# SYNTHESIS 0.1: what future?

Pacor F., D'Amico M., Luzi L., Puglia R.,
Russo E., Gallovic F.

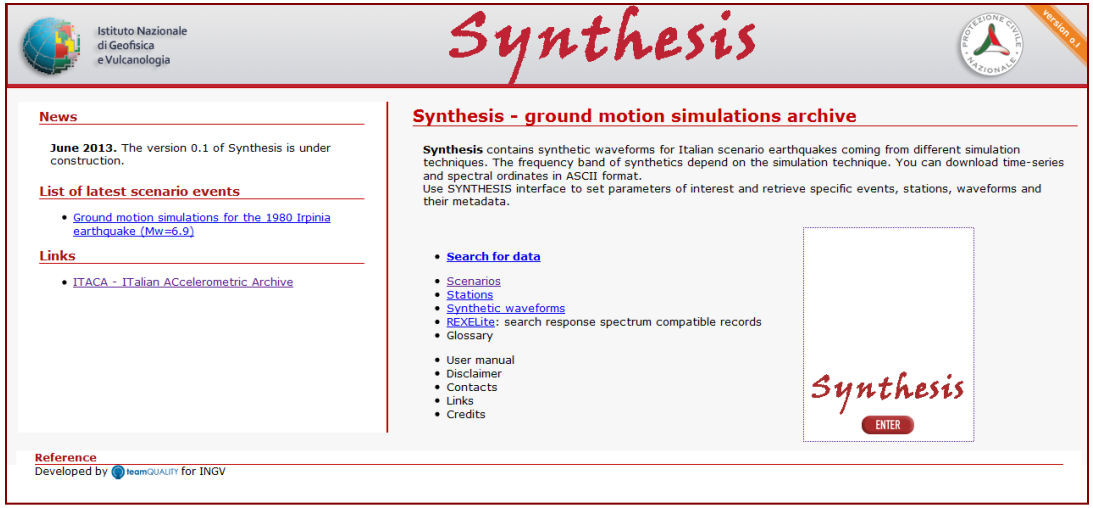
**Napoli 27 Marzo 2014**

# GOALS

- To archive and to distribute through the WEB synthetic waveforms
- To promote the use of synthetic seismograms as integration to the observed ground motion
- To furnish an usable tool for
  - *Scientific purpose*
    - » *Analysis of Ground Motion variability*
    - » *Integration Ground Motion Prediction Equation*
  - *Seismic risk mitigation*
    - » *Damage scenarios*
    - » *Microzonation*
  - *Engineering application*
    - » *Seismic input definition for the structural design*

# WHAT IS SYNTHESIS?

*…. a synthetic waveforms repository*




Synthetic database ensures

a) Trasparency

b) Repeatibility

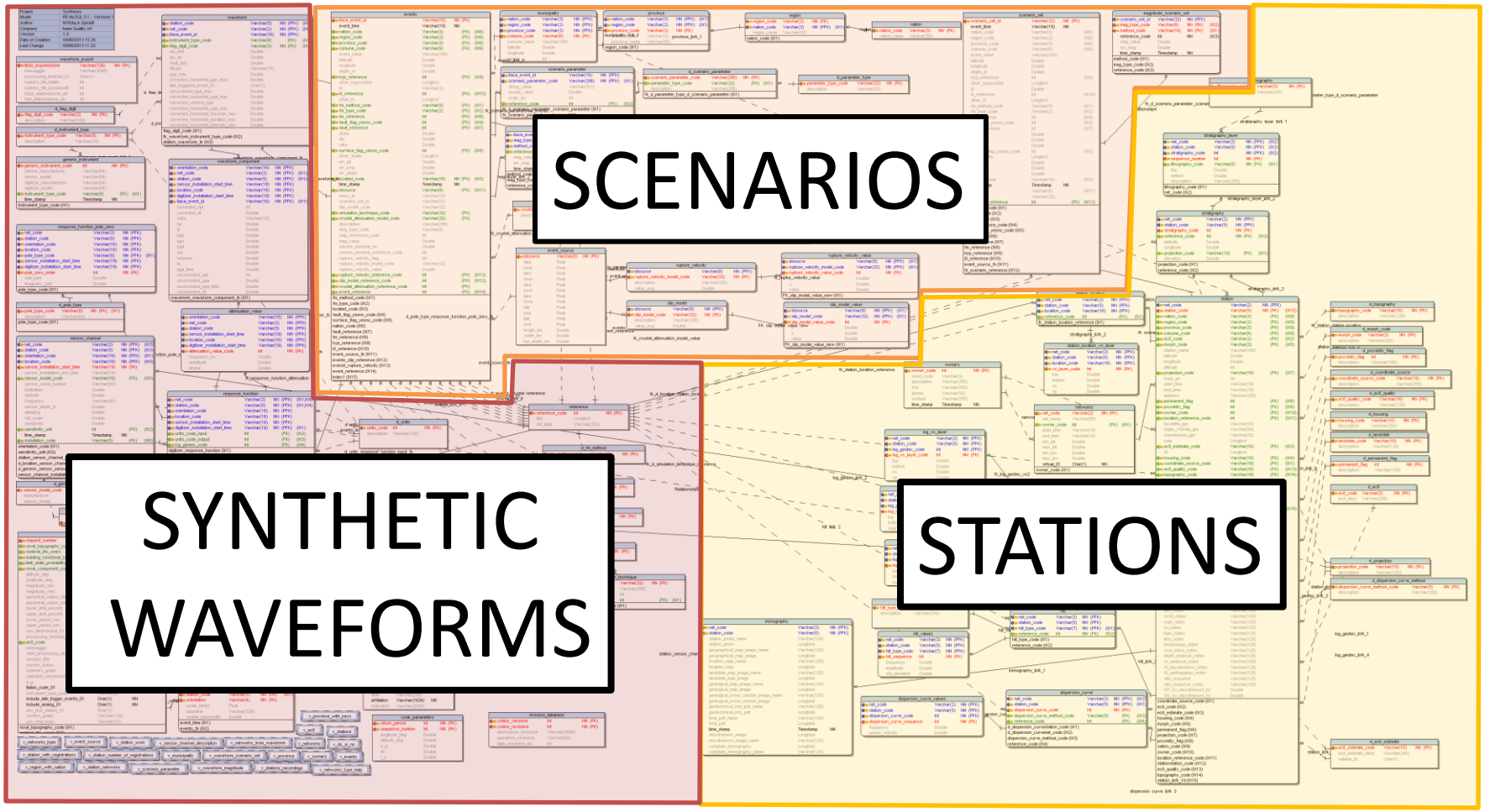
c) Data availability

http://synthesis.mi.ingv.it/

*Progetto Reluis (20010-2012), Progetto INGV-DPC S3 (2005 – 2007)*

# WHAT IS SYNTHESIS?

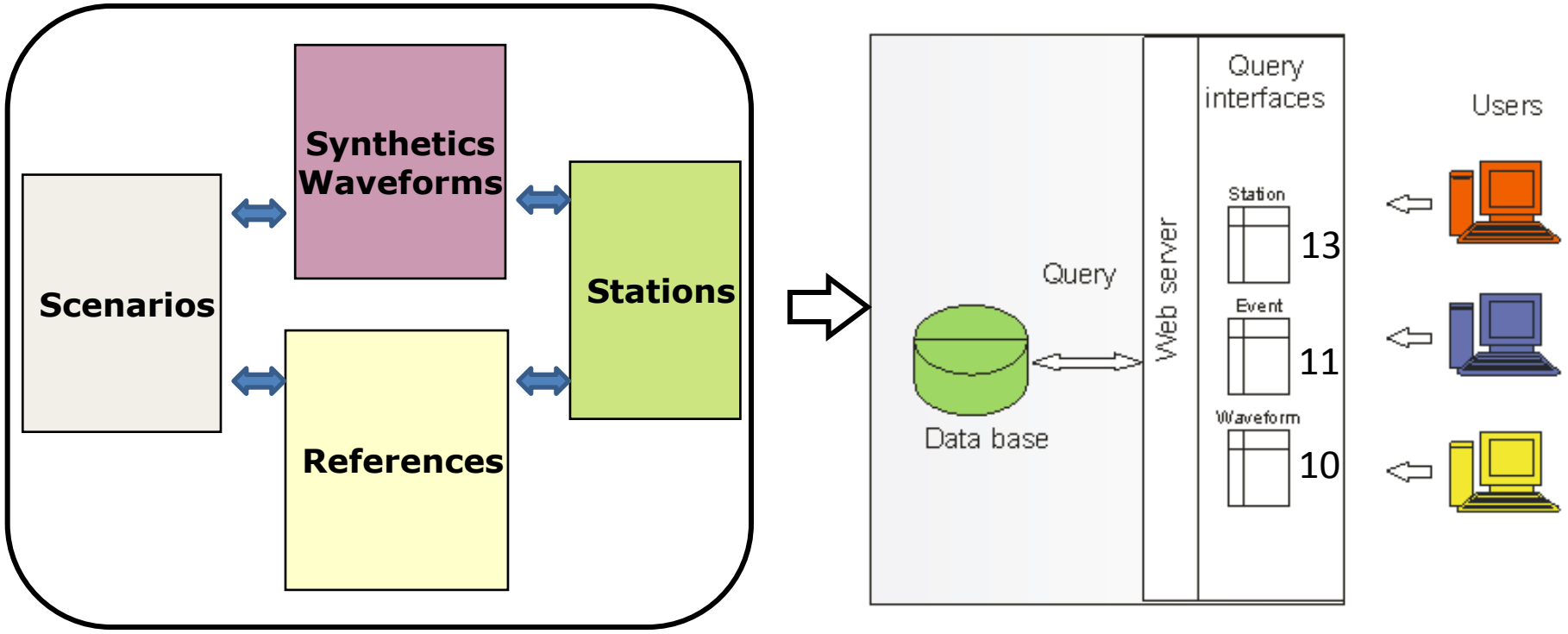
….a relational database management system (Mysql®)




Using the structure of **ITACA**!

# HOW IT WORKS?

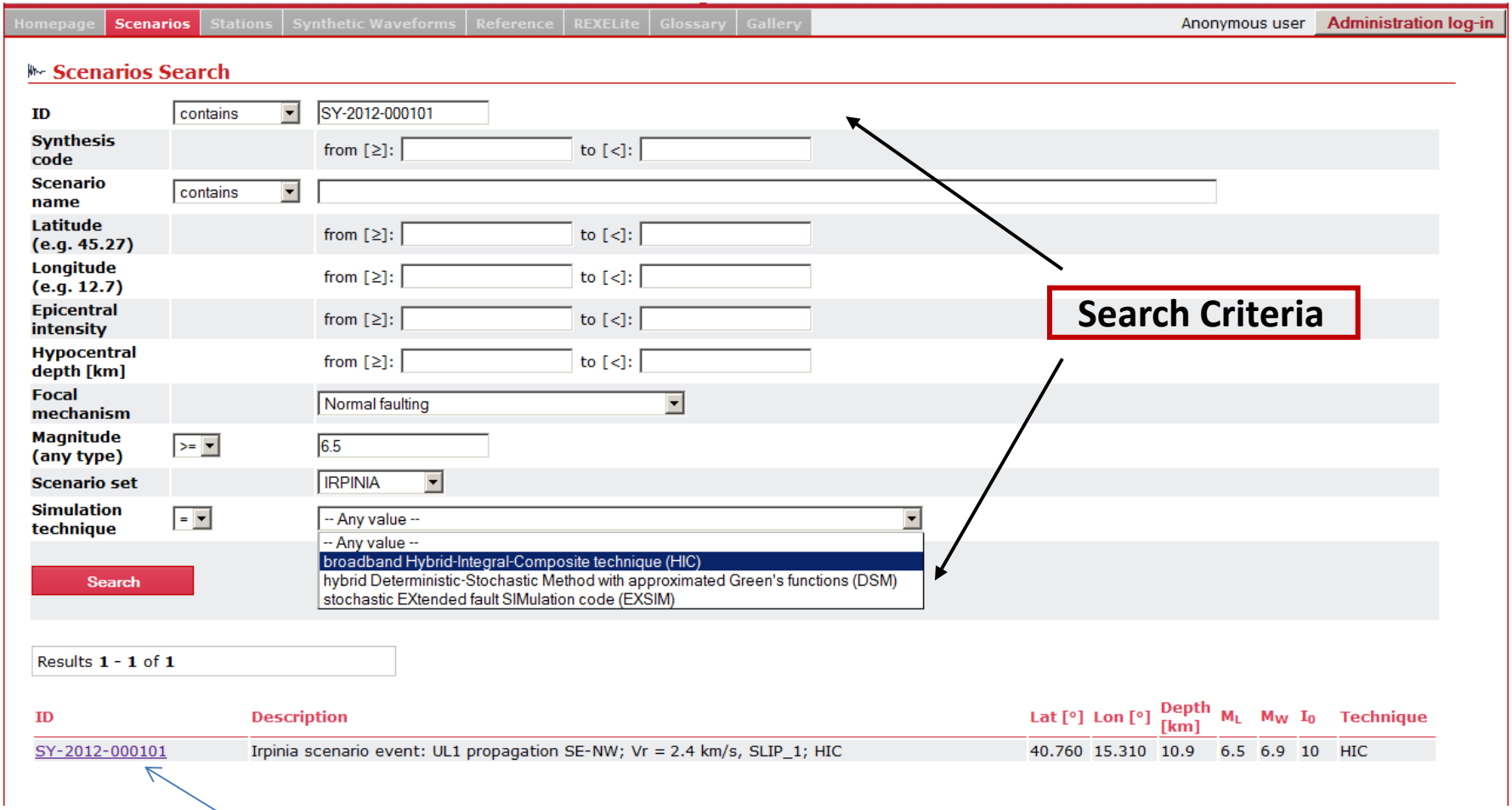
….. the database structure




http://dyna.mi.ingv.it/synthesis/

# EXPLORING SYNTHESIS

*scenarios search*



# SIS

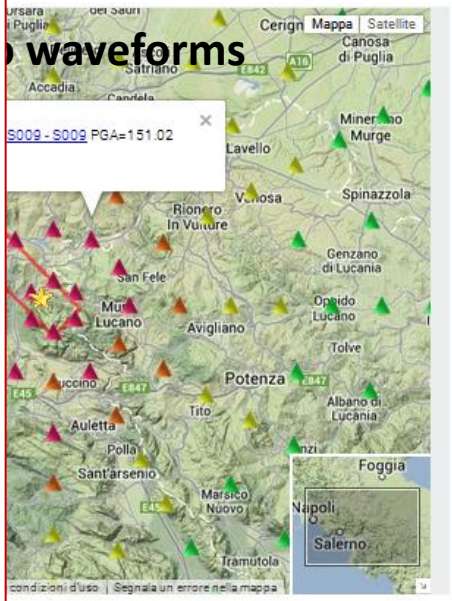
synthesis - Scenario parameters

## Scenario parameters

| Parameter | Value |
|---|---|
| fault length along strike [km] | 35 |
| fault width downdip [km] | 15 |
| top of rupture (can set=0 for surface faulting) | 2.2 |
| latitude of the reference point [degree] | 40.842 |
| longitude of the reference point [degree] | 15.2833 |
| fault strike measured clocwise round from North, with the fault dipping down to the rigth [0 to 360 degree] | 315 |
| fault dip measured down from the Earth surface [0 to 90 degree] | 60 |
| rake angle that define the slip direction [degree] | -90 |
| number of subfaults along strike | 70 |
| number of subfaults along dip | 30 |
| index along strike of the subfault that contains the hypocenter | 5 |
| index downdip of the subfault that contains the hypocenter | 10 |
| moment magnitude of the simulated event | 6.9 |
| seismic moment [N m] | 2e+19 |
| longitude of the nucleation point [decimal degree] | 15.31 |
| latitude of the nucleation point [decimal degree] | 40.76 |
| depth of the nucleation point [km] | 10.9 |
| rupture velocity [km/s] | 2.4 |
| stress drop [bars] | |
| crustal density [g/cm^3] | |
| crustal shear-wave velocity [km/s] | |
| radiation pattern | |
| quality factor of the attenuation model Q(f)=Q0*f*eta | |
| coefficient of the attenuation model Q(f)=Q0*f*eta | |
| kappa factor [s] | 0.03 |
| frequency range [Hz] | 0.1-10 |
| percentage of pulsing area | |
| cross-over frequency [Hz] | 0.5-2.0 |
| number of simulations | |

Anonymous user | Administration log-in

**waveforms**




**eters** **Waveform detail**

| | | | | | | PGD [cm] | Detail |
|---|---|---|---|---|---|---|---|
| VI | | | | | | 31.186 | |
| VI | | | | | | 11.702 | |
| VI | | | | | | 6.659 | |
| VI | S004 | A | 22.800 | 97.956 | 9.064 | 7.387 | |
| VI | S005 | A | 29.300 | 42.220 | 6.251 | 6.721 | |
| VI | S006 | A | 37.400 | 29.316 | 4.821 | 5.425 | |

# EXPLORING SYNTHESIS

*station search*

Istituto Nazionale di Geofisica e Vulcanologia

Synthesis

version 0.1

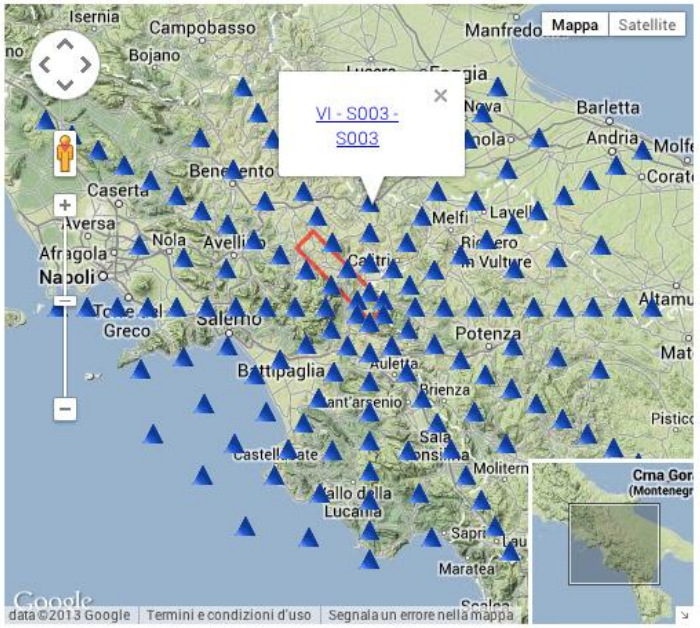
Homepage | Scenarios | **Stations** | Synthetic Waveforms | Reference | REXELite | Glossary | Gallery

Anonymous user | Register or log-in to Synthesis

## Stations search

| | | |
|---|---|---|
| **Network** | | VI |
| **Station Code** | contains | |
| **Scenario set** | contains | IRPINIA |
| **Latitude (e.g. 45.27)** | | from [≥]: to [<]: |
| **Longitude (e.g. 12.7)** | | from [≥]: to [<]: |
| **Nation** | = | -- Any value -- |
| **Region** | contains | |
| **Province** | contains | |
| **Municipality** | contains | |
| **Location** | contains | -- Any value -- |
| **EC8** | | -- Any value -- |
| **Morphology** | | -- Any value -- |
| **Number of Records** | >= | |
| **Export in Google Earth format** | | Export in Google Earth format |

Search




| Network | Stat. Code | Nation | Region | Province | Municipality | Latitude [°] | Longitude [°] | EC8 | Morph. | Rec. | Records |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VI | S001 | Italy | Campania | Province of Salerno | Castelnuovo di Conza | 40.825 | 15.334 | A | Plain | 110 | |
| VI | S002 | Italy | Campania | Province of Avellino | Conza della Campania | 40.915 | 15.334 | A | Plain | 109 | |
| VI | S003 | Italy | Campania | Province of Avellino | Bisaccia | 41.005 | 15.334 | A | Plain | 109 | |
| VI | S004 | Italy | Campania | Province of Avellino | Scampitella | 41.096 | 15.334 | A | Plain | 109 | |

Istituto Nazionale di Geofisica e Vulcanologia

Homepage | Scenarios | Stations | Synth

version 0.1

ration log-in

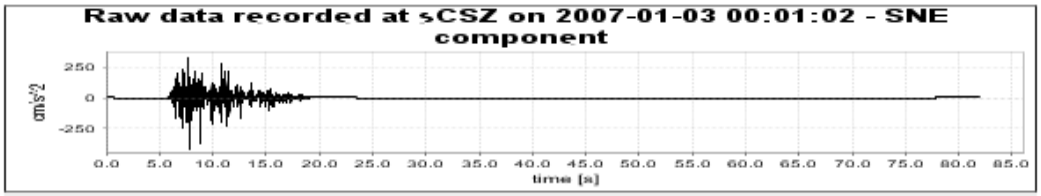
## Waveform

| | |
|---|---|
| **Network** | VC |
| **ID** | SY-20 |
| **Instrument type** | Virtual |
| **Filter type** | BUTTE |
| **Max PGA [cm/s²]** | 452.66 |
| **Max PGV (max)** | 20.089 |
| **Max PGD [cm]** | 4.244 |
| **Arias intensity [cm/s]** | 99.142 |
| **T90 Effective duration [s]** | 6.980 |
| **Housner Int. [cm]** | 23.847 |

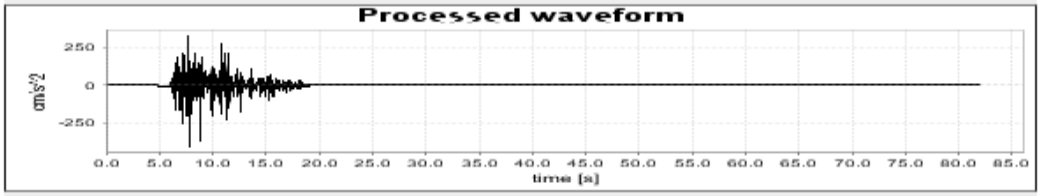
### COMPONENTS

| Orientation | Location |
|---|---|
| East-West SNE | Bedrock |
| North-South SNN | Bedrock |
| Vertical SNZ | Bedrock |

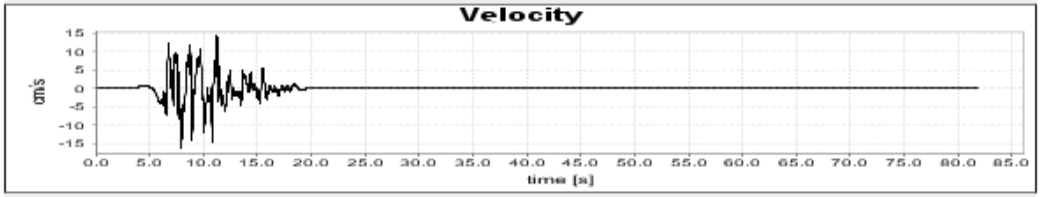
### Waveform Component's Plot



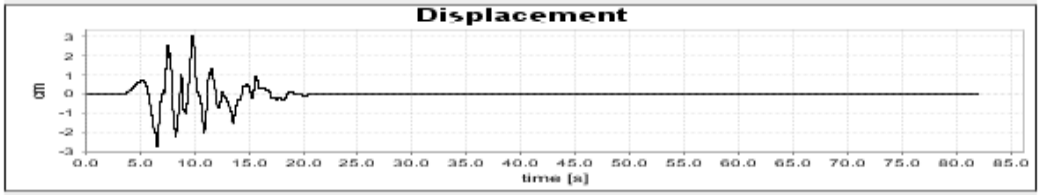

About... Time: 0.000000 Value: 0.000000



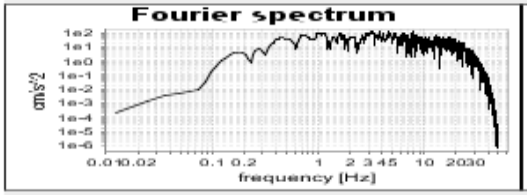

About... Time: 0.000000 Value: 0.000000

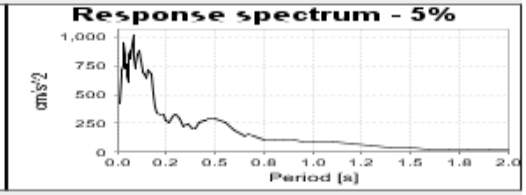



About... Time: 0.000000 Value: 0.000000




About... Time: 0.000000 Value: 0.000000




About... Frequency: 0.000000 Value: About... Period: 0.000000 Value: 0.000000

.890

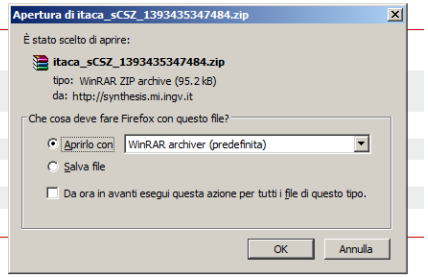
Plots

# Processing...

PLEASE WAIT.

Synthesis is processing your request...

| | |
|---|---|
| **Export Name** | sCSZ_1393435347484 |
| **Total Files** | 6 |
| **Processed Files** | |
| **Started At** | 2014-02-26 18:22:27 |




**Export in Zip file**

**What to export**

| | |
|---|---|
| **Raw data** | ☑ |
| **Processed data** | ☑ |

**What to export - physical quantities**

| | |
|---|---|
| **Acceleration** | ☑ |
| **Velocity** | ☐ |
| **Displacement** | ☐ |

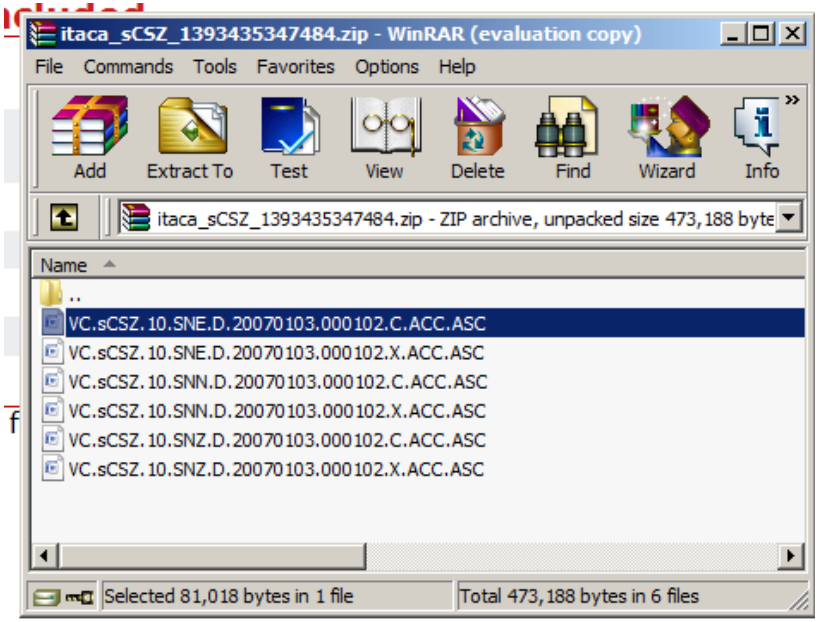
**What to export - spectra**

| | |
|---|---|
| **Fourier spectra** | ☐ |
| **Response spectra** | ☐ |

**How to export - format**

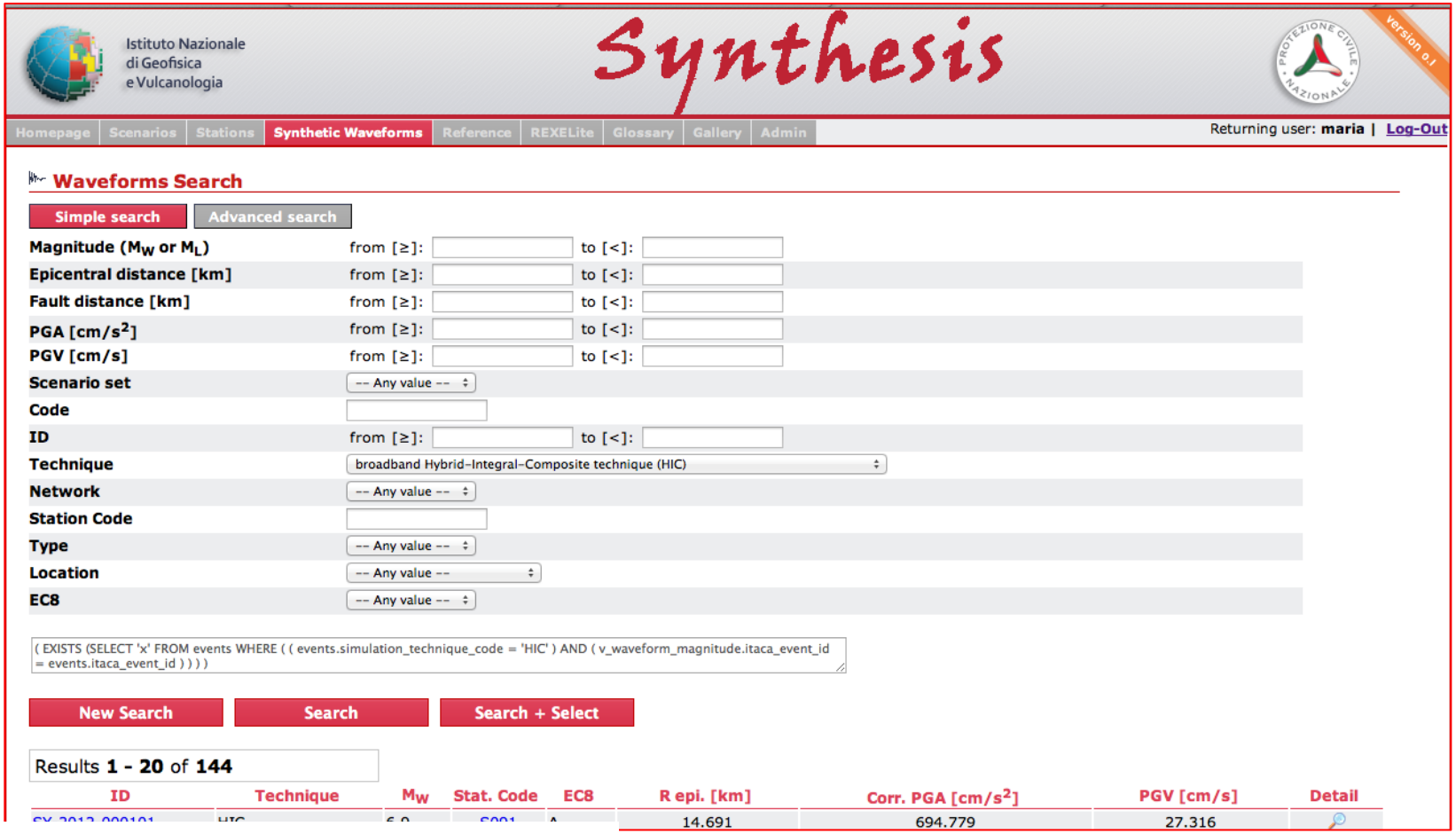
| | |
|---|---|
| **Ascii Synthesis** | ☑ |
| **MiniSEED/SEED** | ☐ |
| **SAC** | ☐ |

Export selected | Search Again



# EXPLORING SINTESIS

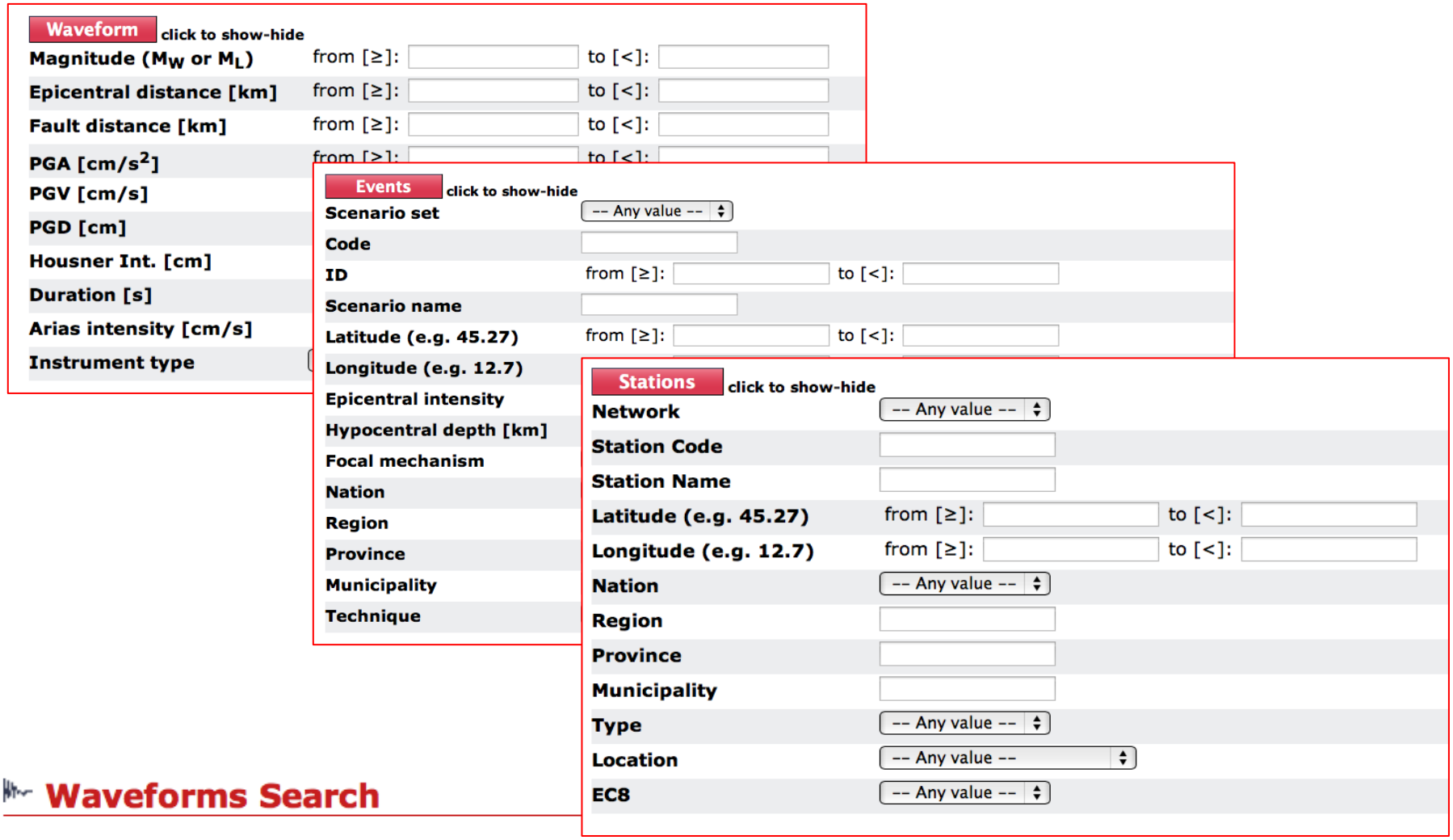
*synthetics waveforms search*




Waveforms Search
Simple search
Advanced search

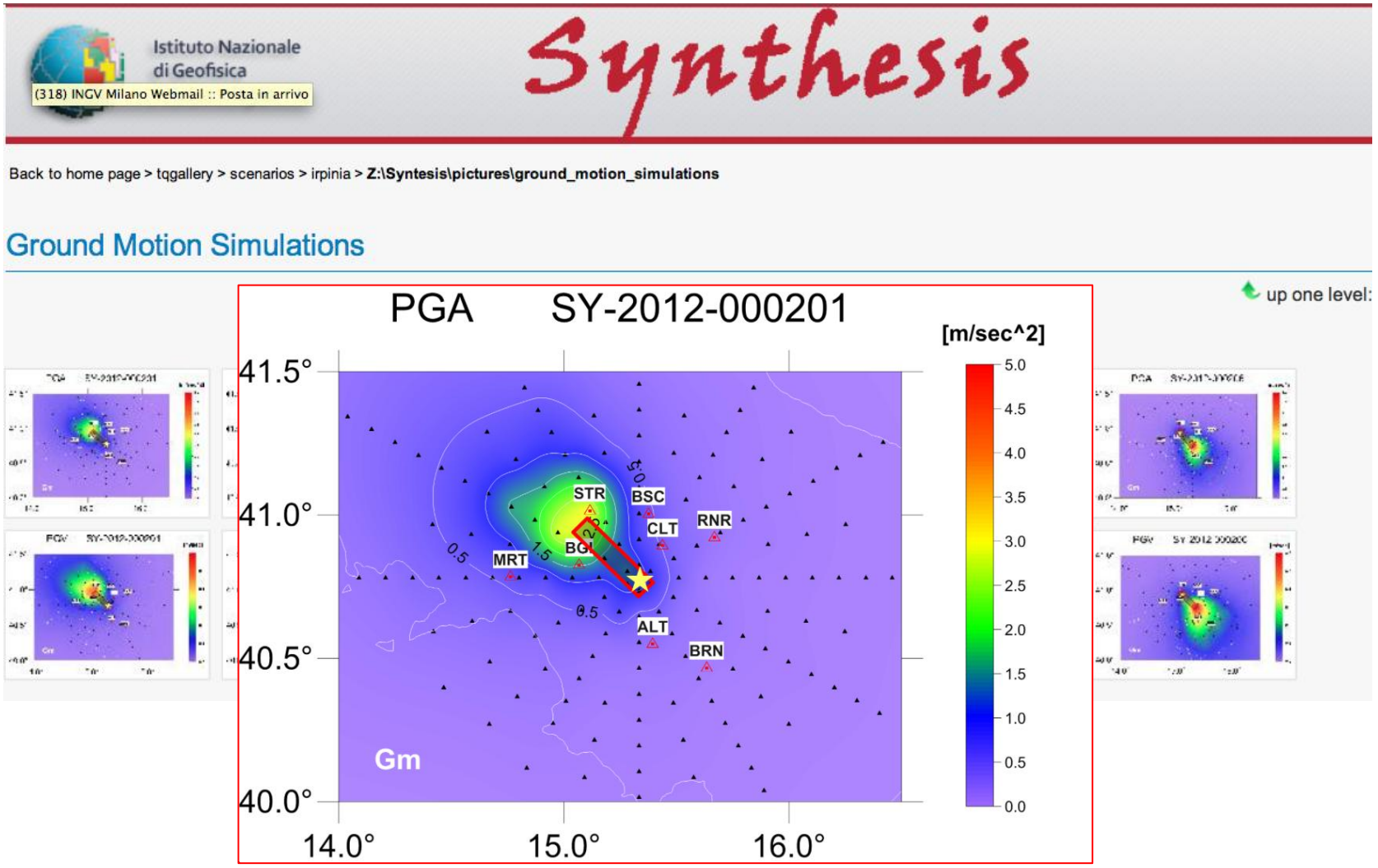
# EXPLORING SINTESIS

*synthetics waveforms search*



# EXPLORING SYNTHESIS

*scenario gallery*



# DATABASE POPULATION

IRPINIA FAULT

*Some numbers*

**3** simulation techniques: HIC, EXSIM, DSM

We include **54** scenarios for each technique

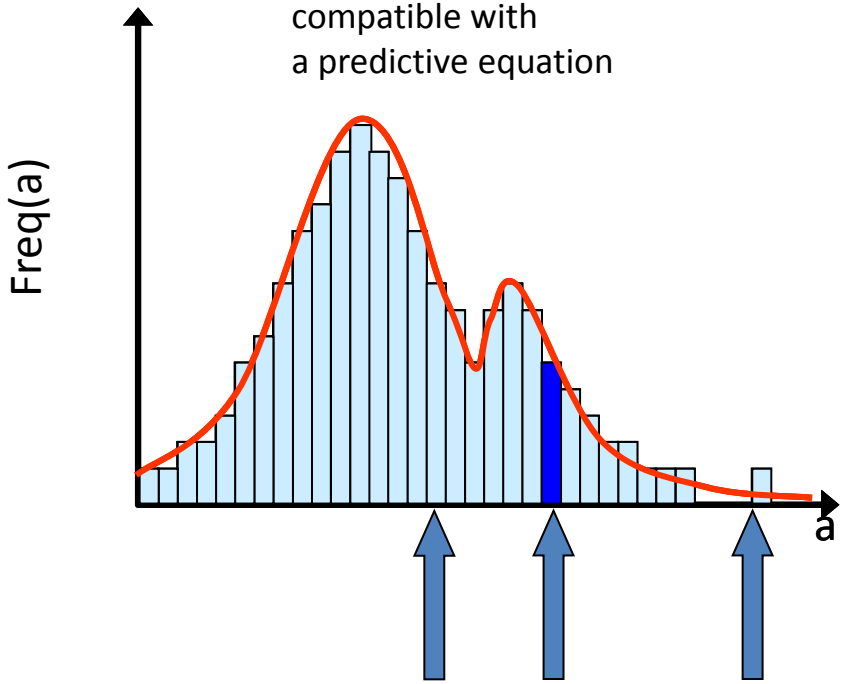
**6** nucleation points x **3** rupture velocities x **3**slip distributions

**144** virtual observers

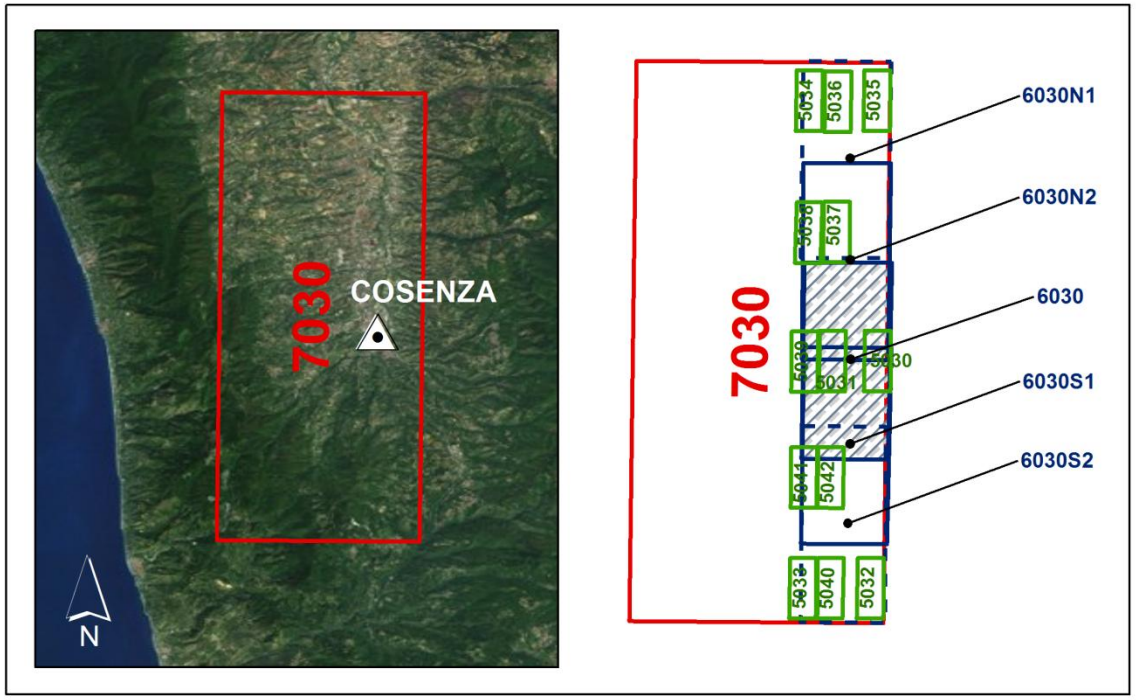
**24084 waveforms!!!!!**

# NEW STRATEGY

- Selection of synthetic waveforms based on specific features of the ground motion parameters



# COSENZAEXAMPLE

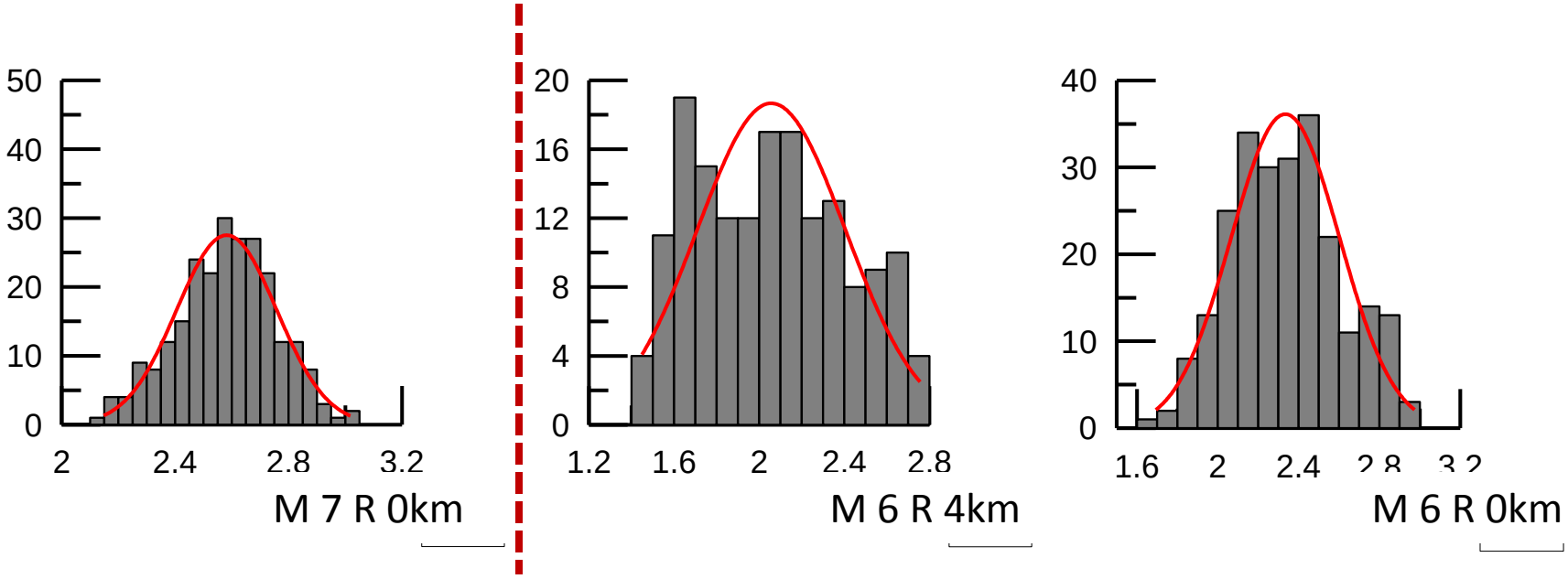



| | Length (km) | Width (km) | Average displacement (m) |
|---|---|---|---|
| M7 | 37 | 26 | 1.4 |
| M6 | 13 | 9 | 0.4 |
| M5 | 4 | 2.7 | 0.13 |

- Cosenza case study:

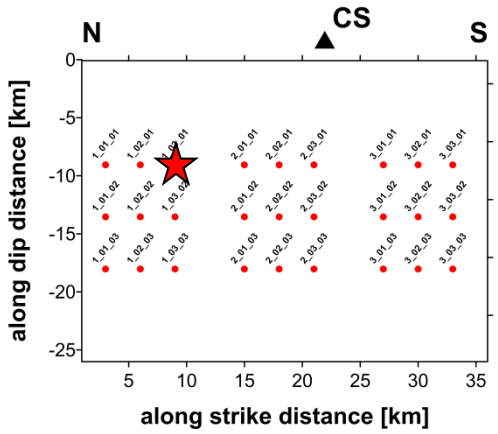
  Three seismic sources were simulated, able to generate events of magnitude M equal to 5.0, 6.0, e 7.0

| M | #Nucleation Point | #rupture velocity | #k | #stress drop | #modeled fault | #simulation |
|---|---|---|---|---|---|---|
| **7.0** | 27 | 3 | 3 | 1 | 1 | 243 |
| **6.0** | 9 | 3 | 3 | 1 | 5 | 405 |
| **5.0** | 1 | 1 | 3 | 4 | 13 | 156 |



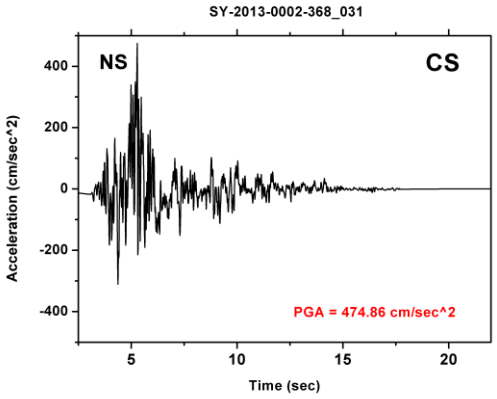
**SY-2013-0002-368_031**
***M7.0***

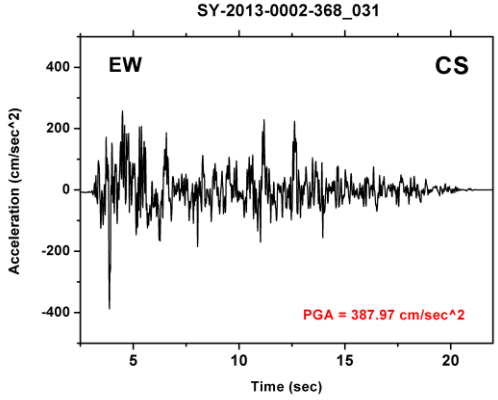
| | |
|---|---|
| ***nucleation point (lon,lat)*** | 16.236,39.405 [degree] |
| ***focal depth*** | 8.8 [km] |
| ***stress drop*** | 30 [bars] |
| ***rupture velocity*** | 2.9 [km/sec] |
| ***slip distribution*** | omogeneous |
| ***radiation pattern*** | 0.63 |
| ***k factor*** | 0.025 [sec] |

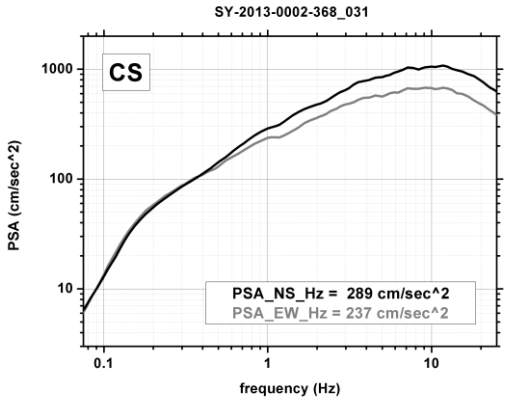



## *ID_source 7030 (M7.0)*

50° percentile PGA

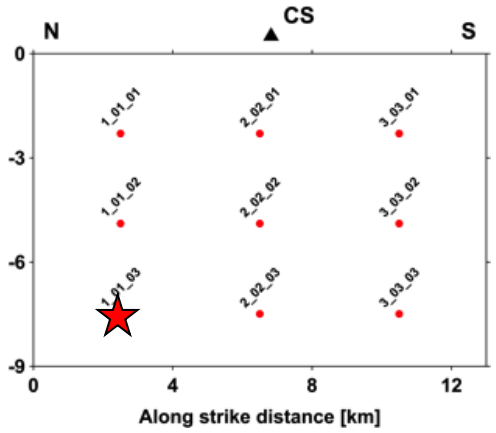


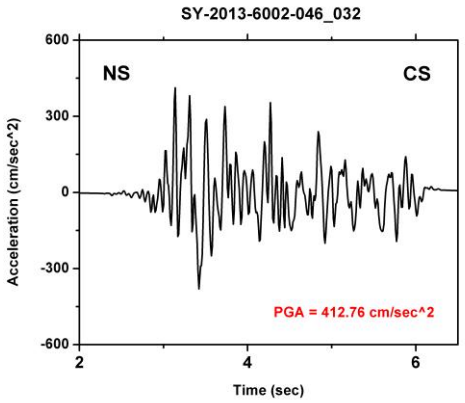
**SY-2013-6002-046_021**
***M6.0***

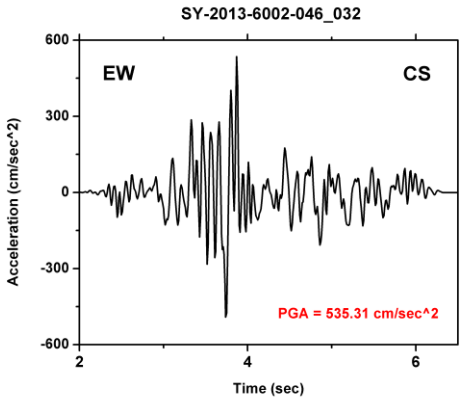
| | |
|---|---|
| ***nucleation point (lon,lat)*** | 16.247,39.337 [degree] |
| ***focal depth*** | 7.5 [km] |
| ***stress drop*** | 50 [bars] |
| ***rupture velocity*** | 2.7 [km/sec] |
| ***slip distribution*** | omogeneous |
| ***radiation pattern*** | 0.62 |
| ***k factor*** | 0.020 [sec] |

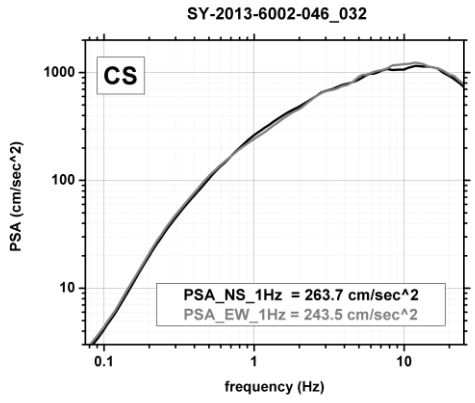



## *ID_source 6030 (M6.0)*

Massimo Valore
PSA 1 Hz



| criteri | ID_source | STA | Mw | PGA [cm/s^2] | PGV [cm/s] | PGD [cm] | PSA_0_5_Hz [cm/s^2] | PSA_1_Hz [cm/s^2] | PSA_3_3_Hz [cm/s^2] | AI [cm/s] | He [cm] | Dur [s] | ID_scenario |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16% PGA | 7030 | sCSZ | 7 | 2.5484 | 1.5309 | 1.5845 | 2.1247 | 2.4697 | 2.7947 | 1.7862 | 1.989 | 0.9427 | SY-2013-0002-315_02301035 |
| 50% PGA | 7030 | sCSZ | 7 | 2.6979 | 1.6334 | 1.7434 | 2.2202 | 2.4861 | 2.907 | 2.0568 | 2.059 | 0.9024 | SY-2013-0002-098_0120103 |
| 84% PGA | 7030 | sCSZ | 7 | 2.8162 | 1.6979 | 2.0755 | 2.3163 | 2.6331 | 2.9844 | 2.3166 | 2.1717 | 0.9488 | SY-2013-0002-445_0330103 |
| MAX PGA | 7030 | sCSZ | 7 | 2.9048 | 1.755 | 2.3944 | 2.3488 | 2.6465 | 3.0183 | 2.4198 | 2.2052 | 1.0171 | SY-2013-0002-283_0230101 |
| MIN PGA | 7030 | sCSZ | 7 | 2.3843 | 1.4061 | 1.5521 | 2.056 | 2.3213 | 2.6213 | 1.6159 | 1.8829 | 1.0867 | SY-2013-0002-015_0110102 |
| 16% PGV | 7030 | sCSZ | 7 | 2.5741 | 1.4844 | 1.5719 | 2.1011 | 2.3952 | 2.764 | 1.8499 | 1.9489 | 1.0342 | SY-2013-0002-176_0210101 |
| 50% PGV | 7030 | sCSZ | 7 | 2.7244 | 1.6397 | 1.9079 | 2.2807 | 2.5141 | 2.8722 | 2.1589 | 2.1006 | 1.0213 | SY-2013-0002-121_0130102 |
| 84% PGV | 7030 | sCSZ | 7 | 2.71 | 1.7288 | 2.2732 | 2.3619 | 2.6469 | 2.917 | 2.161 | 2.1909 | 0.9284 | SY-2013-0002-423_0320102 |
| MAX PGV | 7030 | sCSZ | 7 | 2.8541 | 1.7629 | 1.8565 | 2.3677 | 2.6781 | 3.0504 | 2.3802 | 2.2196 | 0.8498 | SY-2013-0002-259_0220103 |
| MIN PGV | 7030 | sCSZ | 7 | 2.3843 | 1.4061 | 1.5521 | 2.056 | 2.3213 | 2.6213 | 1.6159 | 1.8829 | 1.0867 | SY-2013-0002-015_0110102 |
| 16% PGD | 7030 | sCSZ | 7 | 2.5484 | 1.5309 | 1.5845 | 2.1247 | 2.4697 | 2.7947 | 1.7862 | 1.989 | 0.9427 | SY-2013-0002-315_0230103 |
| 50% PGD | 7030 | sCSZ | 7 | 2.8066 | 1.7528 | 1.8559 | 2.3642 | 2.6714 | 3.0292 | 2.2988 | 2.2117 | 0.8495 | SY-2013-0002-260_0220103 |
| 84% PGD | 7030 | sCSZ | 7 | 2.7911 | 1.6966 | 2.3322 | 2.2966 | 2.5884 | 2.9468 | 2.261 | 2.1408 | 0.963 | SY-2013-0002-259_0220102 |
| MAX PGD | 7030 | sCSZ | 7 | 2.8477 | 1.7374 | 2.4054 | 2.3827 | 2.6288 | 2.9997 | 2.4406 | 2.1991 | 1.0234 | SY-2013-0002-391_0320101 |
| MIN PGD | 7030 | sCSZ | 7 | 2.4289 | 1.4115 | 1.4879 | 2.0753 | 2.311 | 2.6417 | 1.6007 | 1.8917 | 1.0568 | SY-2013-0002-015_0110103 |
| 16% PSA_0_5 | 7030 | sCSZ | 7 | 2.5741 | 1.4844 | 1.5719 | 2.1011 | 2.3952 | 2.764 | 1.8499 | 1.9489 | 1.0342 | SY-2013-0002-176_0210101 |
| 50% PSA_0_5 | 7030 | sCSZ | 7 | 2.6715 | 1.6313 | 1.9074 | 2.2772 | 2.5075 | 2.8517 | 2.0765 | 2.092 | 1.021 | SY-2013-0002-122_0130102 |
| 84% PSA_0_5 | 7030 | sCSZ | 7 | 2.8548 | 1.7444 | 2.3938 | 2.3453 | 2.6398 | 2.9972 | 2.3385 | 2.197 | 1.0174 | SY-2013-0002-284_0230101 |
| MAX PSA_0_5 | 7030 | sCSZ | 7 | 2.8477 | 1.7374 | 2.4054 | 2.3827 | 2.6288 | 2.9997 | 2.4406 | 2.1991 | 1.0234 | SY-2013-0002-391_0320101 |
| MIN PSA_0_5 | 7030 | sCSZ | 7 | 2.3843 | 1.4061 | 1.5521 | 2.056 | 2.3213 | 2.6213 | 1.6159 | 1.8829 | 1.0867 | SY-2013-0002-015_0110102 |
| 16% PSA_1_0 | 7030 | sCSZ | 7 | 2.4879 | 1.4673 | 1.5707 | 2.0942 | 2.3817 | 2.7233 | 1.7171 | 1.9358 | 1.0336 | SY-2013-0002-177_0210101 |
| 50% PSA_1_0 | 7030 | sCSZ | 7 | 2.6715 | 1.6313 | 1.9074 | 2.2772 | 2.5075 | 2.8517 | 2.0765 | 2.092 | 1.021 | SY-2013-0002-122_0130102 |
| 84% PSA_1_0 | 7030 | sCSZ | 7 | 2.7976 | 1.7291 | 2.4054 | 2.3793 | 2.6221 | 2.9787 | 2.358 | 2.1923 | 1.0237 | SY-2013-0002-392_0320101 |
| MAX PSA_1_0 | 7030 | sCSZ | 7 | 2.8541 | 1.7629 | 1.8565 | 2.6781 | 2.6781 | 3.0504 | 2.3802 | 2.2196 | 0.8498 | SY-2013-0002-259_0220103 |
| MIN PSA_1_0 | 7030 | sCSZ | 7 | 2.4289 | 1.4115 | 1.4879 | 2.311 | 2.311 | 2.6417 | 1.6007 | 1.8917 | 1.0568 | SY-2013-0002-015_0110103 |
| 16% PSA_3_3 | 7030 | sCSZ | 7 | 2.5776 | 1.4876 | 1.5499 | 2.1031 | 2.3661 | 2.7354 | 1.8314 | 1.9355 | 0.9704 | SY-2013-0002-337_0310102 |
| 50% PSA_3_3 | 7030 | sCSZ | 7 | 2.7244 | 1.6397 | 1.9079 | 2.2807 | 2.5141 | 2.8722 | 2.1589 | 2.1006 | 1.0213 | SY-2013-0002-121_0130102 |
| 84% PSA_3_3 | 7030 | sCSZ | 7 | 2.8596 | 1.7396 | 2.3934 | 2.3247 | 2.6055 | 2.9717 | 2.3443 | 2.1693 | 1.0274 | SY-2013-0002-229_0220101 |
| MAX PSA_3_3 | 7030 | sCSZ | 7 | 2.8541 | 1.7629 | 1.8565 | 2.6781 | 2.6781 | 3.0504 | 2.3802 | 2.2196 | 0.8498 | SY-2013-0002-259_0220103 |
| MIN PSA_3_3 | 7030 | sCSZ | 7 | 2.3843 | 1.4061 | 1.5521 | 2.3213 | 2.3213 | 2.6213 | 1.6159 | 1.8829 | 1.0867 | SY-2013-0002-015_0110102 |
| 16% AI | 7030 | sCSZ | 7 | 2.5484 | 1.5309 | 1.5845 | 2.1247 | 2.4697 | 2.7947 | 1.7862 | 1.989 | 0.9427 | SY-2013-0002-315_0230103 |
| 50% AI | 7030 | sCSZ | 7 | 2.724 | 1.6038 | 1.6084 | 2.2155 | 2.4898 | 2.8497 | 2.0568 | 2.0548 | 1.0036 | SY-2013-0002-337_0310101 |
| 84% AI | 7030 | sCSZ | 7 | 2.8066 | 1.7528 | 1.8559 | 2.3642 | 2.6714 | 3.0292 | 2.2988 | 2.2117 | 0.8495 | SY-2013-0002-260_0220103 |
| MAX AI | 7030 | sCSZ | 7 | 2.8477 | 1.7374 | 2.4054 | 2.6288 | 2.6288 | 2.9997 | 2.4406 | 2.1991 | 1.0234 | SY-2013-0002-391_0320101 |
| MIN AI | 7030 | sCSZ | 7 | 2.4289 | 1.4115 | 1.4879 | 2.311 | 2.311 | 2.6417 | 1.6007 | 1.8917 | 1.0568 | SY-2013-0002-015_0110103 |
| 16% He | 7030 | sCSZ | 7 | 2.4879 | 1.4673 | 1.5707 | 2.0942 | 2.3817 | 2.7233 | 1.7171 | 1.9358 | 1.0336 | SY-2013-0002-177_0210101 |
| 50% He | 7030 | sCSZ | 7 | 2.6715 | 1.6313 | 1.9074 | 2.2772 | 2.5075 | 2.8517 | 2.0765 | 2.092 | 1.021 | SY-2013-0002-122_0130102 |
| 84% He | 7030 | sCSZ | 7 | 2.8856 | 1.7353 | 1.8694 | 2.3304 | 2.5901 | 3.0183 | 2.3233 | 2.176 | 0.8192 | SY-2013-0002-421_0320103 |
| MAX He | 7030 | sCSZ | 7 | 2.8541 | 1.7629 | 1.8565 | 2.6781 | 2.6781 | 3.0504 | 2.3802 | 2.2196 | 0.8498 | SY-2013-0002-259_0220103 |
| 16% Dur | 7030 | sCSZ | 7 | 2.71 | 1.7288 | 2.2732 | 2.3619 | 2.6469 | 2.917 | 2.161 | 2.1909 | 0.9284 | SY-2013-0002-423_0320102 |
| 50% Dur | 7030 | sCSZ | 7 | 2.5822 | 1.5182 | 1.7041 | 2.1741 | 2.4003 | 2.7764 | 1.8855 | 1.9915 | 0.9929 | SY-2013-0002-122_0130103 |
| 84% Dur | 7030 | sCSZ | 7 | 2.6244 | 1.7019 | 2.3702 | 2.3438 | 2.5791 | 2.8716 | 2.151 | 2.1528 | 1.0484 | SY-2013-0002-069_0120101 |
| MAX Dur | 7030 | sCSZ | 7 | 2.4667 | 1.5054 | 1.6273 | 2.4165 | 2.4165 | 2.7024 | 1.7705 | 1.9685 | 1.1022 | SY-2013-0002-015_0110101 |
| MIN Dur | 7030 | sCSZ | 7 | 2.8856 | 1.7353 | 1.8694 | 2.5901 | 2.5901 | 3.0183 | 2.3233 | 2.176 | 0.8192 | SY-2013-0002-421_0320103 |

## Cosenza scenarios

1 simulation technique: DSM

We simulate 648 scenarios (M 7 and M6), but we include

**55 waveforms!!!!!**

# Proposal

For each scenarios-park

- To establish selection criteria to include synthetic seismograms based on the statistical distribution of the ground motion parameters (i.e. mean, median, percentiles, etc.); Max 5 – 10 synthetics for each observer;

- To populate the database with strong motion parameters for all scenarios

- To reduce the number of virtual observers

- To provide all synthetic dataset on demand

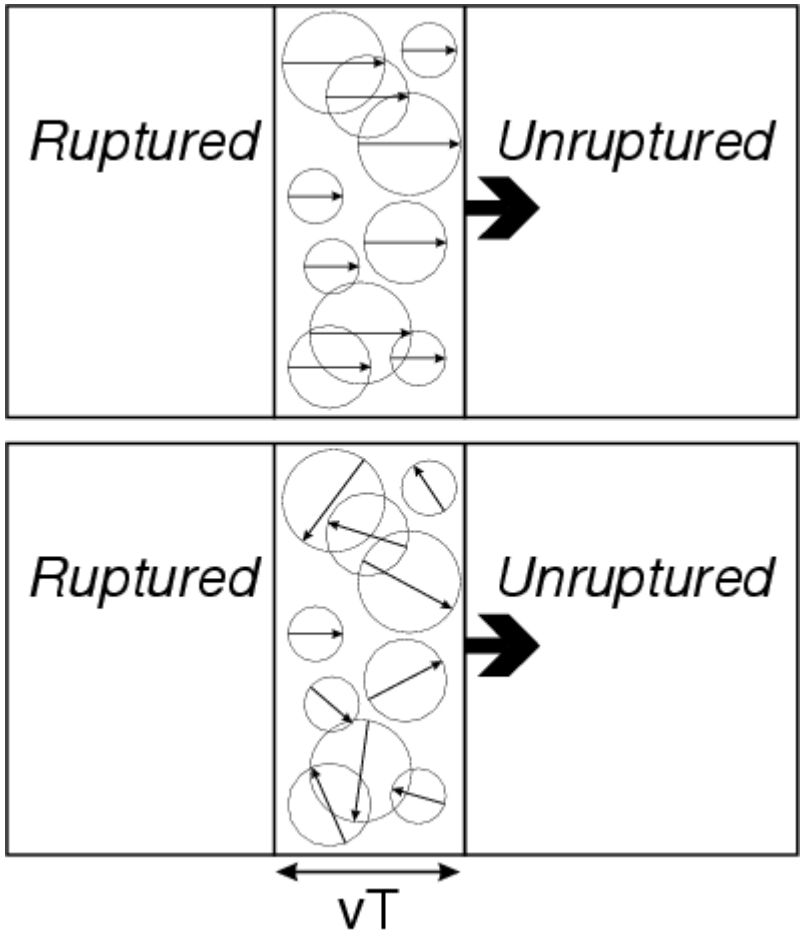
# Generator of slip rates

# Source model

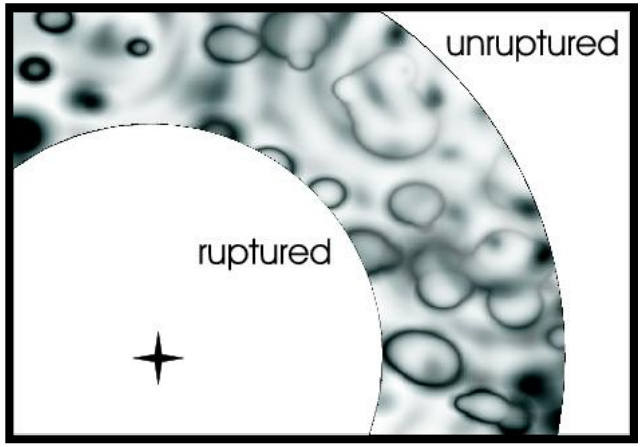
**Basic idea**

Gallovič & Brokešová, 2007

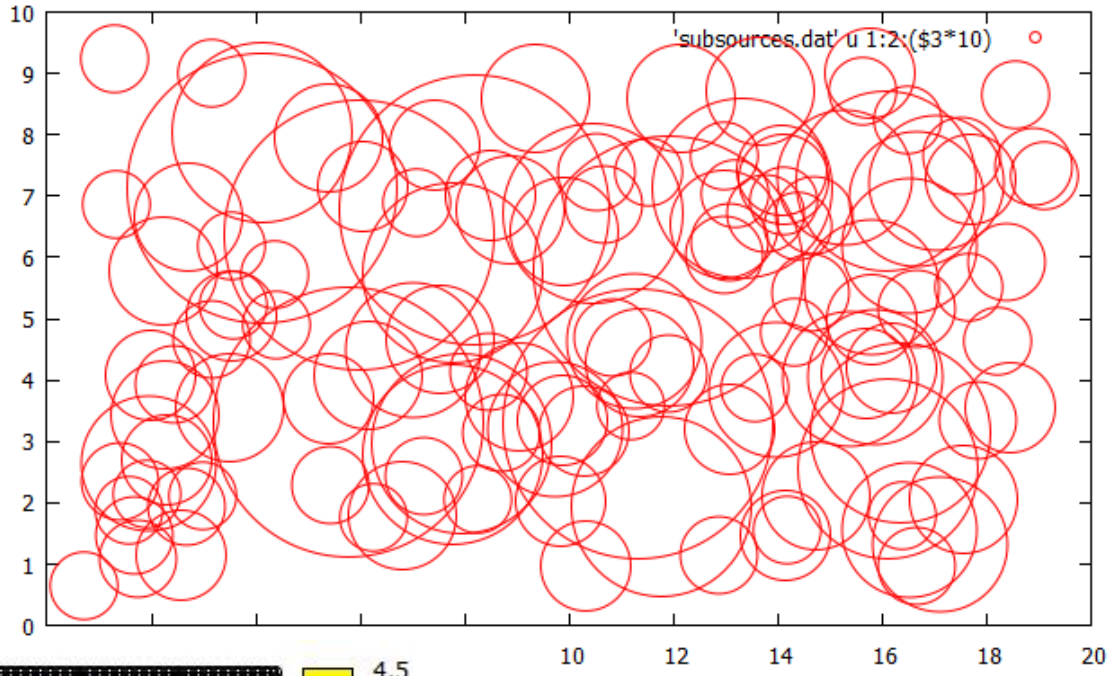
- The earthquake source is coherent at low frequencies (short wavelengths), while incoherent at high frequencies (long wavelengths)

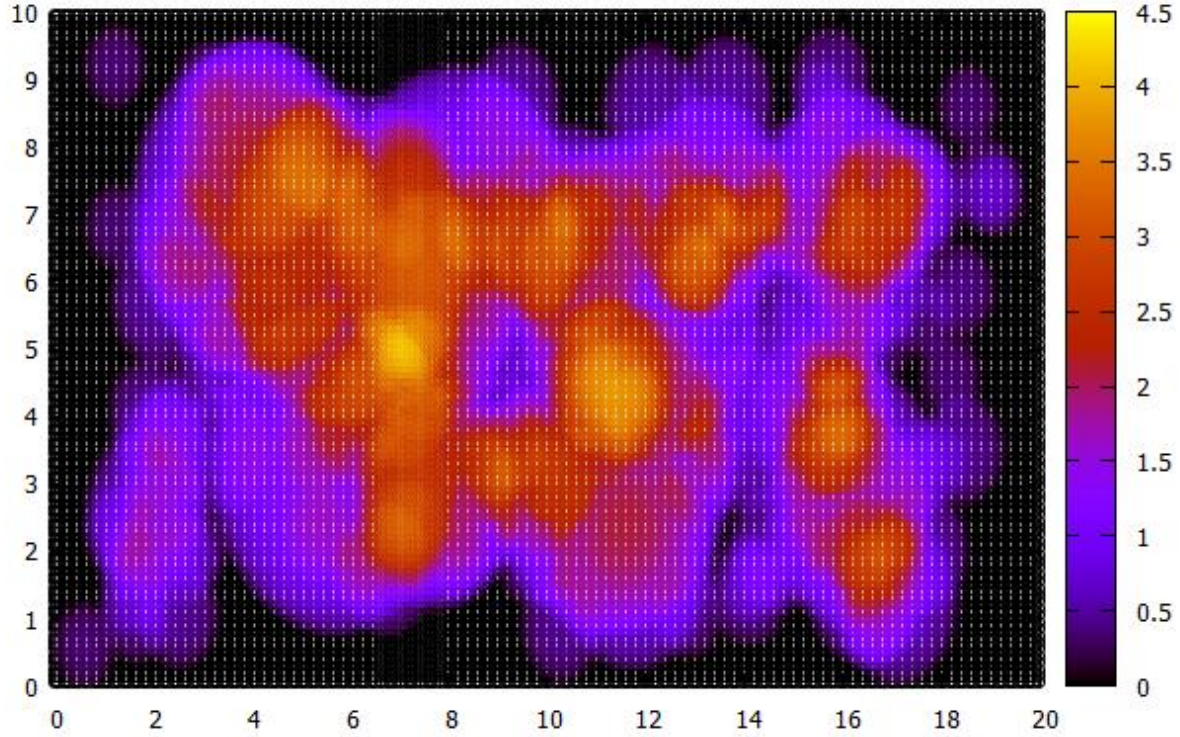



Such a coherent model would overpredict the high-frequency directivity effect!



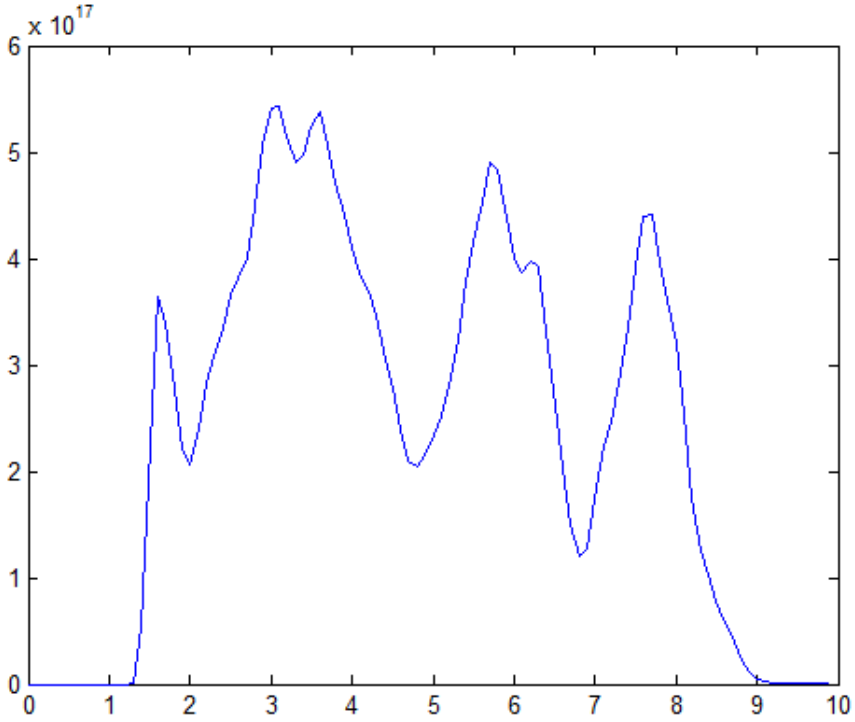
# Subsource distribution and slip

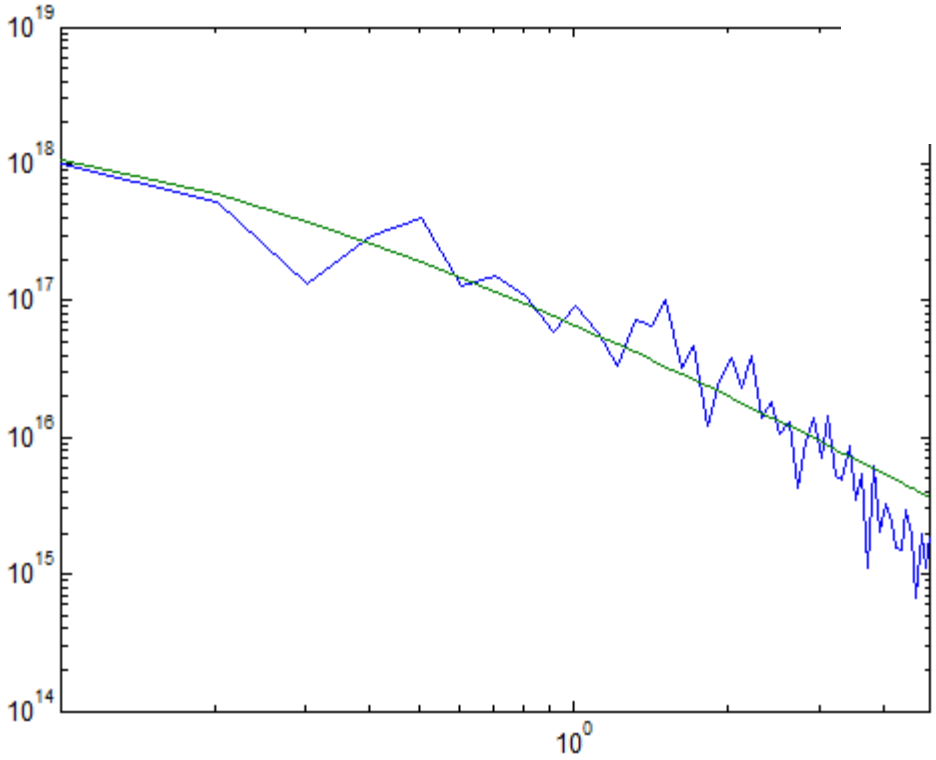


# Moment rate
# a source spectrum

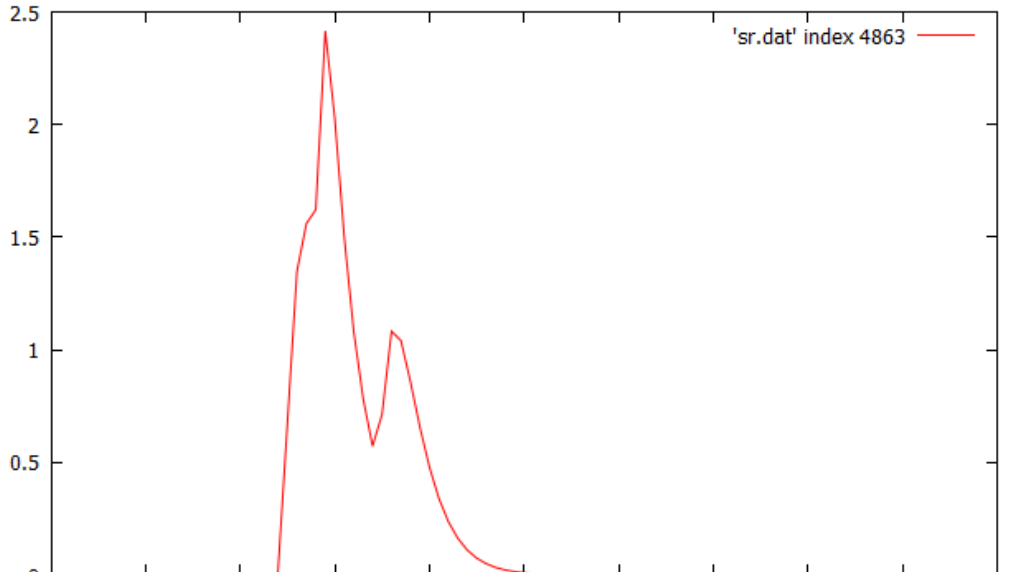
L0 = 0.2L

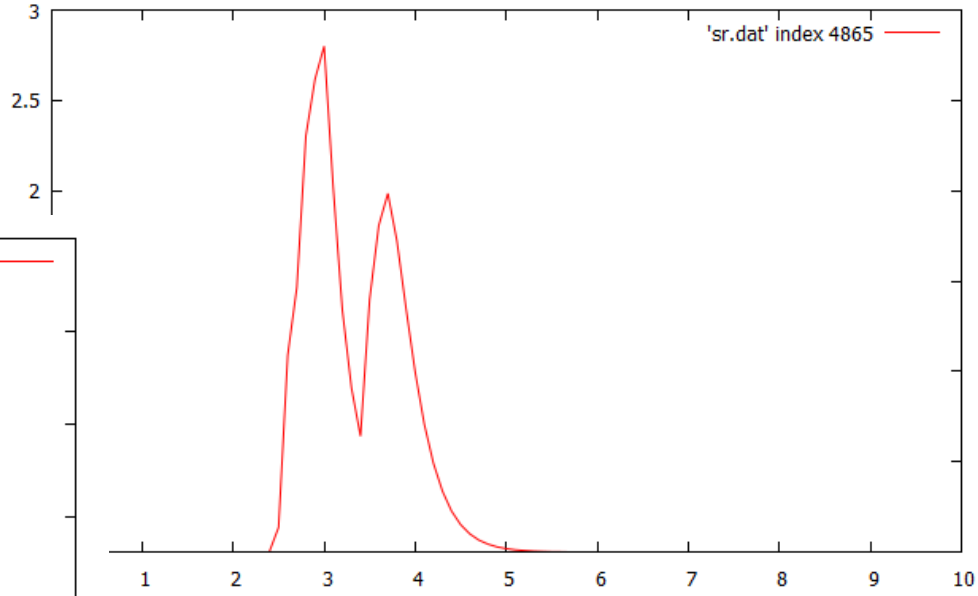


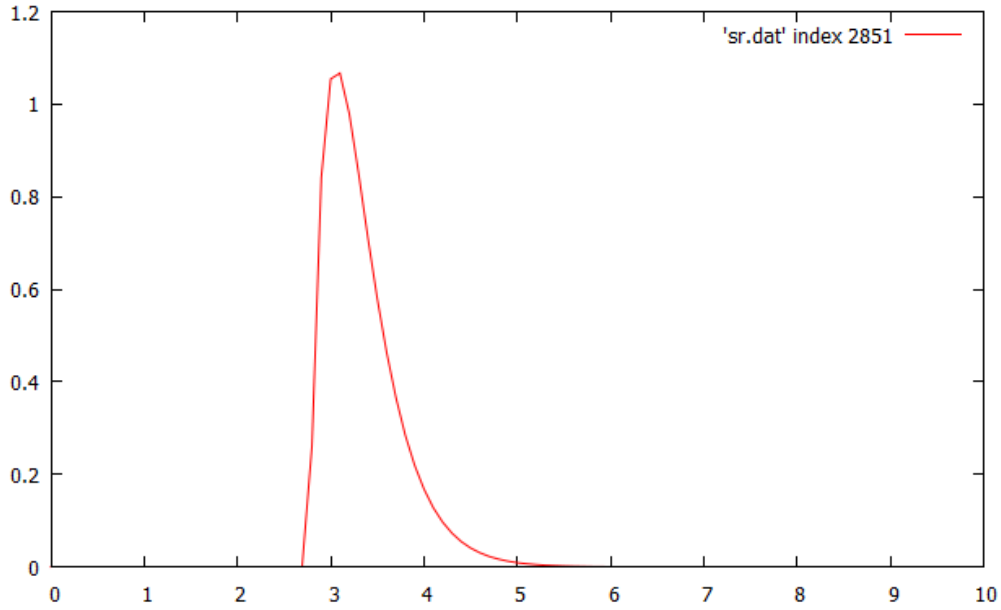



# Examples of slip rates

L0 = 0.2L

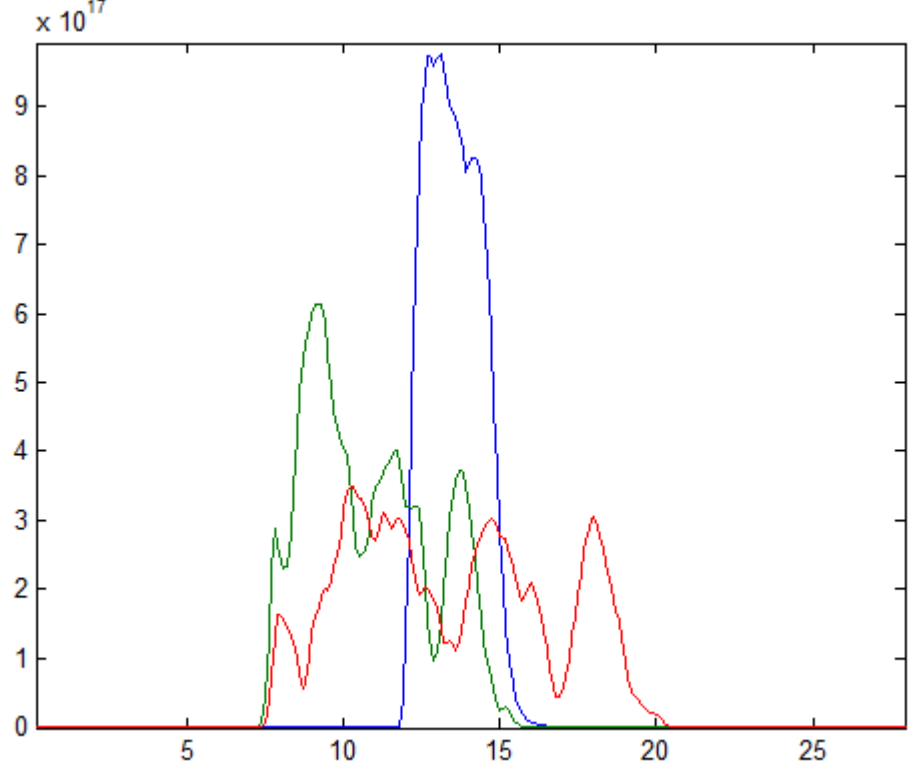


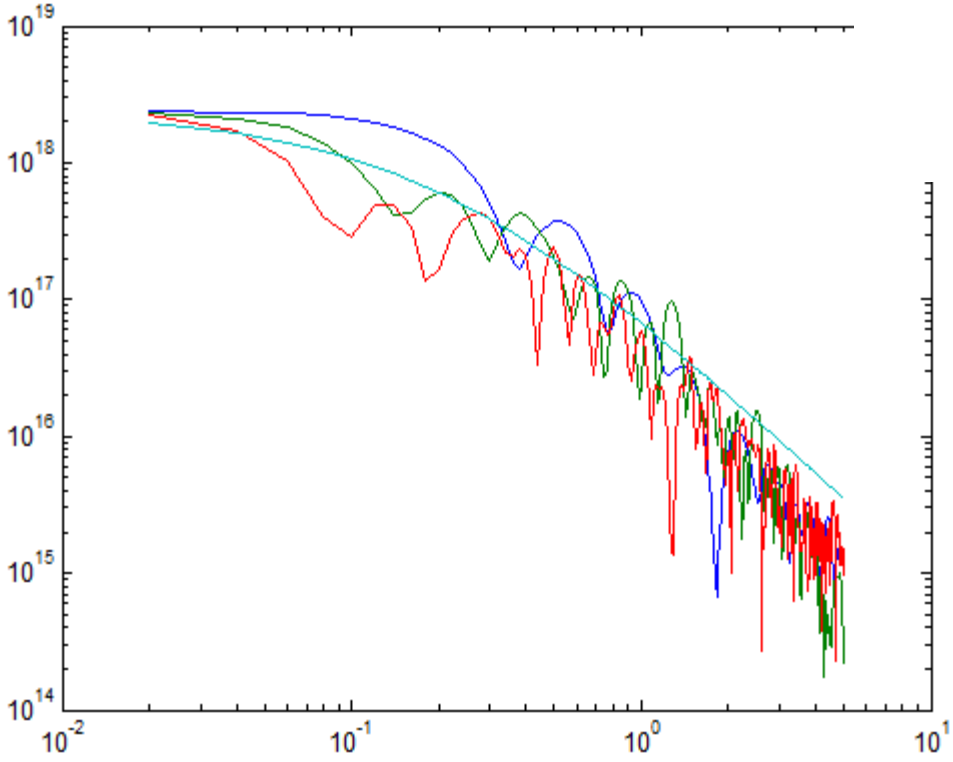



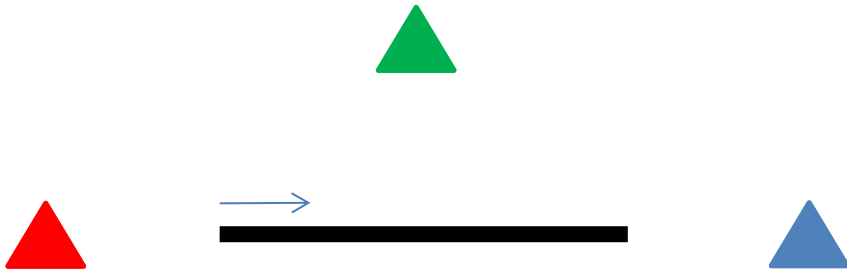



# Seismograms and spectra

L0 = 0.2L

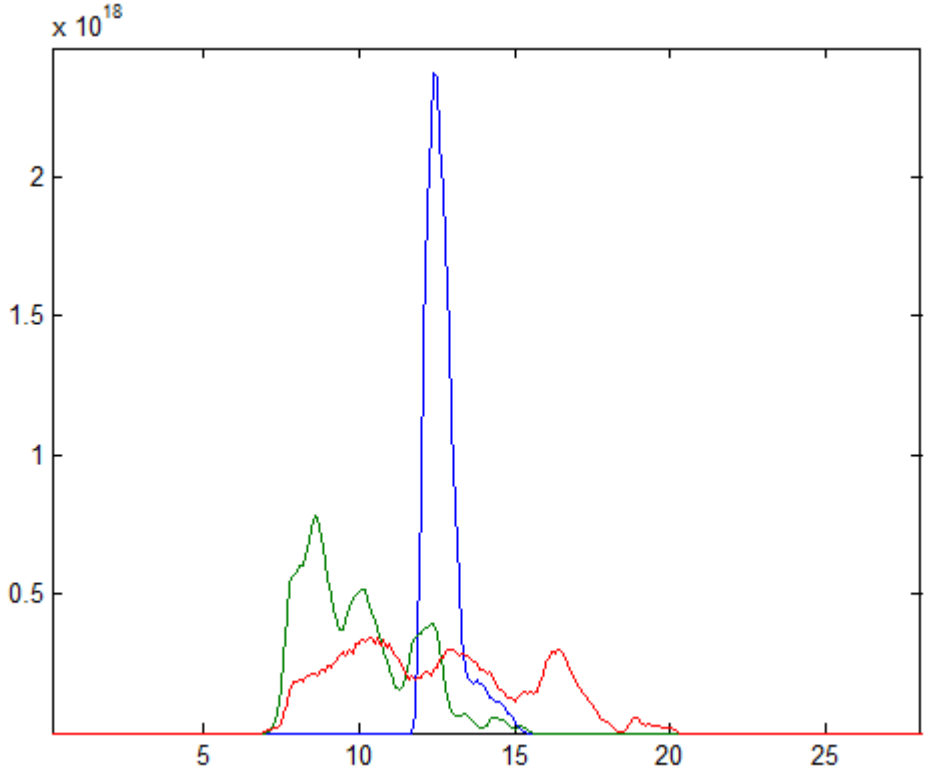


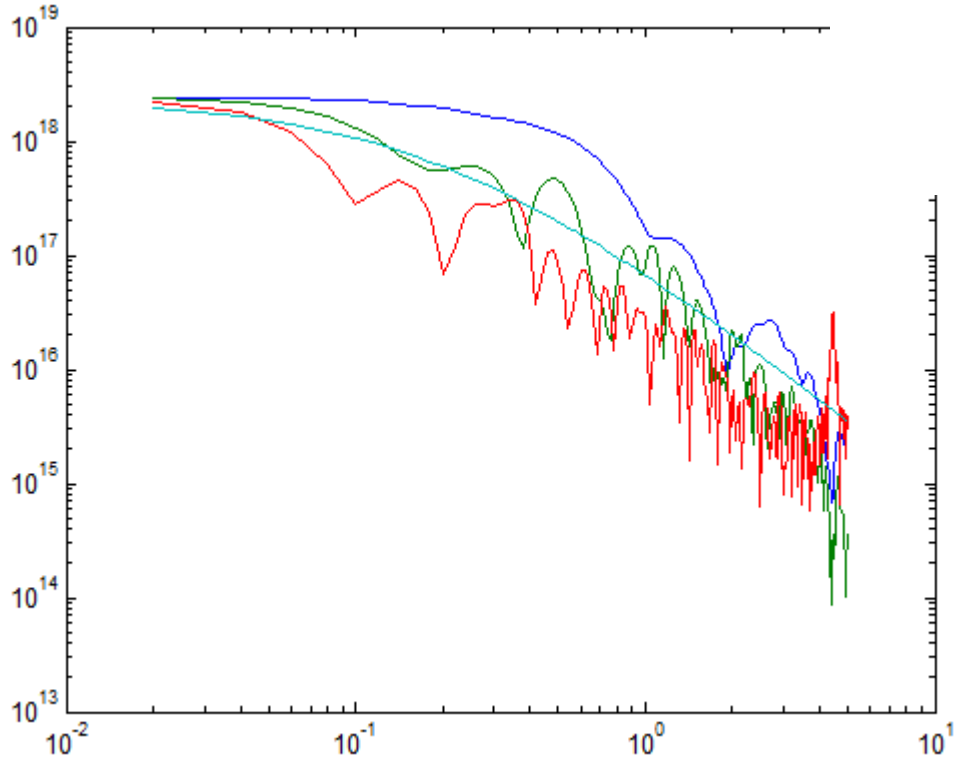



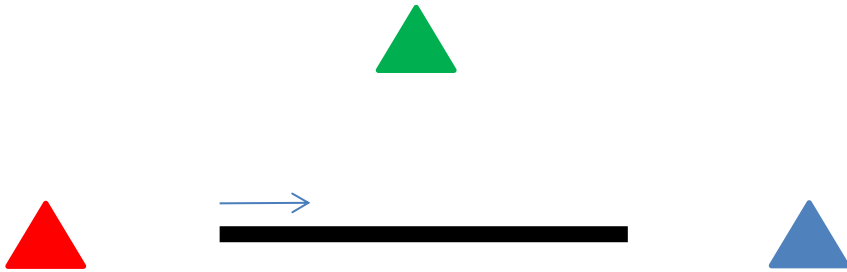



# Seismograms and spectra

L0 = 0.05L



# Drawbacks of the present version

- Constant rupture velocity over the fault
- Does not estimate/correct stress drop
- Rupture on small-scale subsources starts from the middle (not from a random point)

# References


- Bernard, P., Herrero, A., 1994. Slip heterogeneity, body-wave spectra, and directivity of earthquake ruptures. Ann. Geofis. XXXVII, 1679–1690.
- Bernard, P., Herrero, A., Berge, C., 1996. Modeling directivity of heterogeneous earthquake ruptures. Bull. Seism. Soc. Am. 86, 1149–1160.
- Gallovič, F., Burjánek, J. (2007). High-frequency Directivity in Strong Ground Motion Modeling Methods, Annals of Geophysics, Vol. 50, N. 2, 203-211.
- Gallovič, F., Brokešová, J. (2007). Hybrid k-squared Source Model for Strong Ground Motion Simulations: Introduction, Phys. Earth Planet. Interiors, 160, 34-50.
- Gallovič, F., Brokešová, J. (2004). On strong ground motion synthesis with k^-2 slip distributions, J. Seismology, 8, 211-224.
- Herrero, A., Bernard, P., 1994. A kinematic self-similar rupture process for earthquakes. Bull. Seism. Soc. Am. 84, 1216–1228.
- Ruiz, J. A., D. Baumont, P. Bernard, and C. Berge-Thierry (2011). Modeling directivity of strong ground motion with a fractal, k-2, kinematic source model, Geophys. J. Int. 186, 226–244.