Practice:

dynamic rupture in 2D and 2.5D

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Jean-Paul Ampuero

Goals

- Learn to simulate dynamic rupture model
- Explore the effects of fault heterogeneities on dynamic ruptures
- Discussion: seismology problems

2D and 2.5D numerical codes

Download from GitHub

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Jean Paul Ampuero
jpampuero

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Pasadena, CA, USA
Sign in to view email
http://www.seismolab.caltech.edu/a...

Popular repositories

sem2dpack
SEM2DPACK - A spectral element method for 2D wave propagation and fracture dynamics, with emphasis on computational seismology and earthquake source dynamics.
Fortran ★ 4 Forks 3

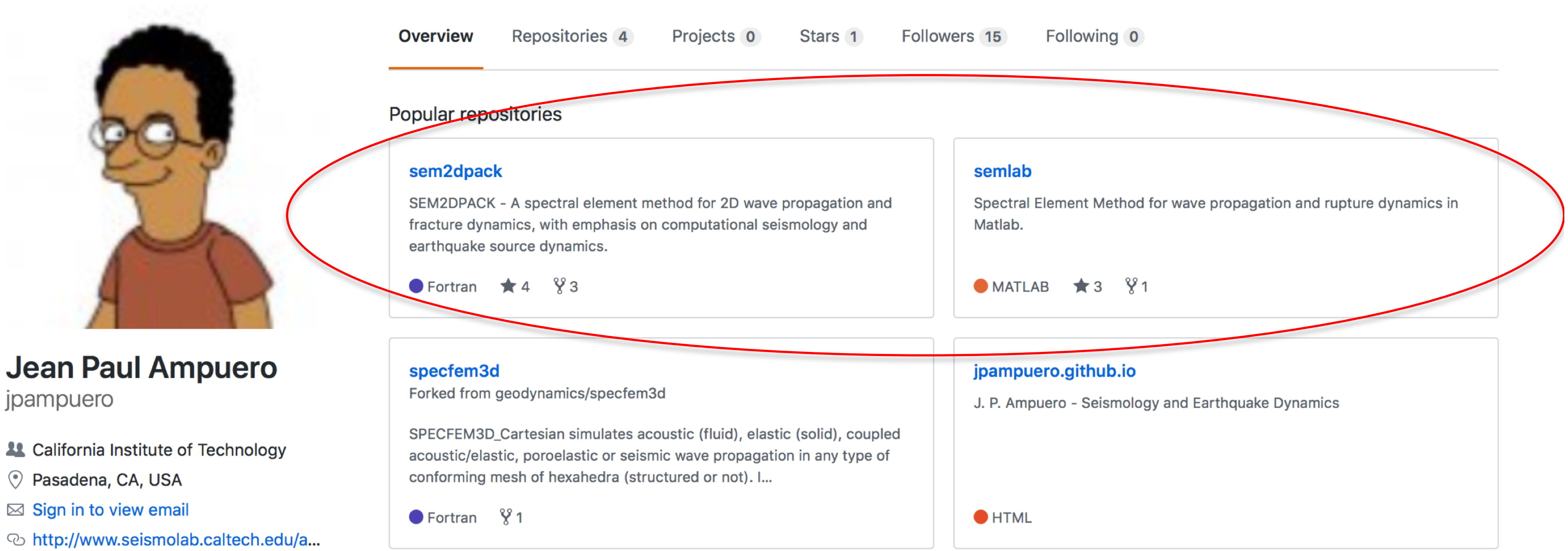
semlab
Spectral Element Method for wave propagation and rupture dynamics in Matlab.
MATLAB ★ 3 Forks 1

specfem3d
Forked from geodynamics/specfem3d
SPECFEM3D_Cartesian simulates acoustic (fluid), elastic (solid), coupled acoustic/elastic, poroelastic or seismic wave propagation in any type of conforming mesh of hexahedra (structured or not). I...
Fortran Forks 1

jpampuero.github.io
J. P. Ampuero - Seismology and Earthquake Dynamics
HTML

2D and 2.5D numerical codes

Download from GitHub



MATLAB code semlab

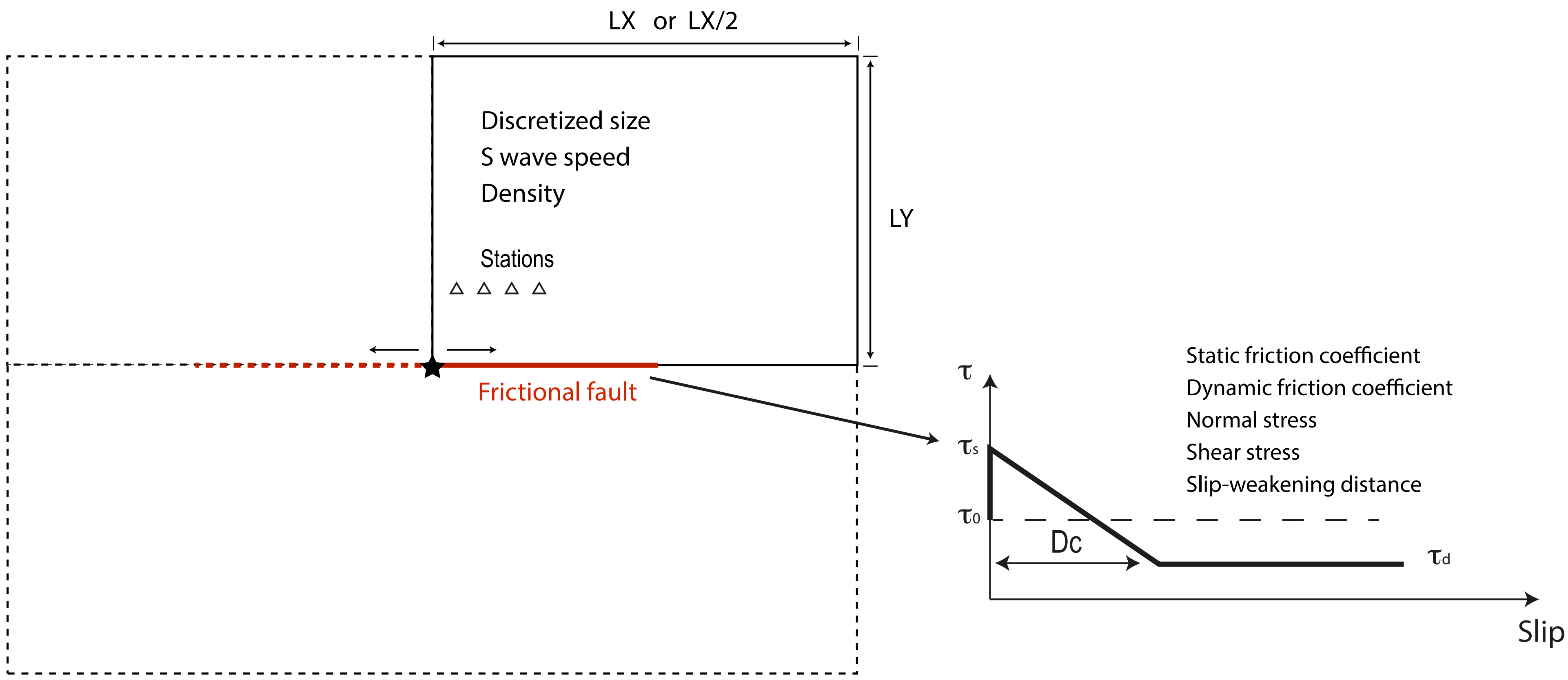
----- run it directly

Fortran code sem2dpack

----- installation is simple

----- simulation is fast

Model parameters



Seismogenic width W

$$\sigma_{ij,j} = \rho \ddot{u}_i$$ (3 equations)

Reduce to 1 equation

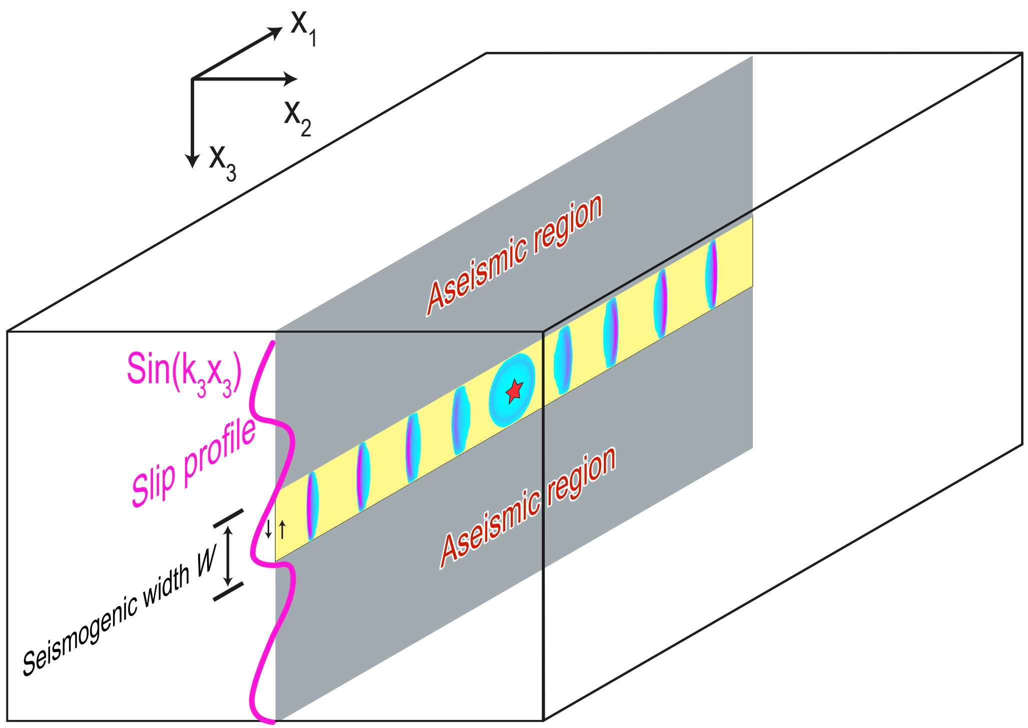
$$\frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 u}{\partial x_2^2} + \frac{\partial^2 u}{\partial x_3^2} = \frac{1}{v_s^2}\frac{\partial^2 u}{\partial t^2}$$

Slip approximation

$$u(x_1, x_2, x_3) = u(x_1, x_2, t)e^{ik_3 x_3}$$

$$k_3 = \pi / W$$

$$\frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 u}{\partial x_2^2} - {k_3}^2 u = \frac{1}{v_s^2}\frac{\partial^2 u}{\partial t^2}$$



Tutorial of semlab

Tutorial of sem2dpack

How to run semlab?

cd ${work_dir}/semlab-master/SEMLAB

matlab &

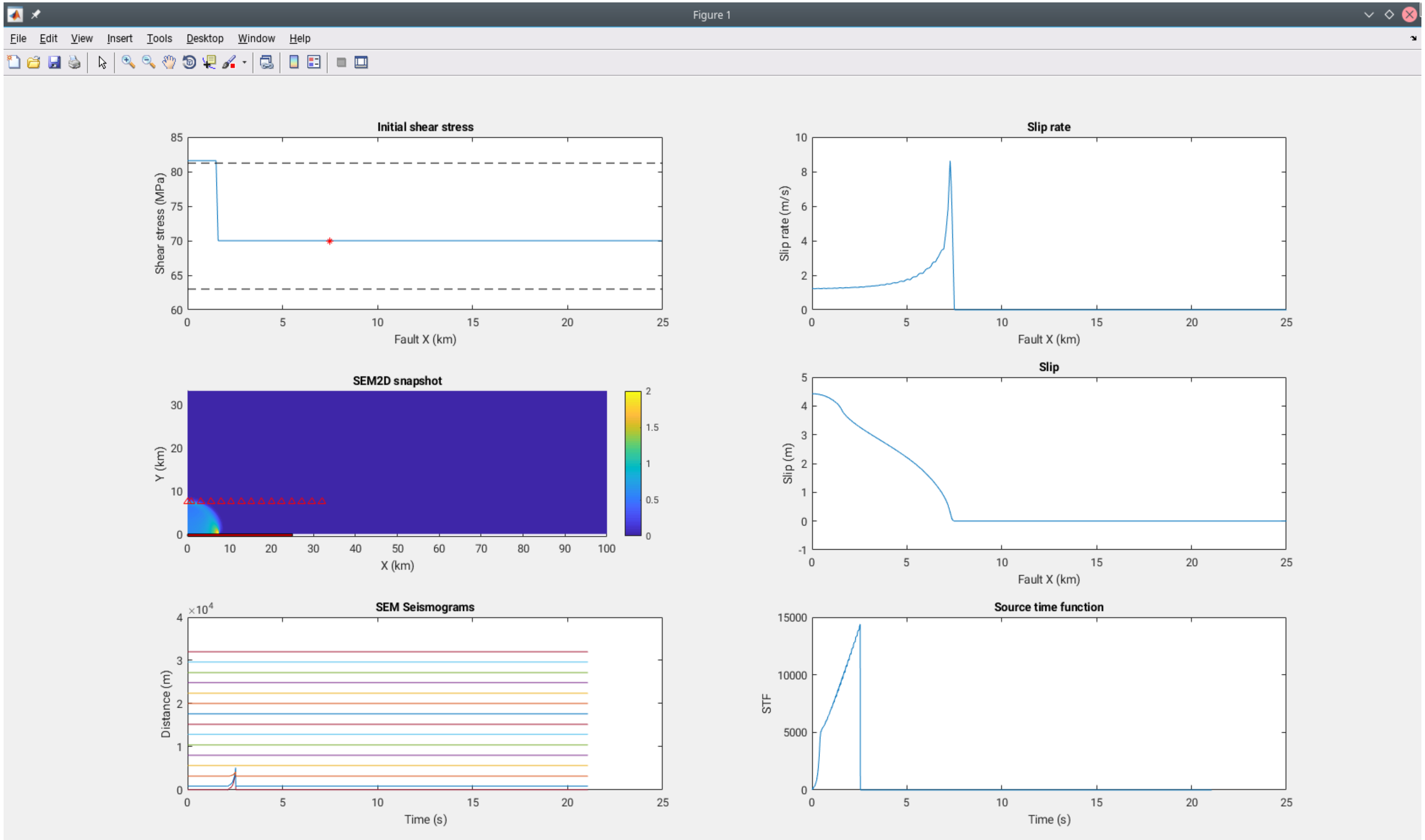
open this file from matlab:

sem2d_eq_dyn_tutorial.m

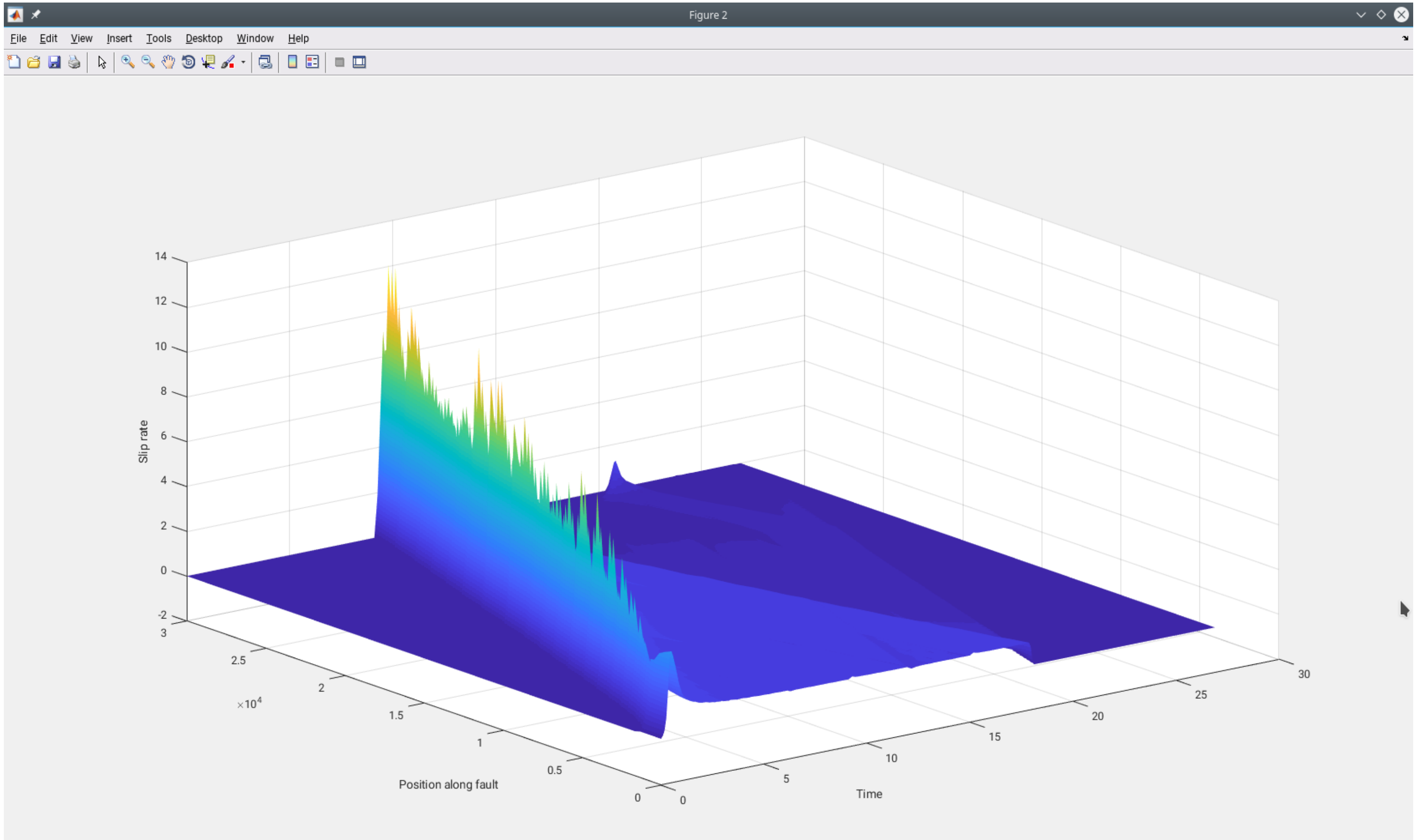
Parameter setup in semlab

```matlab
%------------------------------------------
% Parameters setup
%------------------------------------------

%**** Set here the parameters of the square box domain and mesh : ****
LX=100e3;                     % Horizontal length of the box domain
LY=100e3/3;                   % Vertical length of the box domain
LZ=inf;                       % Thickness of the seismogenic region (approximately accounted for).
                              % Turned off if LZ=inf.
%NELX = 150; NELY = 50; P = 8;% Number of elements; polynomial degree
NELX = 300; NELY = 100; P = 4;% Number of elements; polynomial degree
SYM_X = 1;                    % If SYM_X=1, enforce symmetry with respect to x=0
                              % (the left boundary becomes a free surface)
%********

%**** Set here the parameters of the material and simulated dumping factor : ****
RHO = 2670.;                  % The density (g/m^3)
VS  = 3464.;                  % The S wave speed (m/s)
ETA = 0.2;                    % Kelvin-Voigt viscosity term = ETA*dt*K*v
                              % Artificial viscosity to dump the high-frequency numerical noise
%********

%**** Set here the parameters of the time solver : ****
NT = 2500;                    % Number of timesteps
CFL   = 0.6;                  % Stability number = CFL_1D / sqrt(2)
                              % Ratio of simulation time step to min(Delta_x)/VS.
%********

%**** Set here the parameters of the fault : ****
Normal_stress    = 120e6;     % Fault normal stress
Shear_stress     = 70e6;      % Shear stress
Static_friction  = 0.677;     % Static friction coefficient
Dynamic_friction = 0.525;     % Dynamic friction coefficient
dc               = 0.4;       % Slip-weakening distance
Fault_length     = 25e3;      % Simulated fault length
Nuc_length       = 1.5e3;     % Nucleation length
Nuc_str          = 81.6e6;    % Initial shear stress in nucleation zone
%********

%**** Set here receiver locations : ****
Sta_x = [-16e3:2400:32e3]';   % x coord of receivers
Sta_y = 7.5e3;                % y coord of receivers
OUTdt = 100;                   % steps for output snapshots
%********

%**** Set here properties of heterogeneity: ****
Het_type = 'uniform'      ;   % Options are: uniform, trapezoid, random, box, EQ, and steps
                              % The default option is uniform.
```

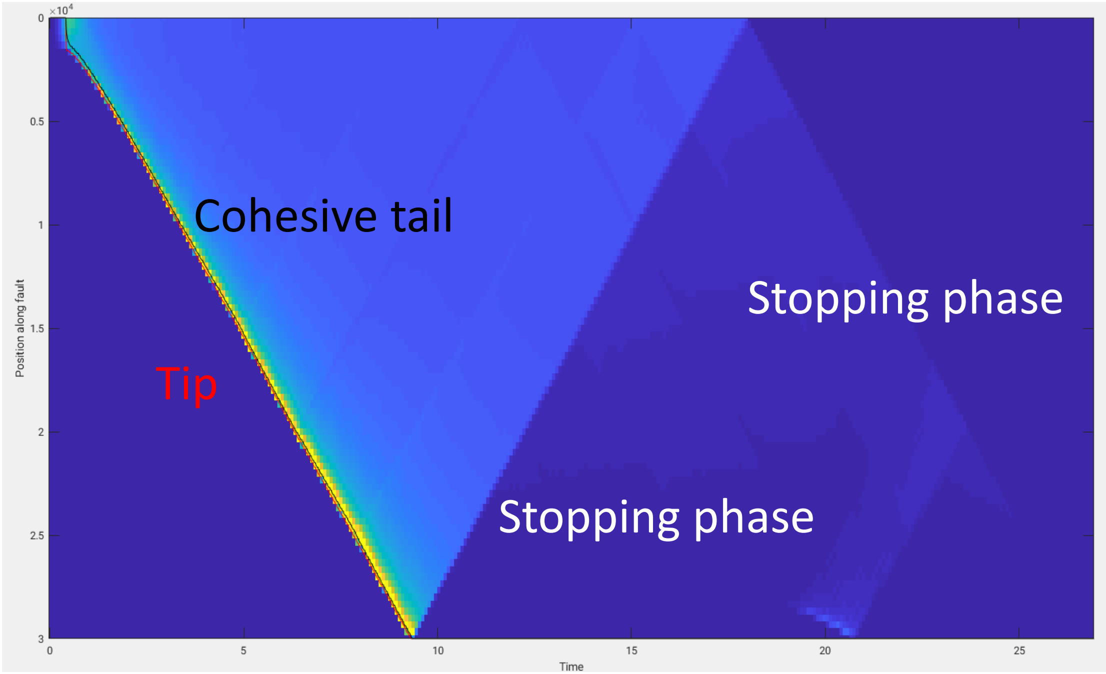
Result presentation (figure1)



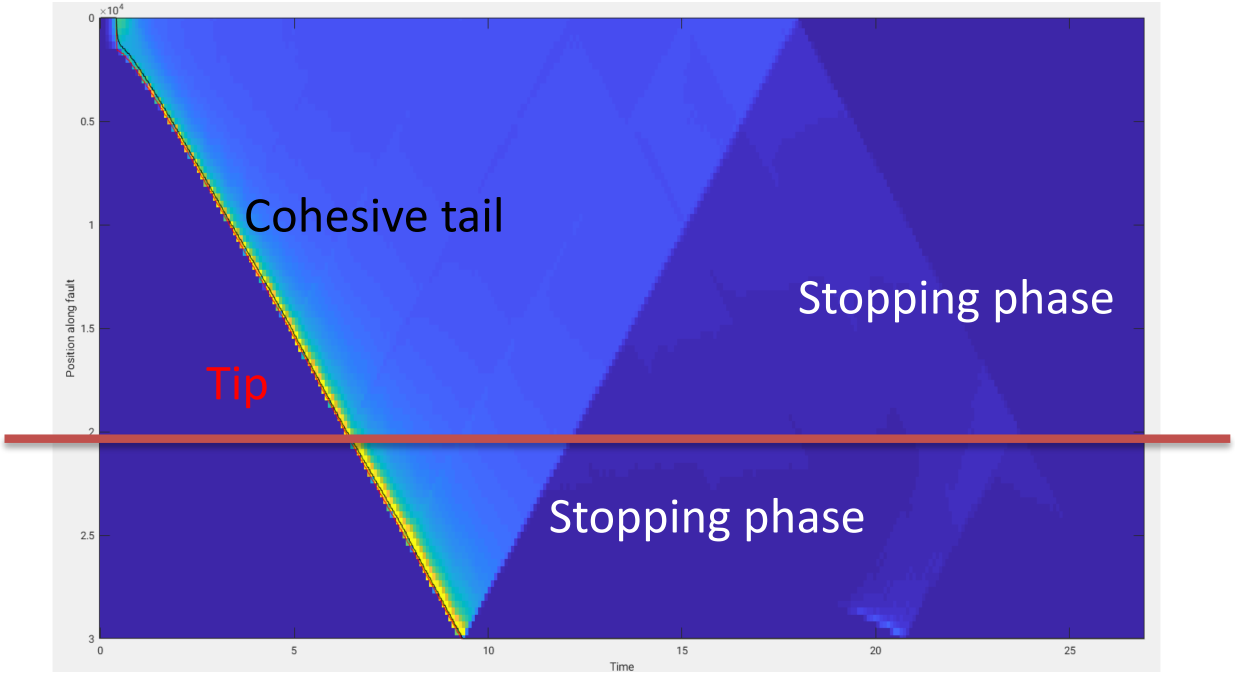
Result presentation (figure2)

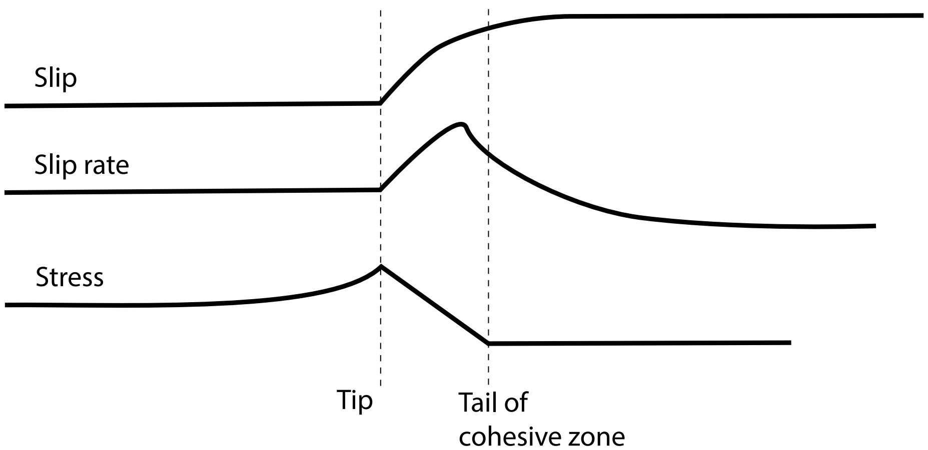


Result presentation (figure3)



Result presentation (figure3)





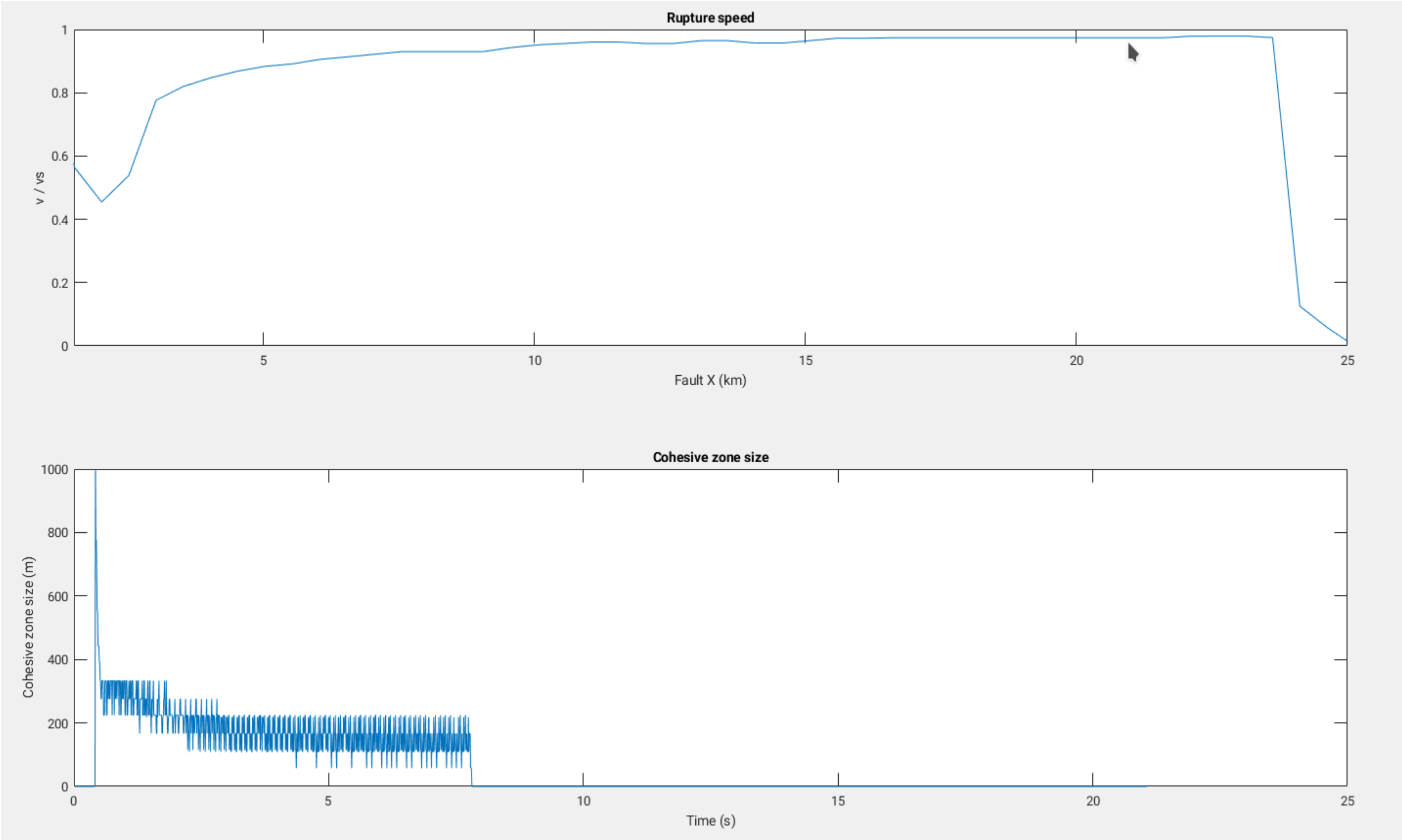
Definition of tip:

Slip rate > threshold

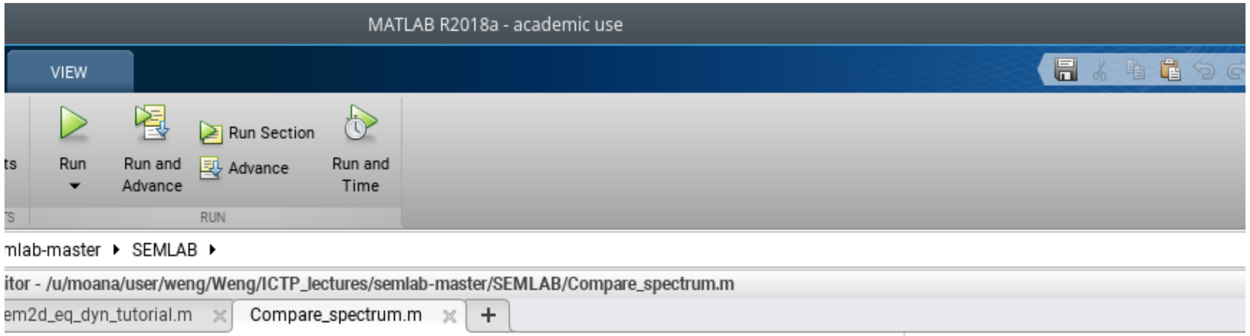
Definition of cohesive tail:

Slip = Dc

Result presentation (figure4)

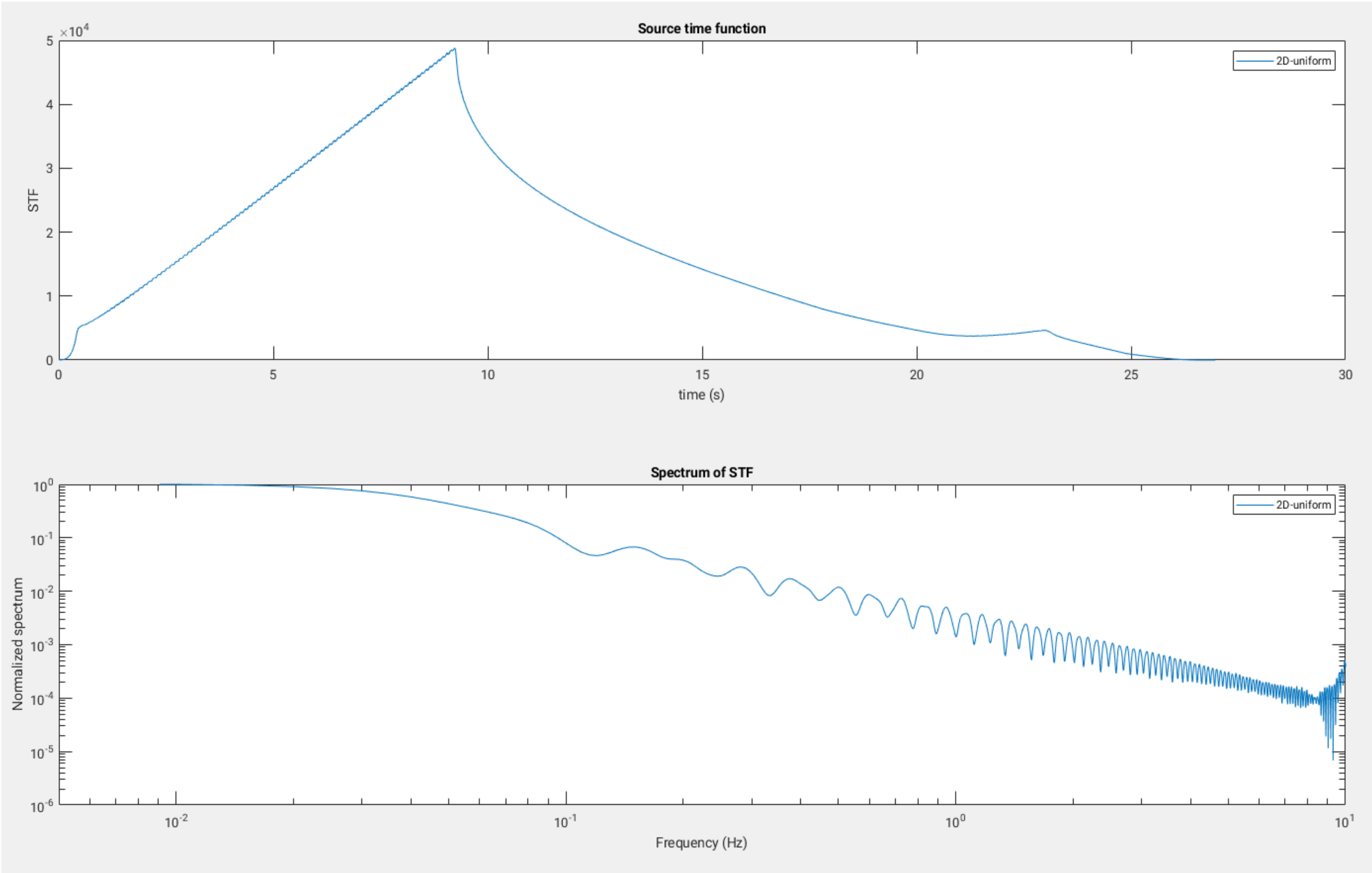


STF and its spectrum (final)




```
%clear all

Compare_all_results = true;  % true if you want to compare all the results in ./output

% if Compare_all_results = false, list the models you want to compare
Compared_list       = ["model_name", ...
                       "model_name",...
                       "model_name"];
                    %   Note: the output files are named by
                    %         ./output/{model_name}-STF.dat
                    %   and
                    %         ./output/{model_name}-spectrum.dat



%------------------------------------------------------
Work_dir = erase(which('Compare_spectrum.m'),'Compare_spectrum.m');
data_dir = [Work_dir '/output/'];

if(Compare_all_results)
    files     = dir(fullfile(data_dir,'*-spectrum.dat'));
else
    files = [];
    for i=1:length(Compared_list)
    files     = [files dir(fullfile(data_dir,'/',strcat(Compared_list(i),'-spectrum.dat')))];
    end
end

model_num = length(files);
if(model_num==0)
    disp('There is no result in the ./output folder!')
end
for k = 1:model_num
files(k).name = erase(files(k).name,'-spectrum.dat');
end
```

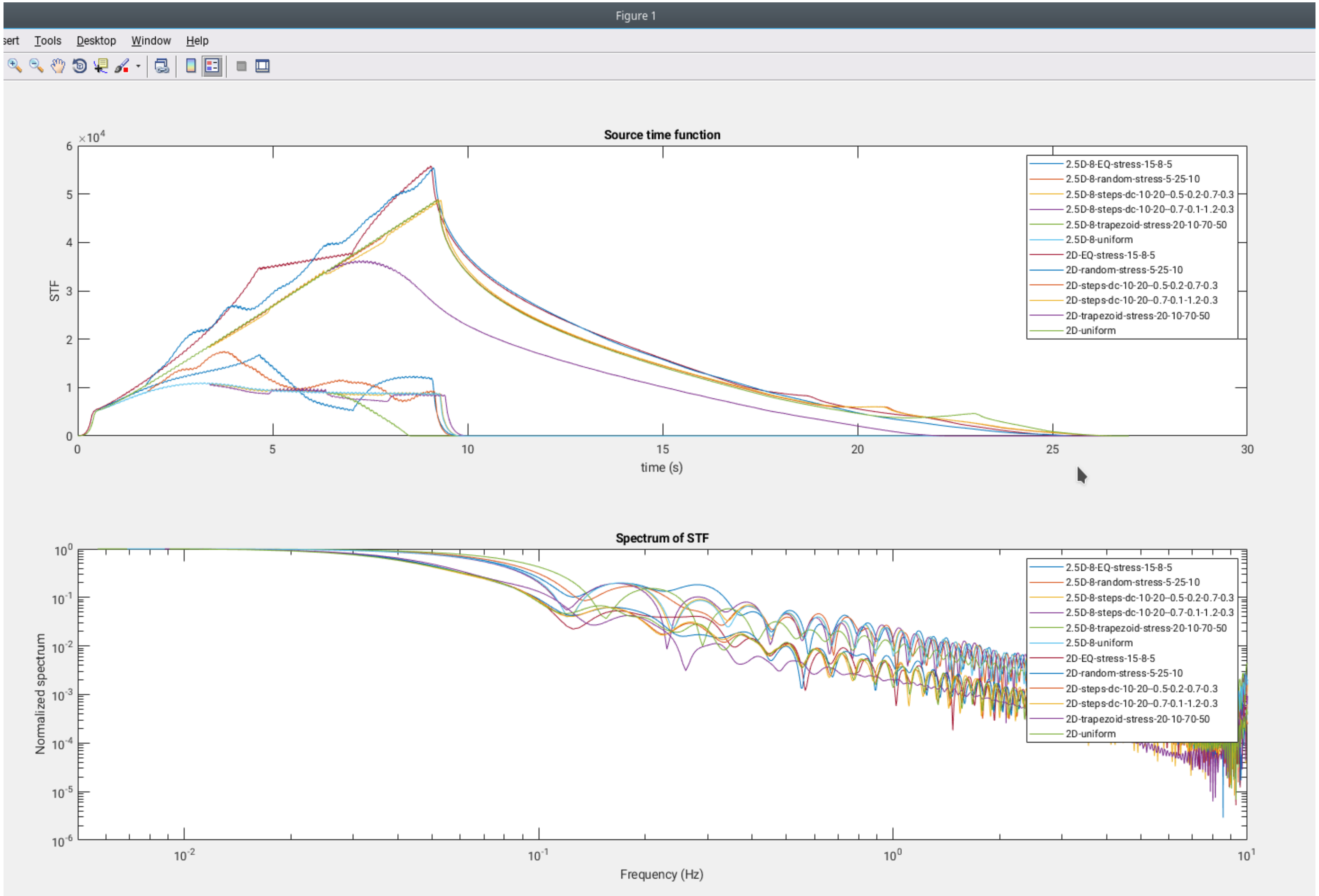
STF and spectra



Add a heterogeneity

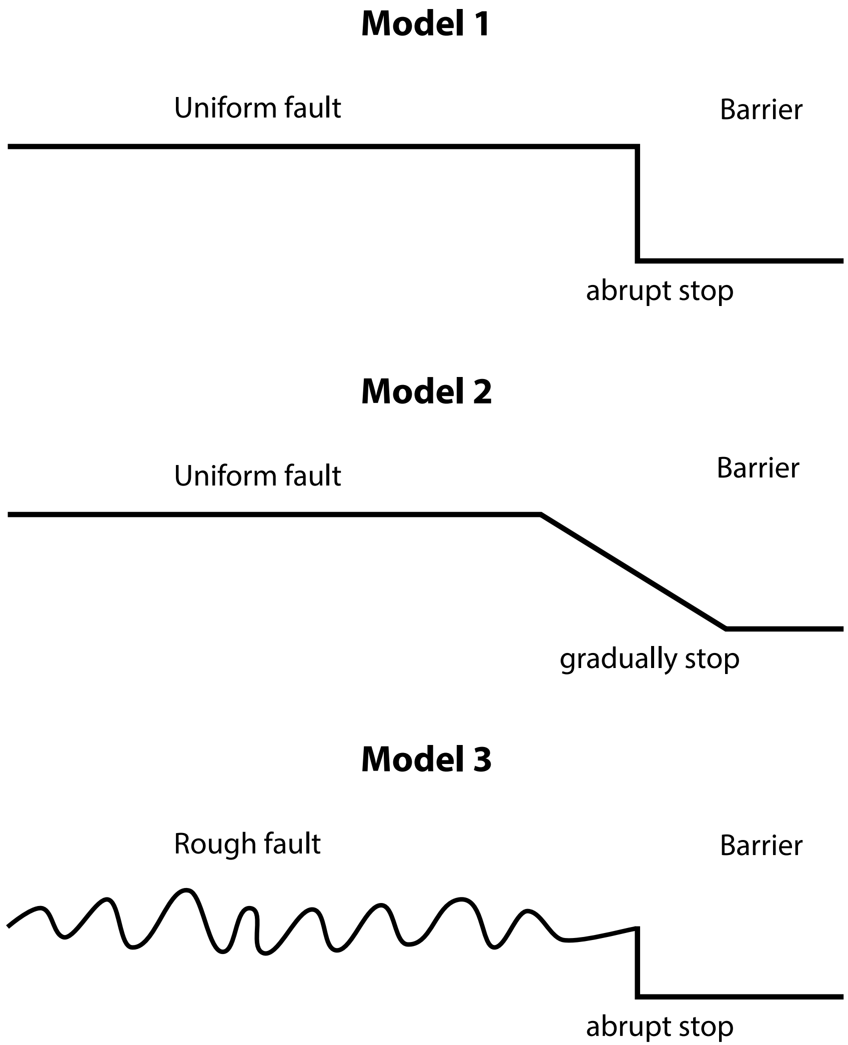
```
%**** Set here properties of heterogeneity: ****
Het_type = 'uniform'        ; % options are: uniform, box, trapezoid, random, EQ, and steps
                         % The default option is uniform.
Het_para = 'stress'       ; % The options are: stress and dc. If Het_type='EQ',
                         % this option shall be stress.
Het_loc  = 20e3        ; % The beginning location of heterogeneity (m)
Het_len  = 10e3         ; % The length of heterogeneity (m)
Het_val  = 50e6         ;
                         % The value of heterogeneity. The unit is Pa for stress and m for dc.
%Het_val  = [70e6, 50e6]        ;
                         % For trapezoid, the format is [val1,val2]
                         % For random,    this value indicates pertubation range
                         % For EQ, this value indicates the stress drop of the previous event.
%Het_val  = [60e6,75e6,53e6]       ;
                         % For steps, the format is [val1, val2, ...]
%********
```

STF comparison



Models to test

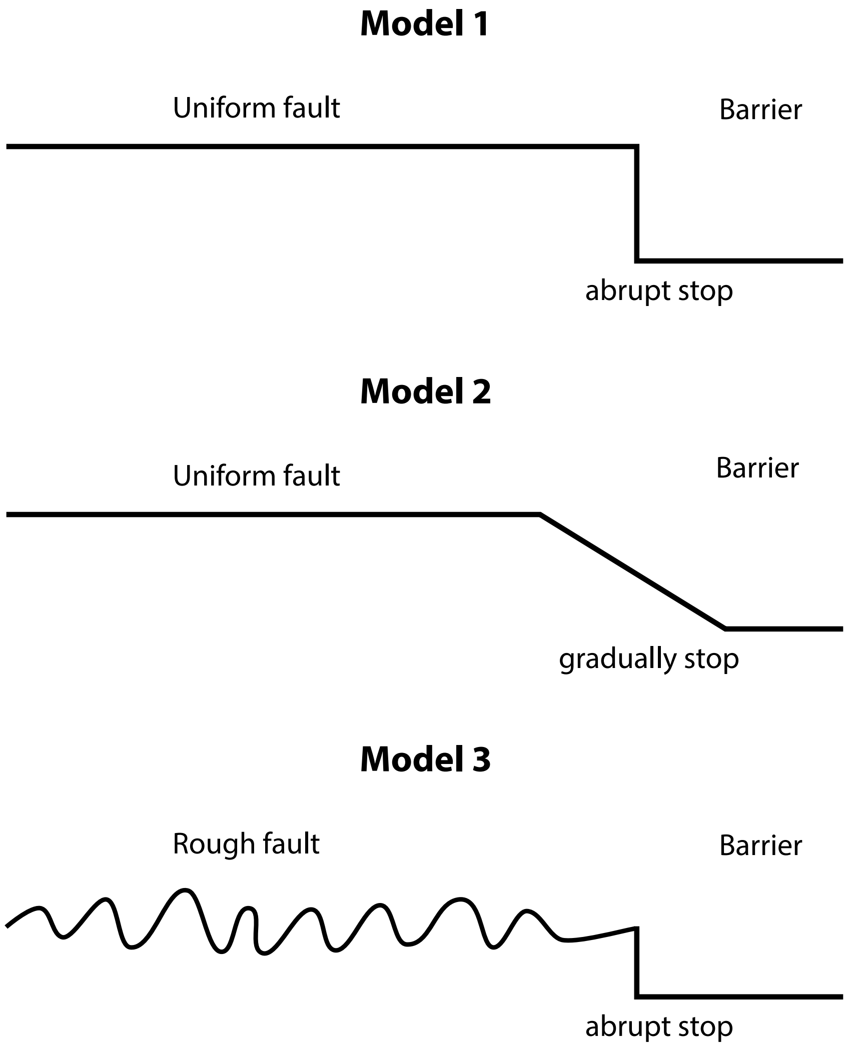
- Heterogeneity can be initial stress or Dc
- Question: what are the differences of STF and spectrum?
- Discussion: what are the differences between 2D and 2.5D models?



Discussion

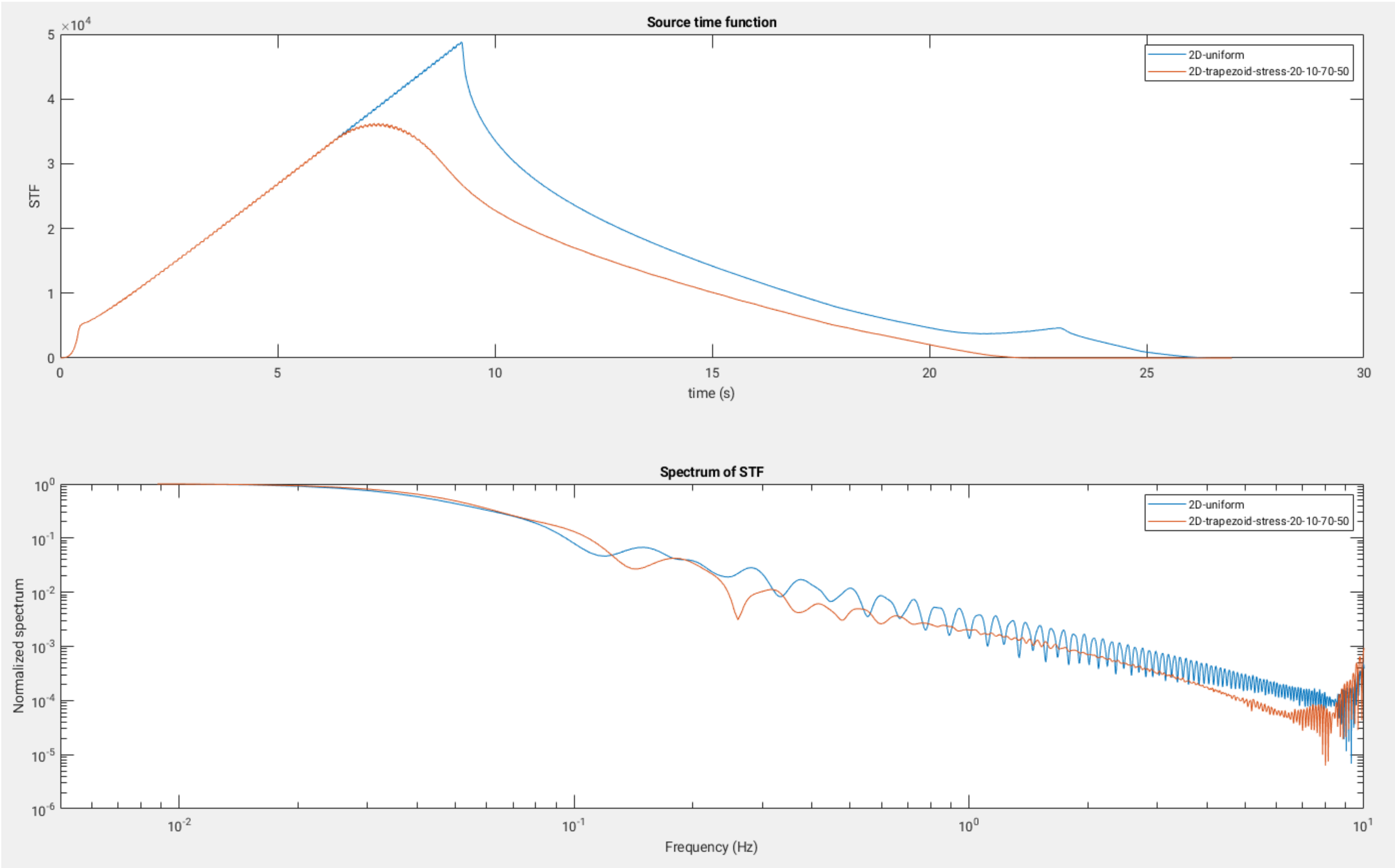
Apple to apple

- model 1 vs. model 2
- model 1 vs. model 3
- 2D vs. 2.5D



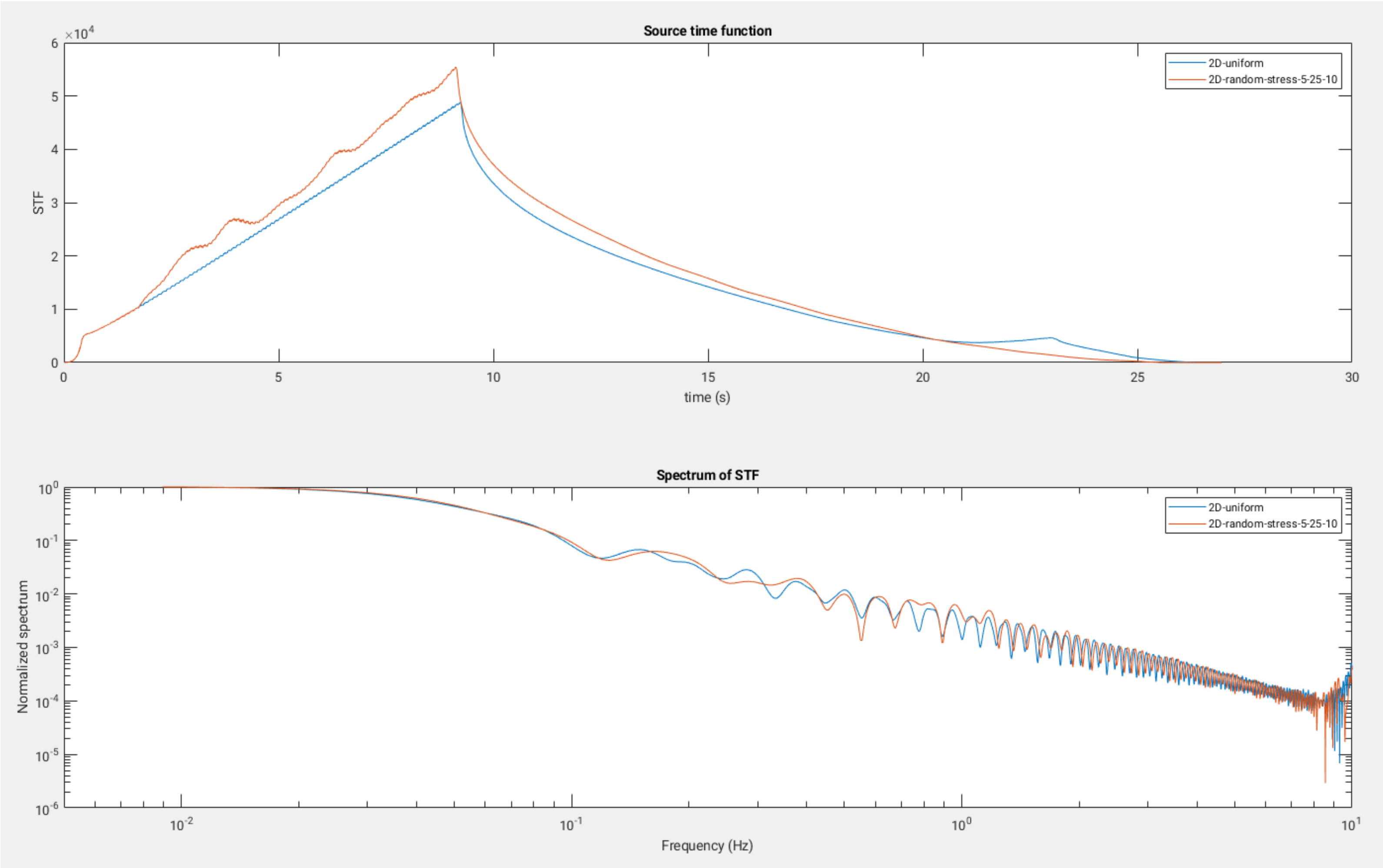
Discussion

- model 1 vs. model 2



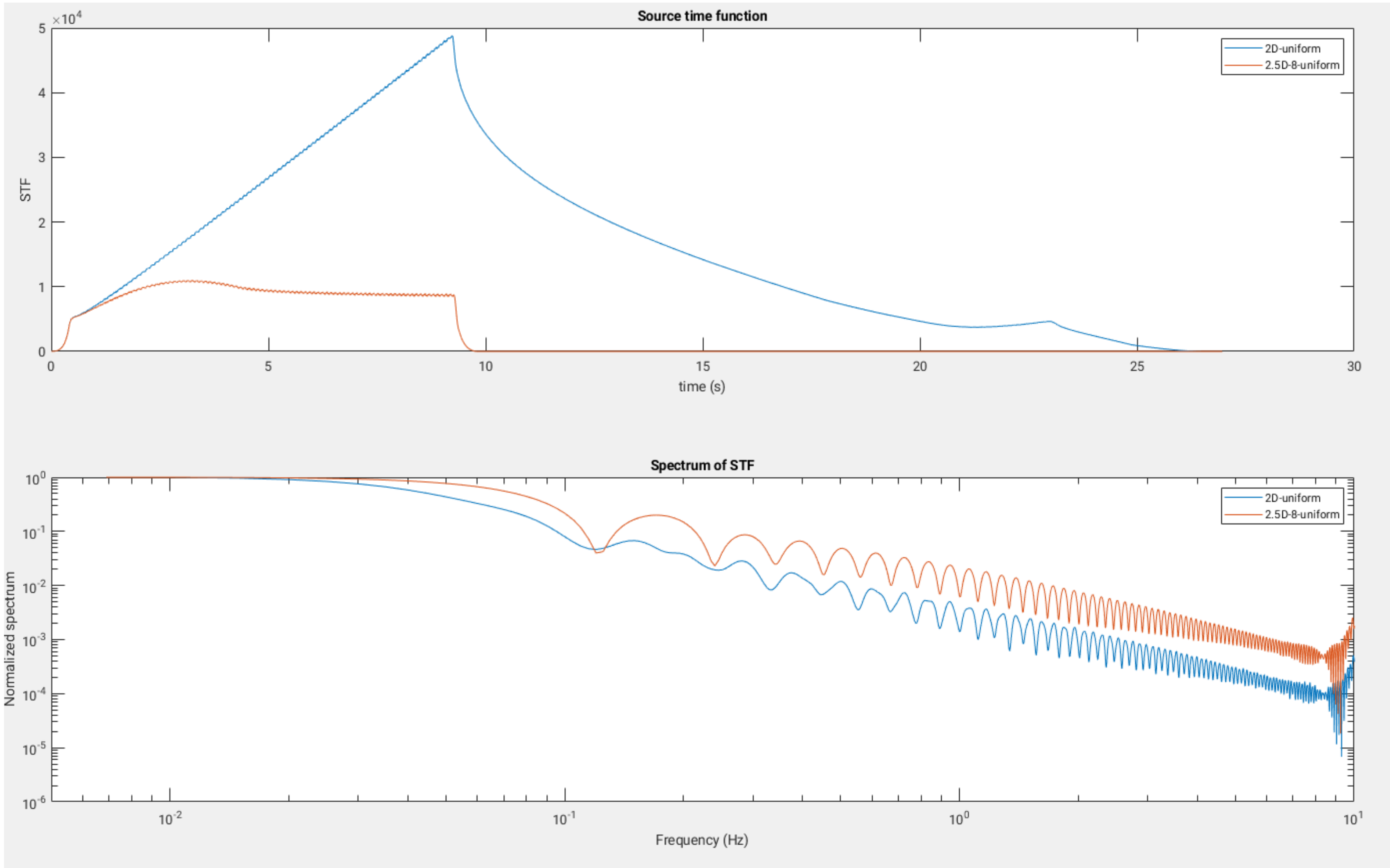
Discussion

- model 1 vs. model 3



Discussion

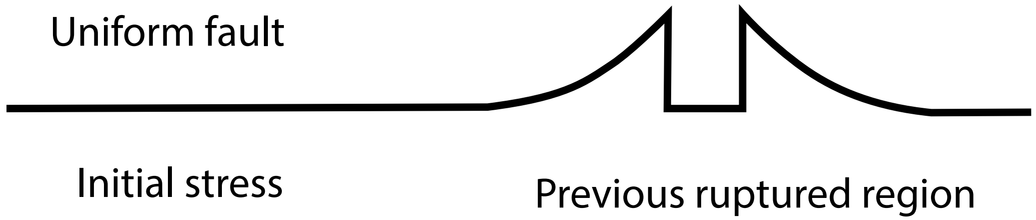
➢ 2D vs. 2.5D



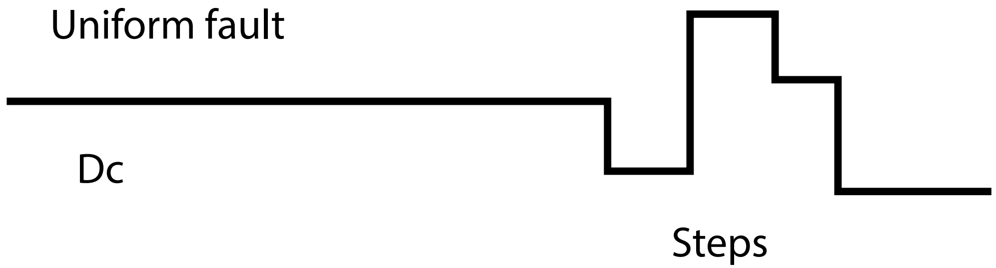
Models to test

- Heterogeneity is initial stress
- Question: do these heterogeneities increase high-frequency radiation?
- Discussion: what parameters may control the high-frequency radiation?

Model 4



Model 5

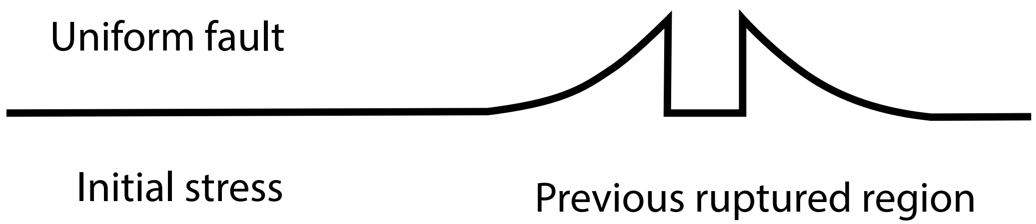


Discussion

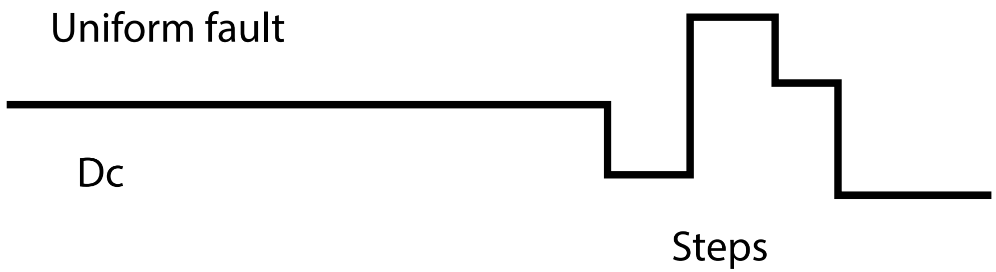
Apple to apple

- model 1 vs. model 4
- model 1 vs. model 5
- 2D vs. 2.5D

Model 4

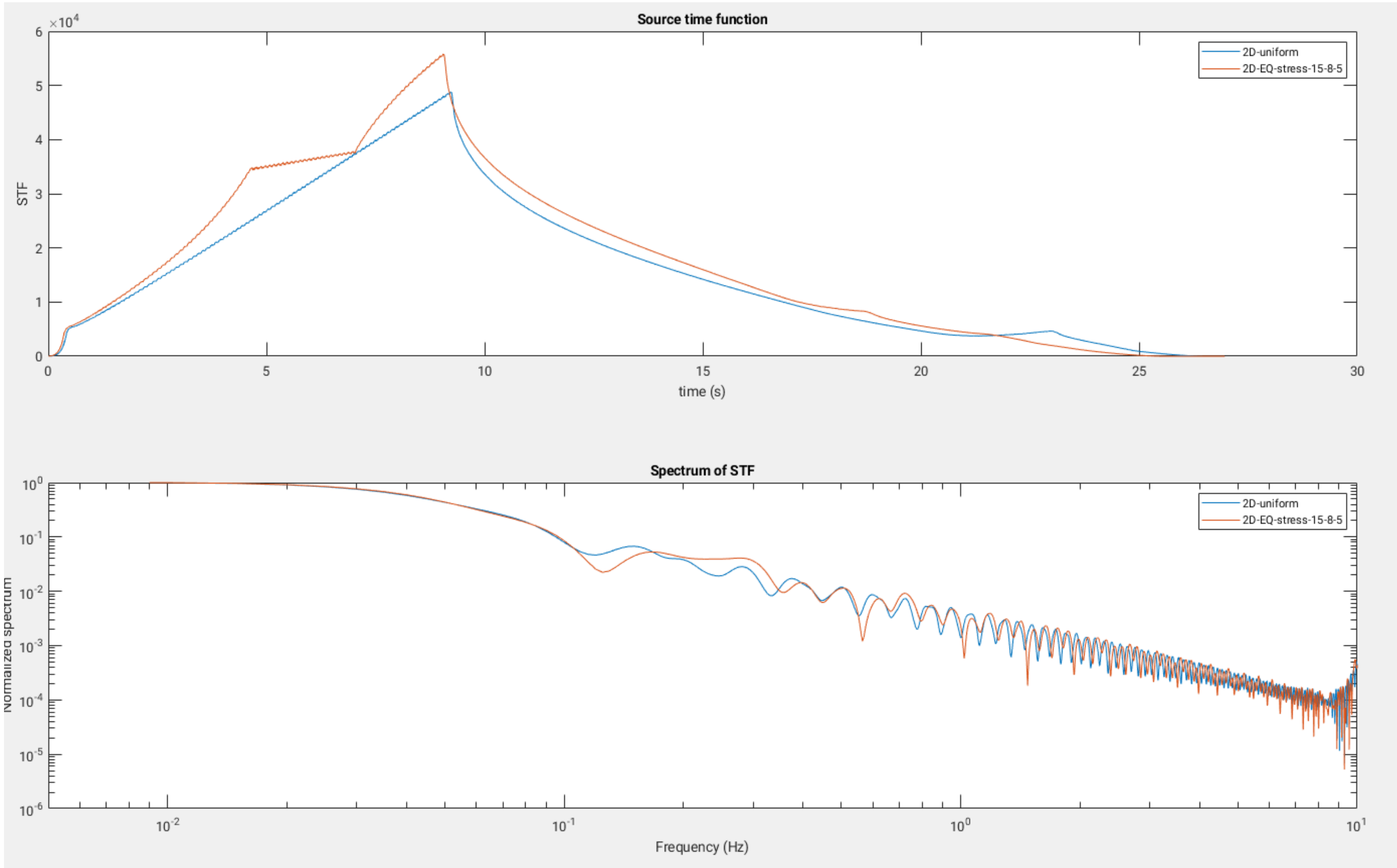


Model 5



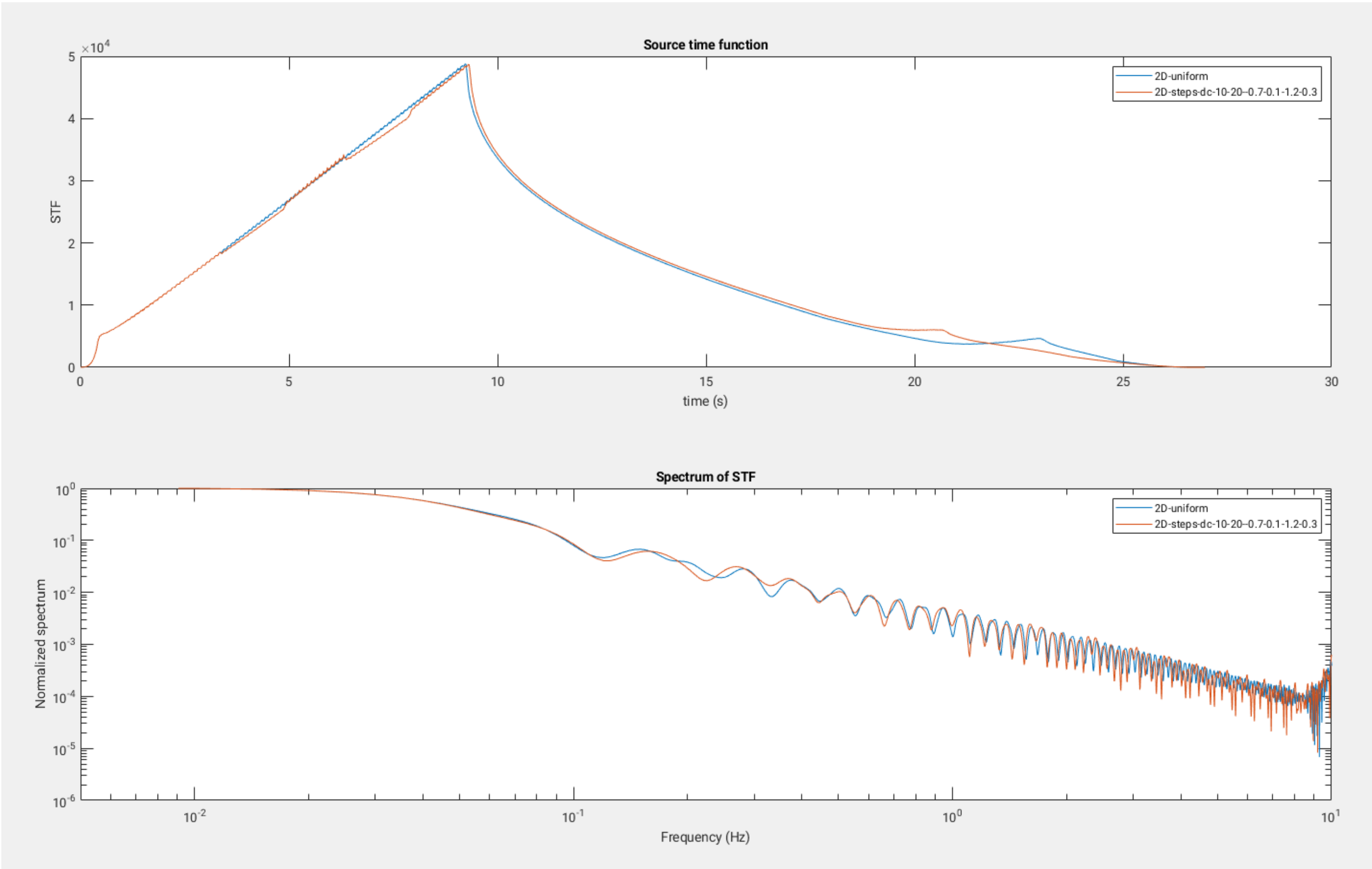
Discussion

- model 1 vs. model 4



Discussion

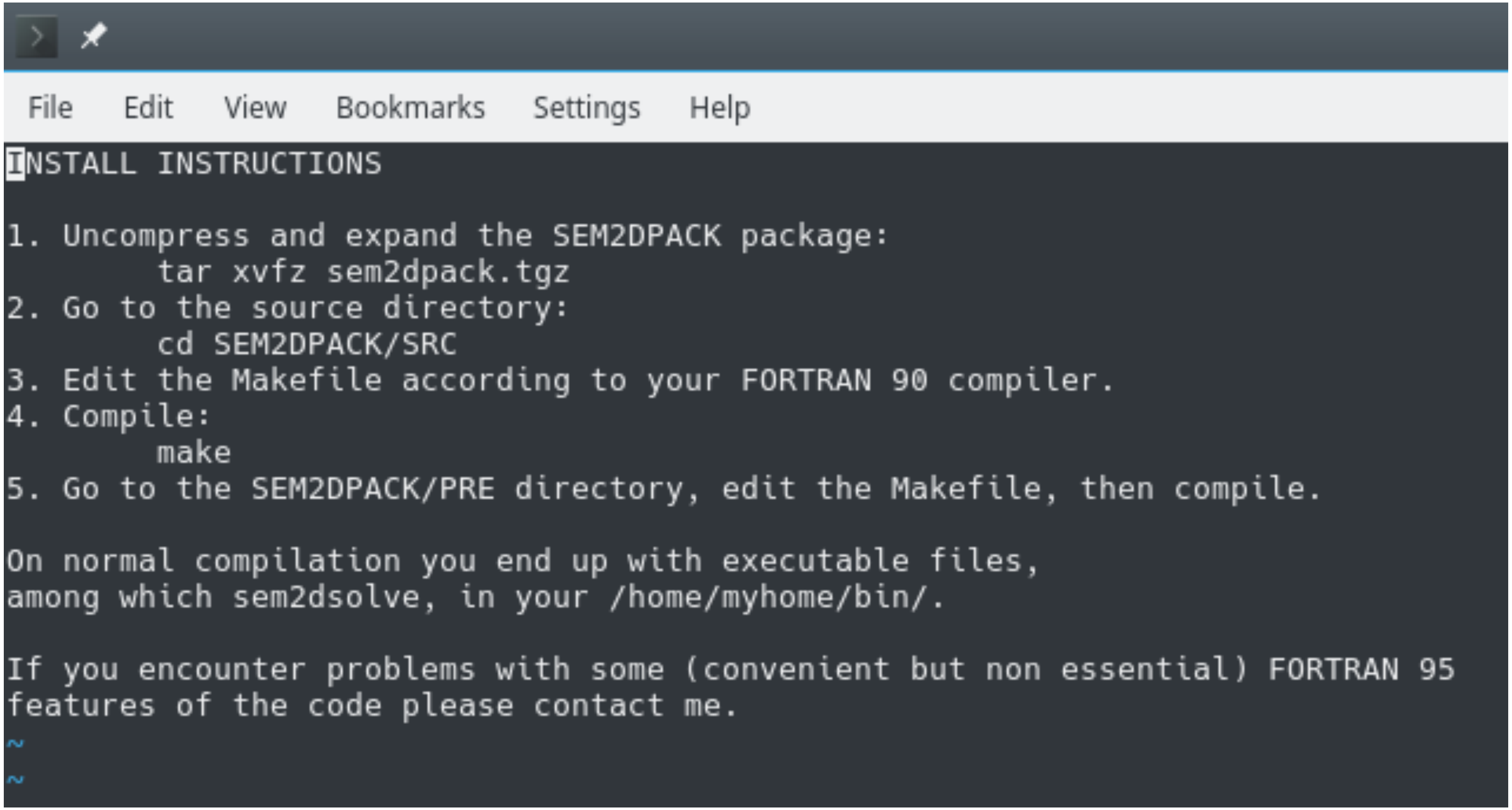
- model 1 vs. model 5



Tutorial of SEMLAB

Tutorial of sem2dpack

Installation of sem2dpack




```
INSTALL INSTRUCTIONS

1. Uncompress and expand the SEM2DPACK package:
        tar xvfz sem2dpack.tgz
2. Go to the source directory:
        cd SEM2DPACK/SRC
3. Edit the Makefile according to your FORTRAN 90 compiler.
4. Compile:
        make
5. Go to the SEM2DPACK/PRE directory, edit the Makefile, then compile.

On normal compilation you end up with executable files,
among which sem2dsolve, in your /home/myhome/bin/.

If you encounter problems with some (convenient but non essential) FORTRAN 95
features of the code please contact me.
~
~
```

How to run sem2dpack?

cd ${work_dir}/sem2dpack-25D/EXAMPLES/2.5D_inplane

open this file by vim or other method:

vi Par.inp

Parameter setup in sem2dpack

File Edit View Bookmarks Settings Help

```
#----- Some general parameters ----------------
&GENERAL iexec=1, ngll=5, fmax=3.d0 , W=10d3, ndof=2 ,
  title = '2.5D elastic in-plane model', verbose='1111' , ItInfo = 400/

#----- Build the mesh --------------------------
&MESH_DEF  method = 'CARTESIAN'/
&MESH_CART xlim=0d3,100d3, zlim=0d3,50d3, nelem=160,80/

#---- Material parameters --------------
&MATERIAL tag=1, kind='ELAST'  /
&MAT_ELASTIC rho=2705.d0, cp=5770.d0, cs=3330.d0 /

#----- Boundary conditions ---------------------
&BC_DEF  tag = 1, kind = 'DYNFLT' /
&BC_DYNFLT friction='SWF','TWF', Tn=-50d6,Tt=30.5d6 /
&BC_DYNFLT_SWF Dc=0.4d0, MuS=0.63d0, MuD=0.54d0 /
&BC_DYNFLT_TWF kind=1, MuS=0.63d0, MuD=0.54d0, Mu0=0.63d0,
               X=0.d0, Z=0.d0, V=0.333d3, L=0.1665d3, T=60d0 /

&BC_DEF  tag = 2 , kind = 'ABSORB' /
&BC_DEF  tag = 3 , kind = 'ABSORB' /
&BC_DEF  tag = 4 , kind = 'DIRNEU' /
&BC_DIRNEU h='N', v='D' /


#---- Time scheme settings ----------------------
&TIME  kind='leapfrog', TotalTime=30 /

#----- Receivers ---------------------------------
#&REC_LINE number = 10 , first = 0d3,10d3, last = 50.d3,10d3, isamp=20, AtNode=F /

#--------- Plots settings ----------------------
&SNAP_DEF itd=100, fields ='DVS',bin=T,ps=F /
&SNAP_PS  vectors=F, interpol=T, DisplayPts=6, ScaleField=0d0   /
```

Parameter setup in sem2dpack

File Edit View Bookmarks Settings Help

```
#----- Some general parameters ----------------
&GENERAL iexec=1, ngll=5, fmax=3.d0 , W=10d3, ndof=2 ,
  title = '2.5D elastic in-plane model', verbose='1111' , ItInfo = 400/

#----- Build the mesh ---------------------------
&MESH_DEF  method = 'CARTESIAN'/
&MESH_CART xlim=0d3,100d3, zlim=0d3,50d3, nelem=160,80/

#---- Material parameters --------------
&MATERIAL tag=1, kind='ELAST'  /
&MAT_ELASTIC rho=2705.d0, cp=5770.d0, cs=3330.d0 /

#----- Boundary conditions ---------------------
&BC_DEF  tag = 1, kind = 'DYNFLT' /
&BC_DYNFLT friction='SWF','TWF', Tn=-50d6,Tt=30.5d6 /
&BC_DYNFLT_SWF Dc=0.4d0, MuS=0.63d0, MuD=0.54d0 /
&BC_DYNFLT_TWF kind=1, MuS=0.63d0, MuD=0.54d0, Mu0=0.63d0,
               X=0.d0, Z=0.d0, V=0.333d3, L=0.1665d3, T=60d0 /

&BC_DEF  tag = 2 , kind = 'ABSORB' /
&BC_DEF  tag = 3 , kind = 'ABSORB' /
&BC_DEF  tag = 4 , kind = 'DIRNEU' /
&BC_DIRNEU h='N', v='D' /


#---- Time scheme settings ----------------------
&TIME  kind='leapfrog', TotalTime=30 /

#----- Receivers ---------------------------------
#&REC_LINE number = 10 , first = 0d3,10d3, last = 50.d3,10d3, isamp=20, AtNode=F /

#--------- Plots settings ----------------------
&SNAP_DEF itd=100, fields ='DVS',bin=T,ps=F /
&SNAP_PS  vectors=F, interpol=T, DisplayPts=6, ScaleField=0d0   /
```

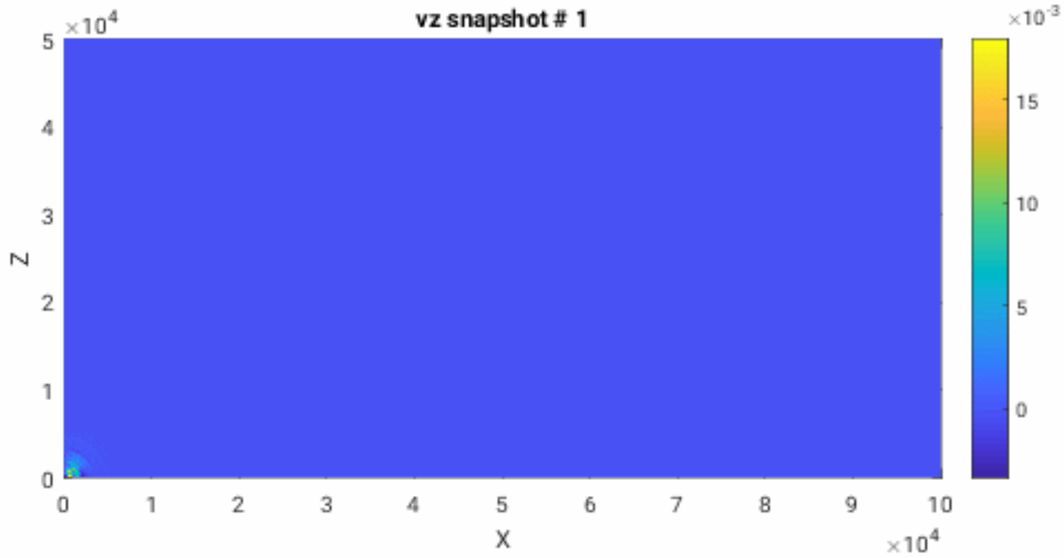
How to present results?

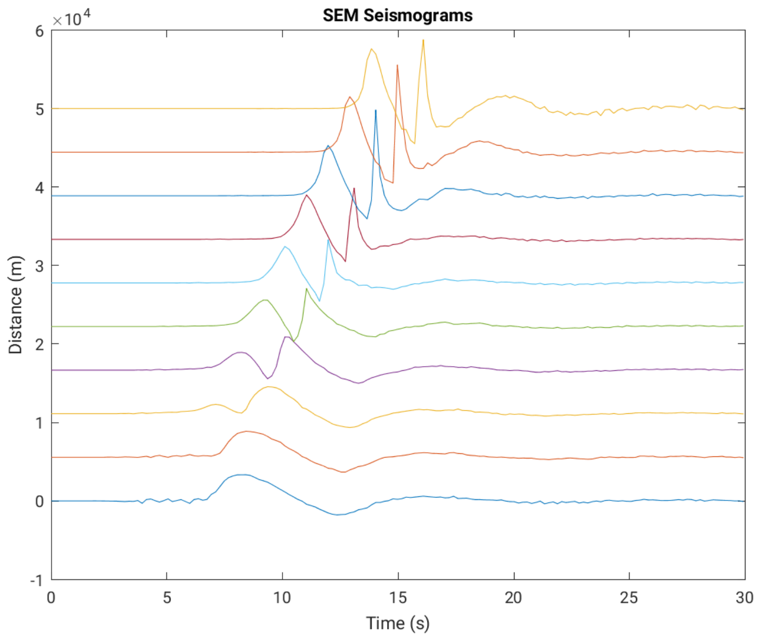
cd ${work_dir}/sem2dpack-25D/POST

open the script by MATLAB:

create_movie.m

run it by MATLAB


vz snapshot # 1
Z
X
×10^4
×10^-3


SEM Seismograms
Distance (m)
Time (s)
×10^4

Discussion

- Find seismic phases, such as P wave front, S wave, Rayleigh wave, etc.

- What parameters may control the formation of supershear rupture?

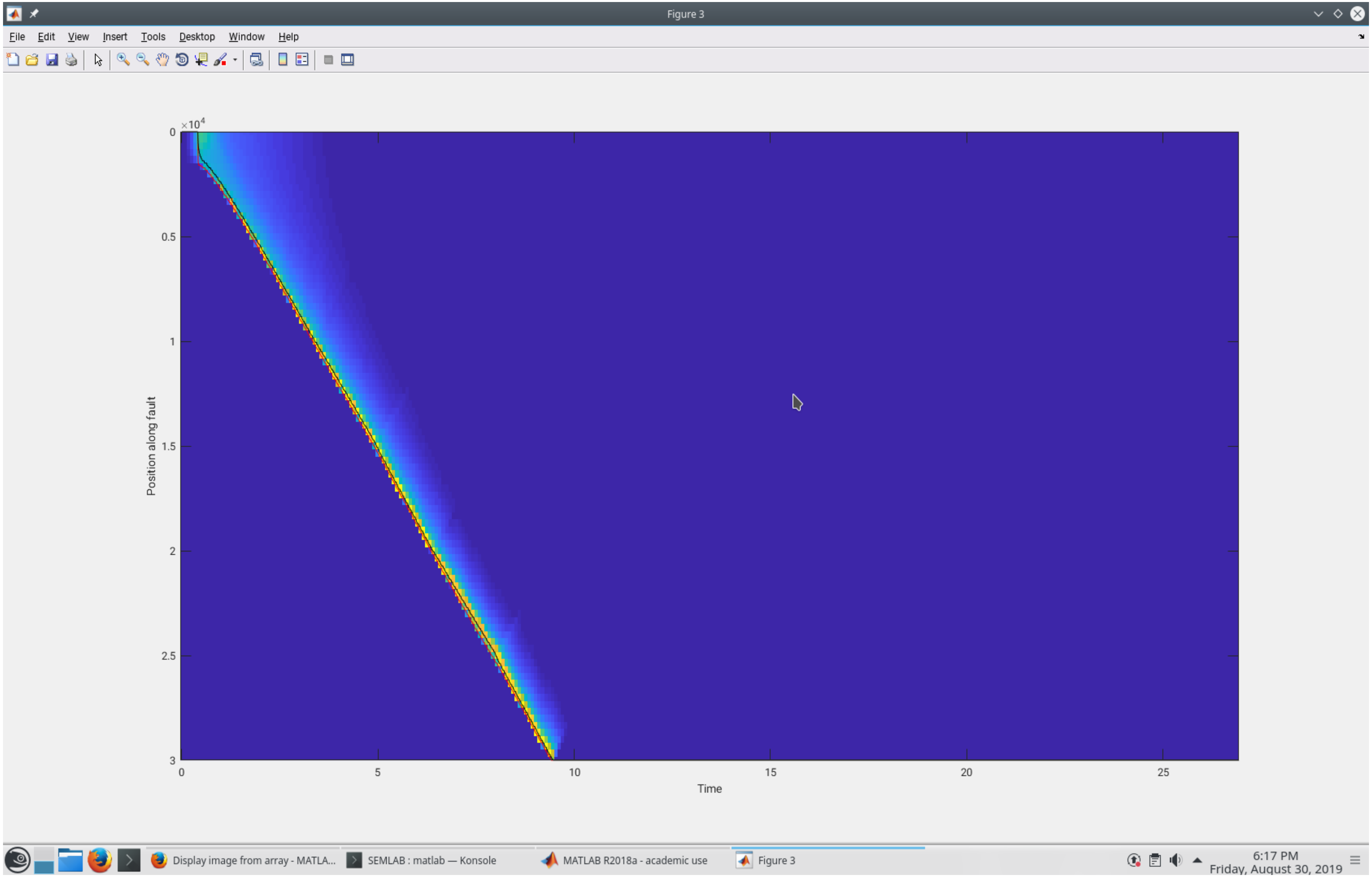


Figure 3
File
Edit
View
Insert
Tools
Desktop
Window
Help
×10^4
0
0.5
1
1.5
2
2.5
3
Position along fault
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Time
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SEMLAB : matlab — Konsole
MATLAB R2018a - academic use
Figure 3
6:17 PM
Friday, August 30, 2019

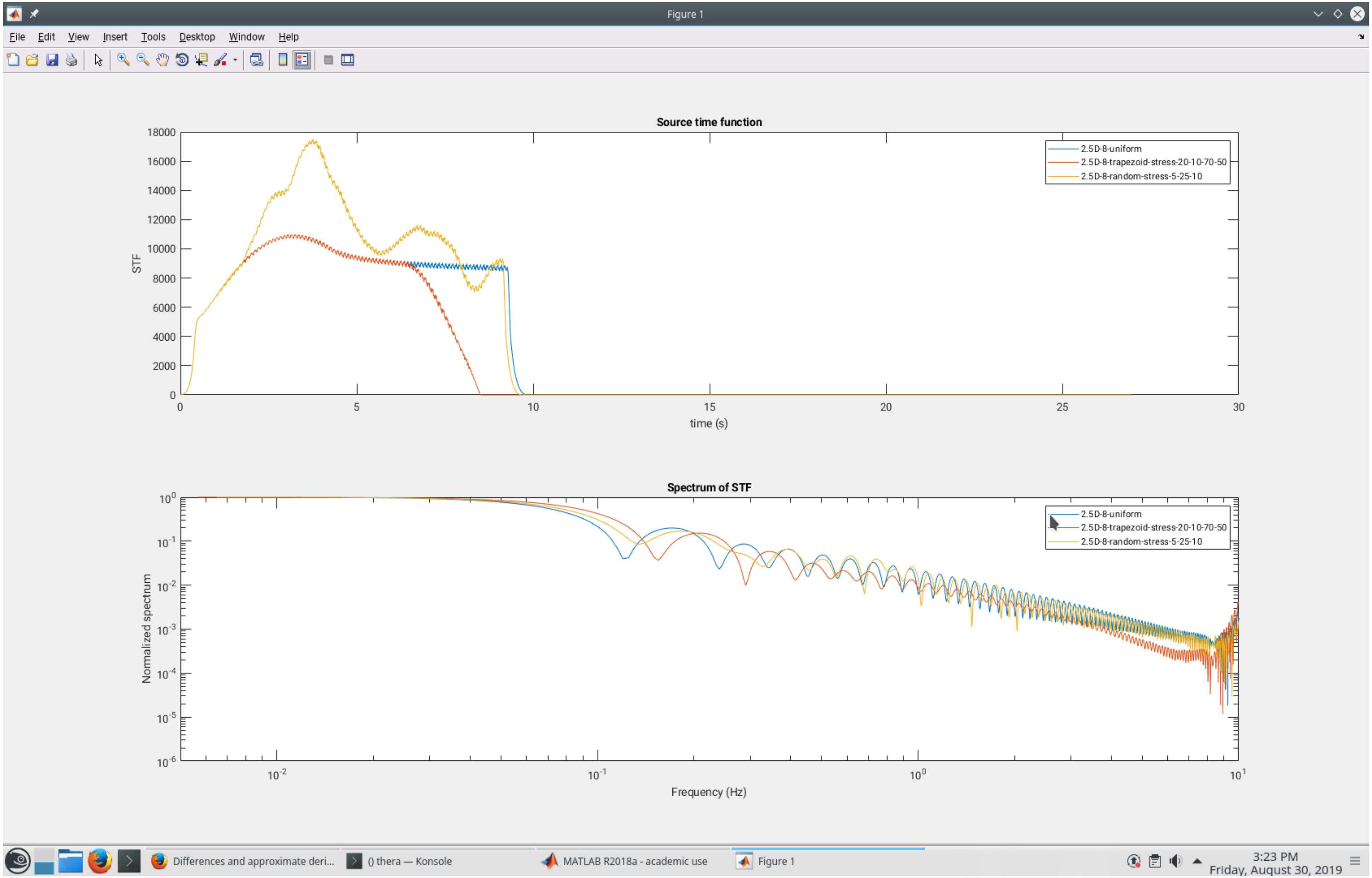
Figure 1
File Edit View Insert Tools Desktop Window Help
Source time function
STF
time (s)
2.5D-8-uniform
2.5D-8-trapezoid-stress-20-10-70-50
2.5D-8-random-stress-5-25-10
Spectrum of STF
Normalized spectrum
Frequency (Hz)
2.5D-8-uniform
2.5D-8-trapezoid-stress-20-10-70-50
2.5D-8-random-stress-5-25-10
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() thera — Konsole
MATLAB R2018a - academic use
Figure 1
3:23 PM
Friday, August 30, 2019

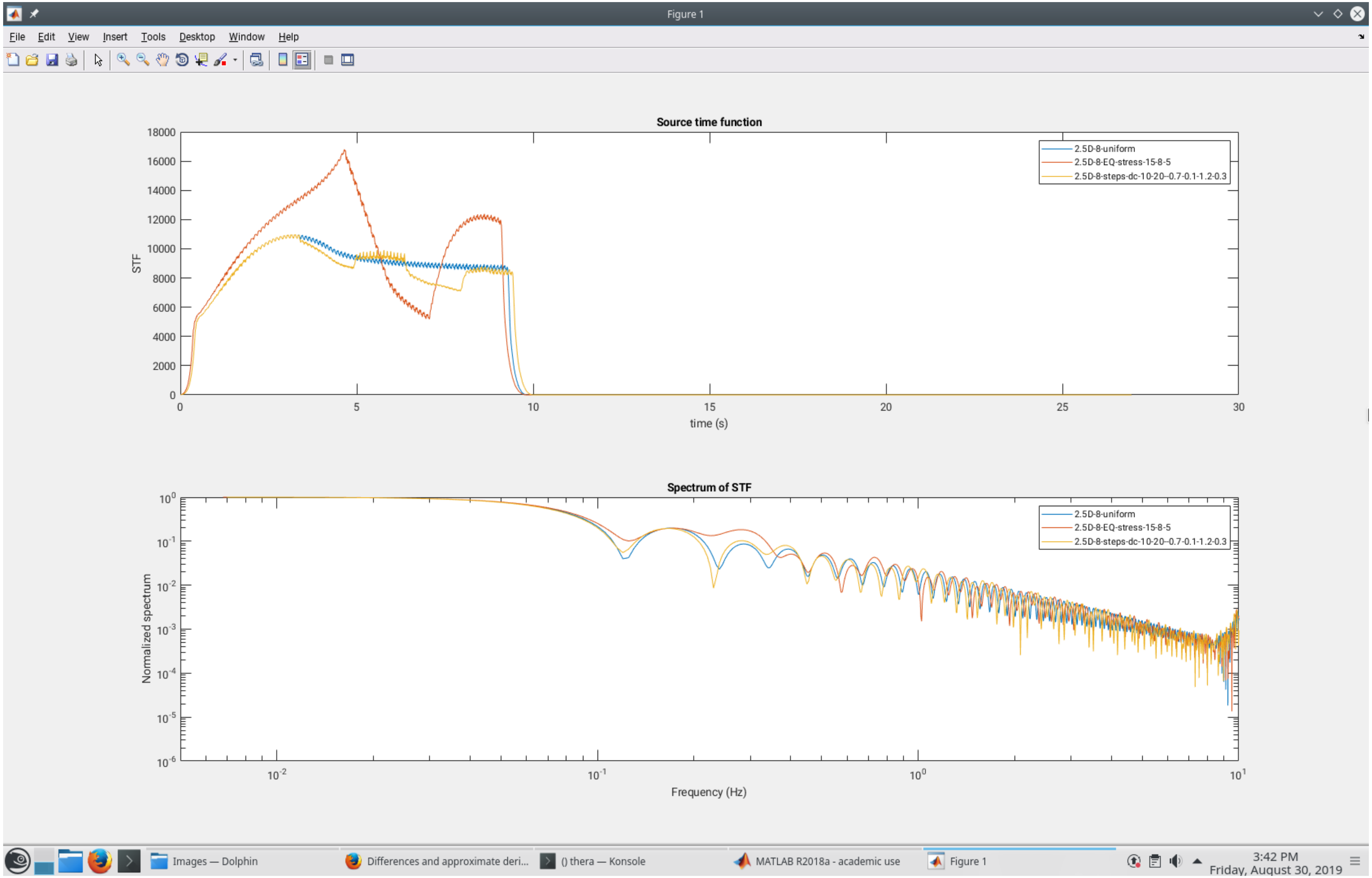
Figure 1
File Edit View Insert Tools Desktop Window Help
Source time function
STF
time (s)
2.5D-8-uniform
2.5D-8-EQ-stress-15-8-5
2.5D-8-steps-dc-10-20-0.7-0.1-1.2-0.3
Spectrum of STF
Normalized spectrum
Frequency (Hz)
2.5D-8-uniform
2.5D-8-EQ-stress-15-8-5
2.5D-8-steps-dc-10-20-0.7-0.1-1.2-0.3
Images — Dolphin
Differences and approximate deri...
() thera — Konsole
MATLAB R2018a - academic use
Figure 1
3:42 PM
Friday, August 30, 2019