Apparent Moment Rate Function Inversion for Small EQs with Near-Source Data

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Processing Procedure

1. Data:
   Iterative deconvolution for AMRFs

2. Method:
   Radon transformation & linear inversion

3. AMRF inversion for 1D Line source

4. AMRF inversion for finite fault model

Code dependency

Linux (centos/ubuntu)

- √ bash (environment)
- √ gcc & gfortran
- √ MATLAB
- √ sac
- √ taup
- √ GMT5 or GMT6 (plotting)

Programme contents

workdir AMRF_FF_2025:

./bin/	scripts & software
./src/	source code
./mainshock_data/	mainshock data
./egf_data/	EGF data
./inp/	input parameters

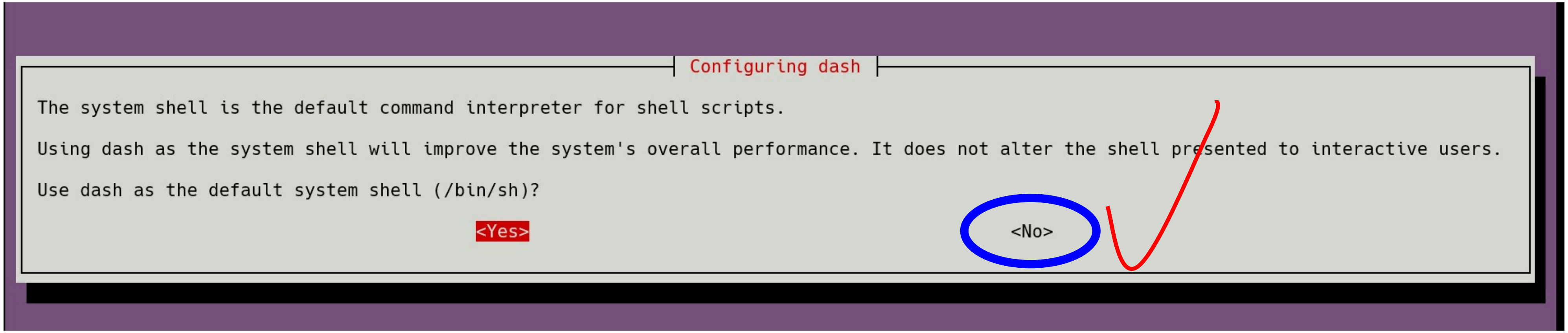
generated dirs by programme:

./dec_results/	decon. results
./Directivity_result/	directivity
./FF_1D_results/	line source result
./FF_2D_results/	FFI results
./figure/	result plots

Code dependency: environment

√ ubuntu system： use bash

$ sudo dpkg-reconfigure dash



’Yes’ -> dash

‘No’-> bash

Code dependency: compilers

√ gcc、gfortran

ubuntu :

```
$ sudo apt install gcc -y
$ sudo apt install gfortran -y
```

centos :

```
$ sudo yum install gcc gcc-c++ kernel-devel -y
$ sudo yum install gcc-gfortran -y
```

√ if lack of libgfortran.so.4

ubuntu : `$ sudo apt-get install libgfortran4`

centos : `$ sudo cp libgfortran.so.4 /usr/lib64/`

Code dependency: MATLAB (<=2024b及)

√ **export MATLAB to environment**

edit ~/.bashrc :

export PATH=${your-according-path}/matlab/bin:$PATH

$ source ~/.bashrc

e.g.:

```
export PATH=/mnt/research/matlab/bin:$PATH
```

```
[seis@localhost 2025_AMRF_FF]$ ls /mnt/research/matlab/
appdata    derived  interprocess           licenses      polyspace  toolbox         VersionInfo.xml
bin        extern   java                   patents.txt   resources  trademarks.txt
cefclient  help     license_agreement.txt  platform      sys        ui
```

Step 1. Iterative deconvolution to get AMRFs

input:

- √ mainshock_data/*.sac & egf_data/*.sac — displacement for MS & EGF
- √ inp/yunnanEYA.nd — 1D velocity model
- √ inp/parameter_egf.txt — parameter

net sta f1(Hz) f2(Hz) dt(s) tshift(s) err zp rp zs rs ts

- net sta: file name
- f1(Hz) f2(Hz): filter passband
- dt(s): sampling rate
- tshift(s): mainshock onset
- err: Error threshold
- zp rp zs rs ts: component flag, 0 - do not use, 1 - use component (P/S wave, Z/R/T component)

pstart pend pshift sstart send sshift

- pstart pend: P window (relative to predicted onset)
- pshift: P-wave time shift between MS & EGF

Step 1. Iterative deconvolution to get AMRFs

workdir: 2025_AMRF_FF/

run： $ sh bin/runs_dec_ye.sh yunnanEYA

outputs：

- √ **dec_results/*.out** — **AMRF for each sta**
- √ **dec_results/*.predict** — **predicted data for each sta (= AMRF * EGF)**
- √ **dec_results/*.txt** — **station information**

NET STA COMP DIST AZ TAKEOFF LOWPASS-FREQ DATA-RECOVERY%

*** example: input 29 ts traces, shall output 29 '*ts.out files' named by station & 1 'egf.ts.txt' file**

Step 2. Manually pick onset & end times

1. read the AMRFs under the dir (./dec_results/*.out) with SAC

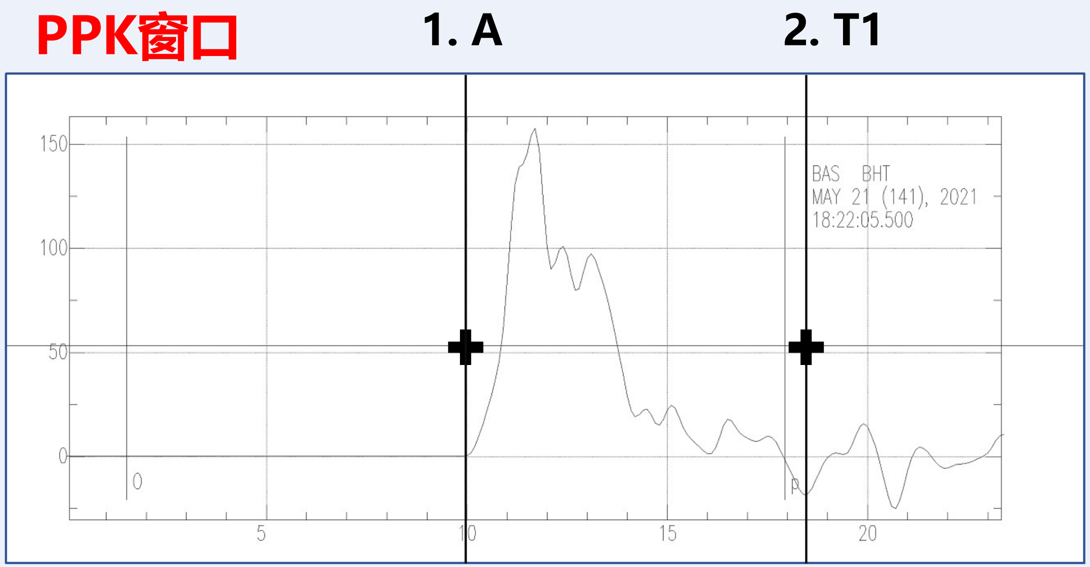
2. manually pick onset with timemarker A, end time with T1

run:

```
$ sac
  r  ./dec_results/*.out
  qdp  off ;  grid  on
  ppk  p  1  a  m

  wh
  q
```

PPK窗口



* prepared data in ./dec_results_picked/
can be directly used for next step: $ cp dec_results_picked/* dec_results/

Step 3. Plot results

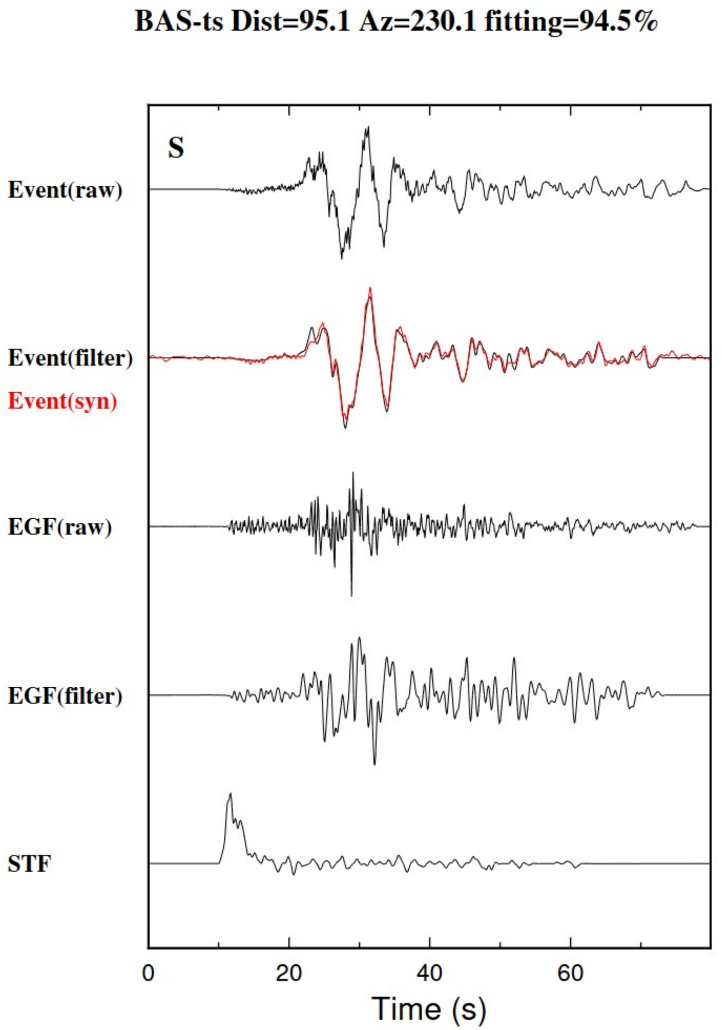
2 inputs: $phase (P, S) , $comp (ts, rs, zp, zs, ts)

```
$ sh   bin/plot_stf.sh   S   ts
```
\# draw deconvolution results for all stations
figure/mainshock_egf_ts.pdf

```
$ sh   bin/plot_az.sh   S   ts
```
\# draw AMRFs aligned with AZ
figure/mainshock_egf_ts.az.pdf

```
$ sh   bin/plot_ray.sh   S   ts
```
\# draw AMRFs aligned with directivity param.
figure/mainshock_egf_ts.ray.pdf

Deconvolution results for all stations



figure/mainshock_egf_ts.pdf

each page shows the deconvolution result for a station

raw data for mainshock

red: AMRF * EGF
black: mainshock data
(filtered to the band in inp/parameter_egf.txt)

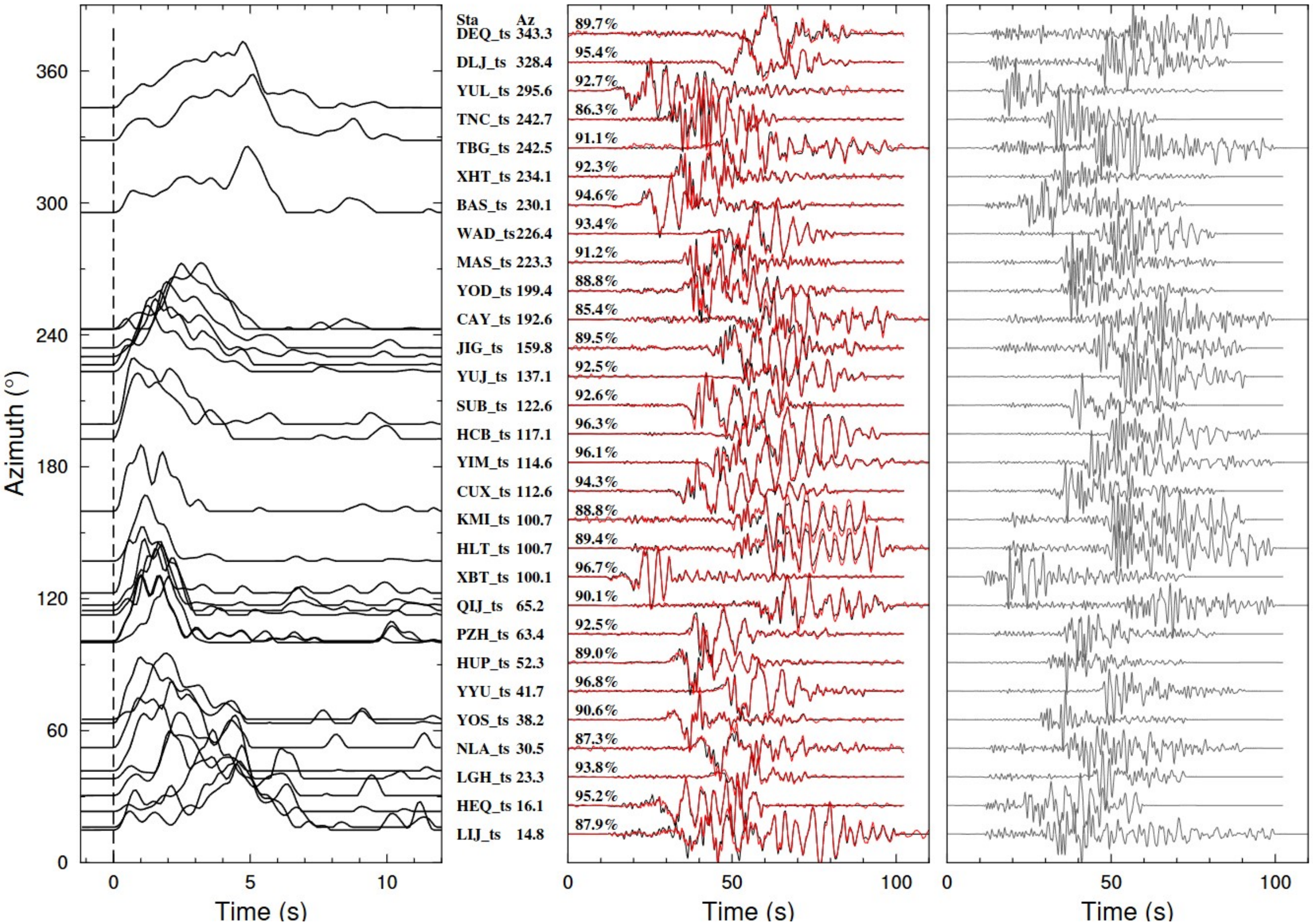
raw data for EGF

EGF (filtered to the band in inp/parameter_egf.txt)

deconvolution result (AMRF)

AMRFs aligned with AZ

figure/mainshock_egf_ts.az.pdf



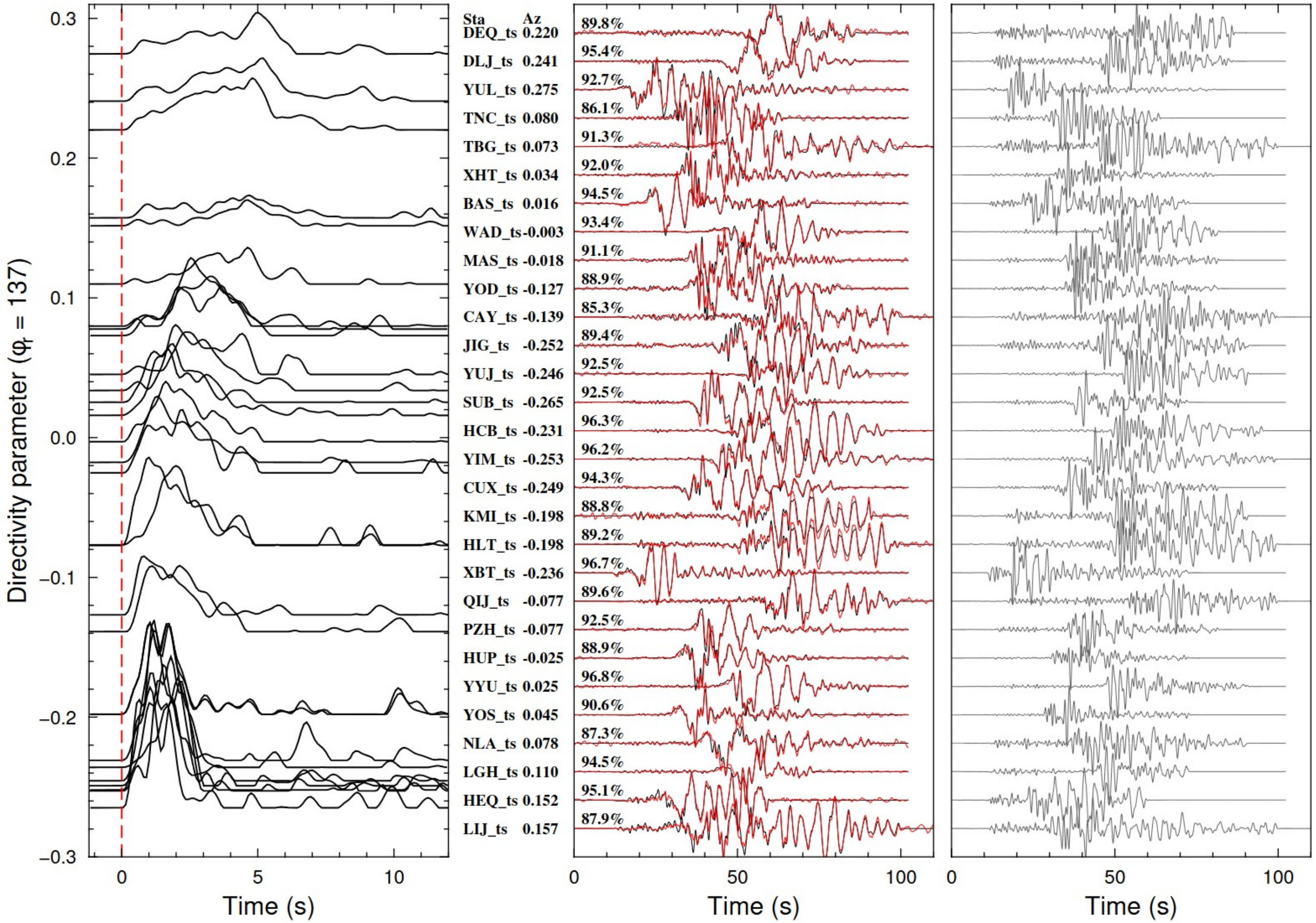
left panel:
deconvoluted AMRFs
aligned by onset &
aligned with AZ

middle panel:
red: AMRF * EGF
black: mainshock data
percentage: data recovery%

right panel: EGF data

AMRFs aligned with AZ

figure/mainshock_egf_ts.ray.pdf



*** set rupture direction in script bin/plot_ray.sh**

(here direction =137° following faultline)

```bash
#!/bin/bash

cha1=$1
cha=$2
Eevent=egf
Tevent=mainshock
duration=12
dir_data=dec_results
Vr_direction=137
```

directivity parameter:

$$\Gamma = -p\cos\theta$$

Step 4. Prepare data for inversion

1. makedir “data_inv/” & copy the AMRFs and station infomation

```
$ cp   dec_results/*.out   data_inv/
$ cp   dec_results/*.txt   data_inv/
$ cd   data_inv/
```

2. rename the data after the format egf.${sta}.${comp}.out

```
$ ls   -l   *out | awk   '{print   $9}' | awk   -F.   '{print   "mv   "$0"   "$1"."$3"."$4"."$5}' | sh
$ cd ..
```

Step 5. Directivity analysis

run: $ sh LSQ_search.sh   **(grid search, runtime is long)**

input: **inp/LSQ_search.txt**   **parameter file for directivity analysis**

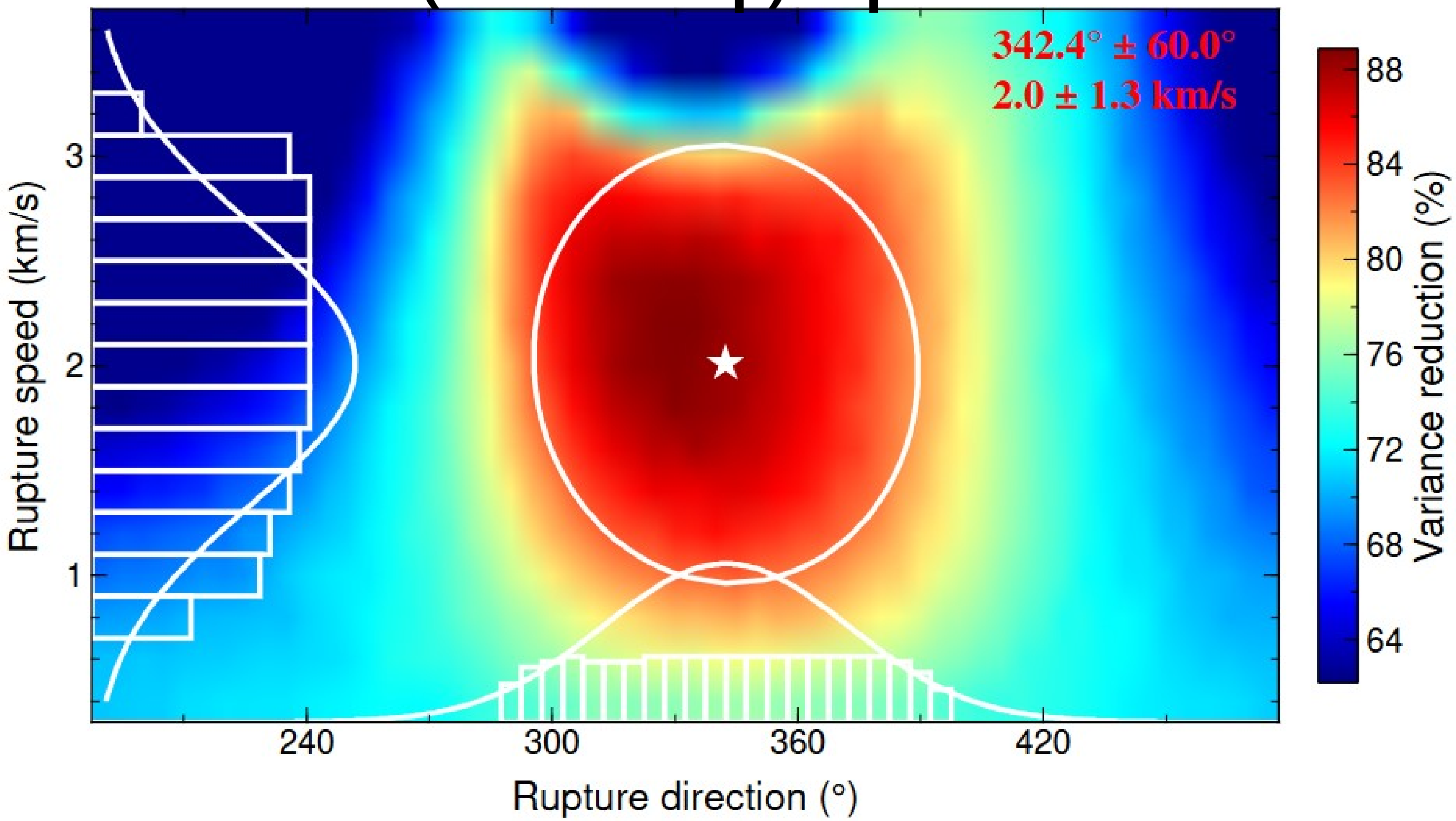
```
data_inv                    # input files
Directivity_results         # output files
weightall_weighted.txt      # weight files
1                    # state of MRF data (1: .out (sac format); 0: MRF.txt file)
0.10 0.10            # data and model sampling(s) (if it's 0, sampling will be equal to AMRFs)
8.00                 # duration (s) of AMRFs will be used. (if it's 0, duration will be length of original AMRFs)
3.36 3.36 2.650      # velocity (km/s) of P wave and S wave and density (g/cm^3) in source zone.
137.0 75.0           # strike and dip (degree) of faults plane
0.4 3.6 0.2          # rupture speed searching range (low,high,interval) (km/s)
190 480 5 120        # rupture direction searching range (low,high,interval,shift)
1.079 18             # moment (N.m) (1) exp (2) or Mw (1) 0.0 (2)
0                    # ts (length of MRFd, default is 0.3 time MRF). if it is 0, default will be used
1                    # state of model (only if r_state and r_end are 0; 1:unilatral; 0:bilateral)
0.01 0.10 0.05       # damping for Moment constriant, temporal smooth, and spatial smooth
```

do 1D line-source inversion with each given pair of (V_rup, direction) and fit the deconvoluted AMRFs

Output: Variance reduction map

figure/plot_search.pdf

on-fault (strike & dip) rupture direction



histograms:
number of stations with variance reduction > 95%
(for standard deviation)

ellipse:
95% confidence interval with a Gaussian distribution

Step 6. Line-source inversion with fixed V_rup & direction

input: inp/LSQ_1D.txt

parameterfile for the 1D line-source AMRF inversion

```
data_inv                 # input files
FF_1D_results            # output files
weightall_weighted.txt   # weight files
1                        # state of MRF data (1: .out (sac format); 0: MRF.txt file)
0.1 0.1                  # data and model sampling(s) (if it's 0, sampling will be equal to AMRFs)
8                        # duration (s) of AMRFs will be used. (if it's 0, duration will be length of original AMRFs)
3.360 3.360 2.650        # velocity (km/s) of P wave and S wave and density (g/cm^3) in source zone.
137.0 75.0               # strike and dip (degree) of faults plane
2.0 342.0                # rupture speed (km/s) and direction relative to strike (anticlock) on the fault plane
1.079 18.0               # moment (N.m) (1) exp (2) or Mw (1) 0.0 (2)
0 0 0 0.3                # r_start, r_end, and r_center, and dr (km) (if r_start and r_end are 0, rupture length, dr, and ts will be s
et using the duration of AMRFs.)
0                        # ts (length of MRFd, default is 0.4 time MRF). if it is 0, default will be used
1                        # state of model (only if r_state and r_end are 0; 1:unilatral; 0:bilateral)
0.01 0.10 0.05           # damping for Moment constriant, temporal smooth, and spatial smooth
```

run:

$ sh bin/caltakeoff.sh yunnanEYA **# generate weighting file weightall.txt**

$ sh LSQ_1D.sh **# run 1D inversion**

Outputs for line-source AMRF inversion

Major output files:

√ FF_1D_results/D0_est.txt location & amplitude for each subevent along line source

√ FF_1D_results/MRFd.txt 1D inversion results, each column:

moment rate density function for a subevent

√ FF_1D_results/AMRF_est.txt model-predicted AMRF

(Radon transformation of MRFd)

√ FF_1D_results/moment_AMRF_est.txt model-predicted moment evolution

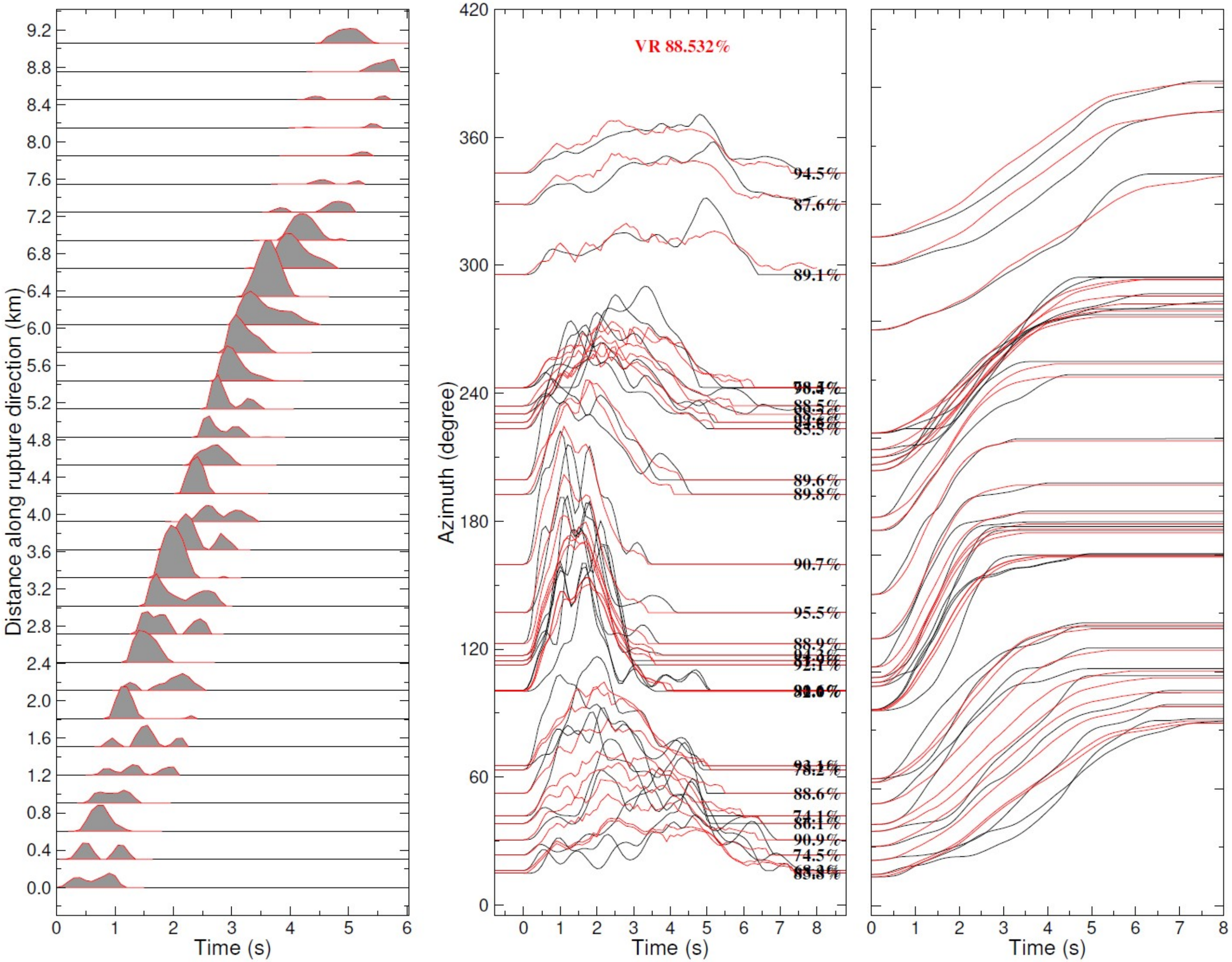
√ FF_1D_results/VR.txt variance reduction for each station

Output figure:

√ figure/plot_1D.pdf plot for line-source inversion result

Plot of line-source inversion result

figure/plot_1D.pdf



left panel:

moment rate density functions (inversion result)

middle panel:

Radon transformation for MRFds

deconvoluted AMRFs

data fitting %

right panel:

seismic moment evolution for inversion results (red) & deconvoluted AMRFs (black)

Step 7. Finite fault inversion with AMRFs

input: inp/LSQ_2D.txt **parameter for AMRF FFI**

```
data_inv                  # input files
FF_2D_results             # output files
weightall_weighted.txt    # weight files
yunnanEYA                 # model file
1                         # state of MRF data (1: .out (sac format); 0: MRF.txt file)
0.10 0.10                 # data and model sampling(s) (if it's 0, sampling will be equal to AMRFs)
8.00                      # duration (s) of AMRFs. (if it's 0, duration will be length of original AMRFs)
137.0 75.0   0.0          # strike, dip, and rake (degree) of faults plane
2.0                       # rupture speed (km/s)
1.079 18                  # moment (N.m) (1) exp (2) or Mw (1) 0.0 (2)
8.0                       # source depth
-4.00 11.0 0.50           # x_start, x_end, and dx(km). x arixs is along strike.
-4.00 8.00 0.50           # y_start, y_end, and dy(km). y arixs is along down-dip
10 5                      # triangle number in a grid unit, and sampling point in a triangle
0.01 0.1 0.05             # damping for Moment constriant, temporal smooth, and spatial smooth
~
```

run: $ sh LSQ_2D.sh

Outputs for AMRF FFI

Major output files:

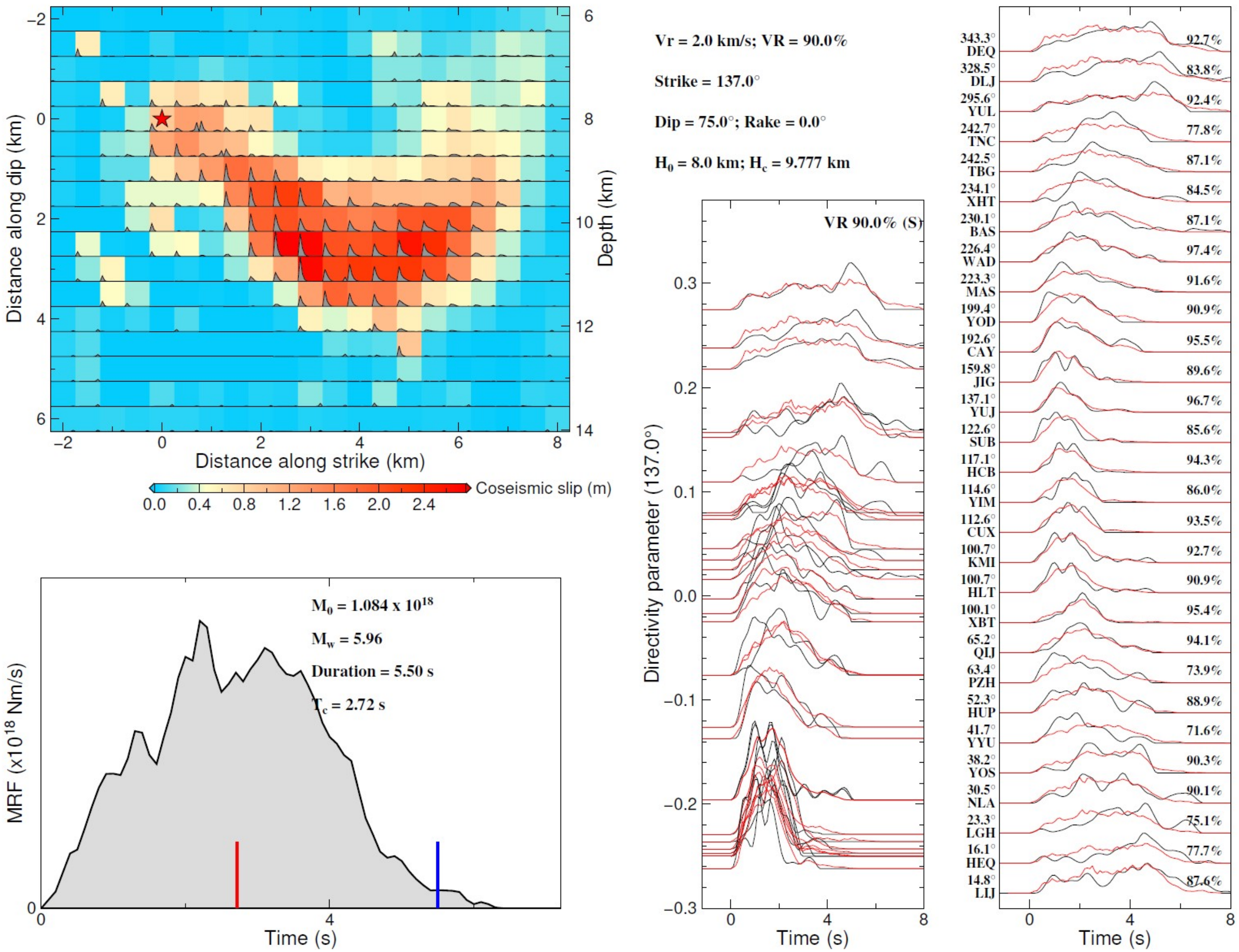
- √ FF_2D_results/D0_est.txt — slip distribution on fault plane
- √ FF_2D_results/time_slip.txt — slip rate evolution with time on each subfault
- √ FF_2D_results/AMRF_est.txt — model-predicted AMRFs (from Radon transformation)
- √ FF_2D_results/moment_AMRF_est.txt — model-predicted seismic moment evolution
- √ FF_2D_results/VR.txt — data fitting

Output figure:

- √ figure/plot_2D.pdf — plot for FFI result

Plot for finite fault inversion result

figure/plot_2D.pdf



left-top:

slip distribution

left-bottom:

moment rate function

middle:

AMRFs aligned by directivity

right:

AMRFs aligned by AZ

red (predicted) black (data)

References

Gong, W., Ye, L., Qiu, Y., Lay, T., & Kanamori, H. (2022). Rupture directivity of the 2021 *Mw* 6.0 Yangbi, Yunnan Earthquake. *Journal of Geophysical Research: Solid Earth*, *127*, e2022JB024321. https://doi. org/10.1029/2022JB024321

Ruff, L. J. (1987). Tomographic imaging of seismic sources. In *Seismic tomography* (pp. 339–366). Springer. https://doi.org/10.1007/978- 94-009-3899-1_15