Extended-fault modeling in SEM3D

starting from Ruiz's kinematic-source model

User's Guide

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Contents

Chapter 1

RIK model

RIK (Ruiz's Integral Kinematic) model is an advanced kinematic source model developed by (Ruiz et al., 2011) and further modified by (Gallovič, 2016). This method allows taking into account frequency-dependent directivity effects. The asperities have a fractal distribution that may follow a given inverted slip distribution.

The kinematic source model could be generated by using the RIKsrf code. It is provided in RIK_MODEL/CODE_GALLOVIC_RIKsrf/ folder of the materials of this manual. Its compilation is verified for gfortran and ifort compilers. Two different sub-folders are available depending on compiler selection. Inside the selected sub-folder, the user should just run 'lancer.sh' file in order to compile the code, which creates the executable 'RIKsrf2'.

RIKsrf code works by calling the executable RIKsrf2 from any example folder. In this manual, a case from South Napa fault model is used as an example. The related folder to this example is 'RIK_MODEL/EXAMPLES/NAPA_ROCHER/'. Two input files are needed to run the RIKsrf code. The first one is 'RIKsrf.in'. The 'RIKsrf.in' file for Napa example is shown in the figure below:

```
1  # Size (length, width) of the complete fault plane
2  15.    10.
3  # Size (length, width) of the strong-motion generation area, location of bottom left corner on the fault.
4  15. 10.    0. 0.
5  # Seismic moment (Nm)
6  1.6e18
7  # Slip rate points on the fault (1: Regular grid followed by no. of points along strike and dip and const. mu, 2: Irregular followed by number of points
   in the file)
8  1
9  150  100   0.
10 # Nucleation point position (along length and width)
11 12.5  0.
12 # Hypocentral depth and fault dip (needed only when mu==0 and/or number of rupture velocity layers==0)
13 10.  82.
14 # Pulse width (ratio between L0 and L), multiplicative factor for rupture velocity on subsources, aparam
15 0.2 1.0 0.5
16 #SUBMIN SUBMAX
17 2 50
18 #PDF for subsource distribution (1: uniform, 2: Gaussian - provide location and width, 3: read from file - specify discretization and filename)
19 3
20 20 16  Napaslipfrominversion.dat
21 # Random seed for slip (idum1) and rupture velocity variations (idum2)
22 -1345  -13456
23 # Slip rate time step, number of timesteps
24 0.025   850
25 # Rupture velocities (number of layers nlayers; if nlayers>0, follow with a list of layer positions and rupture velocities (from bottom to top);
   otherwise, vr are evaluated from crustal.dat assuming constant vp/vs specified below)
26 0
27 0.8
```

Figure 1.1: RIKsrf.in file for RIK model

In line 2, we define the size of fault plan (length and width). For our example, length is equal to 15 km and width is 10 km. The strong-motion generation area is the same as the complete fault plan. Thus, in line 4, we enter 15 and 10 for strong-motion generation area and the location of left bottom point.

In line 6, seismic moment is given in Nm.

In lines 8-9, we specify the choice of grid model. If a regular model is desired, 1 is written in line 8 and followed by the point number along strike and dip. Otherwise, the grid is determined by a given file. In our example, we work with a regular grid. In line 9, after point numbers, a constant rigidity value is specified. Since it is not used in this example, we write 0.

In line 11, we define the location of hypocenter in fault plan. In our test, it is located at (12.5, 0).

In line 13, hypocenter depth and dip angle are written.

In line 15, impulse characteristics are defined based on (Ruiz et al., 2011) model. For more details, please refer to (Ruiz et al., 2011) and (Gallovič, 2016).

In line 17, the upper and lower limits that determine the size-distribution of asperities (subsources) are defined.

In lines 19-20, we specify the choice of slip-inversion data. In our example, we provide inverted slip distribution for Napa model so that in line 19 we enter 1 and in line 20 the file name is given.

In line 22, random seed for slip and rupture velocities are set.

In line 24, the time step and total duration for slip-velocity time histories are specified.

Lastly, in line 26, we define rupture velocities of layers in the model. Either one line is devoted to the property of each layer either it is provided by another file named 'crustal.dat'. In our case, we give another file. For such cases where 'crustal.dat' is used, a constant value (0.8 in this example) is set for rupture-to-shear velocity ratio.

In the following, we explain the content of 'crustal.dat' file in our example, Figure 1.2.

```
1  Crustal model (free format)
2  number of layers:
3     9
4  Parameters of the layers
5  depth of layer top(km)   Vp(km/s)    Vs(km/s)    Rho(g/cm**3)    Qp     Qs
6   0.0000E+00 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
7   0.0500E+00 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
8   0.1000E+00 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
9   0.1000E+01 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
10  0.3000E+01 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
11  0.4000E+01 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
12  0.5000E+01 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
13  1.7000E+01 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
14  2.5000E+01 0.7830E+01 0.4520E+01 0.3260E+01  1000.00   1000.00
```

Figure 1.2: crustal.dat file for RIK model

First, in line 3, total number of layers is given. Then, starting from line 6, for each layer in the model, the depth of top level (positive in downward), pressure and shear wave velocities, density and quality factors for pressure and shear waves are defined.

After the simulation, the code sorts a number of output files such as slipdistribution.dat, subsources.dat etc. In RIK_MODEL/EXAMPLES/python folder, two Python scripts are provided to plot maximum-slip distribution and asperity distribution on fault plan (slip.py and subsources.py respectively). For our example, the resultant figures for maximum-slip distribution and asperity distribution are given in Figures 1.3-1.4.

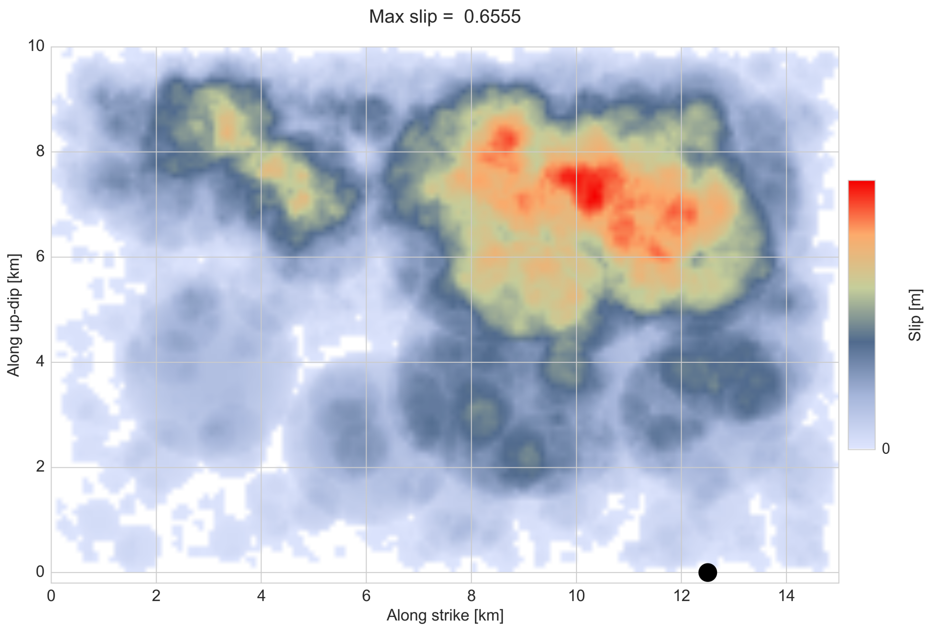

Figure 1.3: Maximum-slip distribution on fault plan of Napa event.

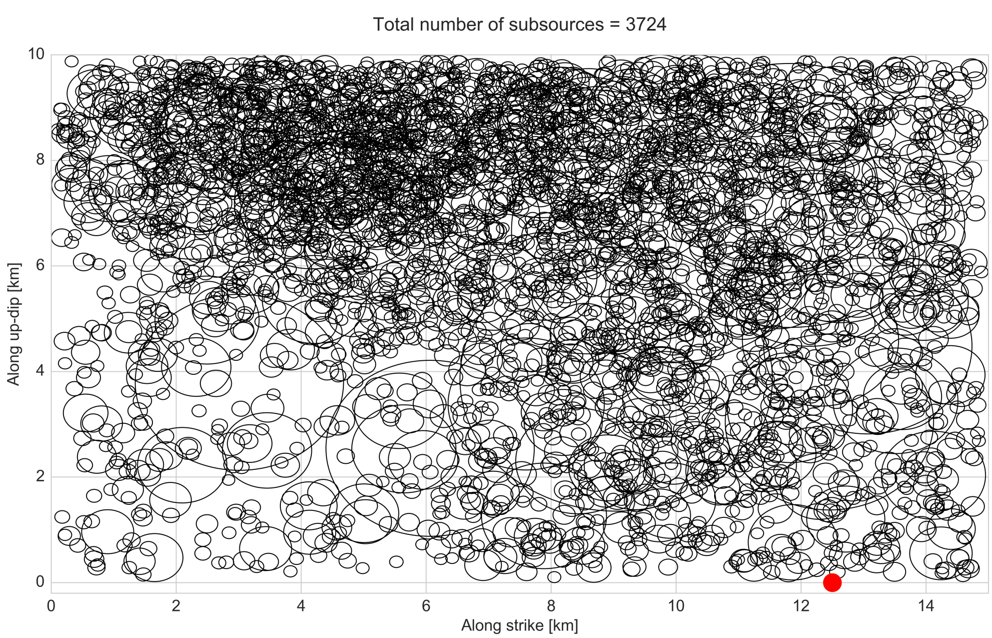

Figure 1.4: Asperity distribution on fault plan of Napa event.

Chapter 2

Convertisseur

Convertisseur is a Python-based script that prepares input files for 'extended source' block of 'input.spec' file of SEM3D code. The input files are in hdf5 format and includes certain attributes. Two different scripts are provided for the cases where input motion is inserted by force-time history (force option) or moment-time history (moment option).

First, for 'moment' option, 'convert_extended_MOMENT.py' file is referred to. The file is self-explanatory and input data are defined between the lines 31-72 of the file, Figure 2.1.

```
30
31  # Plot moment vs time graph for all point sources on the fault plan
32  plot_figure     = True
33  # Figure name
34  figurename = 'Moment_vs_time_Napa_bedrock_model.png'
35
36  # Filename for SEM3D coordinates of all point sources on the fault plan
37  coord_file_name = 'Coordinates_Niigata_Depth14km.dat'
38
39  # Filename of coordinate data of all point sources on the fault plan
40  RIK_slipfile = 'RIK_model_data/slipdistribution.dat'
41
42  # Filename of moment-time history of all point sources on the fault plan
43  mrfile       = 'RIK_model_data/ELIF_MomentRate.dat'
44
45
46  # Number of point on fault plan (along strike)
47  NL = 150
48  # Number of point on fault plan (along dip)
49  NW = 100
50
51  # Strike, dip and rake angles
52  strike = 155.0
53  dip    = 82.0
54  rake   = -172.0
55
56  # Coordinates of hypocenter in RIK model  (in meters)
57  RIK_hypocenter = np.array([0.0, 12.5, 10.0]) * 1e3  # Y_RIK, X_RIK, DEPTH (DOWNWARD POSITIVE)
58
59  # Coordinates of hypocenter in SEM model  (in meters)
60  SEM_hypocenter = np.array([0.0,  0.0,-10.0]) * 1e3  # EST,   NORD,  UPWARD
61
62  # Input files for SEM3D
63  # Fault data
64  kinefile_out  = h5py.File('Napa_kine.hdf5', 'w')
65  # Moment data
66  slipfile_out  = h5py.File('Napa_moment.hdf5','w')
67  #
68  # Moment vs time history
69  # Time duration
70  T_total = 21.25
71  # Time step
72  dt      = 0.025
73
74
75
```

Figure 2.1: The section with user data from convert_extended_MOMENT.py file for Napa example.

In lines 31-34, the user should specify whether saving the figure of moment-time history of all the source points is desired or not.

In line 37, the name of file where the coordinates of the source points based on SEM3D model are written out is determined.

In line 40, the 'slipdistribution.dat' output file of RIK model (See Chapter 1) is defined. Coordinates of each point in RIK fault plan is read by this file. Similarly, in line 43, 'ELIF_MomentRate.dat' file is defined to read moment-rate time history at each source point. The user could modify this part of the code if further modifications are desired concerning the employment of different source models.

In lines 47-49, number of points along strike and dip (the same as what is used in RIK model) are given.

In lines 52-54, strike, dip and rake angles are specified.

In line 57, the hypocenter location of RIK model is written. It should be noted that the first term is the y-coordinate for RIK model, wherease the second term is the x-coordinate. In line 60, hypocenter location in SEM coordinates are written.

In lines 64-66, the names of files where fault properties and moment-time histories are to be written out are defined with hdf5 extension.

Lastly, in lines 70-72, time step and total duration used for moment-time histories are given.

Once the code is executed, it writes out following attributes in 'kinefile_out' file:

- 'Ns' : number of points along strike
- 'Nd' : number of points along dip
- 'Vnormal' : normal vector
- 'Vslip' : slip vector
- 'x' : x-coordinates (SEM3D) of point sources
- 'y' : y-coordinates (SEM3D) of point sources
- 'z' : z-coordinates (SEM3D) of point sources

Slip vector is computed by the formula:

$$V_{slip} = \begin{bmatrix} sin\lambda cos\delta cos\phi + cos\lambda sin\phi \\ sin\lambda cos\delta sin\phi + cos\lambda cos\phi \\ sin\lambda sin\delta \end{bmatrix}$$

where ϕ holds for strike angle and δ corresponds to dip angle and λ is rake angle of the fault plan.

For the computation of normal vector, we refer to the following formula:

$$V_{normal} = \begin{bmatrix} sin\delta cos\phi \\ -sin\delta sin\phi \\ cos\delta \end{bmatrix}$$

The SEM3D coordinates are calculated by rotation and translation. Rotation is applied by multiplication of coordinate vector with rotation matrix. The rotation matrix is shown below:

$$R = \begin{bmatrix} -cos\phi cos\delta & sin\phi & 0 \\ sin\phi cos\delta & cos\phi & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

Following the rotation, translation is applied based on the difference between hypocenter points of RIK and SEM coordinates systems.

By means of provided data, the code integrates the given moment-rate histories to calculate moment-time histories. In the 'slipfile_out' file, calculated moment and time data are prepared as follows:

- 'moment' : moment history for point sources
- 'time' : time history for point sources

The resultant moment-time history for 15000 point sources in this example is shown in Figure 2.2 .

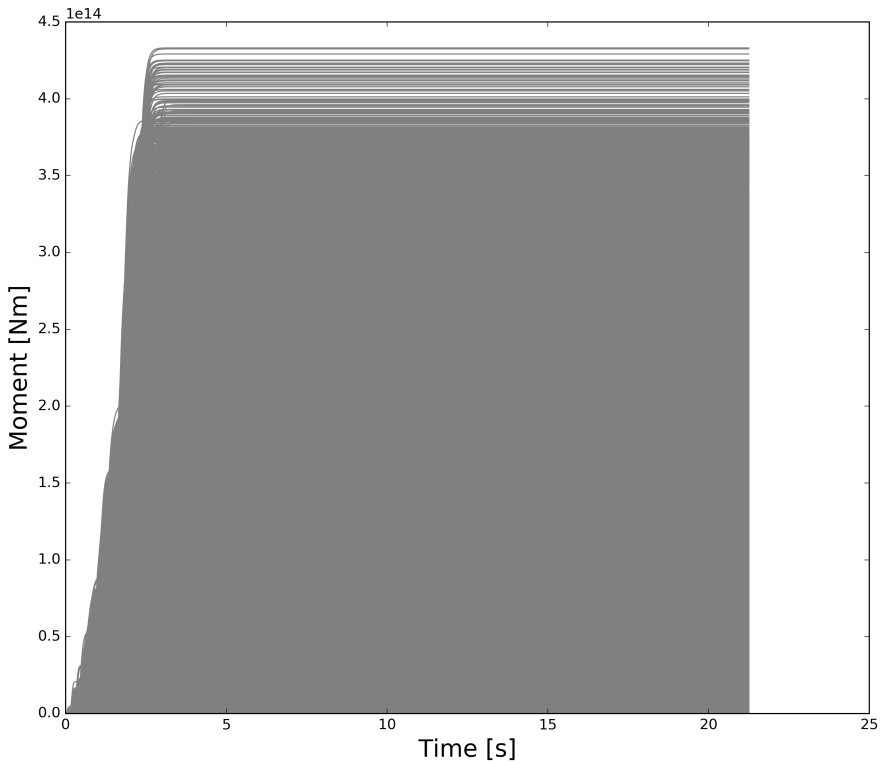

Figure 2.2: Moment-time history of source points on extended fault plan for Napa example.

As a second option, 'convert_extended_FORCE.py' file could be referred to for cases where the source is defined by force-time histories. The file is self-explanatory and input data are defined between the lines 26-76 of the file, Figure 2.3. As an example, we use three point sources of which force-time histories are defined by DM function.

```
26  # Grille de points
27  NL = 1
28  NW = 3
29
30  # Creation des fichiers d'entree pour SEM
31  kinefile_out  = h5py.File('essai_ppts.hdf5', 'w')
32  slipfile_out  = h5py.File('essai_force.hdf5','w')
33
34  # Save the figure into
35  figurename = 'Force_3point.png'
36
37  # Ppts de temps
38  T_total = 0.3
39  dt      = 0.001
40
41  # DM parameter tau
42  tau       = np.zeros((NL, NW))
43
44  # POINT 1
45  tau [0,0] = 0.0016666666666666666
46  # POINT 2
47  tau [0,1] = 0.03166666666666661
48  # POINT 3
49  tau [0,2] = 0.06166666666666658
50
51  # Vecteur directionnel (pareil pour tous les points)
52  Dir = np.array([1.0, 1.0, 0.0])
53
54  # Coordonnees des points dans le repere SEM3D
55  xgrid = kinefile_out.create_dataset('x', (NL, NW), chunks=(1, 1))
56  ygrid = kinefile_out.create_dataset('y', (NL, NW), chunks=(1, 1))
57  depth = kinefile_out.create_dataset('z', (NL, NW), chunks=(1, 1))
58
59  xgrid[:,:] = 0.0
60  ygrid[:,:] = 0.0
61  depth[:,:] = 0.0
62
63  # Coordinates of 3 point sources
64  # POINT 1
65  xgrid[0,0] = 0.0
66  ygrid[0,0] = 0.0
67  depth[0,0] = 0.0
68
69  # POINT 2
70  xgrid[0,1] = 0.0
71  ygrid[0,1] = 100.0
72  depth[0,1] = 0.0
```

Figure 2.3: The section with user data from convert_extended_FORCE.py file for Napa example.

Differently than moment option, here, we define τ parameter (time off-set) in DM function for each point source (Lines 45-49). Also, in line 52, direction vector is given and it is considered the same for all point sources. Lastly, x, y and z-coordinates of the point sources are defined. The resultant kinefile_out comprises of following attributes:

- 'Ns' : number of points along strike
- 'Nd' : number of points along dip
- 'Dir' : direction vector
- 'x' : x-coordinates (SEM3D) of point sources

- 'y' : y-coordinates (SEM3D) of point sources

- 'z' : z-coordinates (SEM3D) of point sources

To save force-time function, the code uses following attributes:

- 'moment' : force history for point sources

- 'time' : time history for point sources

We show the resultant force-time histories for the three point sources in this example, Figure 2.4.

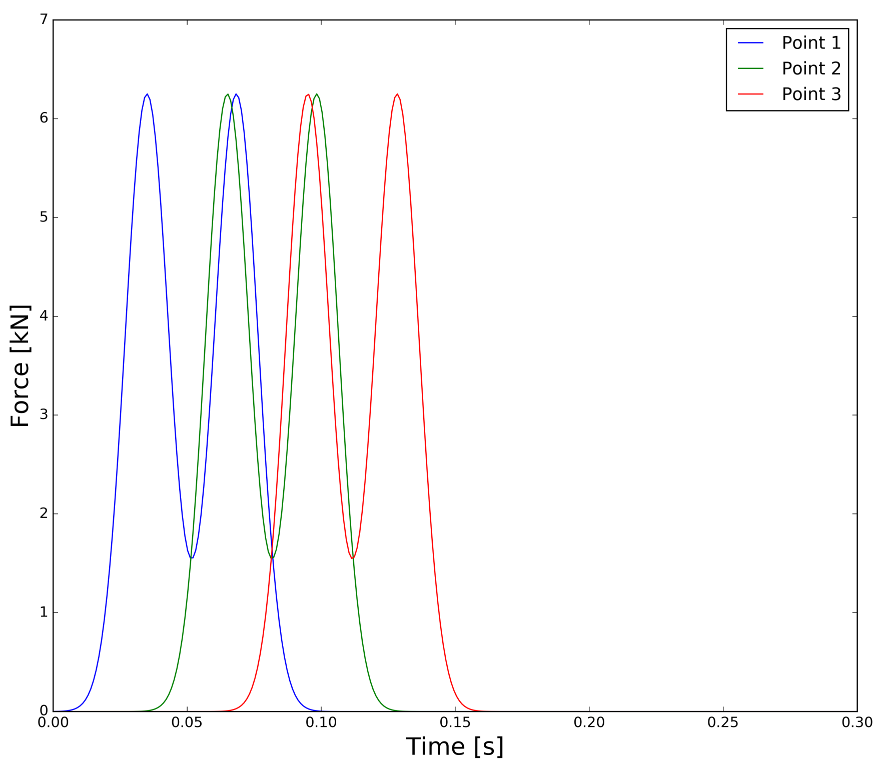

Figure 2.4: Force-time history of the three source points.

Chapter 3

Extended source in SEM3D

A number of modifications are applied to SEM3D code to implement the extended-source model. These changes are detailed in Chapter 4. Here, instructions for extended-source modeling in this new version of SEM3D code are explained.

The only changes apply to the 'input.spec' file. The user should define a block of 'extended source' as shown in Figure 3.1:

```
#extended fault source
extended_source {
    is_force = 0 ;
    # Kinematic rupture file
    kine_file = "Napa_kine.hdf5";
    # Moment History (moment VS temps)
    slip_file = "Napa_moment.hdf5";
};
```

Figure 3.1: Extended source block in input.spec file for moment option.

The first necessary information in 'extended source' block is the choice of force or moment-time history for the extended-source model. Here, we show the example of Napa bedrock case where we calculate moment-time history so that 'is_force' parameter is set to 0. For force option, it should be set to 1.

Second, the name of file containing source properties such as coordinates should be given for 'kine_file'.

Last, the name of file where moment-time history (or force-time history for force option) is stocked is specified as 'slip_file'.

For Napa example, we provide the folder 'SEM_extended_source_Napa_rocher' folder. Even though we use a realistic model of fault plan, for simplicity, we prefer to define a single type of soil in the propagation media. Once the simulation terminates, the procedure to analyze the outputs remain exactly the same as before.

Chapter 4

Modifications made in SEM3D

The major modifications that we applied to SEM3D in order to implement extended-source modeling are listed below for advanced users.

- **SRC/Modules/Sources.f90 :** In 'CompSource' subroutine, for extended sources, 'call Source_File' is added in order to compute the forces at each time step of simulation (with the help of Filippo Gatti).

- **SRC/Modules/Sources.f90 :** Inread_source_file_h5 subroutine, for extended sources, the subroutine reads moment-time history instead of slip-time history.

- **SRC/read_input.f90 :** In 'create_sem_extended_sources' subroutine, definition of src%moment variable of each extended source is changed. It is equated to directional tensor (product of slip and normal vectors of fault plane).

- **SRC/Modules/Extended_source.f90 :** 'is_force' logical variable is added to sExtendSource subdomain of Tdomain domain.

- **SRC/Modules/create_point_sources_from_fault.f90 :** New subroutines (create_point_sources_from_fault_moment and create_point_sources_from_fault_force) are added for orientation to force or moment option. All the necessary computations are made directly in these new subroutines.

Bibliography

Gallovič (2016). Modeling velocity recordings of the m w 6.0 south napa, california, earthquake: unilateral event with weak high-frequency directivity. *Seismological Research Letters*, 87(1):1–14.

Ruiz, J., Baumont, D., Bernard, P., and Berge-Thierry, C. (2011). Modelling directivity of strong ground motion with a fractal, k- 2, kinematic source model. *Geophysical Journal International*, 186(1):226–244.