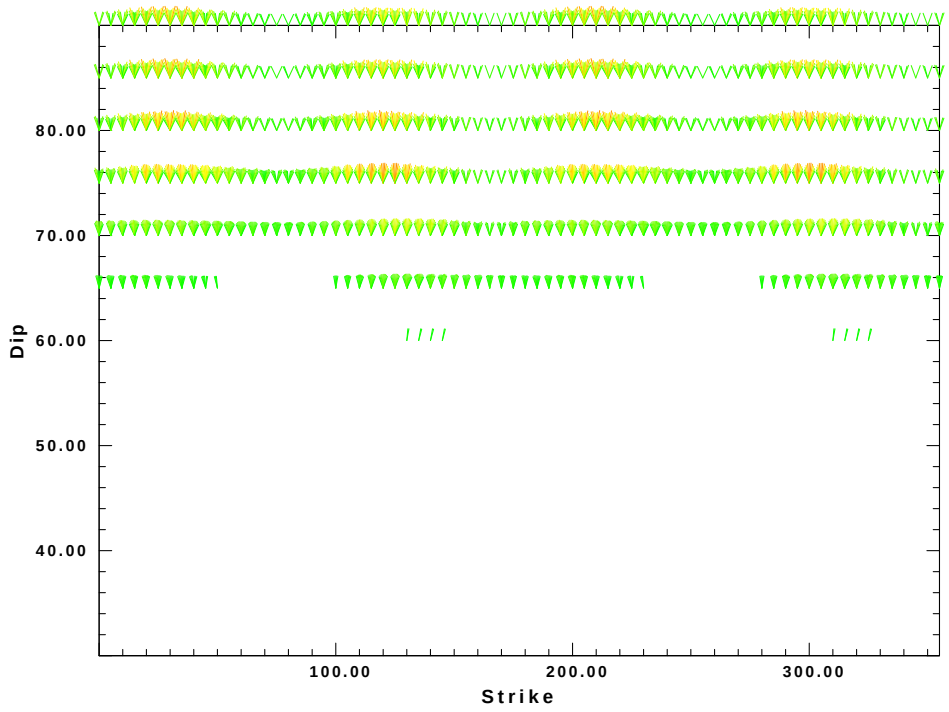


Fig. 5. Search results. Because of `-FMIN` flag in the use of **`srfgrd96`**, only vector solutions with goodness of fit > 0.5 are plotted. The color coding is blue for a fit of 0.00 and red for a fit of 1.0.

Modifying the command to read

```
fmmfit -SMN -2.5 -SMX  62.5 -DS 5 -DMN  67.5 -DMX  92.5 -DD 5 -ID 99 < fmfit020.dat
```

the following plot is found:

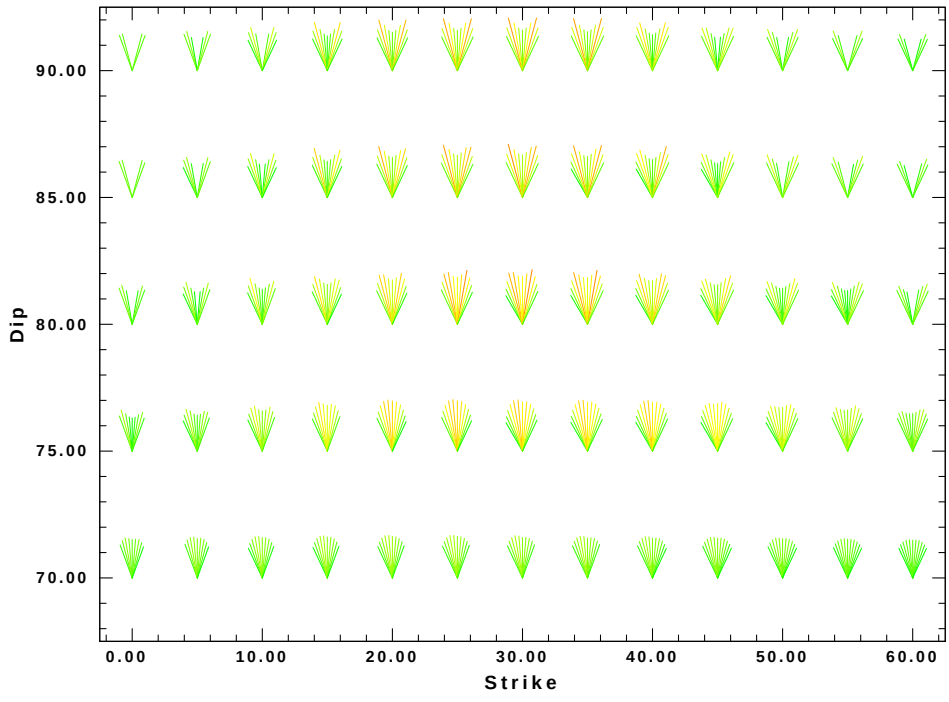


Fig. 6. Search results near the best solution. Because of `-FMIN` flag in the use of **`srfgrd96`**, only vector

solutions with goodness of fit > 0.5 are plotted. The color coding is blue for a fit of 0.0 to red for a fit of 1.0.

The sensitivity to rake angles slightly different from 0° is obvious from this plot. Also note the trick used to avoid plotting search values on the plot axes.

To appreciate the fit to the data, all data are plotted using the automatic flag of `sdprad96`. The radiation patterns are contained in the files `SRADL.PLT` and `SRADR.PLT` for Love and Rayleigh wave data. The following figures show the fit.

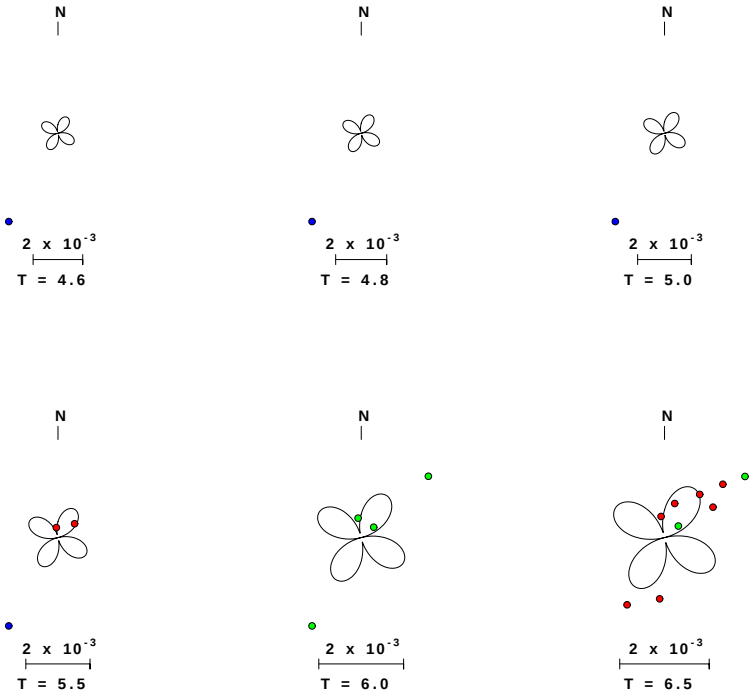


Fig. 7a. Love-wave radiation patterns. The scale indicates spectral amplitude in units of *cm-sec*. Color coding indicates that the observed and predicted spectral amplitudes are with a factor of 2, red, between a factor of 2 and 3, green, or greater than a factor of 3 apart, blue.

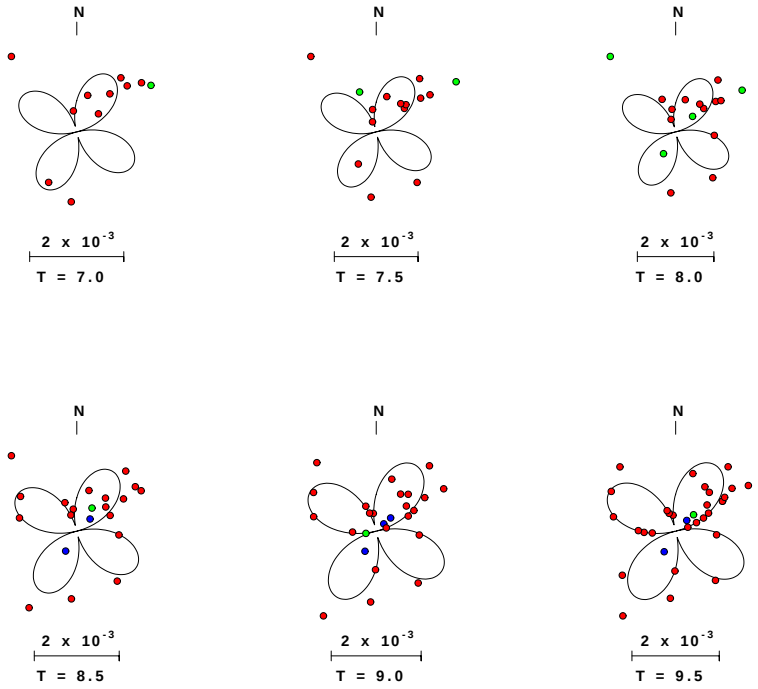


Fig. 7b. (cont'd)

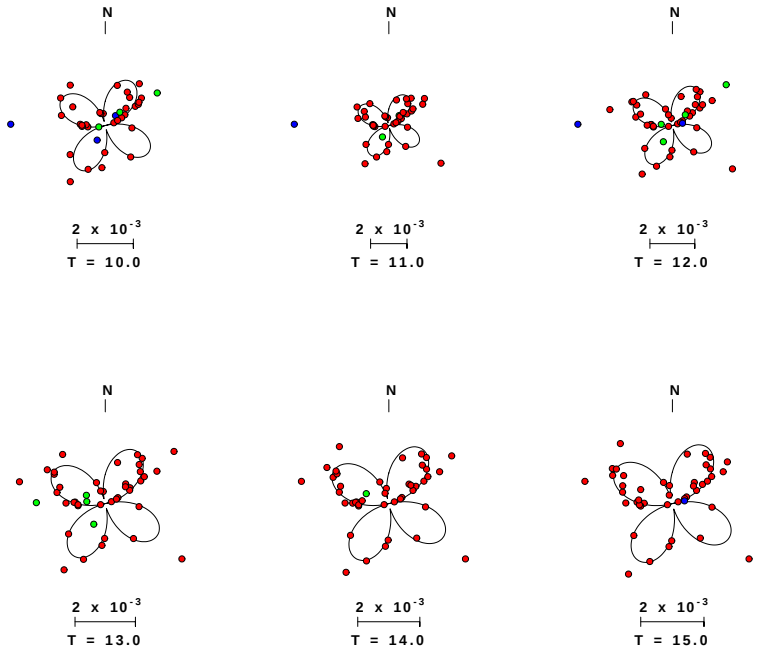


Fig. 7c. (cont'd)

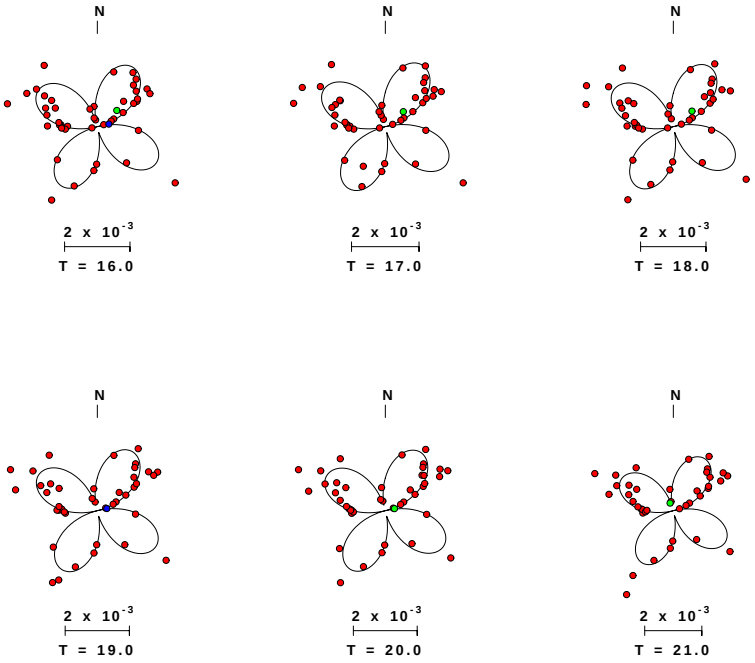


Fig. 7d. (cont'd)

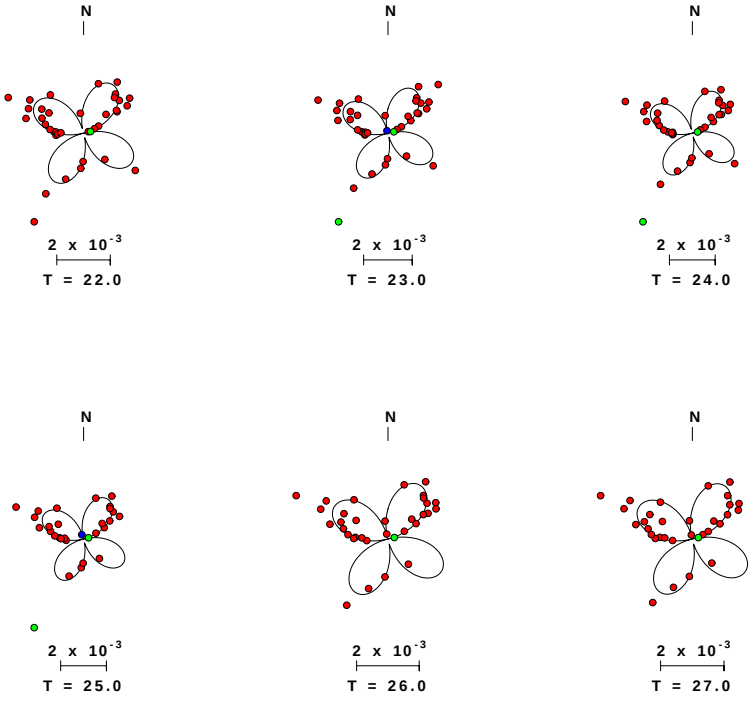


Fig. 7e. (cont'd)

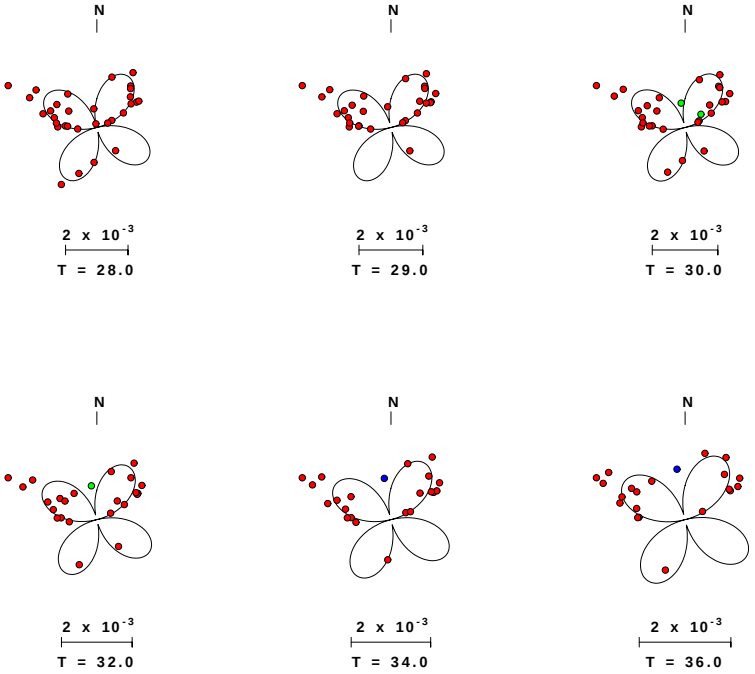


Fig. 7f. (cont'd)

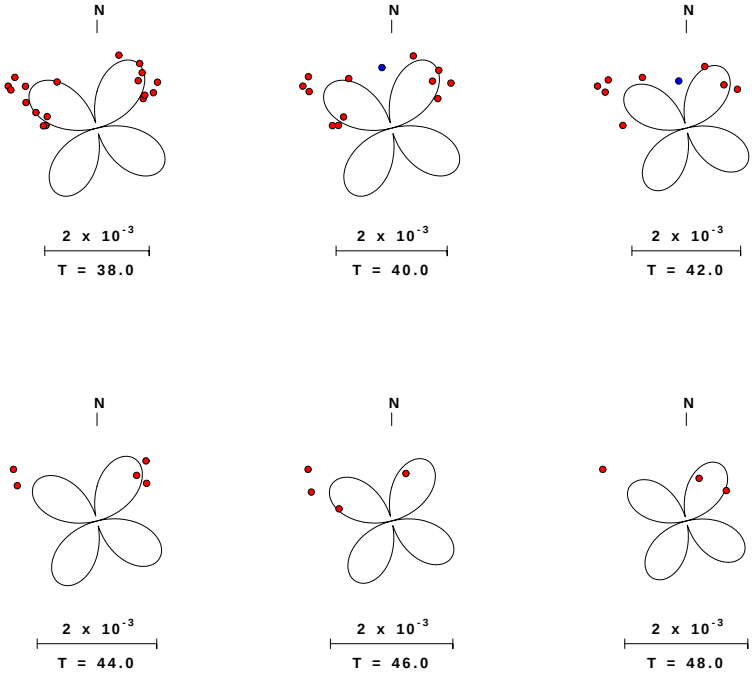


Fig. 7g. (cont'd)

Fig. 8a. Rayleigh-wave radiation patterns. The scale indicates spectral amplitude in units of *cm-sec*. Color coding indicates that the observed and predicted spectral amplitudes are with a factor of 2, red, between a factor of 2 and 3, green, or greater than a factor of 3 apart, blue.

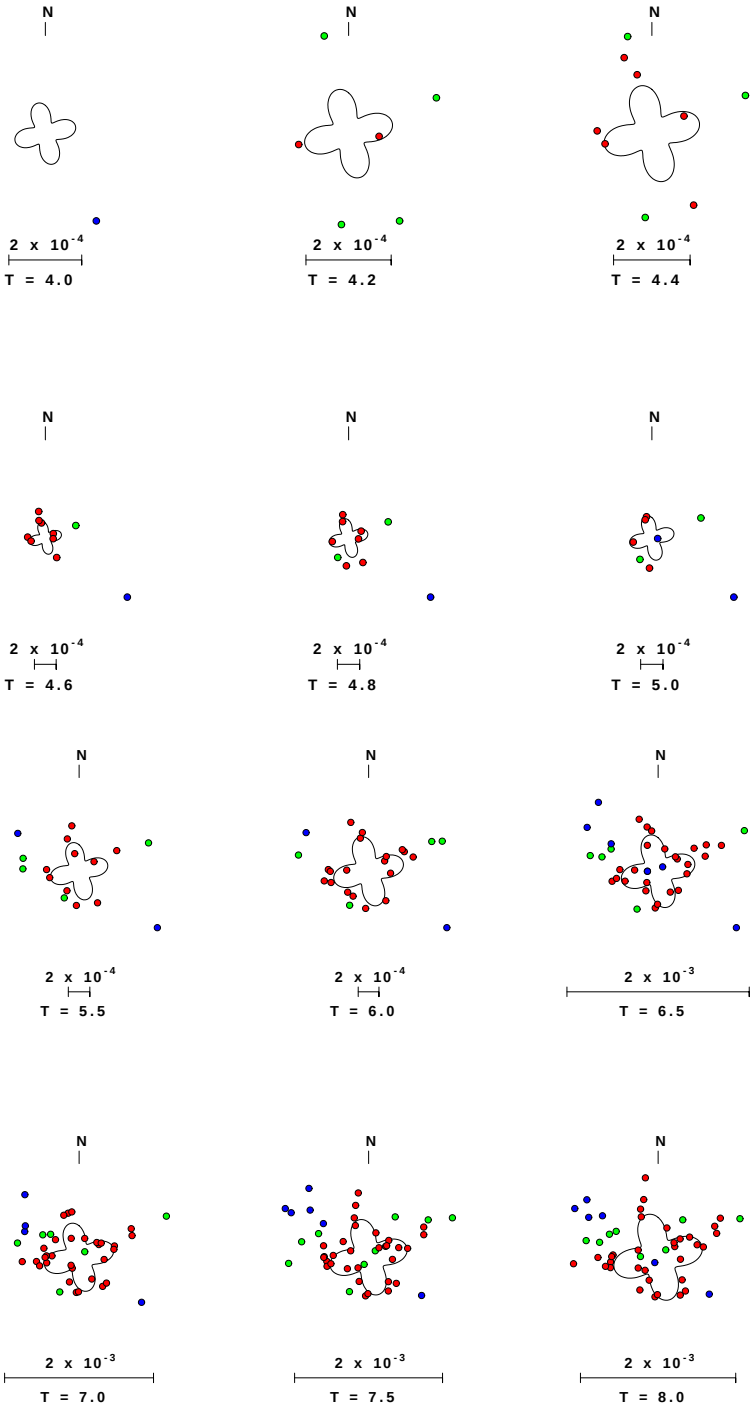

N
2 x 10-4
T = 4.0
N
2 x 10-4
T = 4.2
N
2 x 10-4
T = 4.4
N
2 x 10-4
T = 4.6
N
2 x 10-4
T = 4.8
N
2 x 10-4
T = 5.0
N
2 x 10-4
T = 5.5
N
2 x 10-4
T = 6.0
N
2 x 10-3
T = 6.5
N
2 x 10-3
T = 7.0
N
2 x 10-3
T = 7.5
N
2 x 10-3
T = 8.0

Fig. 8b. (cont'd)

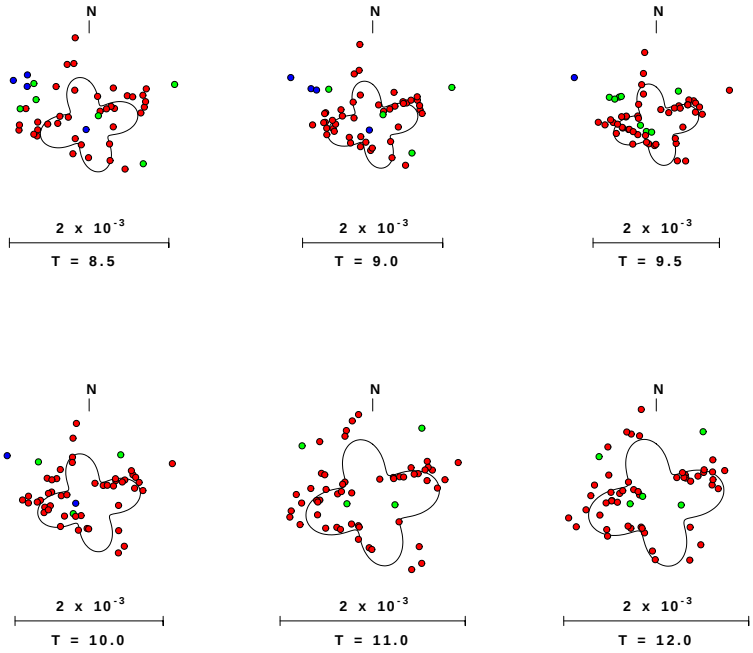


Fig. 8c. (cont'd)

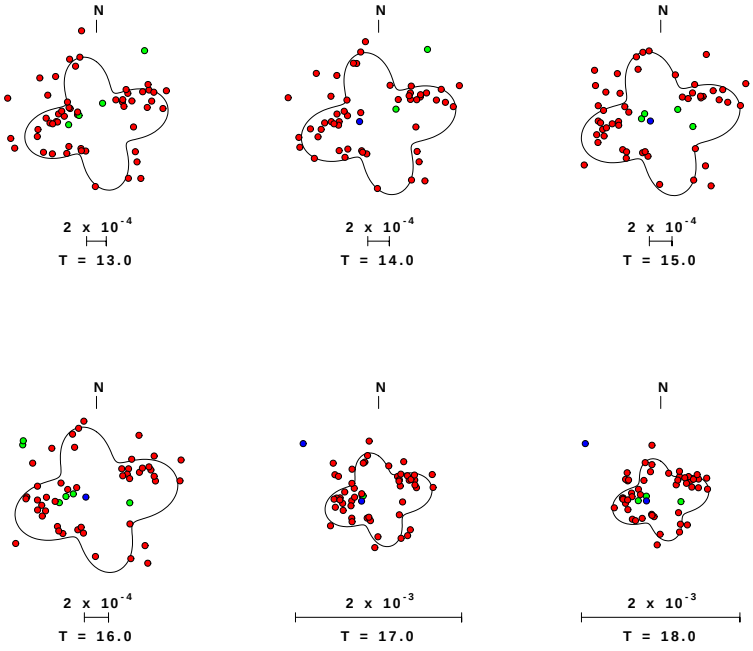


Fig. 8d. (cont'd)

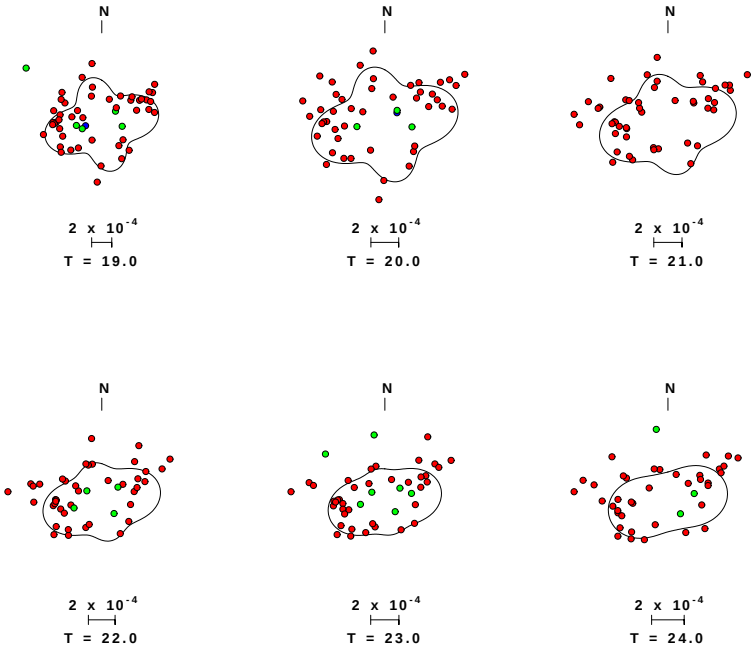


Fig. 8e. (cont'd)

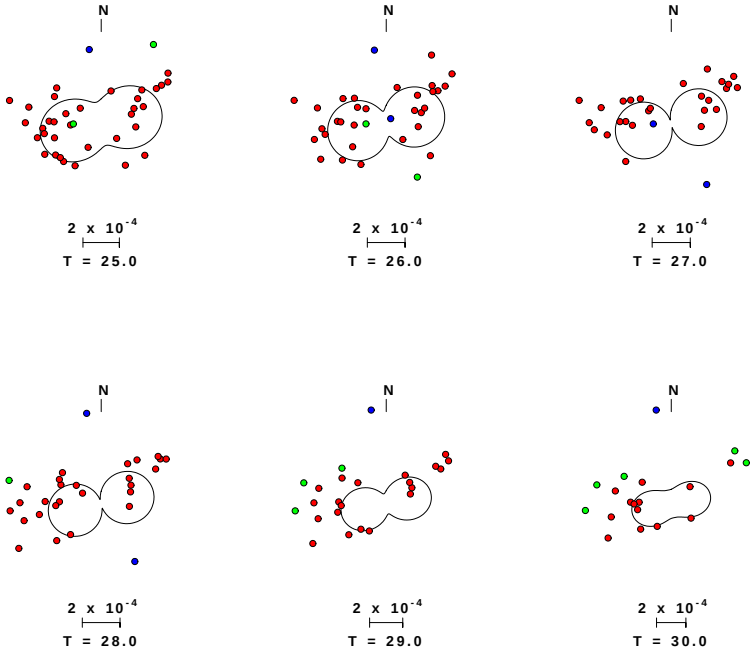


Fig. 8f. (cont'd)

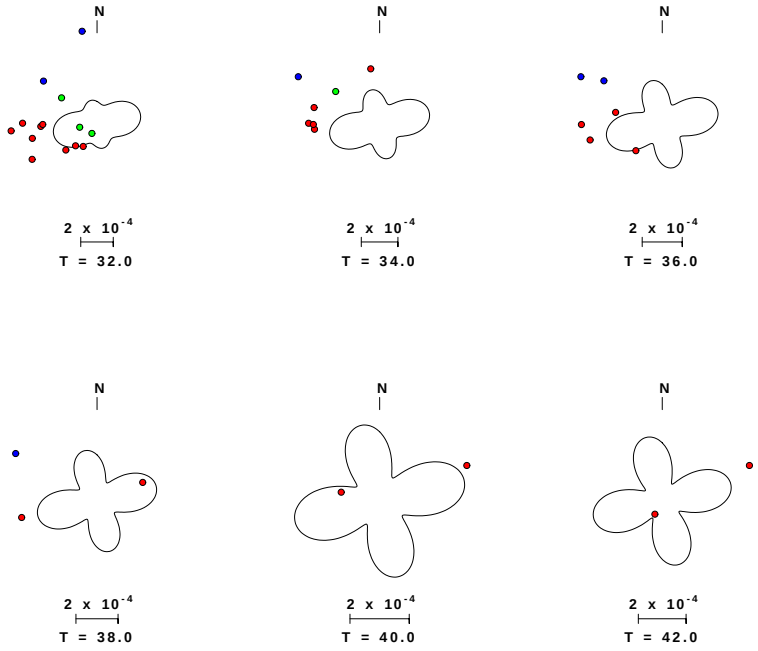


Fig. 8g. (cont'd)

2.2 Search using -N2 Weighting

This weighting scheme attenuates the theoretical predictions using the given Q-model derived anelastic attenuation coefficients. The shell script for performing the grid search is the same as that given above, except that the flag `-N1` is replaced by `-N2`:

```
#!/bin/sh

#####
#              clean up
#####
rm -f fmfit*
#####
#              do a complete search - normally one would use larger values of
#              DD DH DS and DR
#
#              note that since amplitude spectra are being fit, the search over
#              rake need only cover 180 degrees since strike is varied over 360 degrees
#              - hence the restriction to positive values here
#####
srfgrd96 -N2 -PATH . -O ALL.DSP.nopp -DMIN 100 -DMAX 3000 -DMN 30 -DMX 90 -DD 5 \
     -RMN -90 -RMX 90 -DR 5 -SMN 0 -SMX 355 -DS 5 -FMIN 0.5 -HMN 1 -HMX 25 -DH 1
```

The file `fmfit.dat` summarizes the mechanism that provided the best fit for each depth:

```
SRFGRD96     1.  115.   75.  -20. 0.876 0.929   4.21   4.47 0.3351
SRFGRD96     2.   35.   75.   20. 0.889 0.930   4.29   4.47 0.4421
SRFGRD96     3.  125.   80.   -5. 0.872 0.922   4.33   4.45 0.5319
SRFGRD96     4.  125.   80.   -5. 0.854 0.923   4.37   4.45 0.6056
SRFGRD96     5.  130.   80.   -5. 0.829 0.894   4.41   4.44 0.6626
```

```
SRFGRD96     6.  130.   80.   -5. 0.826 0.896   4.44   4.45 0.7132
SRFGRD96     7.  220.   85.   10. 0.832 0.905   4.46   4.46 0.7497
SRFGRD96     8.   35.   85.   10. 0.845 0.934   4.47   4.48 0.7862
SRFGRD96     9.  210.   85.   10. 0.861 0.945   4.49   4.49 0.8111
SRFGRD96    10.   30.   90.  -15. 0.867 0.946   4.50   4.50 0.8138
SRFGRD96    11.  305.   80.  -10. 0.883 0.934   4.50   4.50 0.8221
SRFGRD96    12.  125.   80.  -10. 0.893 0.935   4.51   4.51 0.8332
SRFGRD96    13.  305.   80.  -10. 0.903 0.937   4.51   4.52 0.8363
SRFGRD96    14.  125.   80.  -10. 0.912 0.938   4.52   4.52 0.8368
SRFGRD96    15.  120.   80.   10. 0.902 0.951   4.54   4.54 0.8476
SRFGRD96    16.  120.   80.   10. 0.910 0.952   4.55   4.55 0.8646
SRFGRD96    17.   30.   80.    5. 0.911 0.952   4.56   4.55 0.8644
SRFGRD96    18.   30.   85.   10. 0.929 0.953   4.57   4.56 0.8692
SRFGRD96    19.  210.   85.   10. 0.929 0.953   4.57   4.57 0.8792
SRFGRD96    20.  120.   80.   10. 0.919 0.952   4.58   4.59 0.8731
SRFGRD96    21.  210.   85.   10. 0.920 0.952   4.59   4.59 0.8695
SRFGRD96    22.  210.   85.  -10. 0.905 0.951   4.60   4.60 0.8591
SRFGRD96    23.  210.   85.    5. 0.894 0.950   4.61   4.61 0.8327
SRFGRD96    24.  210.   85.   -5. 0.881 0.950   4.61   4.62 0.8288
SRFGRD96    25.  125.   85.    0. 0.855 0.940   4.62   4.62 0.7974
```

The best solution is seen to be that with a depth of 19 km, and strike, dip and rake angles of 210°, 85° and 10°, respectively and a $\mathbf{M_W = 4.57}$. The sensitivity to depth is seen in Figure 9.

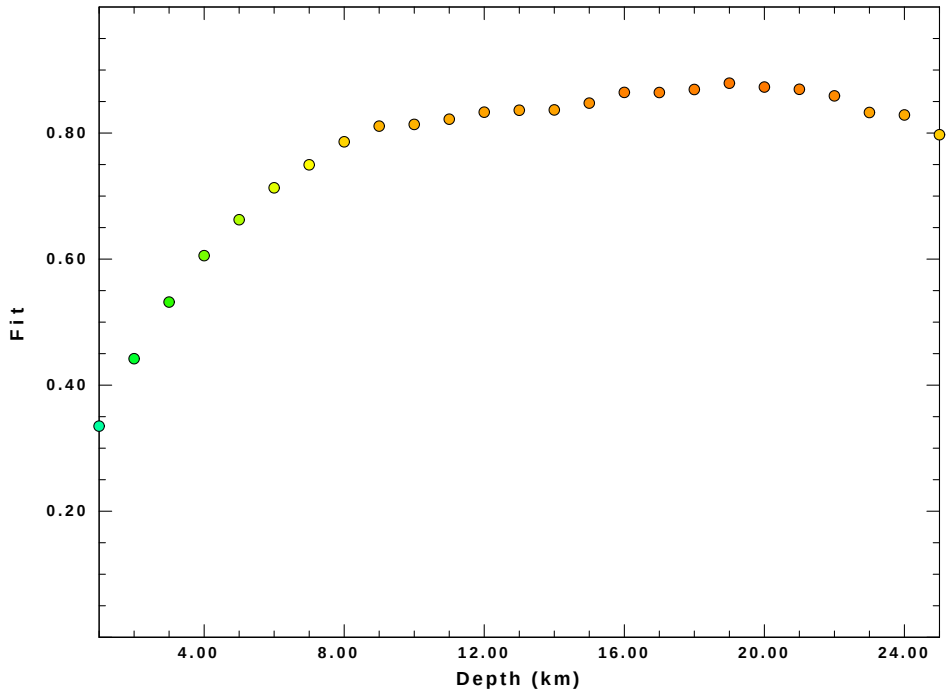


Fig. 9. Goodness of fit as a function of source depth. The best fit is a value of 1.0.

Selecting the 19 km depth, running the command

```
fmmfit -SMN 0. -SMX 355. -DMN 30. -DMX 90. -ID 019 < fmfit019.dat
```

leads to the following plot of the entire search:

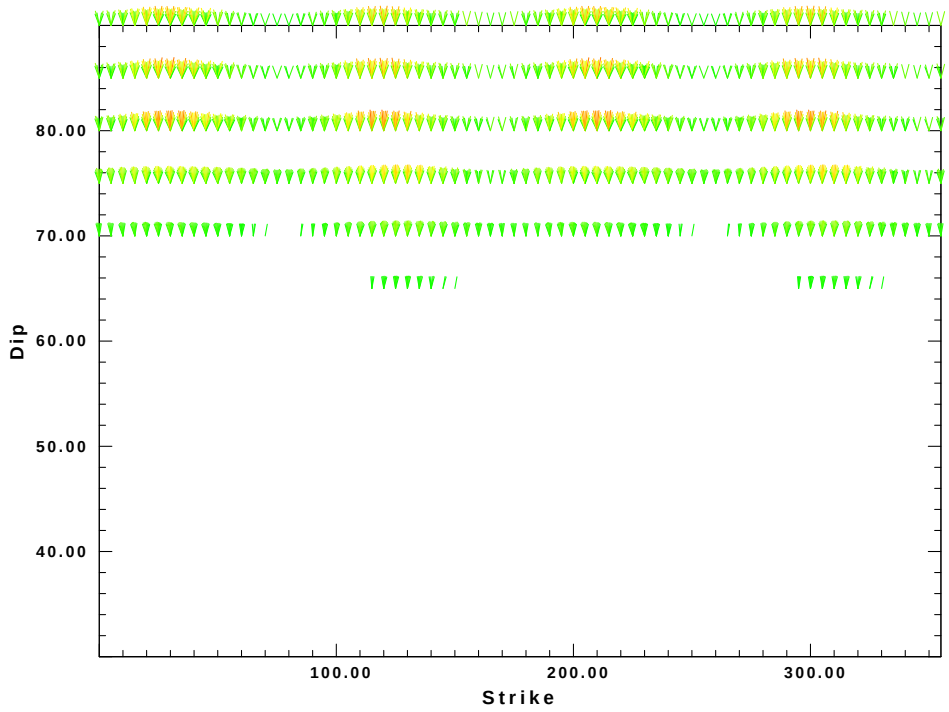


Fig. 10. Search results. Because of `-FMIN` flag in the use of **`srfgrd96`**, only vector solutions with goodness of fit > 0.5 are plotted. The color coding is blue for a fit of 0.00 and red for a fit of 1.0.

Since the focal mechanisms, source depth and seismic moments are virtually the same for the two search criteria, the radiation patterns are not plotted for this study of the use of the *-N2* flag.

2.3 Discussion

Comparing Figures 4 and 9, and 5 and 10, the difference between search results is subtle, even though the `-N2` criteria rejects more mechanisms.

As discussed in the section describing this technique, there are four possible focal mechanisms that fit the surface-wave radiation patterns because there is no phase information and because the radiation pattern shape does not change if the mechanism strike is increased by 180°. Independent data, such as P-wave first motion data, are required to make this choice among these four possible mechanisms:

	Strike	Dip	Rake
(a)	210	85	10
(b)	30	85	10
(c)	210	85	-170
(d)	30	85	-170

The first motion data used are SLM(-), SIUC(-), BLO(e+), CCM(-), WVT(+) and WCI(-). These first motion are plotted together with the focal mechanism in a lower

hemisphere, equal area projection:

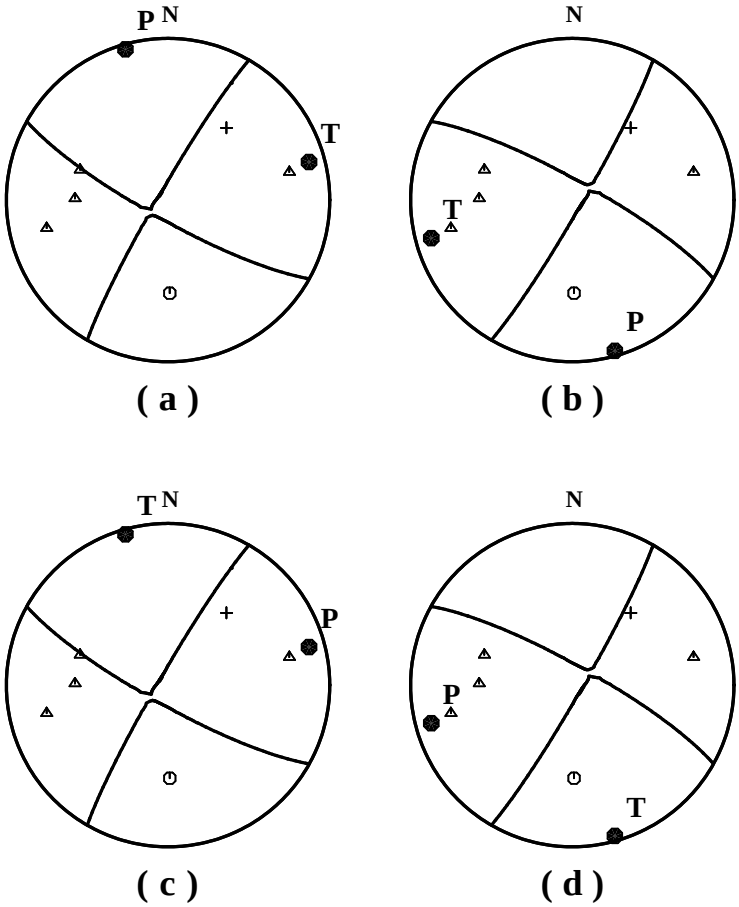


Fig. 11. Focal mechanisms that satisfy surface-wave spectral amplitude data. First motion data at nearby stations can be used to reject mechanisms (a) and (b).

All first motion data are inconsistent with the frist two possible focal mechanisms, and only BLO is inconsistent for mechanisms c) and d). Mechanism d) is preferred because it predicts larger P wave amplitudes at SLM and almost nodal amplitudes for BLO. Dilatations are indicated by triangles, compressions by circles.

Since Figure 1 showed quality waveforms with interesting P, sP and S phases, another way to select among the focal mechanisms is to compare the observed and predicted waveforms. This is done using the program **`wvfmch96`** with the Green's functions and observed data filtered in the same manner: 2-pole high-pass Butterworth filter with corner at 0.01 Hz followed by a 2-pole low-pass Butterworth filter with a corner at 0.15 Hz applied to the velocity time series. Figure 12 compares the observed waveform and the synthetics at the nearest station, WCI, which is 135 km from the source.

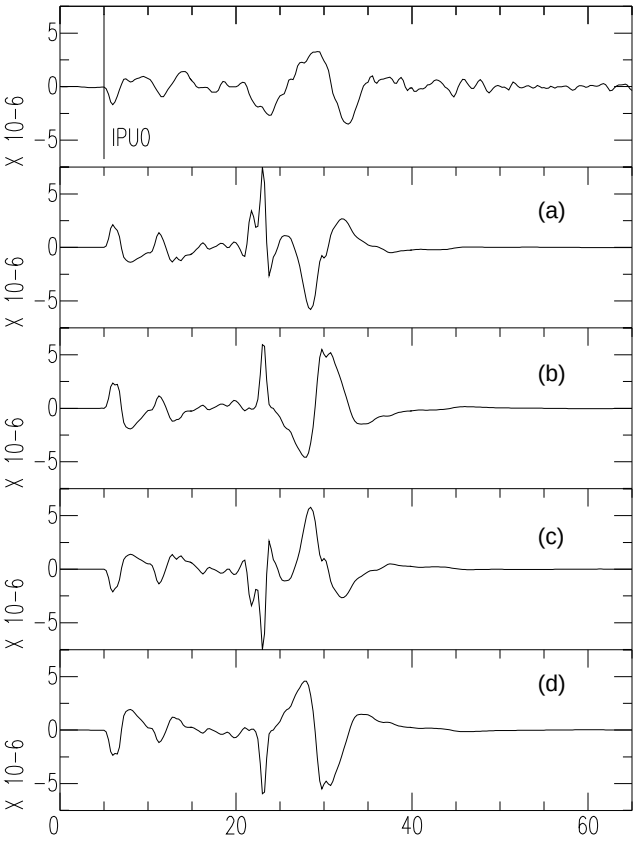


Fig. 12a. Comparison of observed (top) and predicted vertical component waveforms at WCI. Mechanisms (a) and (b) are rejected.

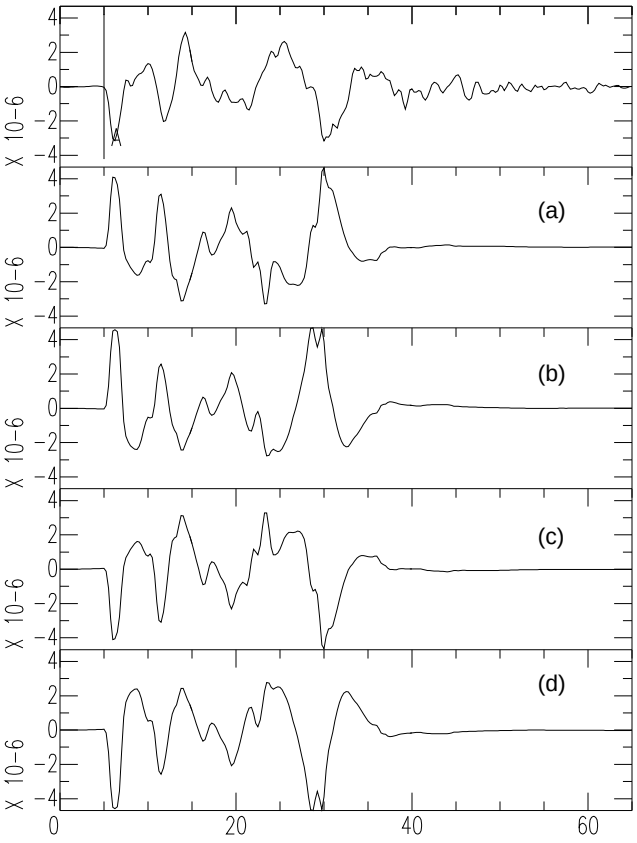


Fig. 12b. Comparison of observed (top) and predicted radial component waveforms at WCI. Mechanisms (a) and (b) are rejected.

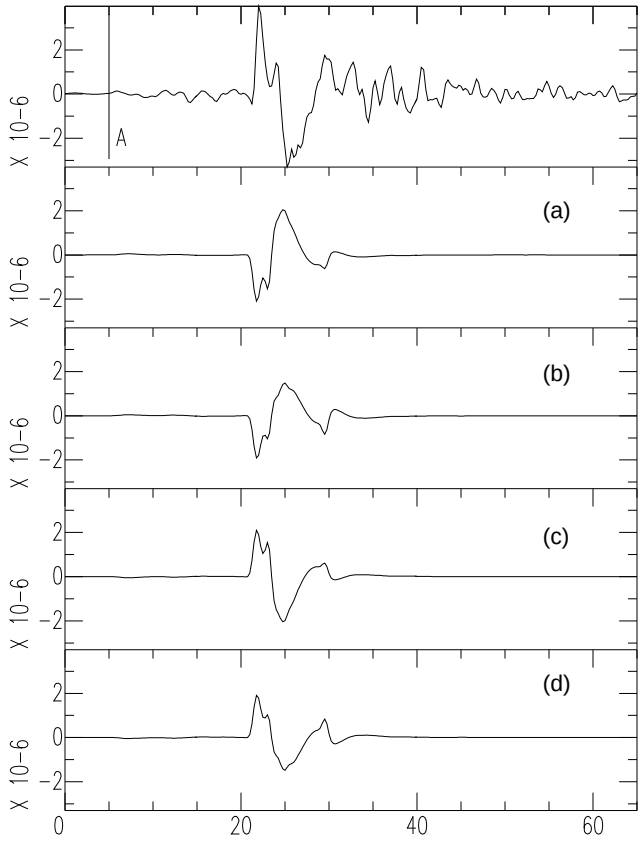
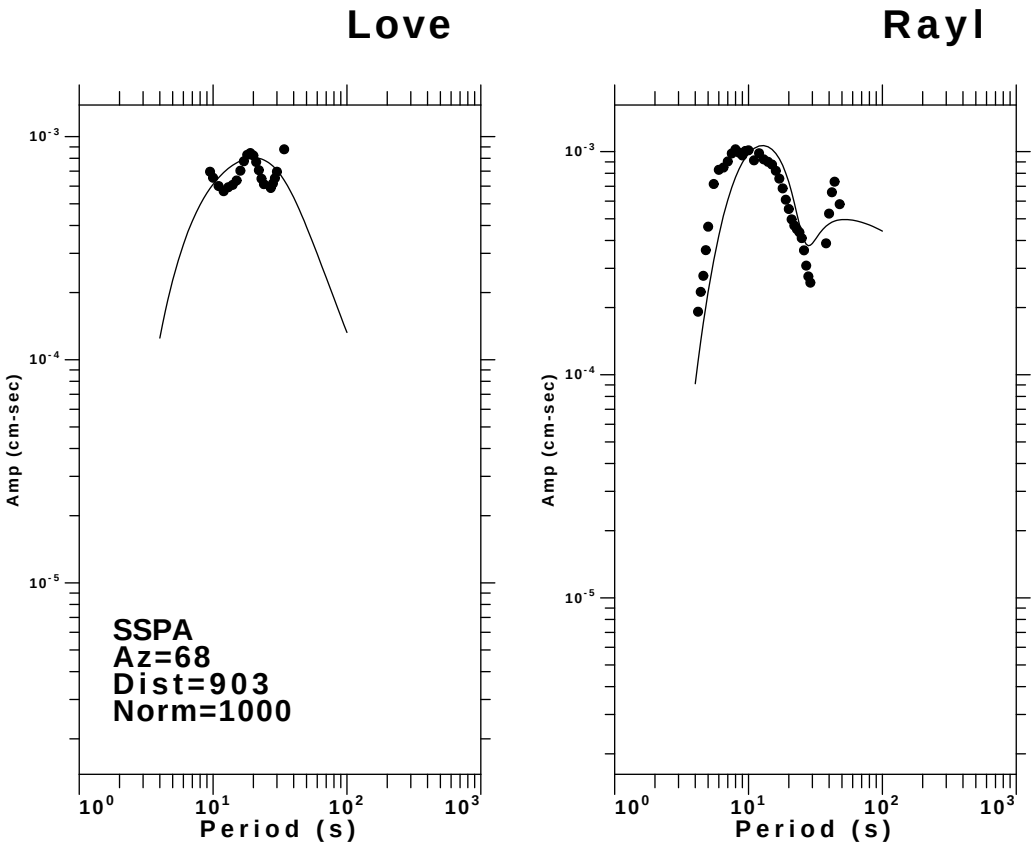


Fig. 12c. Comparison of observed (top) and predicted transverse component waveforms at WCI. Mechanisms (a) and (b) are rejected.

Examination of the waveforms indicates that mechanism (c) may fit the data better, but the actual fit depends upon the crustal model used.

Using the program **sdpspc96** we can compare the observed and predicted spectra at a given station. In this case, the station SSPA at State College, Pennsylvalnia is used.



The program which performs the radiation pattern plots, **sdprad96** creates the text files SRADL.TXT and SRADR.TXT which present information about data fit. For the best **-N2** mechanism, the information for the fundamental mode Love wave at a period of 9.0 sec is

STA	COMP	Period(s)	L/R	MOD	U(km/s)	DIST(km)	AZ	Amp (obs)	RDIST(km)	Amp(corr)	Pred	
BINY	BHT	9.00	L	0	3.390	1110.00	61.	1.127E-03	1000.00	1.683E-03	1.411E-03	
BLA	BHT	9.00	L	0	3.460	656.00	95.	1.701E-03	1000.00	1.693E-03	2.069E-03	
BLO	BHT	9.00	L	0	3.430	173.00	39.	7.509E-03	1000.00	3.298E-03	2.977E-03	
EDM	BHT	9.00	L	0	3.260	2590.00	319.	9.758E-04	1000.00	3.544E-03	2.449E-03	
FCC	BHT	9.00	L	0	3.490	2360.00	351.	2.177E-04	1000.00	7.022E-04	7.252E-04	
GAC	BHT	9.00	L	0	3.500	1330.00	46.	2.355E-04	1000.00	4.125E-04	2.649E-03	-3
GOGA	BHT	9.00	L	0	3.540	639.00	141.	2.671E-03	1000.00	2.610E-03	2.313E-03	
HRV	BHT	9.00	L	0	3.400	1470.00	65.	7.205E-04	1000.00	1.387E-03	1.057E-03	
ISCO	BHT	9.00	L	0	3.220	1560.00	283.	1.231E-03	1000.00	2.510E-03	2.637E-03	
JFWS	BHT	9.00	L	0	3.540	587.00	340.	8.152E-04	1000.00	7.511E-04	5.401E-04	
KAPO	BHT	9.00	L	0	3.510	1340.00	17.	1.204E-03	1000.00	2.124E-03	2.845E-03	
KGNO	BHT	9.00	L	0	3.530	1170.00	50.	9.833E-04	1000.00	1.536E-03	2.371E-03	
LMN	BHT	9.00	L	0	3.440	2090.00	58.	1.118E-03	1000.00	3.117E-03	1.734E-03	
LMQ	BHT	9.00	L	0	3.450	1780.00	48.	3.284E-04	1000.00	7.666E-04	2.549E-03	-3
MCWV	BHT	9.00	L	0	3.400	715.00	72.	3.915E-04	1000.00	4.145E-04	2.609E-04	
MPH	BHT	9.00	L	0	3.370	370.00	212.	5.714E-03	1000.00	3.904E-03	3.144E-03	
NCB	BHT	9.00	L	0	3.440	1320.00	55.	1.327E-03	1000.00	2.308E-03	1.957E-03	
PLAL	BHT	9.00	L	0	3.450	333.00	184.	4.338E-03	1000.00	2.779E-03	2.031E-03	
PLM	BHT	9.00	L	0	3.340	2670.00	268.	2.448E-04	1000.00	9.258E-04	1.404E-03	
RSSD	BHT	9.00	L	0	3.370	1520.00	302.	1.449E-03	1000.00	2.880E-03	3.141E-03	
SADO	BHT	9.00	L	0	3.600	1040.00	41.	1.351E-03	1000.00	1.910E-03	2.906E-03	
SCHQ	BHT	9.00	L	0	3.540	2450.00	33.	5.135E-04	1000.00	1.736E-03	3.126E-03	
SIUC	BHT	9.00	L	0	3.160	129.00	258.	1.100E-03	1000.00	4.114E-04	3.497E-04	
ULM	BHT	9.00	L	0	3.540	1510.00	337.	5.352E-04	1000.00	1.057E-03	8.045E-04	
UTMT	BHT	9.00	L	0	4.110	219.00	209.	1.795E-03	1000.00	8.999E-04	3.154E-03	-3

```
WVT     BHT       9.00     L   0     3.550    204.00  181.  3.133E-03   1000.00  1.509E-03  1.724E-03
  MOM:  0.847488105 R=  0.906505287
  GAMMA(  9.)  ASSUMED:  0.000314280565
  GAMMA(  9.) COMPUTED:  0.000398831558  8.43544622E-05
SURF96 L G X   0   9.000     0.3988E-03 0.8435E-04
SURF96 L U X   0   9.000      3.433     0.2342E-01
```

This provides all data required for the plot as well as the observed amplitude corrected to the reference distance for geometrical spreading and for anelastic attenuation back to the source. The flag at the end indicates that the observed spectral amplitude at GAC, LMQ and UTMT is at least 3 times less than predicted. The bottom entry indicates that a least squares estimate of the spectral level prefers a seismic moment 0.847 of the assumed value - this may be a way to examine the assumption of a step source time function. The observed γ and the γ required by the data are shown. Finally these observations of the γ and the group velocity are formatted into the **`surf96`** dispersion format.

By editing this file and selecting the Distance, Amp(corr) and Pred columns, one can plot the Observed/Predicted ratio as a function of observation distance. This is of value to check the adequacy of the assumed γ value and the source parameters.

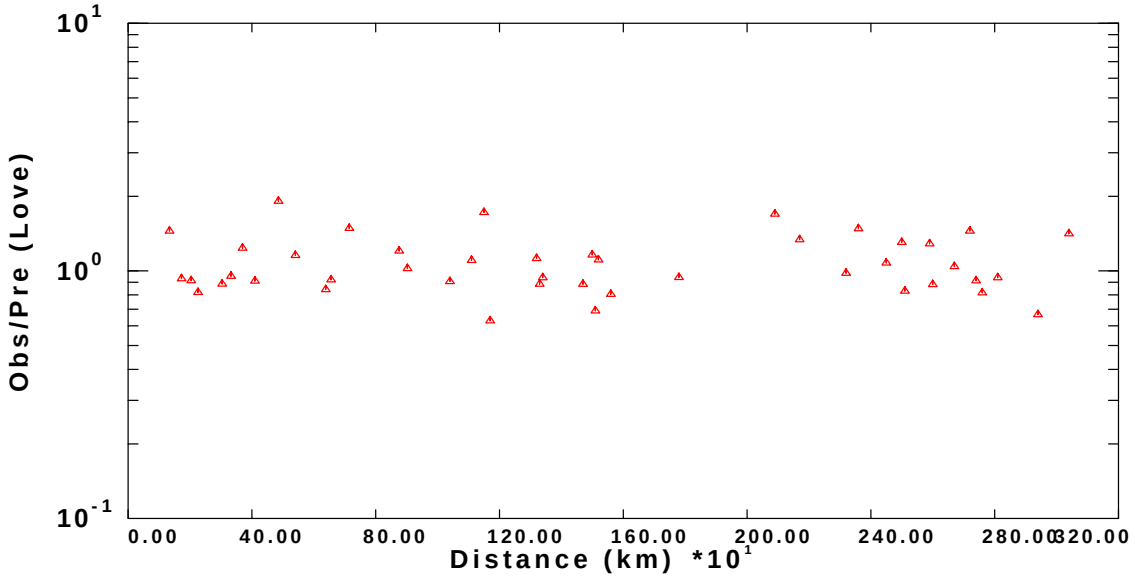


Fig. 13. Plot of the observed-to-predicted amplitude ratio for Love wave data at a period of 20 sec. The data do not require a change to the model gamma value

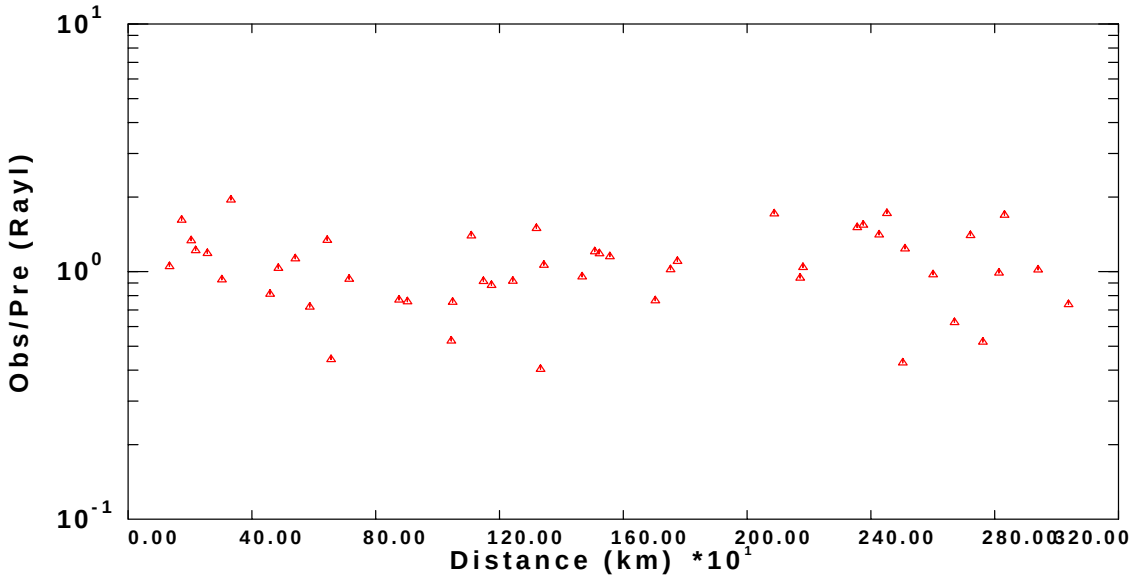


Fig. 14. Plot of the observed-to-predicted amplitude ratio for Rayleigh wave data at a period of 20 sec. The model gamma was 8.85E-05 km^{-1} - the data require a value of 8.57E-05 km^{-1}.

We can easily compare the actual group velocity and γ dispersion from this data set to that assumed in the model, by the following sequence of commands:

```
#####
#             create the dispersion data set
#####
grep SURF96 SRADL.TXT >  disp.d
grep SURF96 SRADR.TXT >> disp.d

#####
#             create the sobs.d file - normally this is done interactively,
#             as part of surf96, but is presented here to show the file
#####
cat > sobs.d << EOF
  0.00499999989  0.00499999989  0.  0.00499999989  0.
    0    1    1    1    1    1    1    0    1    0
cusq.mod
disp.d
EOF

#####
#             run surf96 to calculate the model predictions
#             and then run srfphv96 to make the plots
#####
surf96 1
srfphv96 -V
srfphv96 -G
plotnps -F7 -W10 -EPS -K < SRFPHV96.PLT > phv.eps
plotnps -F7 -W10 -EPS -K < SRFPHG96.PLT > phg.eps
#####
#             clean up
#####
surf96 39
```

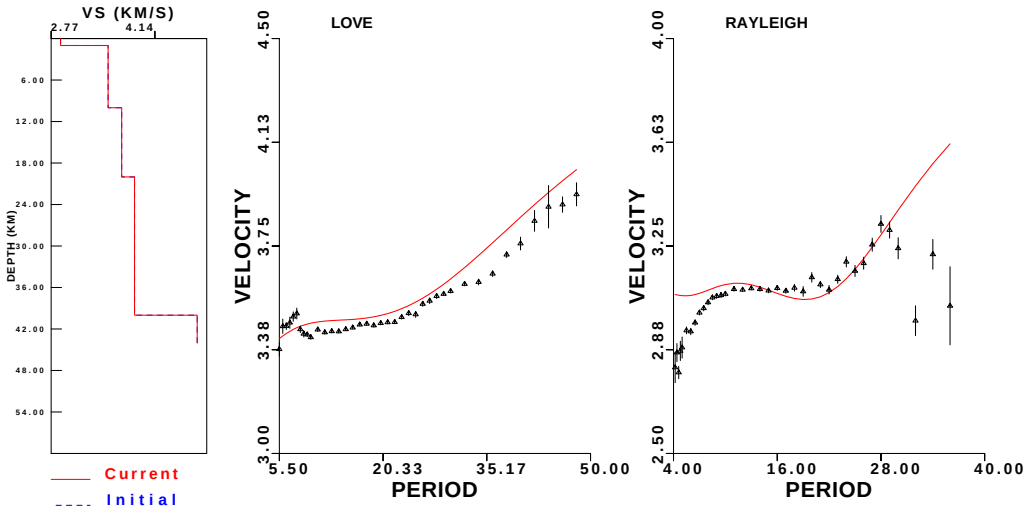


Fig. 15. Comparison of model and observed group velocities

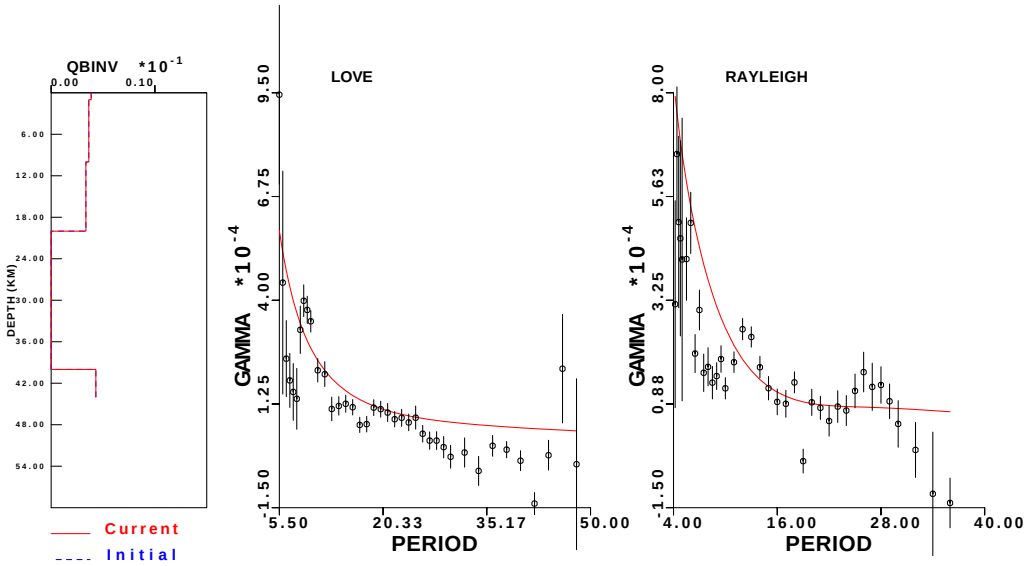


Fig. 16. Comparison of model and observed anelastic attenuation coefficients

Since the dispersion data are from wave propagation over a continent, use of **`surf96`** to obtain a single earth model would not be appropriate. On the other hand the validation of the γ values is necessary since the correction for anelastic attenuation is essential for the focal mechanism search.

3. Waveform Inversion

Waveform inversion is performed using the three programs **`wvfgrd96`, `wvfmtd96`** and **`wvfmt96`**. Of these programs, the grid search takes the longest since an exhaustive search is made over all possible focal mechanisms. As seen in Figure 1, the use of a 2-pole Butterworth high-pass filter at 0.01 Hz followed by a 2-pole Butterworth

low-pass filter with corner at 0.15 Hz, yields waveforms with a simple appearance at WCI, waveforms that show the distinct P, sP and S phases. Since the Green's functions were generated using a sample rate of $\Delta \mathbf{t} = \mathbf{0.25}$ sec, the observed data were decimated to have the same sampling interval. In addition the observed and predicted velocity waveforms were bandpass filtered with the bands just mentioned.

To facilitate the use of different inversion techniques, consider using a directory structure similar to this one:

```
.
.
|
|-------/DATA     (location of deconvolved waveforms with P arrival picked)
|
|
|-------/GRD      (work area for waveform grid search)
|
|
|-------/MTD      (work area for deviatoric moment tensor inversion)
|
|
|-------/MT       (work area for moment tensor inversion)
|
```

In addition assume that the path to the top layer of the Green's function directory for the chosen earth model is known.

There are several steps to prepare the data for inversion:

- Copy waveforms to be inverted from the DATA directory to the work directory. The observed data must have the same sampling interval as the synthetics, must be identified as vertical, radial or transvers components of motion, and must have the *A* value set in the SAC header to indicate the first P-wave arrival time.
- Filter observed waveforms
- For each source depth, associate a theoretical Green's function with a given observation, copy those Green's functions to the work directory. Finally filter the Green's functions in a manner identical to the observed data.
- Assign subjective weights to observations according to the quality and distance.

Since we have chosen to precompute the regional Green's functions as described in Chapter 2, two shell scripts are used to cycle through the different depths and to select the proper Green's functions. The top level script, is called **DOGRD** if it is run in the *GRD* subdirectory with the program **wvfgrd96**. The top level script for the other two directories, *MTD* and *MT*, are called **DOMTD** and **DOMT**, and differ only by the use of the programs **wvfmtd96** and **wvfmt96**, respectively, in place of the call to **wvfgrd96**. **DOGRD** is simply

```
#!/bin/sh

rm -fr FMDSUM
for HS in 0005 0010 0020 0030 0040 0050 0060 0070 0080 0090 \
       0100 0110 0120 0130 0140 0150 0160 0170 0180 0190  \
       0200 0210 0220 0230 0240 0250 0260 0270 0280 0290
do
DOSTA ${HS}
wvfgrd96 -N 40 << EOF
WW
Oout.${HS}
```

```
EOF
cat fmdfit.dat >> FMDSUM
cat fmdfit.dat
for GRN in ZDD RDD ZDS RDS TDS ZSS RSS TSS ZEX REX
do
       rm *.${GRN}
done
done
```

Once this is designed for all computed source depths, this script need not be changed. The more complicated script is **DOSTA** which produces the control file *ww*. For the Evansville earthquake data set analysis in this section, the control file *ww*, used by all the programs in this section, is as follows:

```
2 'BLOR' 'BLO' 1.0
3 'BLOT' 'BLO' 1.0
1 'BLOZ' 'BLO' 1.0
2 'CCMR' 'CCM' 0.25
3 'CCMT' 'CCM' 0.25
1 'CCMZ' 'CCM' 0.25
2 'PLALR' 'PLAL' 0.25
3 'PLALT' 'PLAL' 0.25
1 'PLALZ' 'PLAL' 0.25
2 'SIUCR' 'SIUC' 1.0
3 'SIUCT' 'SIUC' 1.0
1 'SIUCZ' 'SIUC' 1.0
2 'SLMR' 'SLM' 1.0
3 'SLMT' 'SLM' 1.0
1 'SLMZ' 'SLM' 1.0
2 'WCIR' 'WCI' 1.0
3 'WCIT' 'WCI' 1.0
1 'WCIZ' 'WCI' 1.0
2 'WVTR' 'WVT' 1.0
3 'WVTT' 'WVT' 1.0
1 'WVTZ' 'WVT' 1.0
```

The script **DOSTA** is longer and more complicated. It can be further tailored to the data set. The simple version used in the section is

```
#!/bin/sh

if [ $# -eq 0 ]
then
       echo Usage: DOSTA DEPTH
       exit 0;
fi
HS=$1

#####
#      initialize
#####
       rm -f ww
#####
#      define the path to the Green's Function Directory
#####
GREEN=/home/rbh/PROGRAMS.310t/CUS
#####
#      define CUT LIMITS
#####
       CUTL=-5
       CUTH=80
```

```
#####
#      define filter bands
#####
       FHIGHPASS=0.02
       FLOWPASS=0.15
       NPOLE=2
       PASS=1


#####
#      awk program for assigning distance weights
#####
cat > dwt << FOE
{ Dist = \(Do3 ;
if (Dist < 200)                printf "1.0" ;
if (Dist >= 200 && Dist < 300) printf "1.0" ;
if (Dist >= 300 && Dist < 500) printf "0.25" ;
if (Dist >= 500              ) printf "0.10" ;
}
FOE
#####
#      create a list of unique distances - distince is in 3rd column
#####

for TRACE in ../DAT/*[ZRT].sac
do

#####
#      get information from trace header
#####
       KSTNM=‘saclhdr -KSTNM ${TRACE}‘
       KCMPNM=‘saclhdr -KCMPNM ${TRACE}‘
       DELTA=‘saclhdr -DELTA ${TRACE}‘
       DIST=‘saclhdr -DIST ${TRACE}‘
#####
#      define the components
#####
       case ${KCMPNM} in
       BHZ|HHZ) COMP=1 ; NAM=Z;;
       BHR|HHR) COMP=2 ; NAM=R;;
       BHT|HHT) COMP=3 ; NAM=T;;
       *) break;;
       esac
       echo PROCESSING $TRACE $KSTNM $KCMPNM $DELTA $DIST $COMP $NAM
#####
#      search over source depth These depths are the subdirectory
#      names in the Green’s Function Directory
#####
cat > awkprog << FOE
# This works under gawk - on Solaris try nawk
BEGIN { MDIF = 10000.0 }
{DIF = $DIST - \(Do1 ;
if( DIF < 0 ) DIF = - DIF ;
if(DIF < MDIF) { MDIF = DIF ; Dfile = \(Do7 ; Rate = \(Do2 ; Dist = \(Do1 }
}
END { print Dfile , Rate, Dist }
FOE

       cat ${GREEN}/${HS}/W.CTL | awk -f awkprog > j
       rm awkprog
#####
#      define the distance dependent weight
#####
       WT=‘awk -f dwt < j ‘
#####
```

```
#      copy the Green's function files here
#      and rename
#####
       for DFILE in 'awk '{print $1}' < j '
       do
       echo Copying and Renaming $DFILE for this distance ${DIST}
       for GRN in ZDD RDD ZDS RDS TDS ZSS RSS TSS ZEX REX
       do
       cp ${GREEN}/${HS}/${DFILE}.${GRN} ${KSTNM}.${GRN}
#####
#      cut and filter Green
#####
sac2000 > /dev/null << FOE
cuterr fillz
cut a ${CUTL}  a ${CUTH}
r ${KSTNM}.${GRN}
rtr
taper
hp c  ${FHIGHPASS} np ${NPOLE} p ${PASS}
lp c  ${FLOWPASS} np ${NPOLE} p ${PASS}
w ${KSTNM}.${GRN}
FOE
#hp c ${FHIGHPASS} np ${NPOLE} p ${PASS}
#lp c ${FLOWPASS} np ${NPOLE} p ${PASS}

       done
#####
#      define the
       echo ${COMP} \(cq${KSTNM}${NAM}\(cq \(cq${KSTNM}\(cq ${WT} >> ww
#####
#      cut and filter observed
#####
sac2000 > /dev/null << FOE
cuterr fillz
cut a ${CUTL}  a ${CUTH}
r ${TRACE}
rtr
taper
hp c  ${FHIGHPASS} np ${NPOLE} p ${PASS}
lp c  ${FLOWPASS} np ${NPOLE} p ${PASS}
w ${KSTNM}${NAM}
FOE

       done
#####
#      Ensure the sample rate the observed = sample rete Green
#      Here ASSUME THAT OBSERVED RATE >= GREEN RATE
#####
#####
#      get the Green sampling interval - this only works if the division is OK
#      and the ratio <=5 (sac limitation)
#####
GDELTA='saclhdr -DELTA ${KSTNM}.ZSS'

sac2000 << EOF
r ${KSTNM}${NAM}
interpolate DELTA $GDELTA
w ${KSTNM}${NAM}
quit
EOF

#####
#      clean up
#####
       rm -f j
```

```
done
```

Note that this script works only because the component names are BHZ, BHR and BHT. The distance weighting is simple, with higher weights at shorter distances. Other weights can eb used. The filtering was applied to the ground velocities. One could also integrate to consider displacements or change the filter bands according to the data quality.

The reason for using these two scripts is to be able to quickly cycle through the data depths quickly and to easily add or remove traces from consideration. In addition a prototype ahs been created for routine processing of other data sets.

3.1 wvfgrd96

After executing **DOGRD**, the summary output in the file *FMDSUM* is

```
WVFGRD96    0.5   205    90     0   3.92 0.2697
WVFGRD96    1.0   205    90     0   3.99 0.3216
WVFGRD96    2.0    25    90     5   4.08 0.3798
WVFGRD96    3.0    25    90     5   4.12 0.3788
WVFGRD96    4.0    25    85     5   4.14 0.3662
WVFGRD96    5.0   205    85     5   4.16 0.3567
WVFGRD96    6.0   205    85    10   4.17 0.3498
WVFGRD96    7.0    25    85    10   4.19 0.3399
WVFGRD96    8.0    30    80    10   4.22 0.3277
WVFGRD96    9.0    30    80    10   4.24 0.3181
WVFGRD96   10.0   210    80    15   4.25 0.3116
WVFGRD96   11.0   300    75     5   4.30 0.3365
WVFGRD96   12.0   125    90    10   4.34 0.3599
WVFGRD96   13.0   305    90   -10   4.36 0.3839
WVFGRD96   14.0   305    90   -10   4.38 0.4033
WVFGRD96   15.0   125    85    15   4.39 0.4117
WVFGRD96   16.0   125    85    15   4.41 0.4273
WVFGRD96   17.0   125    85    15   4.42 0.4448
WVFGRD96   18.0   125    85    15   4.44 0.4536
WVFGRD96   19.0   300    90   -15   4.45 0.4748
WVFGRD96   20.0   300    90   -15   4.48 0.4882
WVFGRD96   21.0   300    85   -10   4.49 0.4896
WVFGRD96   22.0   120    90    10   4.50 0.4901
WVFGRD96   23.0   300    85   -10   4.51 0.4843
WVFGRD96   24.0   300    85   -10   4.52 0.4691
WVFGRD96   25.0   300    85   -10   4.52 0.4498
WVFGRD96   26.0   300    80    -5   4.52 0.4249
WVFGRD96   27.0   300    80    -5   4.52 0.3977
WVFGRD96   28.0   300    80    -5   4.51 0.3667
WVFGRD96   29.0   300    80    -5   4.51 0.3333
```

The corresponding plot make using **`fmdfit -HMN 0 -HMX 30 _M < FMDSUM`** is

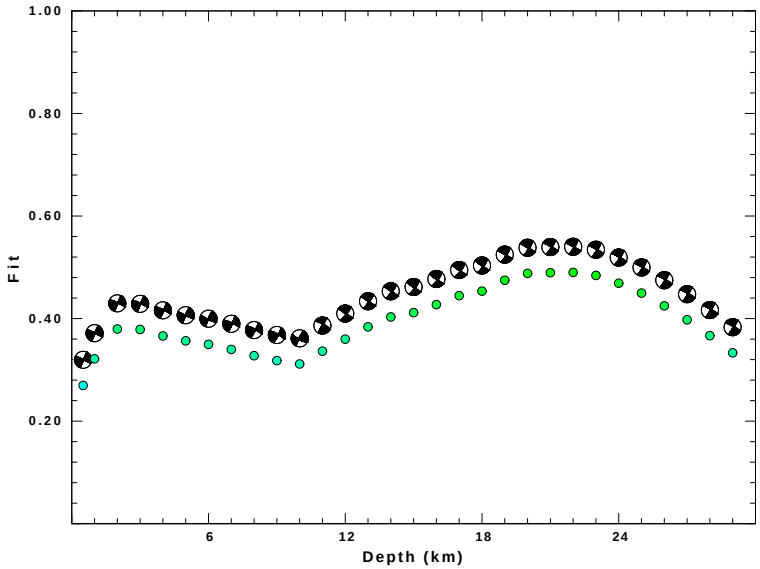


Fig. 17. Depth sensitivity of goodness of fit parameter using the grid search.

Figure 18 presents the observed and predicted waveforms for the 22 km depth solution with dip of 90°, strike of 120°, rake of 10 ° and $\mathbf{M_W = 4.50}$.

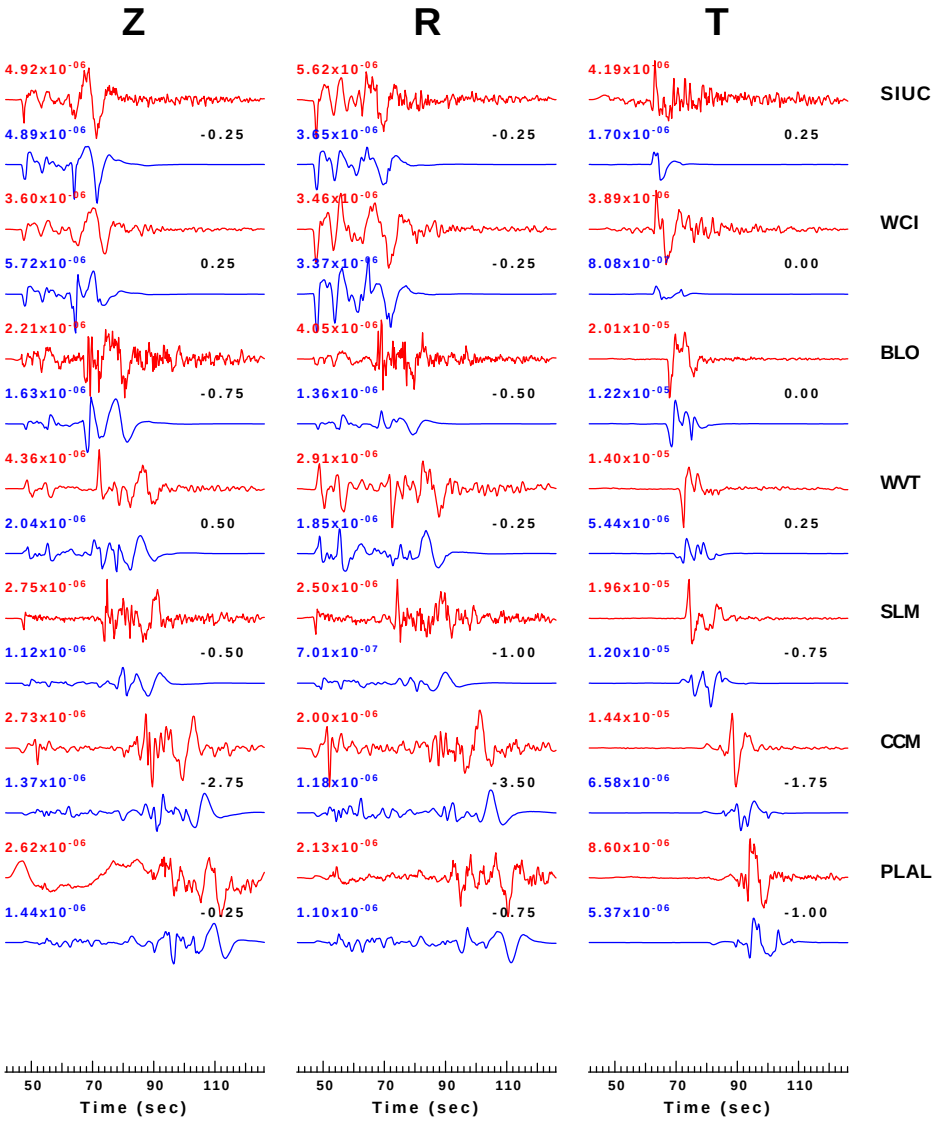


Fig. 18. Comparison of observed and predicted waveforms for the best fitting solution using the waveform grid search technique. For each station, the upper trace is the observed and the low is the predicted. All traces are filtered velocity in units of *m/sec*. Each trace pair is plotted using the same scale. For example, the predicted T component at WCI is about 3 times smaller than observed. Each trace is annotated with the peak amplitude. All traces start 5 seconds before P and end 80 seconds after the first P-arrival and are bandpass filtered between 0.01 and 0.15 Hz. The number ot the right of each predicted trace is the time shift required for maximum correlation between observed and predicted traces. A negative number means that the predicted trace is too late and should be adjusted to earlier time. This plot is made using the command *pltsac* in a shell script.

3.2 wvfmtd96

After executing **DOMTD**, the summary output in the file *FMDSUM* is

```
WVFMTD96  0.5 242. 74. -78. 3.67  0.008 0.157E-05  0.015 0.177E-05  3.9
WVFMTD96  1.0 237. 54. -79. 3.80  0.010 0.156E-05  0.024 0.176E-05 57.5
WVFMTD96  2.0 235. 48. -86. 4.04 -0.012 0.158E-05 -0.020 0.180E-05 74.3
WVFMTD96  3.0 241. 48. -85. 4.05 -0.041 0.160E-05 -0.074 0.185E-05 64.4
WVFMTD96  4.0 248. 49. -84. 4.02 -0.040 0.160E-05 -0.073 0.185E-05 37.9
WVFMTD96  5.0 254. 50. -80. 3.99 -0.037 0.160E-05 -0.051 0.183E-05  6.0
WVFMTD96  6.0 268. 50. -64. 4.05 -0.018 0.159E-05 -0.008 0.179E-05 49.8
WVFMTD96  7.0 284. 60. -40. 4.13 -0.010 0.158E-05  0.037 0.175E-05 70.6
WVFMTD96  8.0 294. 74. -20. 4.20  0.014 0.156E-05  0.095 0.170E-05 67.0
WVFMTD96  9.0 298. 80. -12. 4.28  0.016 0.156E-05  0.154 0.164E-05 56.5
WVFMTD96 10.0 298. 80. -12. 4.35  0.049 0.153E-05  0.226 0.157E-05 49.1
WVFMTD96 11.0 299. 84. -10. 4.39  0.048 0.153E-05  0.257 0.154E-05 47.9
WVFMTD96 12.0 299. 85. -10. 4.41  0.055 0.153E-05  0.287 0.151E-05 45.6
WVFMTD96 13.0 299. 86. -11. 4.43  0.065 0.152E-05  0.313 0.148E-05 43.4
WVFMTD96 14.0 300. 88. -10. 4.45  0.072 0.151E-05  0.356 0.143E-05 32.9
WVFMTD96 15.0 299. 87. -10. 4.46  0.062 0.152E-05  0.385 0.140E-05 24.8
WVFMTD96 16.0 299. 90. -10. 4.46  0.070 0.152E-05  0.402 0.138E-05 12.2
WVFMTD96 17.0 119. 90.  11. 4.47  0.076 0.151E-05  0.413 0.137E-05  8.4
WVFMTD96 18.0 119. 90.  11. 4.47  0.066 0.152E-05  0.409 0.137E-05  5.4
WVFMTD96 19.0 119. 89.  10. 4.48  0.071 0.152E-05  0.425 0.135E-05  1.8
WVFMTD96 20.0 299. 89. -10. 4.49  0.051 0.153E-05  0.424 0.135E-05  4.2
WVFMTD96 21.0 299. 88. -10. 4.50  0.059 0.153E-05  0.423 0.135E-05  4.3
WVFMTD96 22.0 299. 89. -10. 4.51  0.061 0.152E-05  0.413 0.137E-05  8.0
WVFMTD96 23.0 299. 88. -10. 4.52  0.036 0.154E-05  0.388 0.139E-05 11.5
WVFMTD96 24.0 299. 87. -10. 4.52  0.030 0.155E-05  0.373 0.141E-05 14.9
WVFMTD96 25.0 300. 88. -11. 4.51  0.029 0.155E-05  0.337 0.145E-05 20.5
WVFMTD96 26.0 300. 88. -11. 4.51  0.000 0.157E-05  0.302 0.149E-05 22.7
WVFMTD96 27.0 300. 87. -11. 4.51 -0.020 0.159E-05  0.275 0.152E-05 24.7
WVFMTD96 28.0 120. 90.  13. 4.48 -0.018 0.159E-05  0.218 0.158E-05 25.3
WVFMTD96 29.0 300. 90. -11. 4.48 -0.041 0.160E-05  0.190 0.160E-05 25.5
```

The corresponding plot make using **`fmdfit`** is

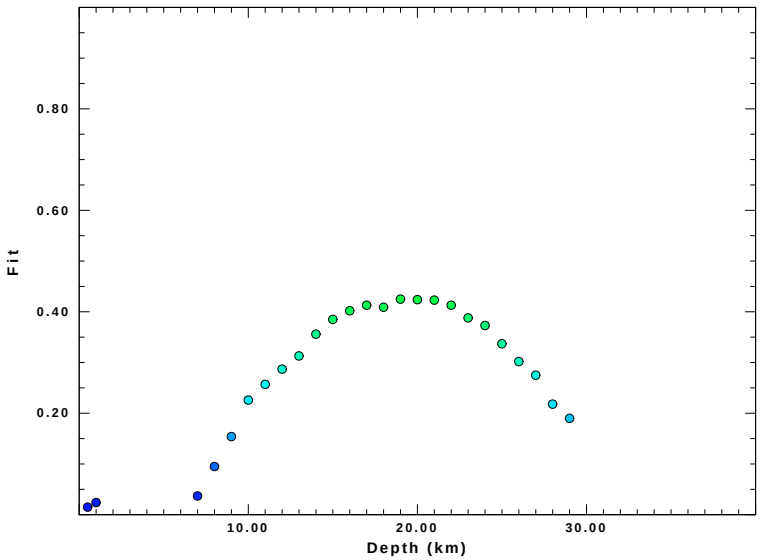


Fig. 18. Depth sensitivity of goodness of fit parameter using the inversion for the deviatoric moment tensor.

The output of the 19 km source depth run, stored in *oout.0190* is as follows:

```
Singular Values of A:
5.77239285E-07
5.06800052E-07
1.46244041E-07
1.99046929E-07
3.46372049E-07
3.04262496E-07
INPUT MOMENT TENSOR
 0.4950569E+23 -0.3005453E+23  0.9632885E+22
-0.3005453E+23 -0.4927519E+23  0.4389753E+22
```

```
 0.9632885E+22  0.4389753E+22 -0.2304993E+21

 EIGENVALUES                EIGENVECTORS
-0.5850831E+23   -0.2759166 -0.9539770  0.1174649
-0.5346954E+21   -0.0993570  0.1498618  0.9837020
 0.5904301E+23    0.9560325 -0.2597488  0.1361336

 SEISMIC MOMENT OF THE INPUT MOMENT TENSOR:   0.5877748E+23

 ISOTROPIC COMPONENT (TRACE OF MOMENT TENSOR):   0.2516582E+08

 INPUT MOMENT TENSOR IS PURELY DEVIATORIC
 EIGENVALUES OF THE PURELY DEVIATORIC MOMENT TENSOR
-0.5850831E+23 -0.5346954E+21  0.5904301E+23

 EPSILON    % OF CLVD     % OF DC
 0.009056    1.811206   98.188794

 ------------------------------------------------------------

 DECOMPOSITION INTO MAJOR AND MINOR DOUBLE COUPLE

 SEISMIC MOMENT OF ISOTROPIC PART, MAJOR, AND MINOR COUPLE
 0.8388608E+07  0.5904301E+23  0.5346954E+21

 EIGENVALUES AND EIGENVECTORS OF THE MAJOR DC
-0.5904301E+23   -0.2759166 -0.9539770  0.1174649
 0.0000000E+00   -0.0993570  0.1498618  0.9837020
 0.5904301E+23    0.9560325 -0.2597488  0.1361336

 NODAL PLANES
  STK=  119.40372
  DIP=   89.24355
 SLIP=   10.32429
  OR
  STK=   29.26592
  DIP=   79.67662
 SLIP=  179.23111

          X-DIR          Y-DIR          Z-DIR
 X:       0.4809191     -0.8582400      0.1792792
 Y:       0.8711022      0.4909197      0.0133717
 Z:      -0.0994878      0.1497398      0.9837074
 T:       0.9560234     -0.2597346      0.1362248
 P:      -0.2759012     -0.9540000      0.1173143

       TREND       PLUNGE
 X    299.26096    10.32338
 Y     29.40556     0.76124
 Z    123.59713    79.64265
 T    344.79978     7.82491
 P    253.87397     6.73254

 EIGENVALUES AND EIGENVECTORS OF THE MINOR DC
 0.5346954E+21   -0.2759166 -0.9539770  0.1174649
-0.5346954E+21   -0.0993570  0.1498618  0.9837020
 0.0000000E+00    0.9560325 -0.2597488  0.1361336

 NODAL PLANES
  STK=  170.91599
  DIP=   52.22620
 SLIP=  -80.08315
  OR
  STK=  334.98633
  DIP=   38.86514
 SLIP= -102.52940

          X-DIR          Y-DIR          Z-DIR
 X:      -0.2654953     -0.5685232      0.7786486
 Y:       0.1251518      0.7804763      0.6125306
 Z:       0.9559547     -0.2600732      0.1360611
 T:      -0.2762292     -0.9538867      0.1174632
 P:      -0.0992378      0.1498735      0.9837123

       TREND       PLUNGE
 X    244.97143    51.13486
 Y     80.89446    37.76983
 Z    344.77984     7.81545
 T    253.85397     6.74112
 P    123.50718    79.64421

 ------------------------------------------------------------

 DECOMPOSITION INTO THREE DOUBLE COUPLES

 SEISMIC MOMENTS OF ISOTROPIC PART, EMT1, EMT2, EMT3
 0.8388608E+07  0.1932454E+23  0.1985923E+23  0.3918377E+23

 EMT1
-0.6625816E-01 -0.2781079E+00 -0.6532717E-01
-0.2781079E+00 -0.8876135E+00  0.2594781E+00
-0.6532717E-01  0.2594781E+00  0.9538716E+00

 EIGENVALUES                EIGENVECTORS
-0.1000000E+01   -0.2759166 -0.9539770  0.1174649
 0.5474261E-16    0.9560325 -0.2597488  0.1361336
 0.1000000E+01   -0.0993570  0.1498618  0.9837020

 NODAL PLANES
  STK=  170.91599
  DIP=   52.22620
 SLIP=   99.91686
  OR
  STK=  334.98633
  DIP=   38.86514
 SLIP=   77.47060

          X-DIR          Y-DIR          Z-DIR
 X:       0.1249861      0.7805214      0.6125070
 Y:      -0.2654953     -0.5685232      0.7786486
 Z:       0.9559763     -0.2599379      0.1361672
 T:      -0.0993550      0.1499054      0.9836956
 P:      -0.2761120     -0.9539186      0.1174798

       TREND       PLUNGE
 X     80.90684    37.76812
 Y    244.97143    51.13486
 Z    344.78772     7.82159
 T    123.53270    79.63890
 P    253.86097     6.74208

 EMT2
 0.9041264E+00 -0.2334384E+00  0.2278859E+00
-0.2334384E+00  0.4501086E-01 -0.1827799E+00
 0.2278859E+00 -0.1827799E+00 -0.9491373E+00

 EIGENVALUES                EIGENVECTORS
-0.1000000E+01   -0.0993570  0.1498618  0.9837020
 0.1086537E-15    0.2759166  0.9539770 -0.1174649
 0.1000000E+01    0.9560325 -0.2597488  0.1361336

 NODAL PLANES
  STK=  248.78675
  DIP=   53.17656
 SLIP=  -98.43910
  OR
  STK=   82.69037
  DIP=   37.64418
 SLIP=  -78.91014

          X-DIR          Y-DIR          Z-DIR
 X:      -0.7462229      0.2897828      0.5993140
 Y:       0.6057577     -0.0777519      0.7918411
 Z:      -0.2760597     -0.9539290      0.1175179
 T:       0.9559947     -0.2598863      0.1361372
 P:      -0.0993239      0.1499285      0.9836952

       TREND       PLUNGE
 X    158.77601    36.81785
 Y    352.68540    52.35582
 Z    253.86404     6.74428
 T    344.79089     7.81985
 P    123.52037    79.63877

 EMT3
 0.8378682E+00 -0.5115463E+00  0.1625587E+00
-0.5115463E+00 -0.8426026E+00  0.7669825E-01
 0.1625587E+00  0.7669825E-01  0.4734370E-02
```

```
 EIGENVALUES                EIGENVECTORS
-0.1000000E+01   -0.2759166 -0.9539770  0.1174649
 0.0000000E+00   -0.0993570  0.1498618  0.9837020
 0.1000000E+01    0.9560325 -0.2597488  0.1361336

 NODAL PLANES
  STK=  119.40372
  DIP=   89.24355
 SLIP=   10.32429
  OR
  STK=   29.26592
  DIP=   79.67662
 SLIP=  179.23111

          X-DIR          Y-DIR          Z-DIR
 X:       0.4809191     -0.8582400      0.1792792
 Y:       0.8711022      0.4909197      0.0133717
 Z:      -0.0994878      0.1497398      0.9837074
 T:       0.9560234     -0.2597346      0.1362248
 P:      -0.2759012     -0.9540000      0.1173143

       TREND       PLUNGE
 X    299.26096    10.32338
 Y     29.40556     0.76124
 Z    123.59713    79.64265
 T    344.79978     7.82491
 P    253.87397     6.73254

 ---------------------------------------------------------------

 DECOMPOSITION INTO THREE VECTOR DIPOLES

 SEISMIC MOMENTS OF ISOTROPIC PART, EMT1, EMT2, EMT3
 0.8388608E+07  0.5346954E+21  0.5850831E+23  0.5904301E+23

           DIPOLE AXES
-0.0993570  0.1498618  0.9837020
-0.2759166 -0.9539770  0.1174649
 0.9560325 -0.2597488  0.1361336

 ---------------------------------------------------------------

 DECOMPOSITION INTO THREE COMPENSATED LINEAR VECTOR DIPOLES

 SEISMIC MOMENTS OF ISOTROPIC PART, EMT1, EMT2, EMT3
 0.8388608E+07  0.3087065E+21  0.3377979E+23  0.3408850E+23

 EIGENVALUE          AXES OF CLVD
      -1   -0.2759166 -0.9539770  0.1174649
       2   -0.0993570  0.1498618  0.9837020
      -1    0.9560325 -0.2597488  0.1361336

 EIGENVALUE          AXES OF CLVD
       2   -0.2759166 -0.9539770  0.1174649
      -1   -0.0993570  0.1498618  0.9837020
      -1    0.9560325 -0.2597488  0.1361336

 EIGENVALUE          AXES OF CLVD
      -1   -0.2759166 -0.9539770  0.1174649
      -1   -0.0993570  0.1498618  0.9837020
       2    0.9560325 -0.2597488  0.1361336

 ---------------------------------------------------------------

 DECOMPOSITION INTO A DOUBLE COUPLE AND A CLVD

 SEISMIC MOMENTS OF ISOTROPIC PART, DC, CLVD
 0.8388608E+07  0.5797362E+23  0.5346954E+21

 EIGENVALUES AND EIGENVECTORS OF THE DC
-0.5904301E+23   -0.2759166 -0.9539770  0.1174649
 0.0000000E+00   -0.0993570  0.1498618  0.9837020
 0.5904301E+23    0.9560325 -0.2597488  0.1361336

 NODAL PLANES
  STK=  119.40372
  DIP=   89.24355
 SLIP=   10.32429
  OR
  STK=   29.26592
  DIP=   79.67662
 SLIP=  179.23111

          X-DIR          Y-DIR          Z-DIR
 X:       0.4809191     -0.8582400      0.1792792
 Y:       0.8711022      0.4909197      0.0133717
 Z:      -0.0994878      0.1497398      0.9837074
 T:       0.9560234     -0.2597346      0.1362248
 P:      -0.2759012     -0.9540000      0.1173143

       TREND       PLUNGE
 X    299.26096    10.32338
 Y     29.40556     0.76124
 Z    123.59713    79.64265
 T    344.79978     7.82491
 P    253.87397     6.73254

 EIGENVALUE          AXES OF CLVD
      -1   -0.2759166 -0.9539770  0.1174649
      -1   -0.0993570  0.1498618  0.9837020
       2    0.9560325 -0.2597488  0.1361336

Covariance Matrix
   xx          yy          xy          xz          yz          zz
 0.286E+14
 0.791E+13  0.217E+14
-0.525E+13  0.960E+12  0.561E+13
-0.436E+12  0.152E+13  0.549E+12  0.951E+13
 0.103E+13 -0.563E+12 -0.358E+12 -0.255E+13  0.406E+13
 0.646E+13  0.157E+14  0.228E+13  0.545E+12 -0.582E+12  0.285E+14

 file,weight,sum_square_error,fractional_error,ls_scale_factor
BLOR  4.000 0.947E-10 0.651 0.109E+01
BLOT  4.000 0.114E-08 0.394 0.105E+01
BLOZ  4.000 0.787E-10 0.962 0.520E+00
CCMR  0.250 0.132E-09 1.931-0.614E+00
CCMT  0.250 0.237E-08 1.438-0.212E+00
CCMZ  0.250 0.217E-09 1.698-0.370E+00
MPHR  0.250 0.591E-09 0.995 0.672E+00
MPHT  0.250 0.907E-08 1.152-0.651E+00
MPHZ  0.250 0.194E-09 1.095 0.407E-01
PLAL  0.250 0.497E-10 0.880 0.609E+00
PLAL  0.250 0.746E-09 0.915 0.593E+00
PLAL  0.250 0.411E-09 0.963 0.634E+00
SIUC  4.000 0.207E-09 0.401 0.112E+01
SIUC  4.000 0.181E-09 1.134 0.353E+00
SIUC  4.000 0.937E-10 0.282 0.926E+00
SLMR  1.000 0.644E-10 1.026 0.397E+00
SLMT  1.000 0.191E-08 0.877 0.586E+00
SLMZ  1.000 0.778E-10 1.034 0.414E+00
WCIR  4.000 0.857E-10 0.309 0.967E+00
WCIT  4.000 0.102E-09 0.625 0.260E+01
WCIZ  4.000 0.175E-09 0.599 0.780E+00
WVTR  1.000 0.631E-10 0.444 0.929E+00
WVTT  1.000 0.617E-09 0.663 0.890E+00
WVTZ  1.000 0.114E-09 0.678 0.693E+00

 Misfit Summary:

Fractional Misfit: 0                                                1
                   |         |         |         |         |
BLOR         0.65 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxx                 |
BLOT         0.39 |xxxxxxxxxxxxxxxxxx                              |
BLOZ         0.96 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx |
CCMR         1.93 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
CCMT         1.44 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
CCMZ         1.70 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
MPHR         0.99 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
MPHT         1.15 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
MPHZ         1.10 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
PLALR        0.88 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx      |
PLALT        0.91 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx    |
PLALZ        0.96 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx |
SIUCR        0.40 |xxxxxxxxxxxxxxxxxx                            |
SIUCT        1.13 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
SIUCZ        0.28 |xxxxxxxxxxxxxx                                |
SLMR         1.03 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
SLMT         0.88 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx      |
SLMZ         1.03 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|
WCIR         0.31 |xxxxxxxxxxxxxxx                               |
WCIT         0.62 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxx                 |
WCIZ         0.60 |xxxxxxxxxxxxxxxxxxxxxxxxxxxx                  |
```

```
WVTR          0.44 |xxxxxxxxxxxxxxxxxxxx                          |
WVTT          0.66 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx              |
WVTZ          0.68 |xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx             |
                   |         |         |         |         |         |


 Unweighted SSE,Weighted SSE,Unweighted RMS,Weighted RMS
  2.29813976E-12  1.82695786E-12  1.51596169E-06  1.3516501E-06
 Total Error divided by sum of all seismogram amplitudes
 Unweighted, weighted
  0.929462194  0.574764073

 ij       Mij     StdErr Mij
 ij       Mij     StdErr Mij
 xx   0.4951E+23  0.8114E+21
 yy  -0.4928E+23  0.7066E+21
 xy  -0.3005E+23  0.3592E+21
 xz   0.9633E+22  0.4674E+21
 yz   0.4390E+22  0.3056E+21
 zz  -0.2305E+21  0.8089E+21
 Fnorm =    0.1974E-01
```

The last 10 lines of output are new to version 3.25. These repeat the moment tensor elements but also list the estimated errors (1 standard deviation) for each moment tensor element. The last entry, *Fnorm*, is a measure of the quality of the moment tensor. It is computed as

$$Fnorm = \frac{\left(\sum_i s_i^2\right)^{1/2}}{\left(\sum_i M_i^2\right)^{1/2}}$$

where i talks on values xx, yy, xy, xz, yz, xy, xz, yz and zz, M_i and s_i are the specific moment tensor and its standard error, respectively. The xy, xz and yz are counted twice to ensure that all nine elements of the symmetric matrix are included.

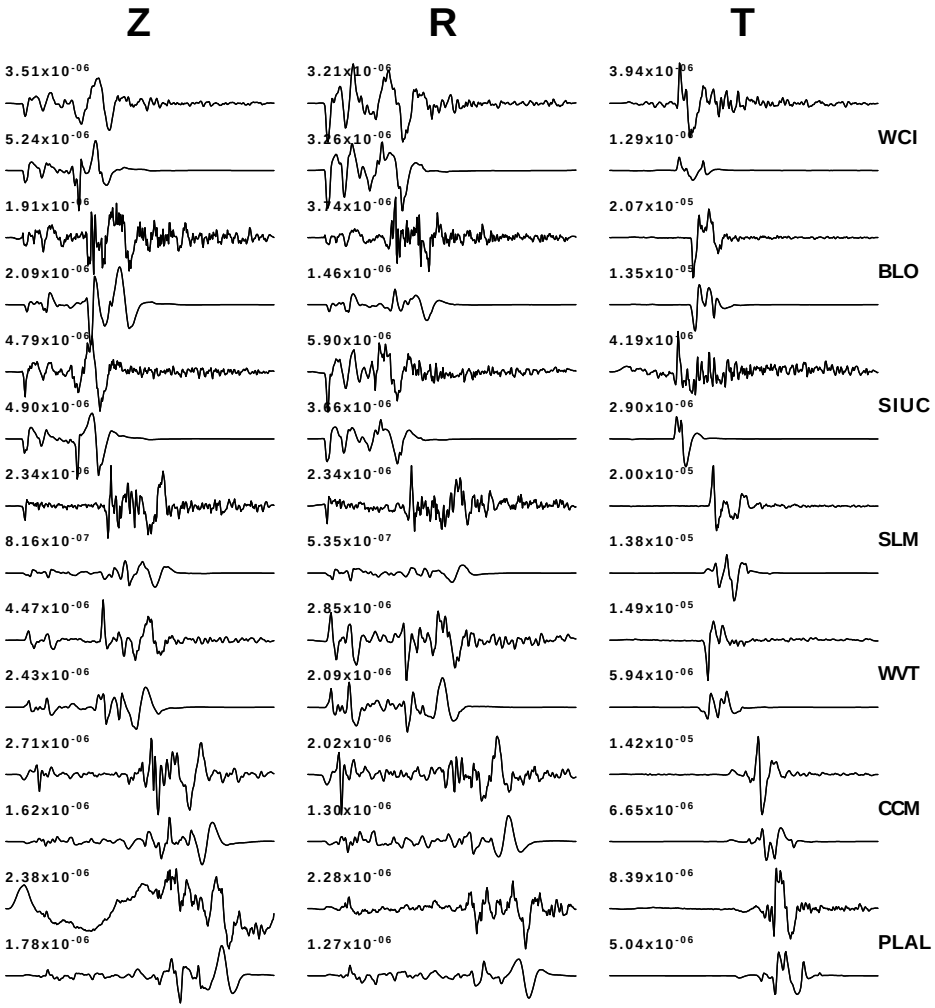


Fig. 19. Comparison of observed and predicted waveforms for the best fitting solution using the waveform deviatoric moment tensor inversion technique. For each station, the upper trace is the observed and the low is the predicted. All traces are filtered velocity in units of *m/sec*. Each trace pair is plotted using the same scale. For example, the predicted T component at WCI is about 3 times smaller than observed. Each trace is annotated with the peak amplitude. All traces start 5 seconds before P and end 80 seconds after the first P-arrival. Note that the predicted traces are for the deviatoric moment tensor which contains a 17% CLVD contribution.

3.2 wvfmt96

After executing **DOMT**, the summary output in the file *FMDSUM* is

```
WVFMTD96  0.5 236. 64. -81. 3.79  0.009 0.156E-05 0.018 0.176E-05 42.1
WVFMTD96  1.0 237. 53. -80. 3.83  0.009 0.156E-05 0.024 0.176E-05 59.0
WVFMTD96  2.0 245. 53. -78. 3.77  0.008 0.156E-05 0.030 0.175E-05 20.1
WVFMTD96  3.0 254. 54. -74. 3.79  0.004 0.156E-05 0.035 0.175E-05 23.2
WVFMTD96  4.0 267. 57. -60. 3.86  0.006 0.156E-05 0.041 0.174E-05 58.2
WVFMTD96  5.0 285. 70. -34. 3.93  0.002 0.156E-05 0.049 0.173E-05 69.6
WVFMTD96  6.0 292. 76. -19. 4.02  0.013 0.155E-05 0.079 0.171E-05 50.0
WVFMTD96  7.0 295. 80. -14. 4.11  0.013 0.155E-05 0.103 0.169E-05 43.1
WVFMTD96  8.0 297. 83. -11. 4.19  0.029 0.154E-05 0.143 0.165E-05 40.2
WVFMTD96  9.0 298. 83.  -9. 4.28  0.026 0.154E-05 0.189 0.160E-05 39.7
WVFMTD96 10.0 299. 82.  -9. 4.34  0.055 0.152E-05 0.250 0.154E-05 31.8
WVFMTD96 11.0 299. 85.  -8. 4.38  0.052 0.152E-05 0.276 0.151E-05 32.3
WVFMTD96 12.0 300. 86.  -9. 4.41  0.058 0.152E-05 0.301 0.149E-05 32.5
WVFMTD96 13.0 300. 87. -10. 4.43  0.067 0.151E-05 0.323 0.146E-05 32.3
WVFMTD96 14.0 300. 88. -10. 4.45  0.070 0.151E-05 0.358 0.143E-05 32.5
WVFMTD96 15.0 299. 87. -10. 4.47  0.060 0.152E-05 0.386 0.139E-05 25.5
WVFMTD96 16.0 299. 89. -10. 4.47  0.069 0.151E-05 0.404 0.137E-05 22.2
WVFMTD96 17.0 299. 89. -11. 4.48  0.076 0.150E-05 0.415 0.136E-05 19.4
WVFMTD96 18.0 299. 89. -11. 4.48  0.066 0.151E-05 0.411 0.137E-05 15.1
WVFMTD96 19.0 299. 90. -10. 4.49  0.070 0.151E-05 0.428 0.135E-05 13.5
WVFMTD96 20.0 299. 89. -10. 4.50  0.048 0.153E-05 0.426 0.135E-05  7.4
WVFMTD96 21.0 299. 88. -10. 4.51  0.057 0.152E-05 0.424 0.135E-05  7.5
WVFMTD96 22.0 299. 89. -10. 4.52  0.058 0.152E-05 0.415 0.136E-05 10.1
WVFMTD96 23.0 299. 88. -10. 4.52  0.033 0.154E-05 0.390 0.139E-05 12.6
WVFMTD96 24.0 299. 87.  -9. 4.53  0.026 0.154E-05 0.374 0.141E-05 15.3
WVFMTD96 25.0 300. 89. -10. 4.52  0.025 0.154E-05 0.339 0.145E-05 15.7
WVFMTD96 26.0 300. 88. -11. 4.52 -0.004 0.157E-05 0.304 0.148E-05 19.0
WVFMTD96 27.0 300. 87. -11. 4.52 -0.025 0.158E-05 0.276 0.151E-05 22.3
WVFMTD96 28.0 120. 90.  12. 4.48 -0.021 0.158E-05 0.219 0.157E-05 21.1
WVFMTD96 29.0 300. 90. -11. 4.49 -0.046 0.160E-05 0.190 0.160E-05 24.3
```

The corresponding plot make using **`fmdfit`** is

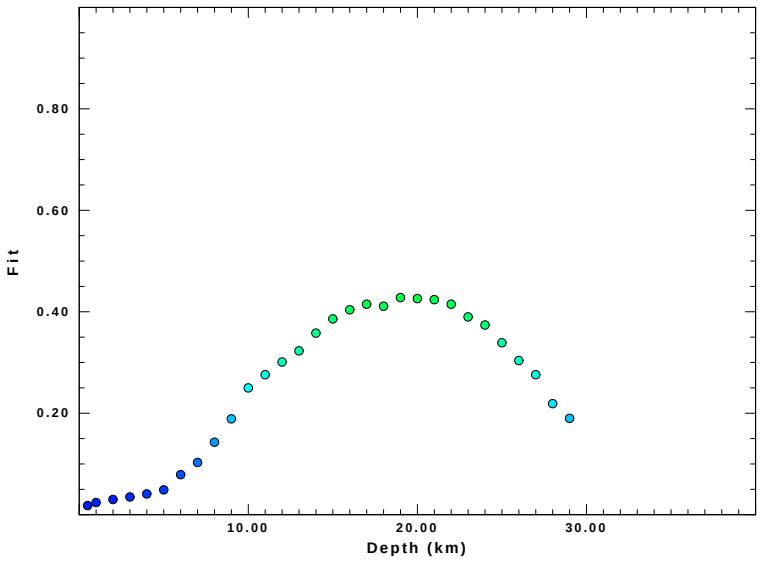


Fig. 20. Depth sensitivity of goodness of fit parameter using the inversion for the moment tensor.

3.3 Model sensitivity

Herrmann and Ammon (1997) proposed the use of the Hamburg model for wave propagation in this area. This model was designed to fit the broadband waveforms of the September 26, 1990 New Hamburg, Missouri, earthquake. The model has many more layers than the simpler Central United States model. It would be interesting to compare some of the program output for this model.

```
MODEL.01
1990 Hamburg - CCM waveform model
ISOTROPIC
KGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE 08
LINE 09
LINE 10
LINE 11
H     Vp    Vs    Rho  Qp     Qs     EtaP  EtaS  FrefP FrefS
 1.00000  4.93730  2.85063  2.48621   0.0050  0.010 0.0 0.0 1.0 1.0
 2.00000  5.76166  3.32659  2.65233   0.0005  0.001 0.0 0.0 1.0 1.0
 2.00000  6.25036  3.60875  2.77511   0.0005  0.001 0.0 0.0 1.0 1.0
 3.00000  6.13773  3.54372  2.74132   0.0005  0.001 0.0 0.0 1.0 1.0
 3.00000  6.23542  3.60013  2.77063   0.0005  0.001 0.0 0.0 1.0 1.0
 4.00000  6.41363  3.70302  2.82409   0.0005  0.001 0.0 0.0 1.0 1.0
 4.00000  6.36432  3.67455  2.80930   0.0005  0.001 0.0 0.0 1.0 1.0
 5.50000  6.58451  3.80168  2.87197   0.0005  0.001 0.0 0.0 1.0 1.0
 5.50000  6.53322  3.77207  2.85864   0.0005  0.001 0.0 0.0 1.0 1.0
 5.50000  6.74437  3.89398  2.91354   0.0005  0.001 0.0 0.0 1.0 1.0
 5.50000  6.63982  3.83362  2.88635   0.0005  0.001 0.0 0.0 1.0 1.0
 1.25000  7.33234  4.23346  3.08635   0.0005  0.001 0.0 0.0 1.0 1.0
 1.25000  7.36506  4.25234  3.09682   0.0005  0.001 0.0 0.0 1.0 1.0
 2.50000  7.76689  4.48435  3.23074   0.0005  0.001 0.0 0.0 1.0 1.0
 2.50000  7.84198  4.52770  3.25627   0.0005  0.001 0.0 0.0 1.0 1.0
 5.00000  7.87842  4.54874  3.26866   0.0005  0.001 0.0 0.0 1.0 1.0
 2.50000  8.06097  4.65414  3.33195   0.0005  0.001 0.0 0.0 1.0 1.0
 2.50000  8.06097  4.65414  3.33195   0.0005  0.001 0.0 0.0 1.0 1.0
```

After executing **DOMTD**, the summary output in the file *FMDSUM* is

```
WVFMTD96  0.5  56. 59.  -89. 3.57  0.006 0.156E-05  0.015 0.177E-05 21.3
WVFMTD96  1.0  63. 50.  -92. 3.89  0.001 0.156E-05  0.024 0.176E-05 54.0
WVFMTD96  2.0  64. 49.  -93. 4.01 -0.038 0.159E-05 -0.056 0.183E-05 61.3
WVFMTD96  3.0  64. 49.  -94. 4.09 -0.067 0.162E-05 -0.100 0.187E-05 55.4
WVFMTD96  4.0  63. 50.  -97. 4.04 -0.076 0.162E-05 -0.097 0.186E-05 28.4
WVFMTD96  5.0  60. 51. -101. 4.01 -0.072 0.162E-05 -0.072 0.184E-05  8.8
WVFMTD96  6.0  57. 50. -109. 4.08 -0.075 0.162E-05 -0.047 0.182E-05 41.0
WVFMTD96  7.0  52. 51. -117. 4.11 -0.066 0.161E-05 -0.023 0.180E-05 55.2
WVFMTD96  8.0  46. 54. -126. 4.15 -0.056 0.161E-05 -0.001 0.178E-05 61.5
WVFMTD96  9.0  39. 59. -137. 4.18 -0.043 0.160E-05  0.027 0.176E-05 66.0
WVFMTD96 10.0  34. 65. -148. 4.23 -0.029 0.159E-05  0.062 0.172E-05 66.4
WVFMTD96 11.0  31. 74. -157. 4.29 -0.013 0.157E-05  0.135 0.166E-05 53.9
WVFMTD96 12.0  30. 74. -160. 4.33  0.007 0.156E-05  0.164 0.163E-05 51.3
WVFMTD96 13.0  29. 80. -167. 4.36  0.032 0.154E-05  0.217 0.157E-05 41.5
WVFMTD96 14.0  29. 81. -169. 4.40  0.061 0.152E-05  0.276 0.151E-05 35.3
WVFMTD96 15.0  29. 82. -170. 4.43  0.083 0.150E-05  0.331 0.146E-05 30.5
WVFMTD96 16.0  30. 82. -171. 4.46  0.092 0.149E-05  0.379 0.140E-05 26.2
WVFMTD96 17.0  29. 83. -170. 4.49  0.122 0.147E-05  0.457 0.131E-05 21.0
WVFMTD96 18.0  29. 84. -170. 4.51  0.117 0.147E-05  0.489 0.127E-05 16.5
WVFMTD96 19.0  29. 86. -168. 4.51  0.105 0.148E-05  0.491 0.127E-05  8.5
WVFMTD96 20.0  29. 87. -167. 4.52  0.131 0.146E-05  0.530 0.122E-05  8.1
WVFMTD96 21.0  29. 87. -167. 4.53  0.090 0.149E-05  0.530 0.122E-05  7.8
WVFMTD96 22.0  30. 87. -167. 4.53  0.093 0.149E-05  0.531 0.122E-05  8.6
WVFMTD96 23.0  30. 87. -166. 4.54  0.109 0.148E-05  0.540 0.121E-05 11.1
WVFMTD96 24.0  29. 86. -165. 4.50  0.069 0.151E-05  0.439 0.133E-05  8.6
WVFMTD96 25.0  30. 86. -166. 4.53  0.061 0.152E-05  0.470 0.130E-05 15.9
WVFMTD96 26.0  30. 85. -166. 4.52  0.044 0.153E-05  0.441 0.133E-05 20.3
WVFMTD96 27.0  31. 84. -164. 4.52  0.024 0.155E-05  0.382 0.140E-05 21.2
WVFMTD96 28.0  31. 82. -169. 4.52  0.019 0.155E-05  0.374 0.141E-05 28.5
WVFMTD96 29.0  31. 81. -168. 4.53 -0.001 0.156E-05  0.348 0.144E-05 34.8
WVFMTD96 30.0  31. 79. -166. 4.53 -0.023 0.158E-05  0.297 0.149E-05 39.1
WVFMTD96 31.0 299. 83.  -11. 4.53 -0.024 0.158E-05  0.281 0.151E-05 44.2
WVFMTD96 32.0 299. 82.  -11. 4.53 -0.039 0.159E-05  0.259 0.153E-05 47.6
WVFMTD96 33.0 299. 82.  -11. 4.53 -0.054 0.161E-05  0.223 0.157E-05 50.4
WVFMTD96 34.0 299. 81.  -11. 4.53 -0.062 0.161E-05  0.197 0.159E-05 52.6
WVFMTD96 35.0 300. 86.  -11. 4.53 -0.068 0.162E-05  0.184 0.161E-05 55.0
WVFMTD96 36.0 300. 84.   -8. 4.53 -0.081 0.163E-05  0.168 0.162E-05 49.4
WVFMTD96 37.0  31. 84. -172. 4.53 -0.092 0.163E-05  0.148 0.164E-05 48.2
WVFMTD96 38.0 300. 89.   -7. 4.54 -0.109 0.165E-05  0.151 0.164E-05 36.5
WVFMTD96 39.0  30. 87. -176. 4.56 -0.128 0.166E-05  0.133 0.166E-05 33.8
WVFMTD96 40.0  30. 88. -175. 4.57 -0.137 0.167E-05  0.117 0.167E-05 33.7
```

Figure 21 compares the observed and predicted waveforms for a source at a depth of 21 km (the source is slightly deeper because the velocity model is slightly faster).

While the Hamburg model may be better for the source region, it does not perform as well in characterizing mid-continent fundamental surface-wave dispersion, as indicated in Figures 22 and 23. This is a very interesting observation since this indicates something about the heterogeneity of the crust.

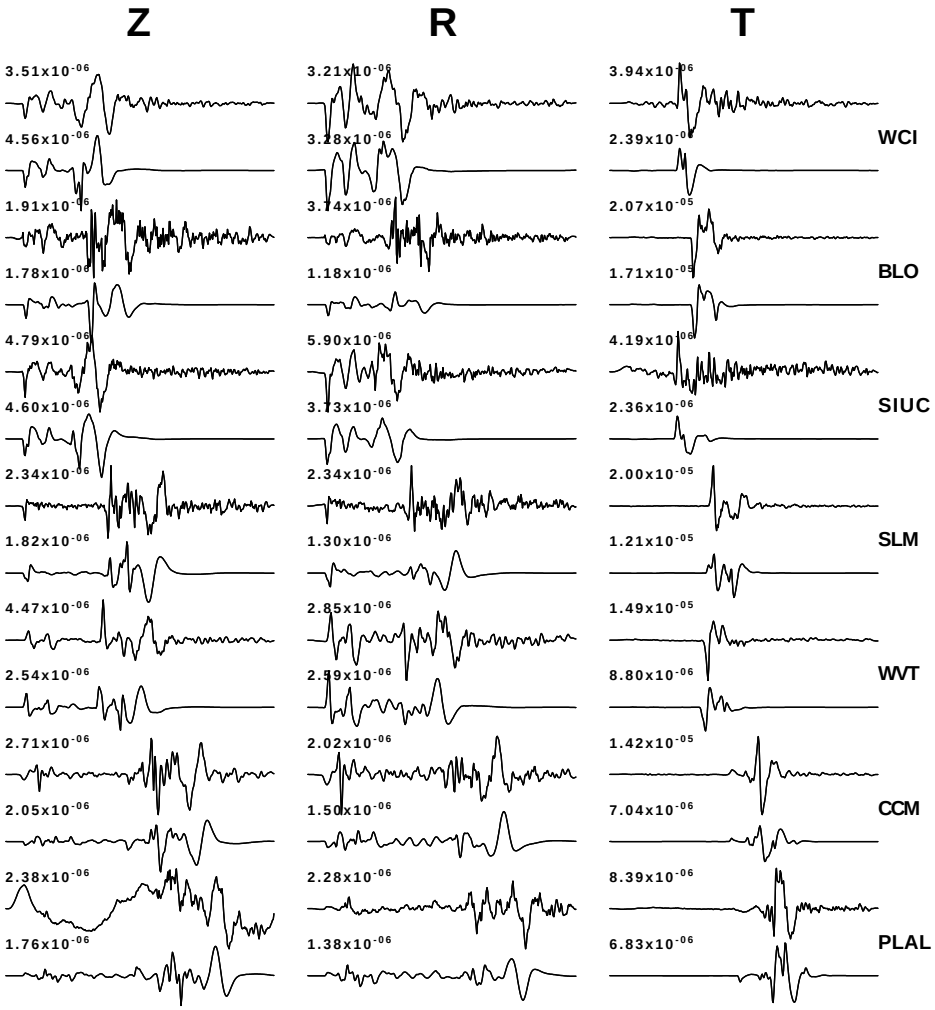


Fig. 21. Comparison of observed and predicted waveforms for the best fitting solution using the waveform deviatoric moment tensor inversion technique for the Hamburg model. For each station, the upper trace is the observed and the low is the predicted. All traces are filtered velocity in units of *m/sec*. Each trace pair is plotted using the same scale. For example, the predicted T component at WCI is about 3 times smaller than observed. Each trace is annotated with the peak amplitude. All traces start 5 seconds before P and end 80 seconds after the first P-arrival and are bandpass filtered between 0.01 and 0.15 Hz. Note that the predicted traces are for the deviatoric moment tensor which contains a 1% CLVD contribution.

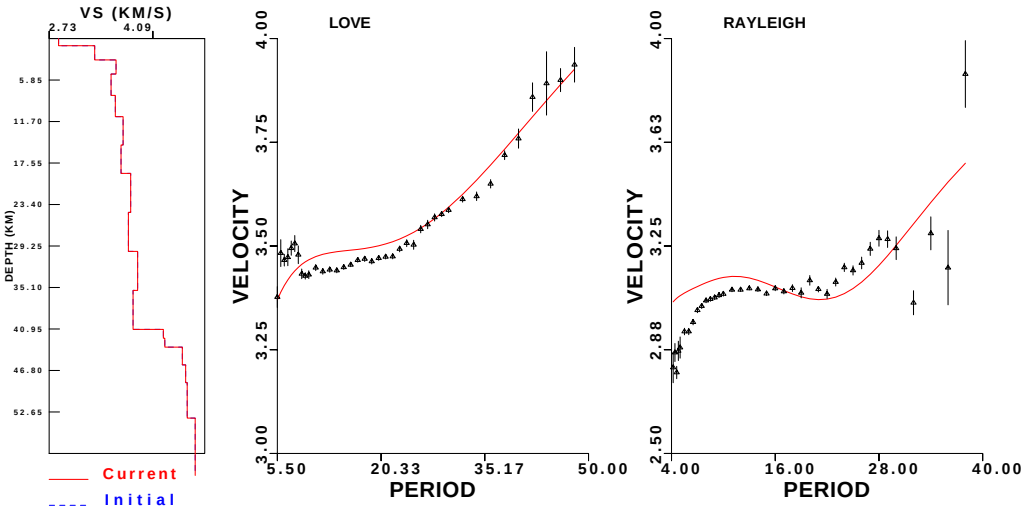


Fig. 22. Comparison of model and observed group velocities

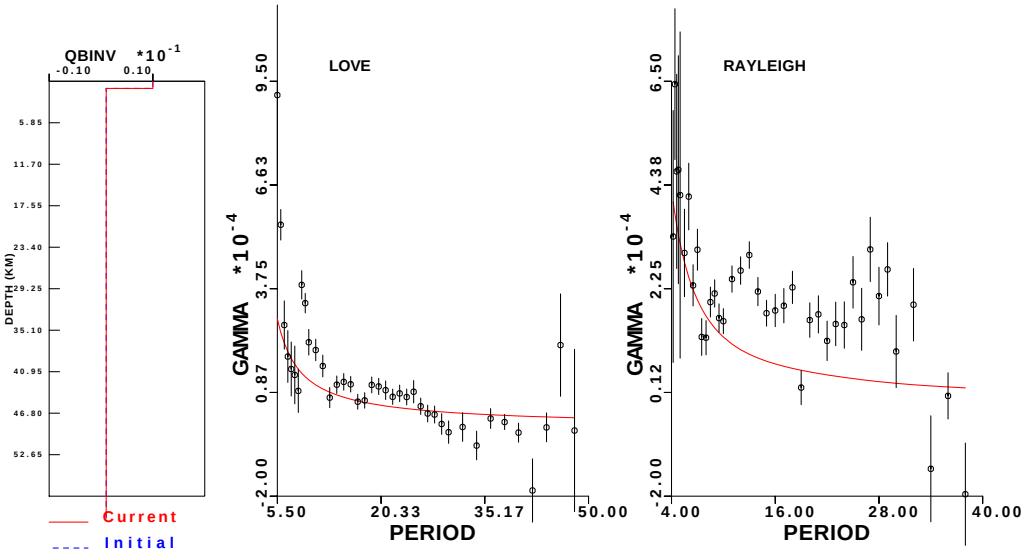


Fig. 23. Comparison of model and observed anelastic attenuation coefficients

4. Summary

The results of the two grid searches and the deviatoric moment tensor inversion using the CUS model indicate that the solution can be

	srfgrd96 (a)	wvfgrd96 (b)	wvfmtd96 (c)
Depth (km)	19	19	19
Strike (°)	120	120	120
Dip (°)	80	80	90
Rake (°)	-175	10	10
M_W	4.57	4.45	4.48

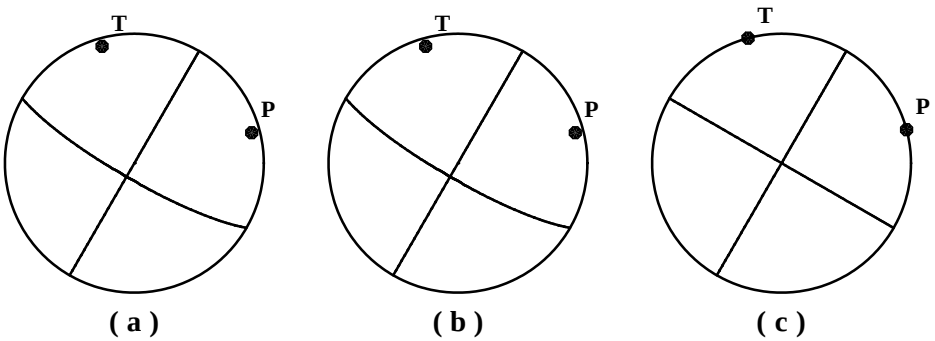


Fig. 24. Focal mechanisms obtained using the three techniques. A lower hemisphere, equal area projection is used.

5. References

Herrmann, R. B., and C. J. Ammon (1997). Faulting parameters of earthquakes in the New Madrid, Missouri region, Engineering Geology 46, 299-311.