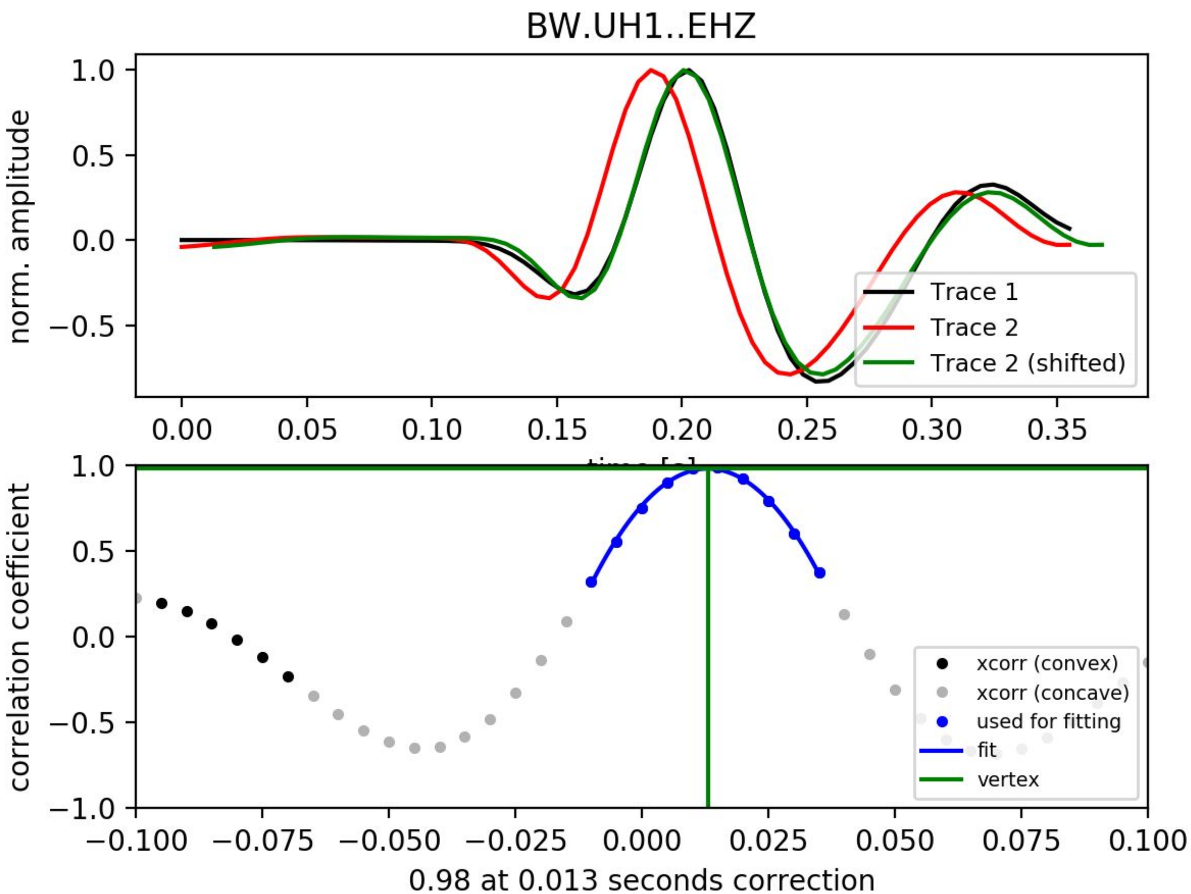
Earthquake detection and location



Blaž Vičič
Quantectum AG
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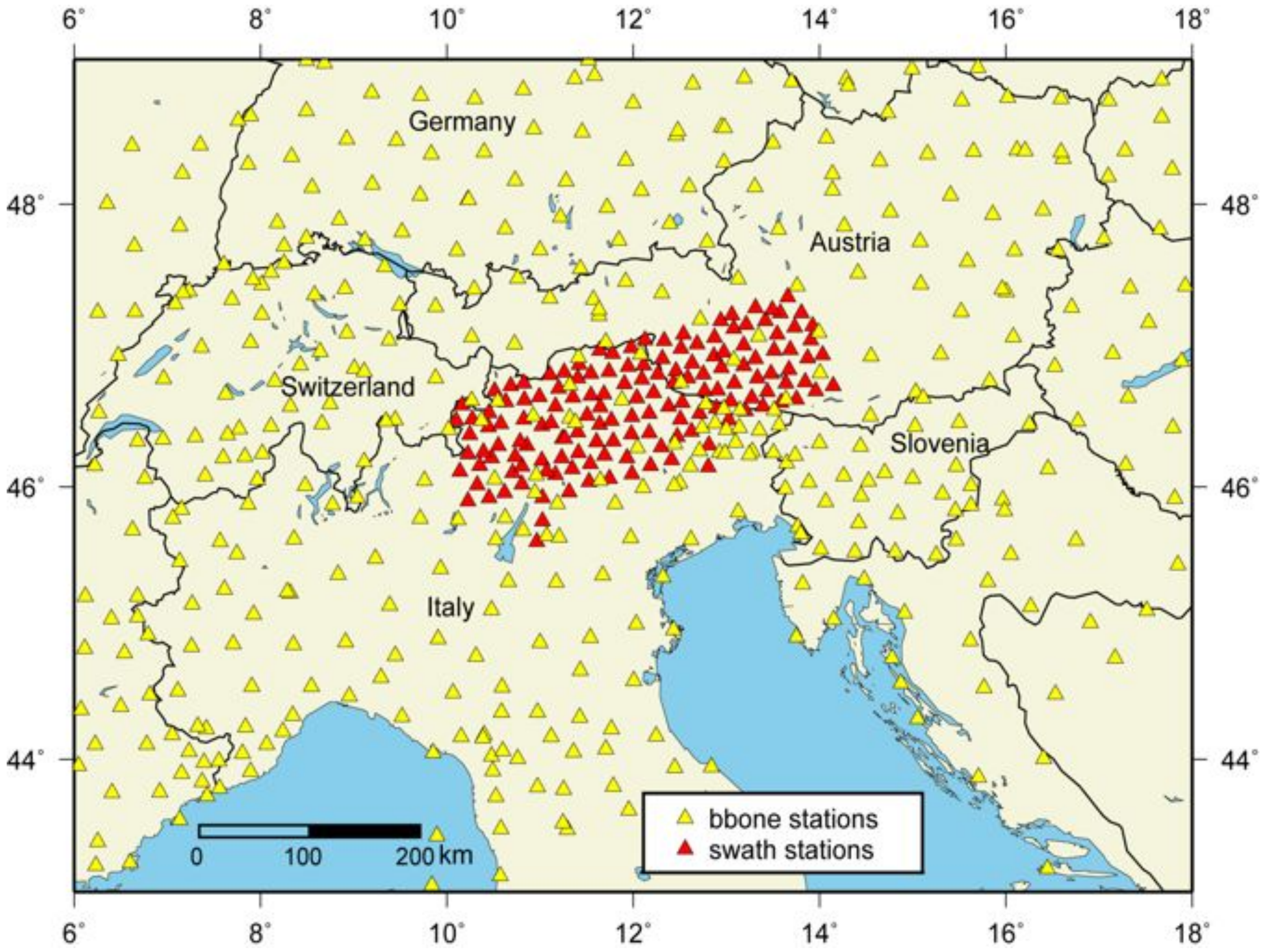
Errors

Sources of error: network configuration or geometry

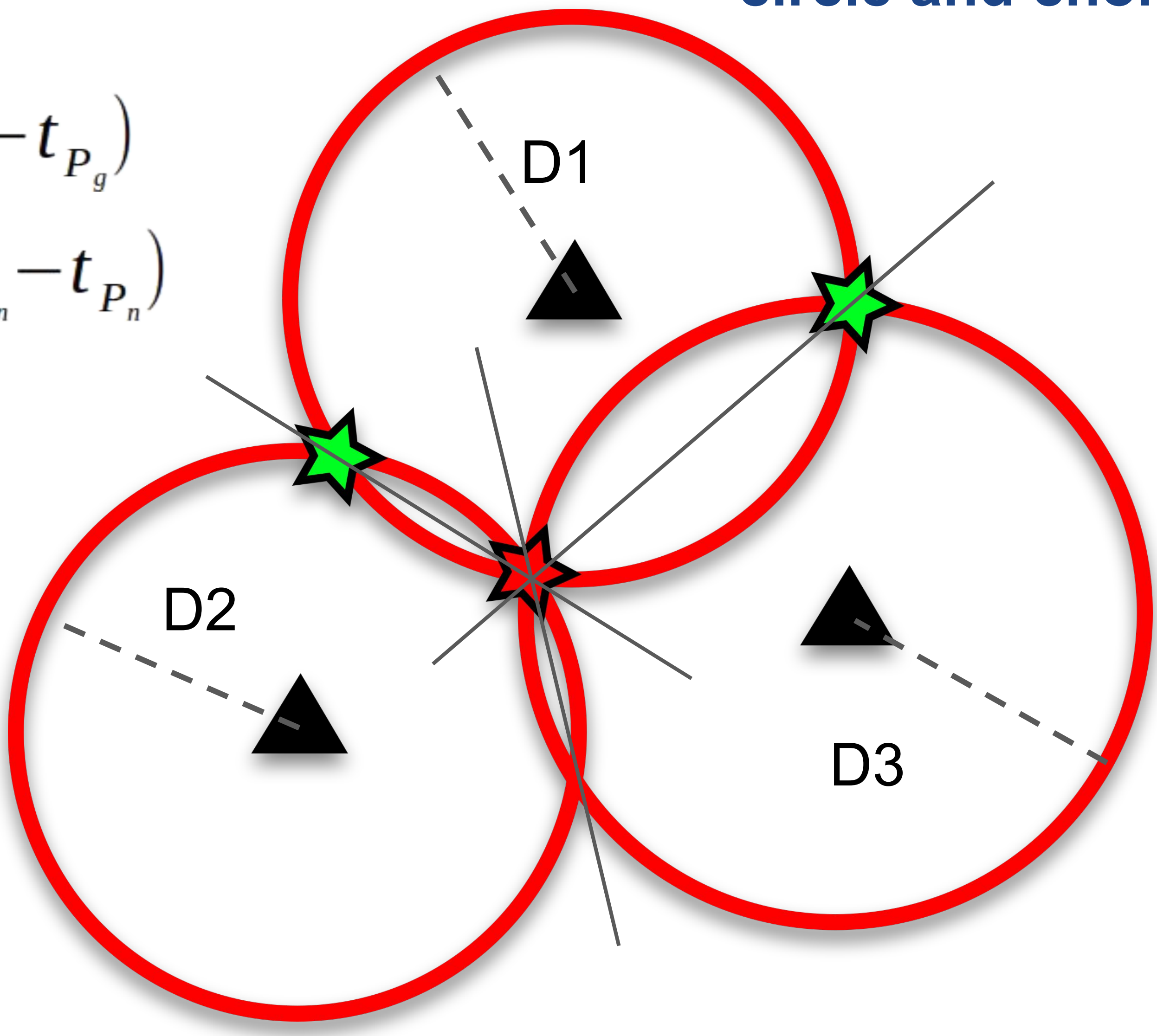


Sources of error: network configuration or geometry

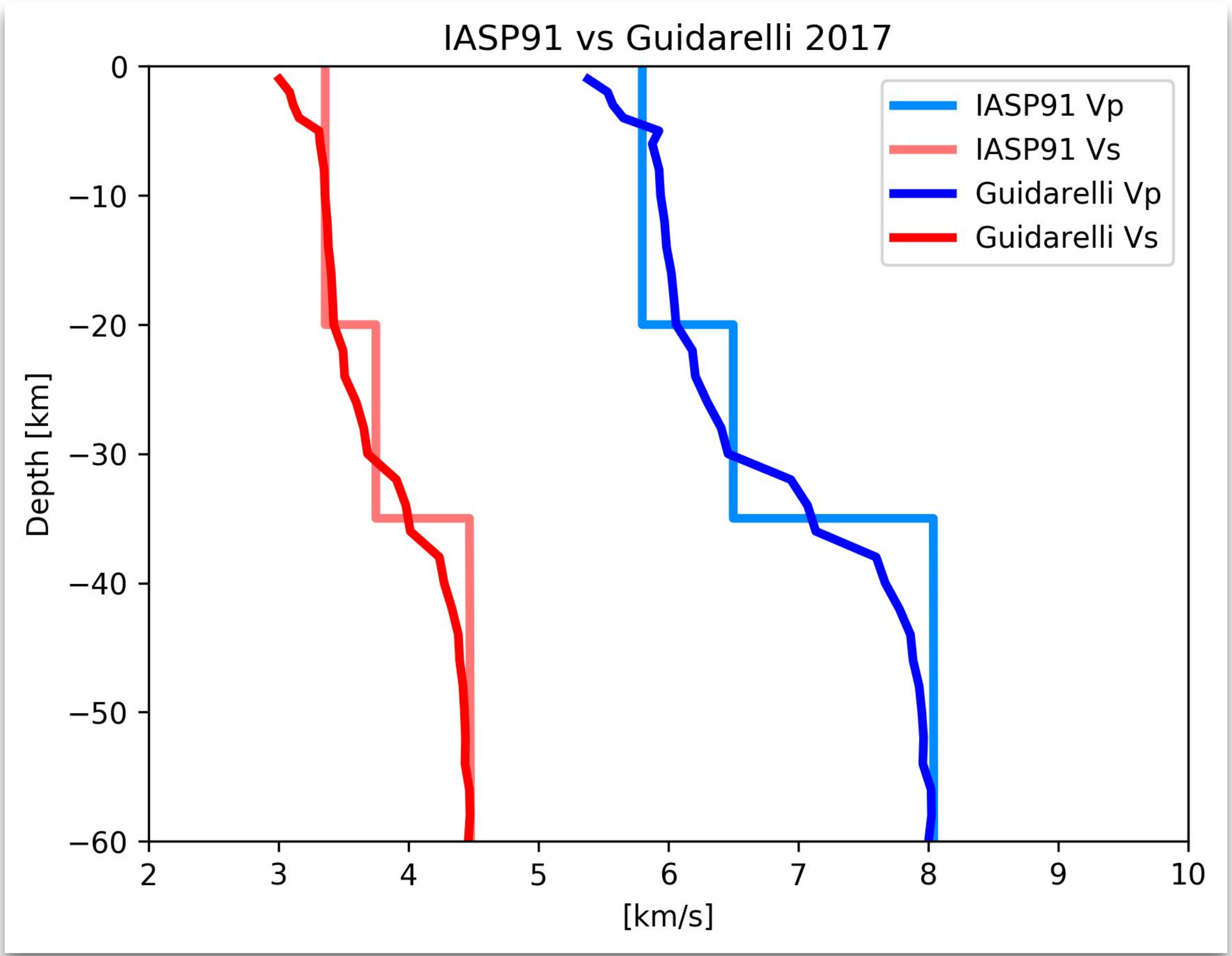
"circle and chord" method

$$D = 8\left(t_{S_g} - t_{P_g}\right)$$

$$D = 10\left(t_{S_n} - t_{P_n}\right)$$

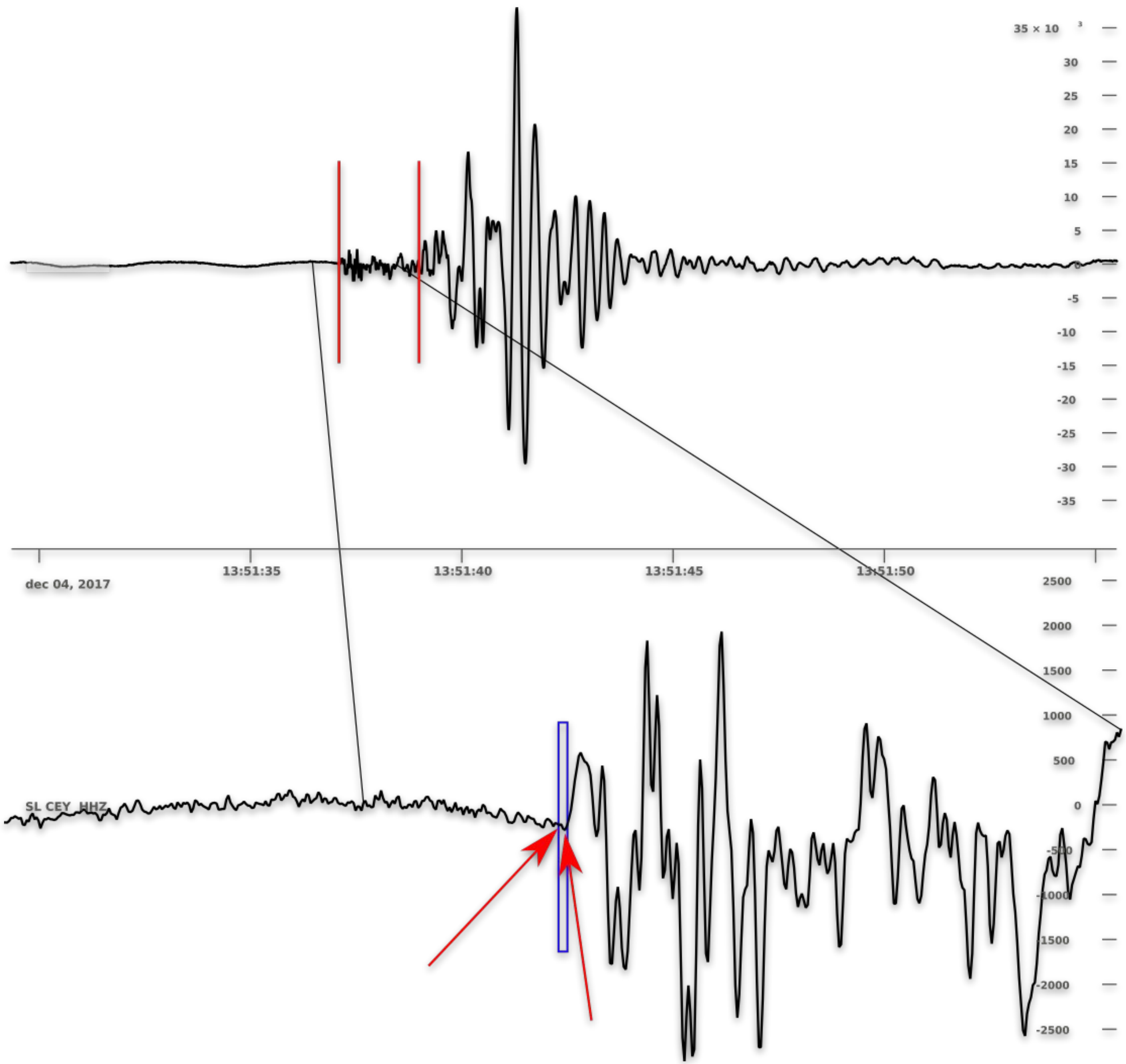


Errors



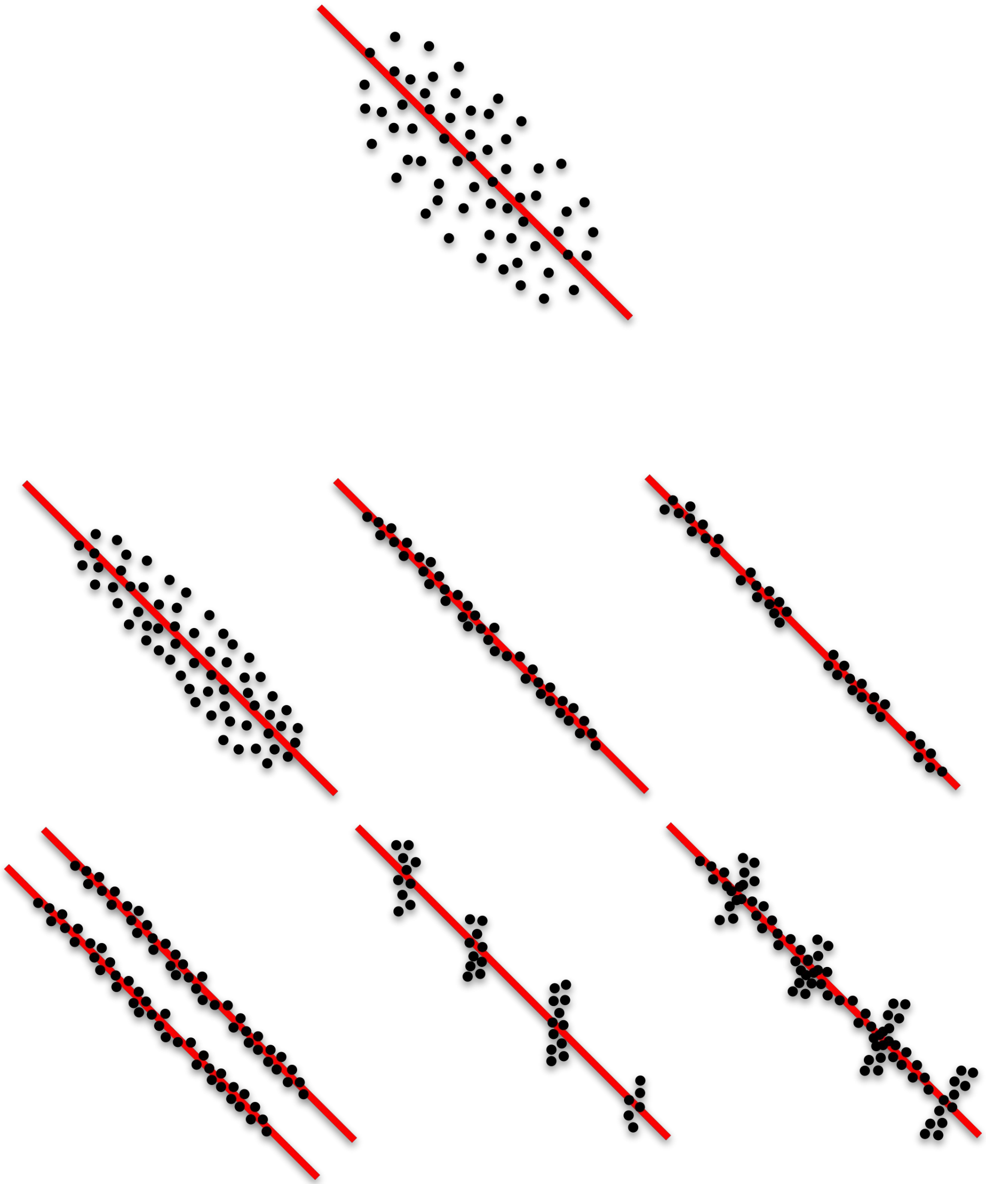
IASP91 vs Guidarelli 2017
IASP91 Vp
IASP91 Vs
Guidarelli Vp
Guidarelli Vs
Depth [km]
0
−10
−20
−30
−40
−50
−60
2
3
4
5
6
7
8
9
10
[km/s]

Errors



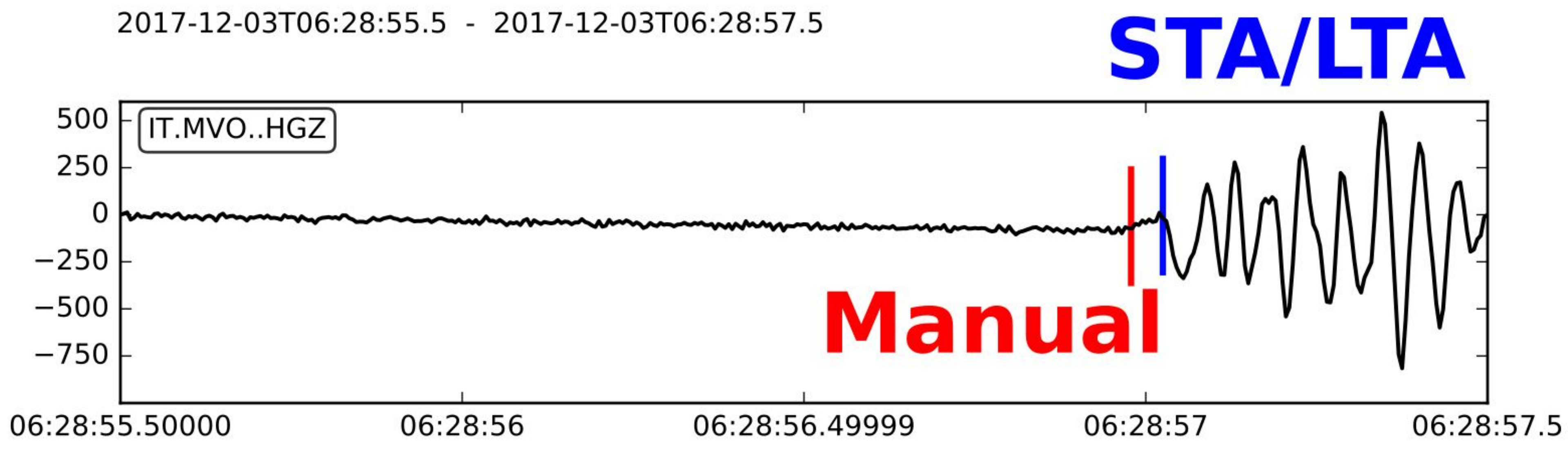
35 x 10 3
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
dec 04, 2017
13:51:35
13:51:40
13:51:45
13:51:50
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
SL CEY HHZ

Errors

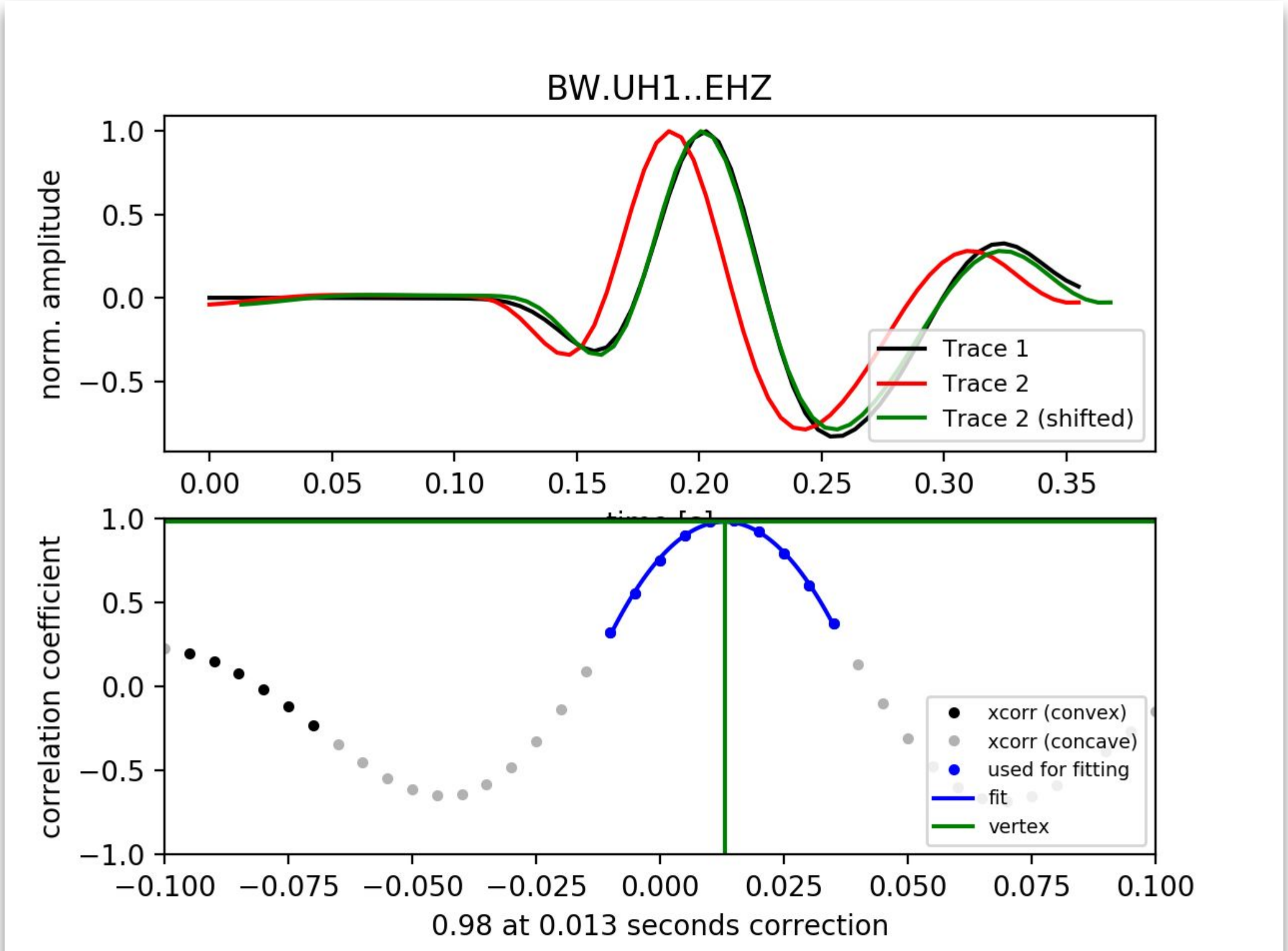


STA/LTA vs MANUAL

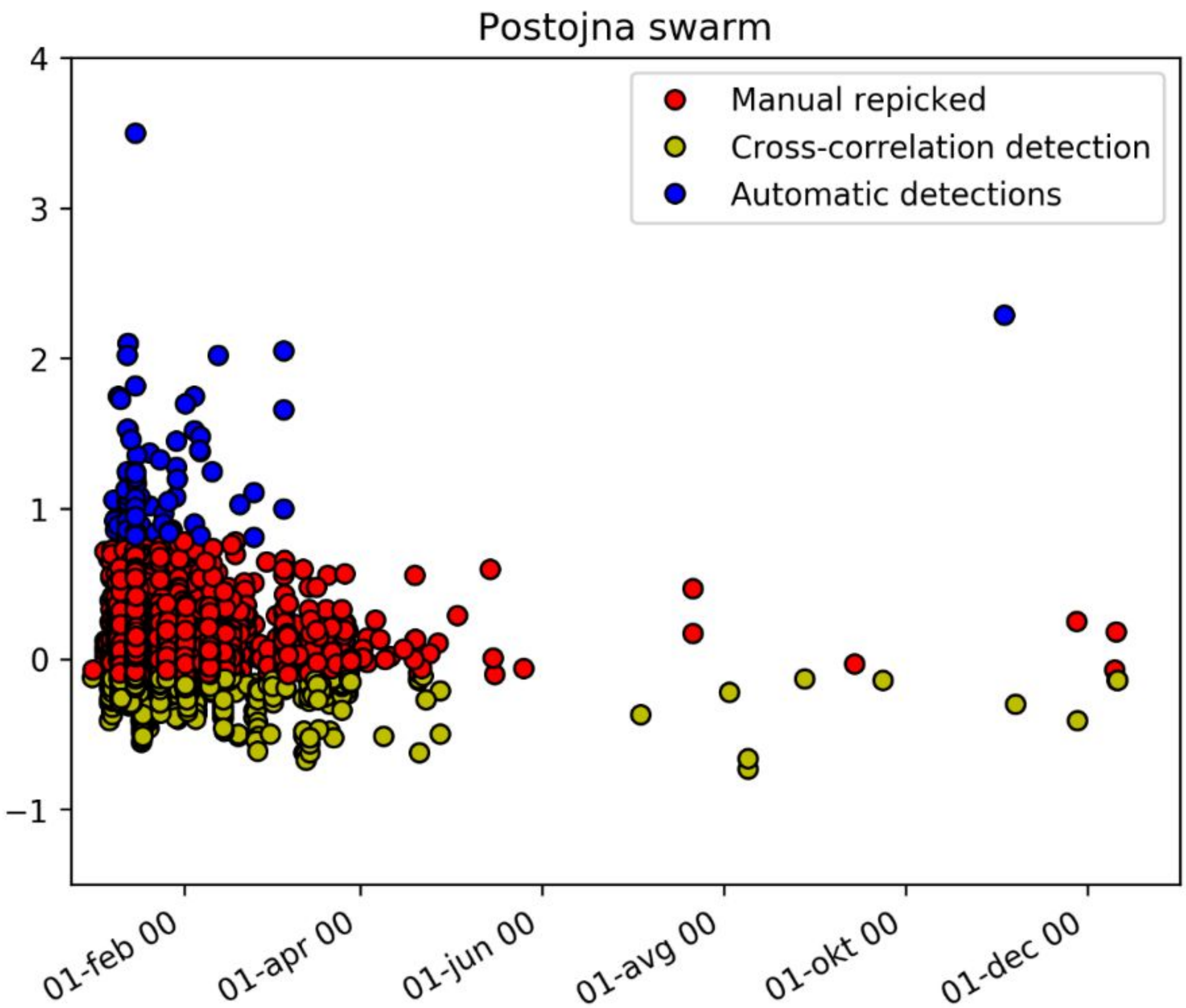
STA/LTA vs MANUAL



MANUAL vs CROSS CORRELATION



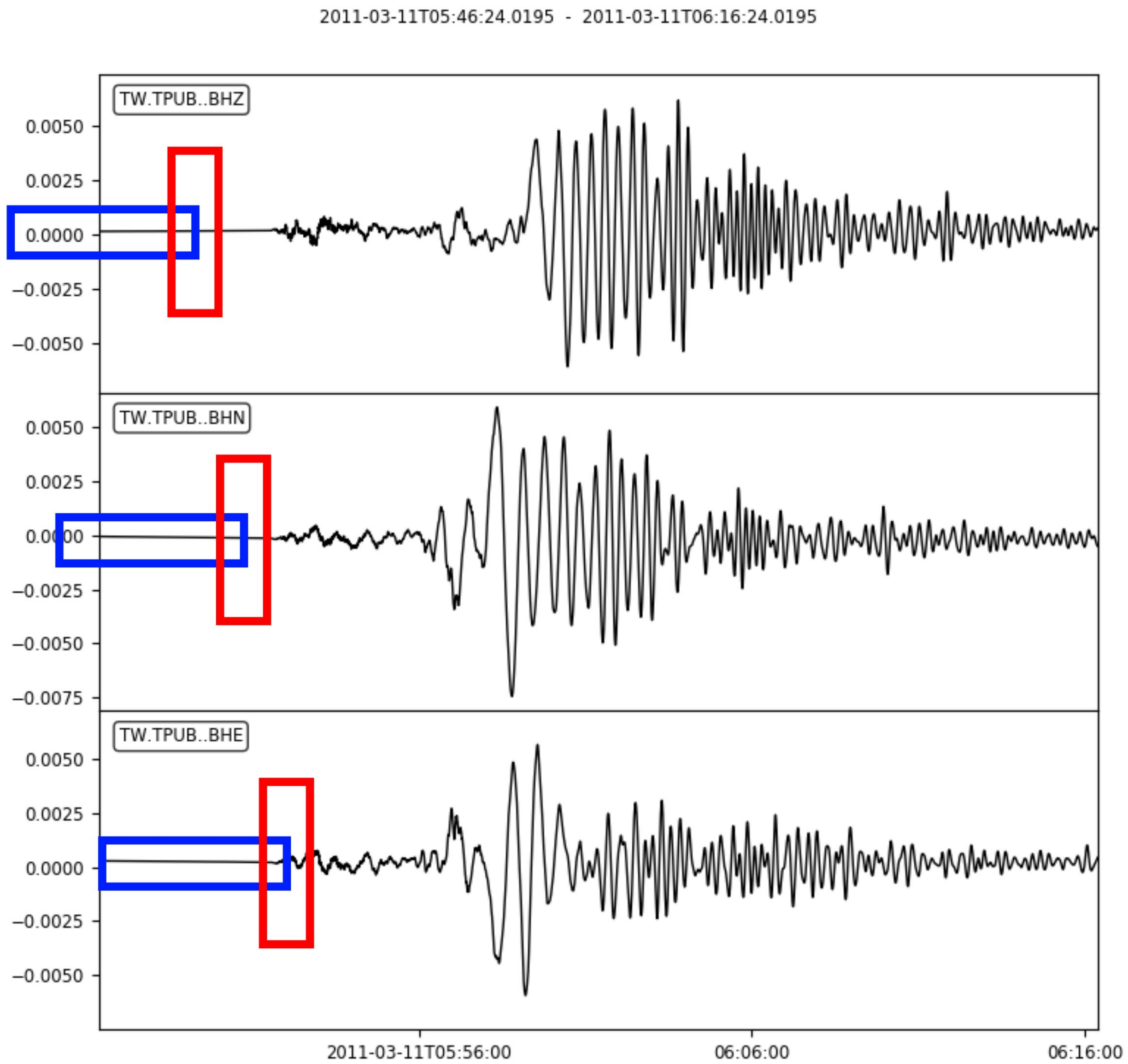
Less then ML 0.0 ?



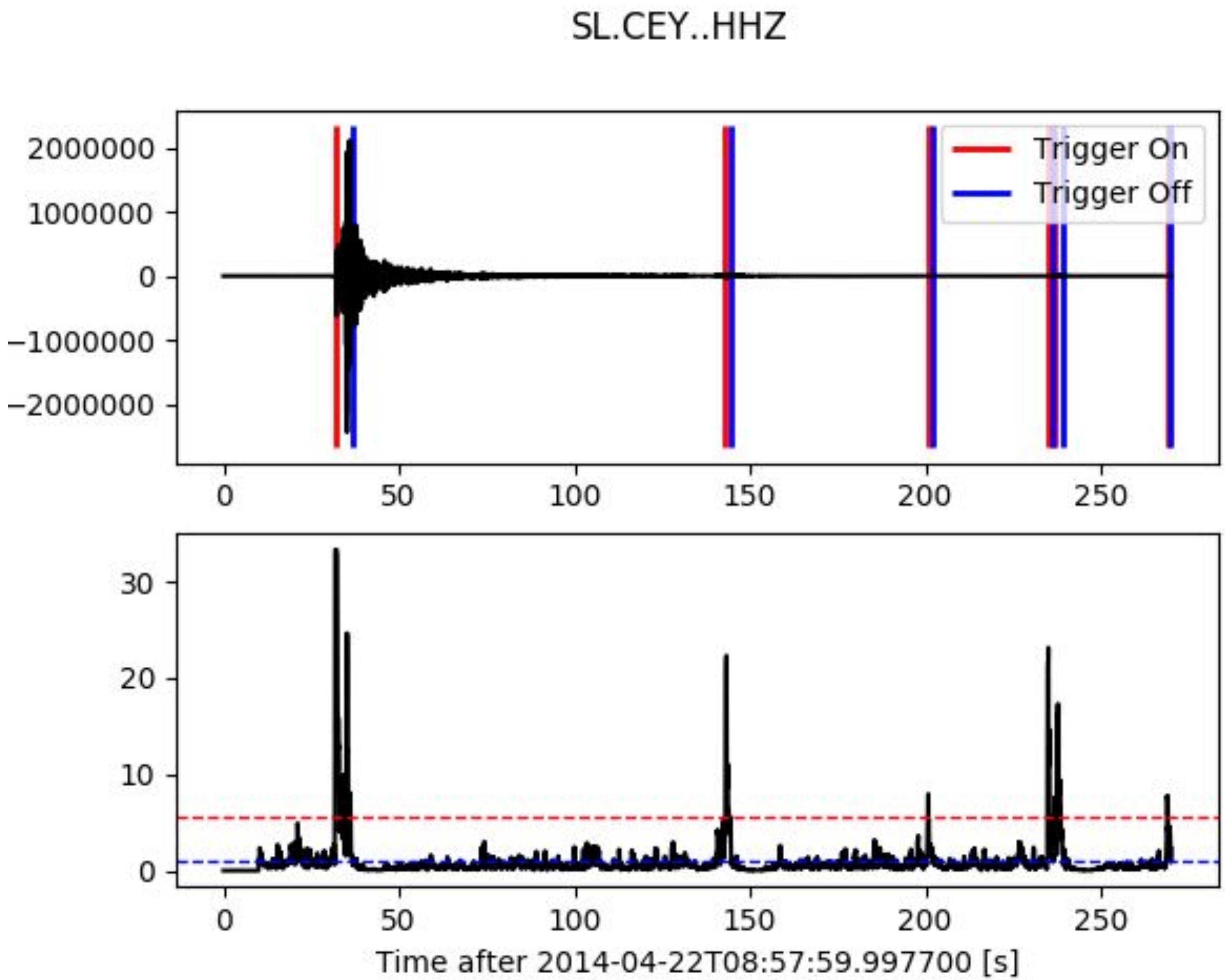
BUT HOW? ...

1. Detect!
2. Locate!
3. Relocate!

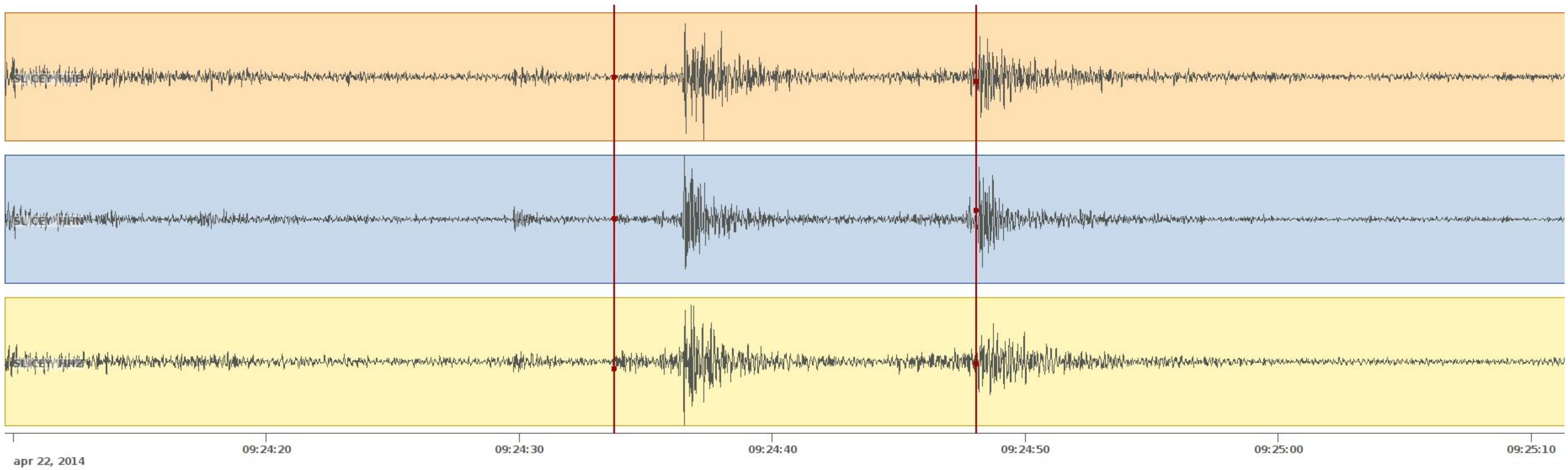
STA / LTA detection



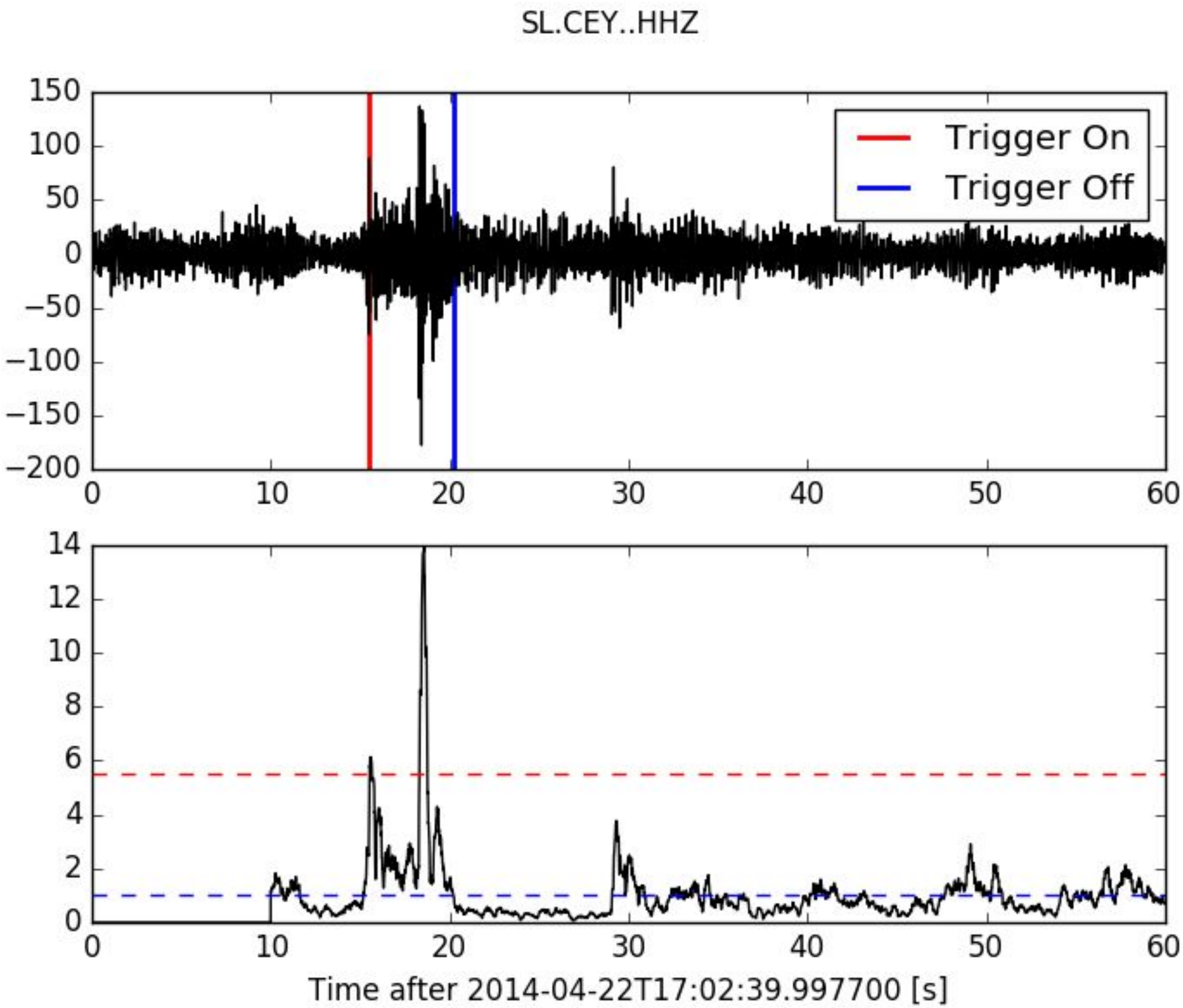
STA / LTA detection



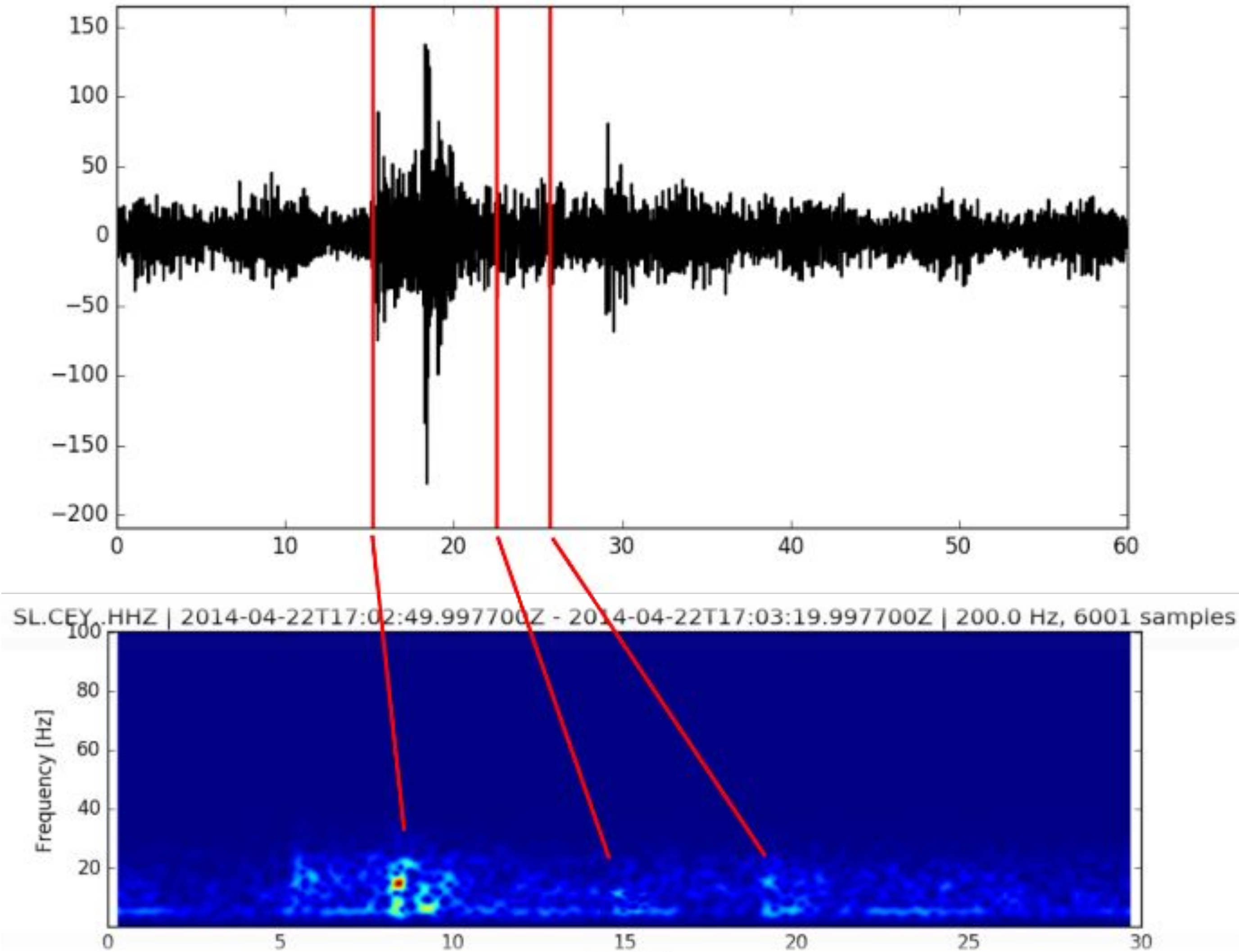
STA / LTA detection is not all powerful !!!



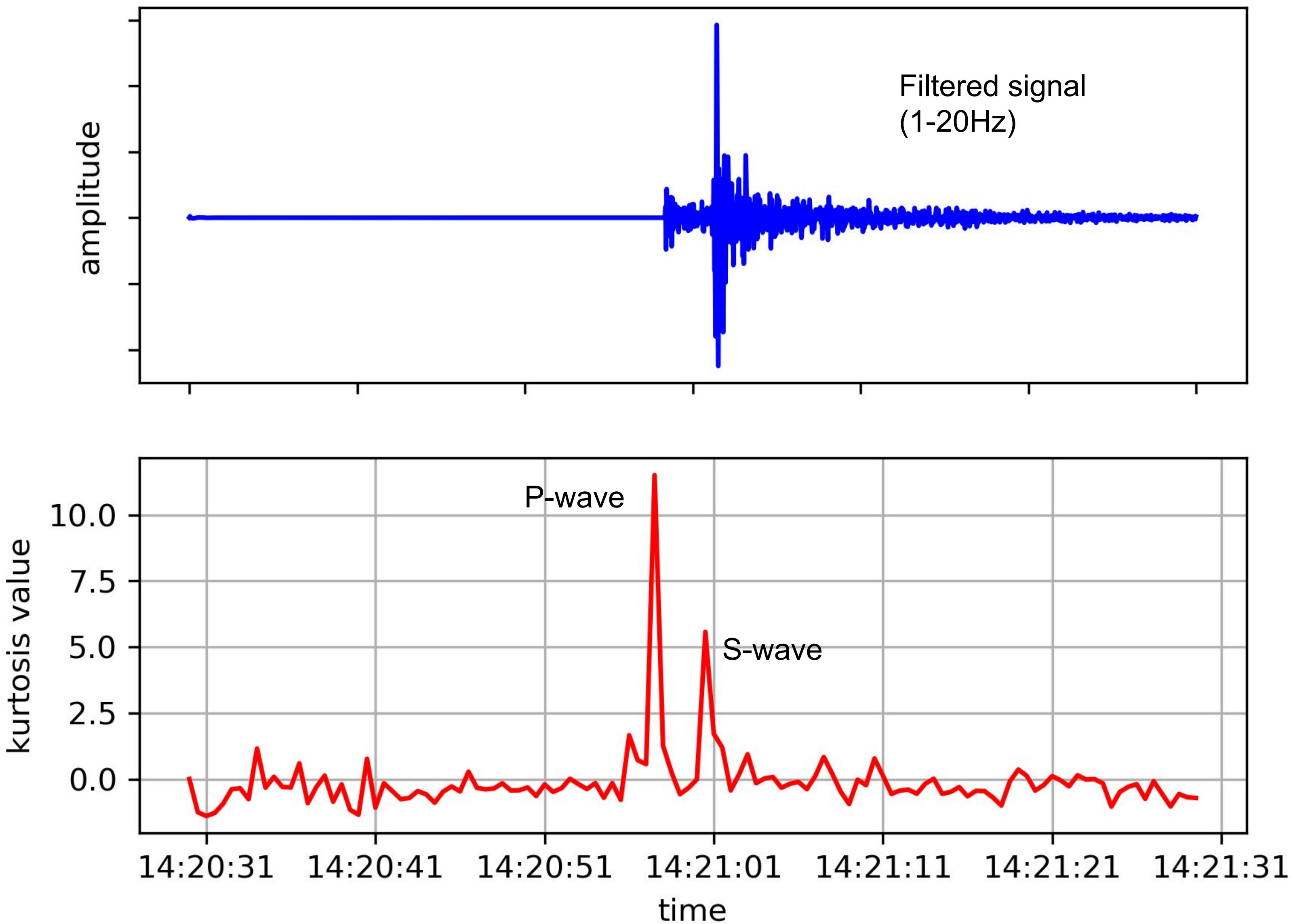
STA / LTA detection is not all powerful !!!



STA / LTA detection is not all powerful !!!



Application of Kurtosis in detecting earthquake



Kurtosis is...

- a measure of the "**tailedness**" of the probability distribution of a real-valued random variable
- based on a scaled version of the **fourth moment** of the data or population, which is related to the tails of the distribution (not its peak)

$$\operatorname{Kurt}[X] = \operatorname{E}\left[\left(\frac{X-\mu}{\sigma}\right)^4\right] = \frac{\mu_4}{\sigma^4} = \frac{\operatorname{E}[(X-\mu)^4]}{(\operatorname{E}[(X-\mu)^2])^2},$$

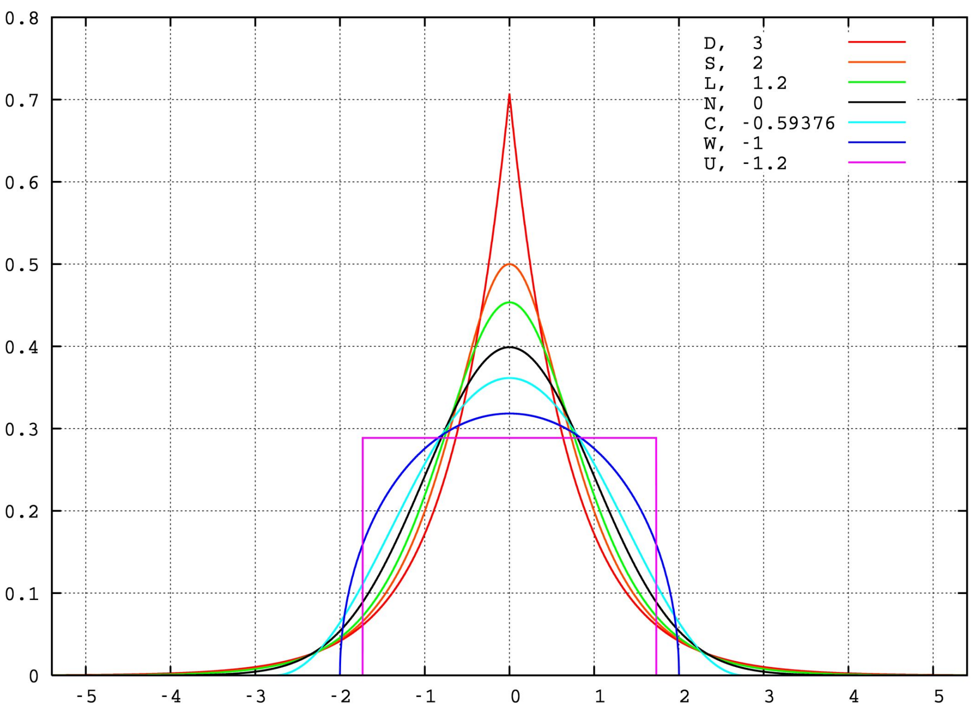
- related to the **outliers or infrequent extreme deviations**:

  Kurtosis < 3 : distribution produces fewer and less extreme outliers than the normal distribution; uniform distribution (no outliers)

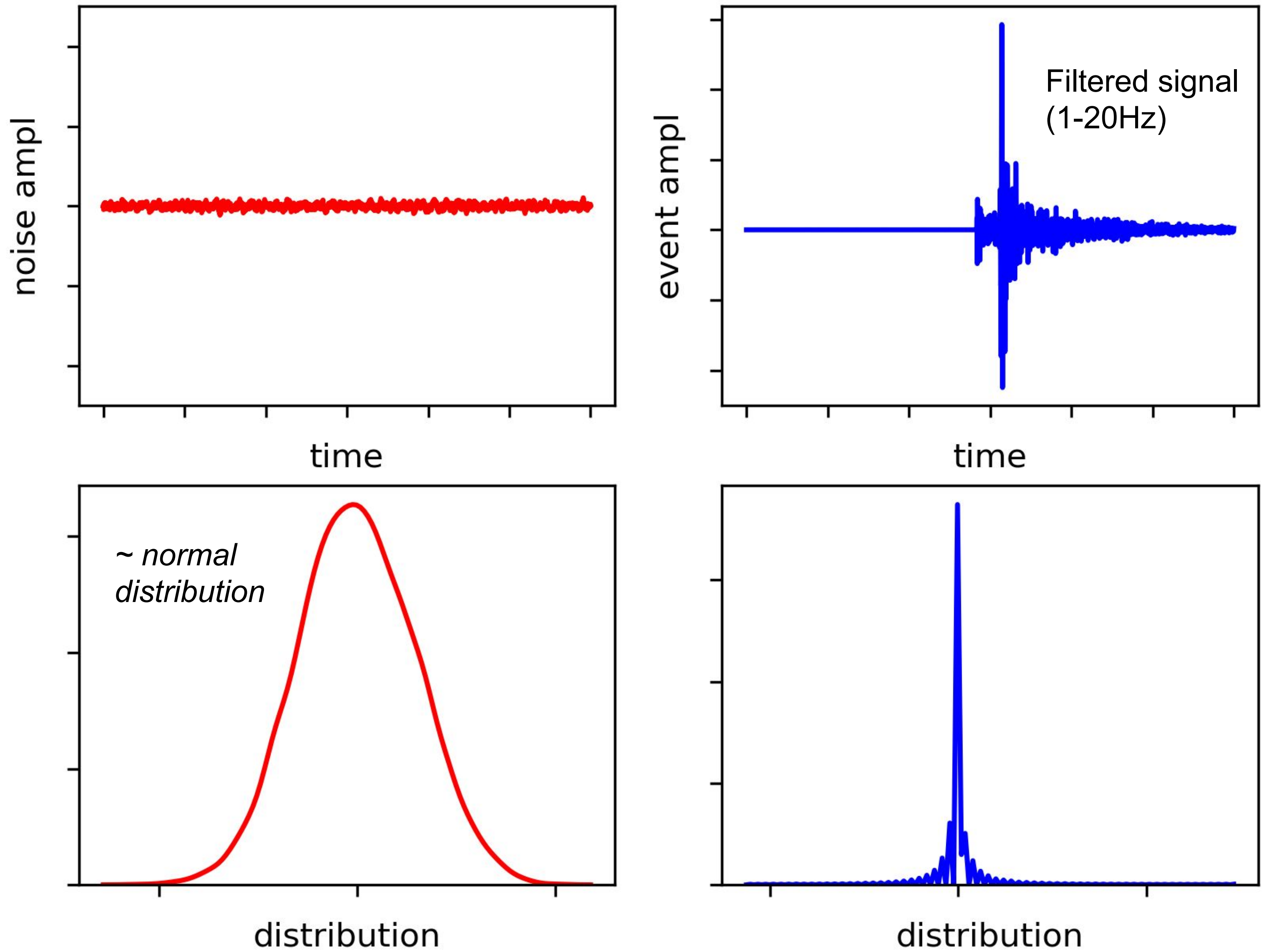
  Kurtosis = 3: normal distribution (Gaussian)

  Kurtosis > 3: distribution that produces more outliers than the normal distribution; laplace distribution

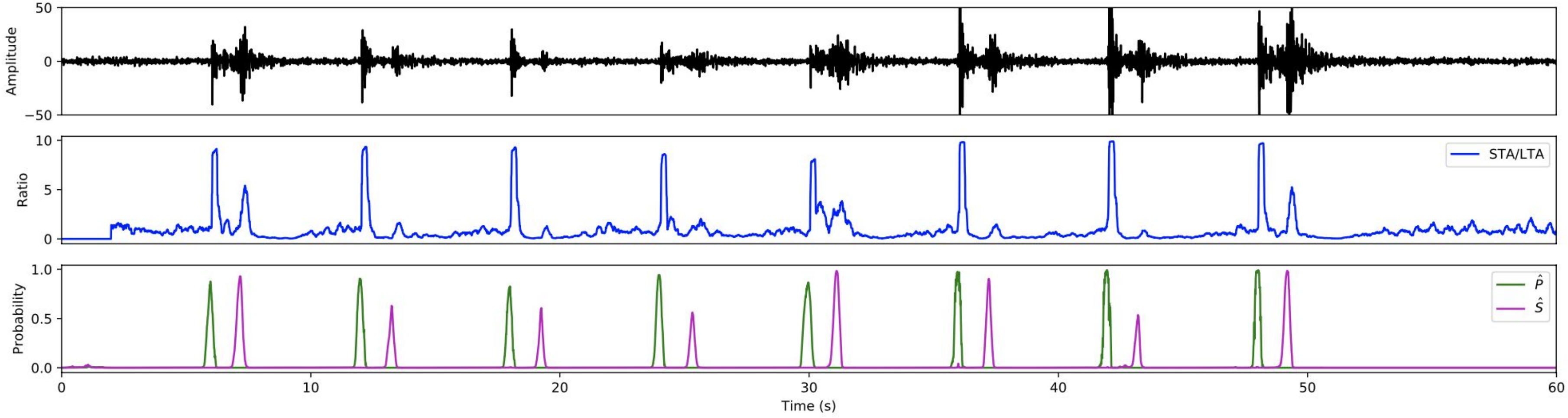
Excess kurtosis



Signal distribution: noise vs. event



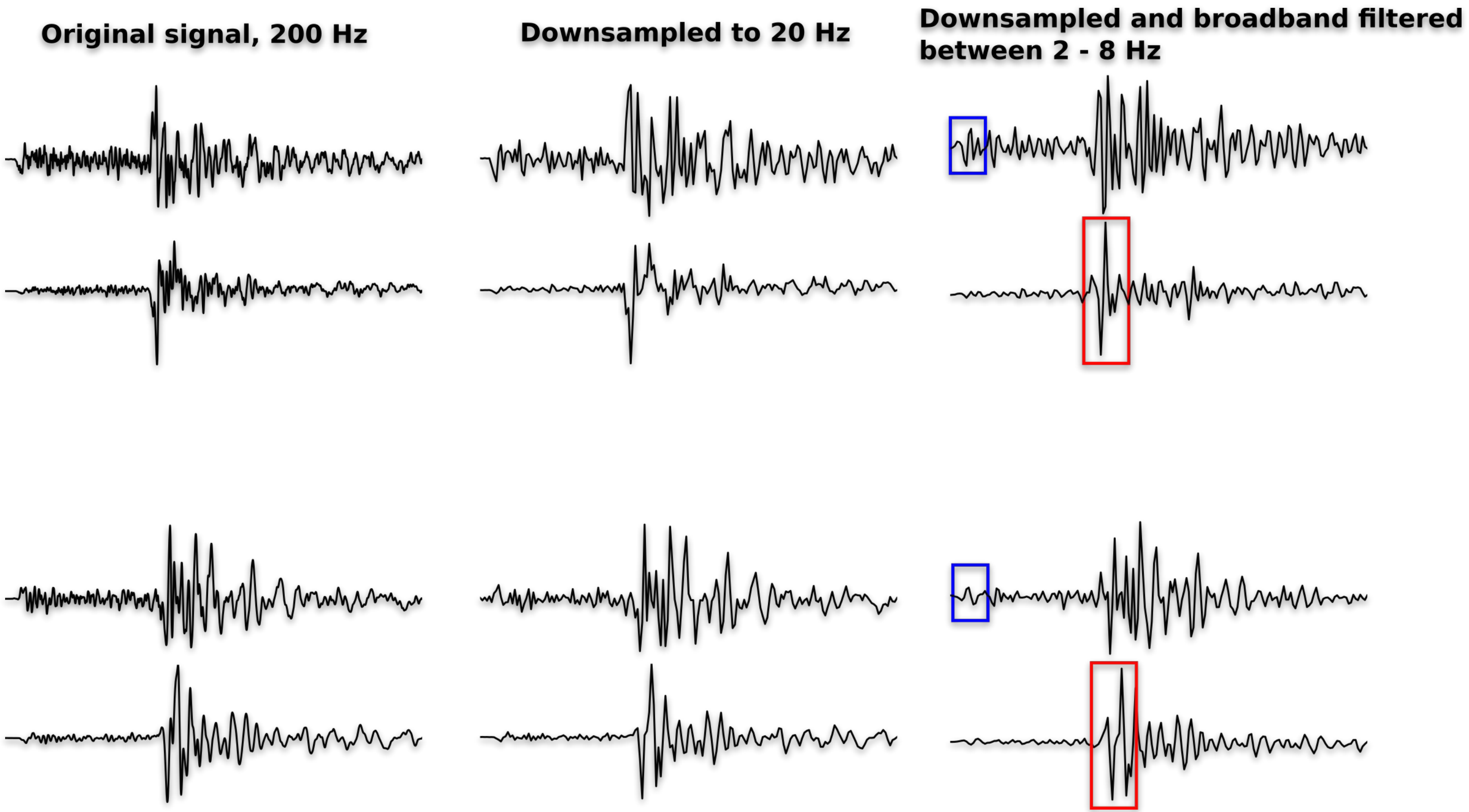
Machine learning phase picking



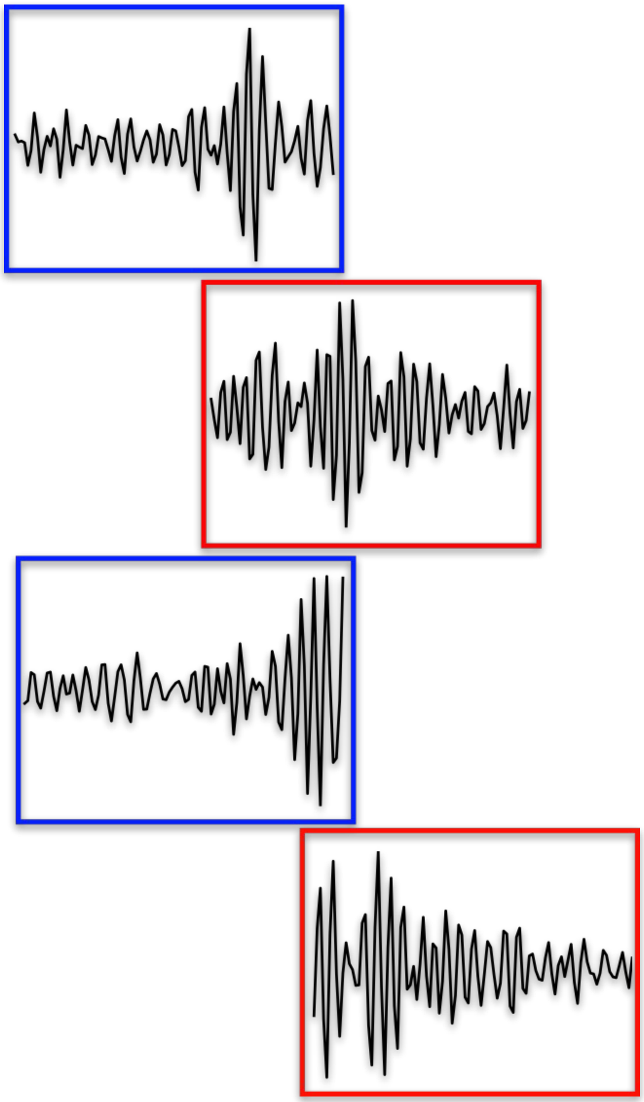
Seems very nice, but requires hudge amounts of already high quality processed datasets for estimation. Also, requires relatively powerful hardware.

This case: almost 780.000 events used for training.

Matched filter detection algorithm



Template



Correlation

$$R(x,y) = \frac{\sum_{x',y'} \left(T'(x',y') \cdot I'(x+x', y+y')\right)}{\sqrt{\sum_{x',y'} T'(x',y')^2 \cdot \sum_{x',y'} I'(x+x',y+y')^2}}$$

I' is the normalized source image

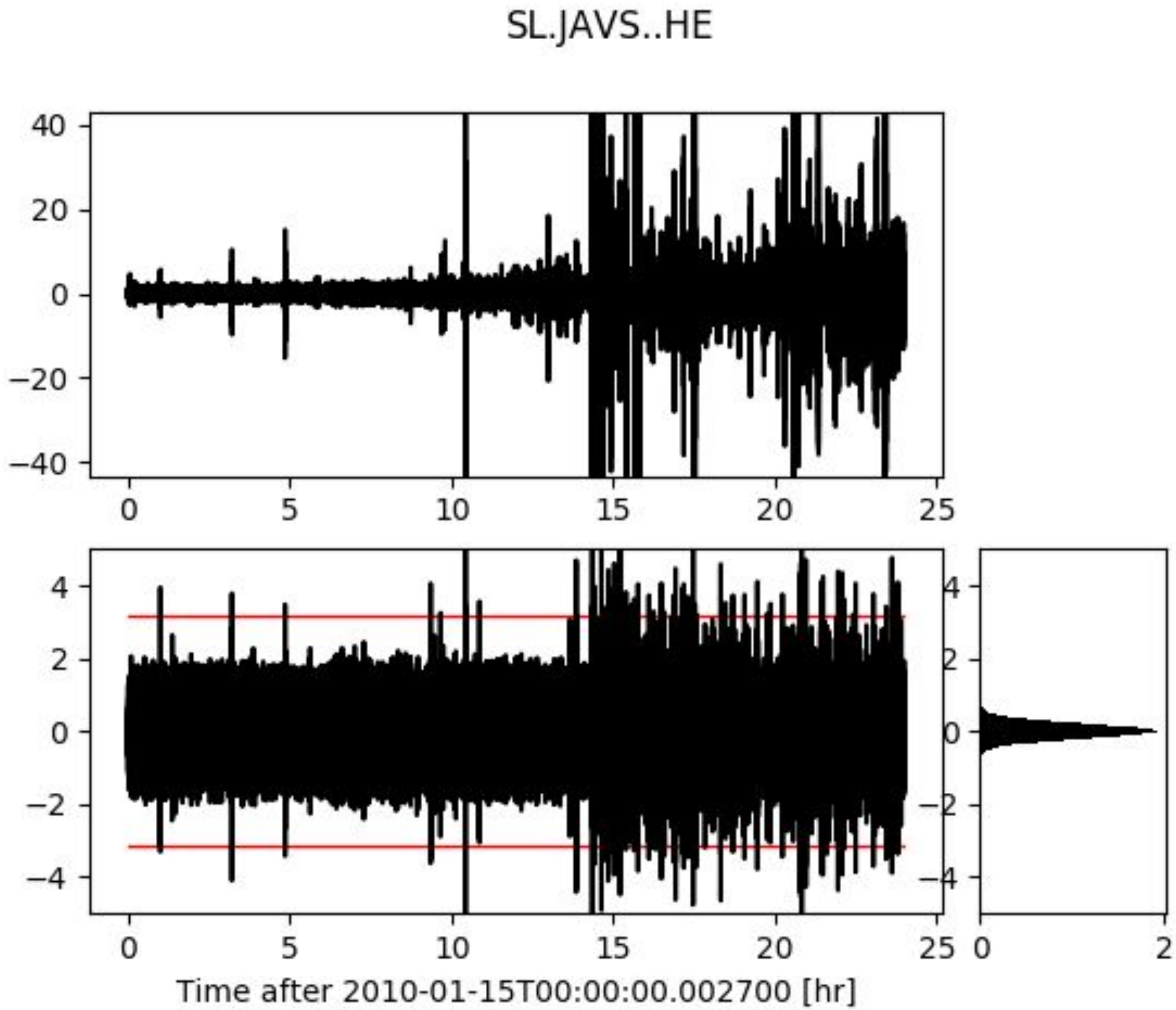
T' is the normalised template image

R is the result. (x, y)

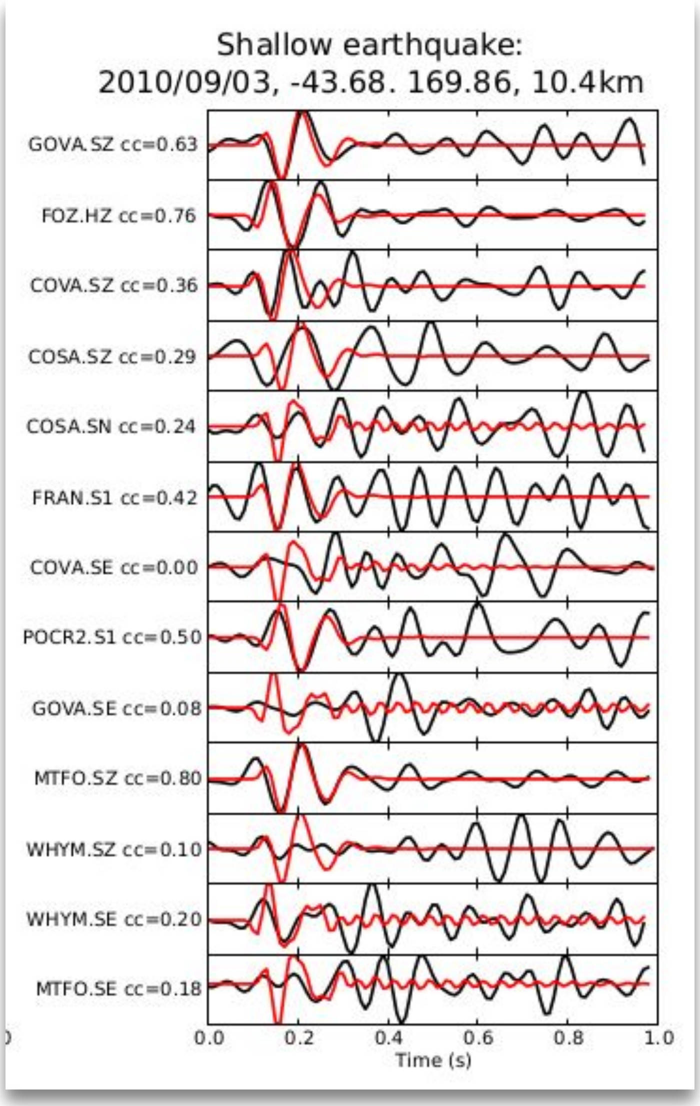
No need of y in seismology, its a 1D problem

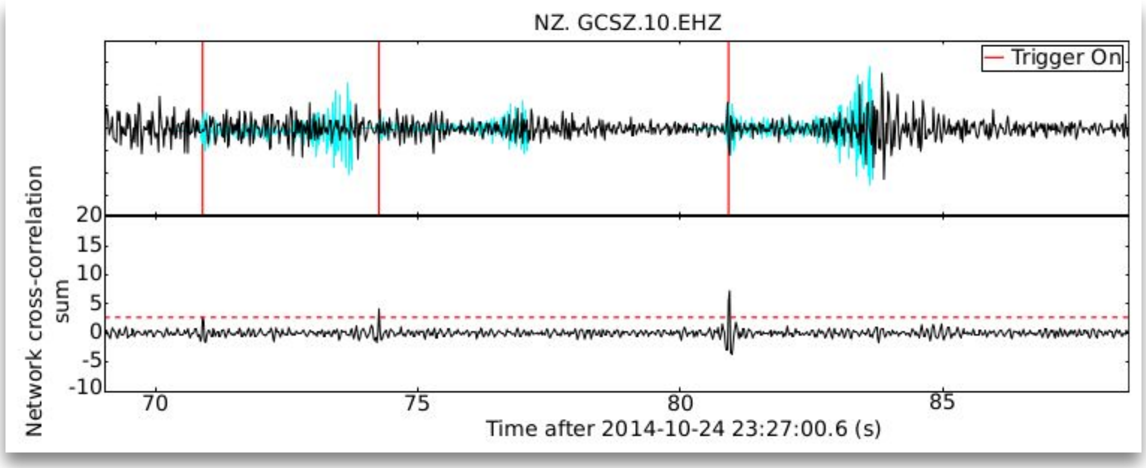
Median absolute deviation

MAD = median (| Xi - median(X) |)

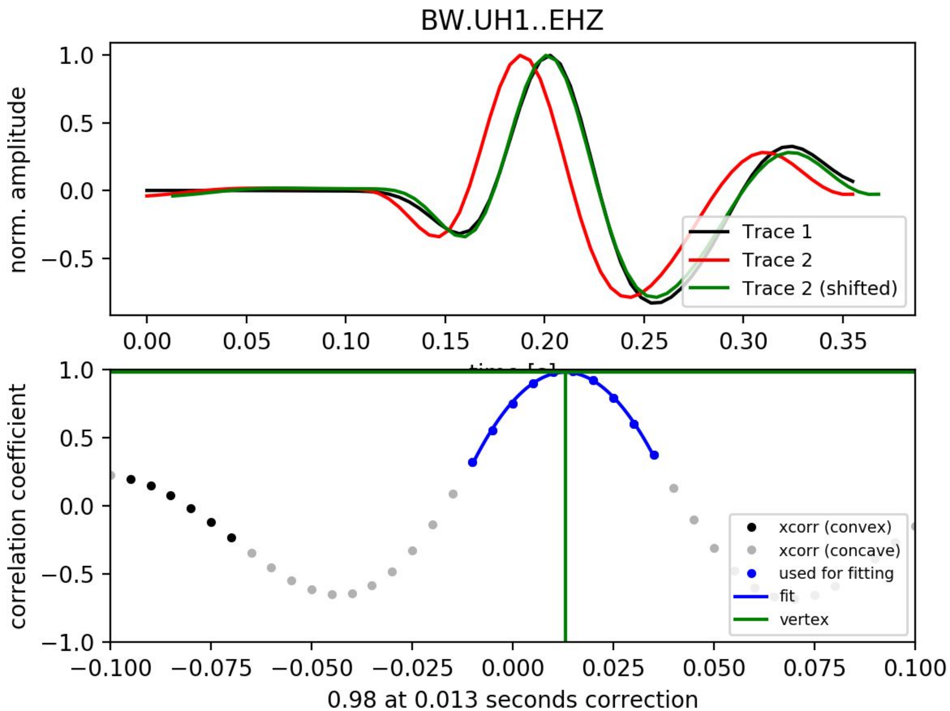


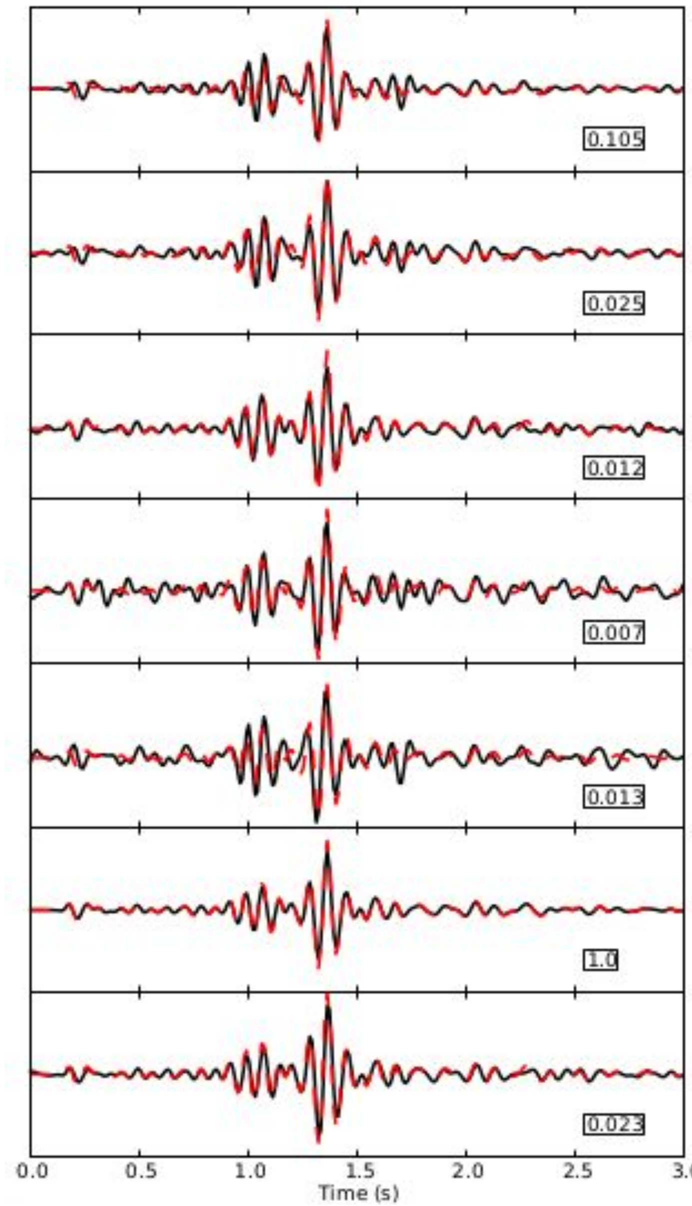
Matching of the template and continuous data stream





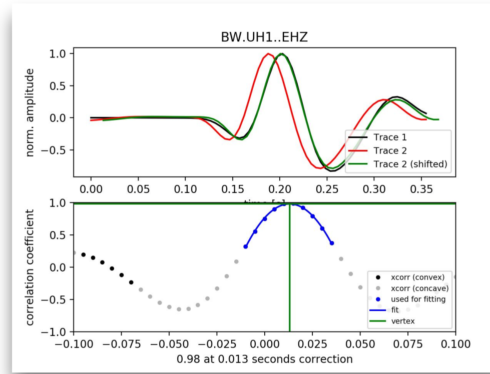
Matching of the template and continuous data stream





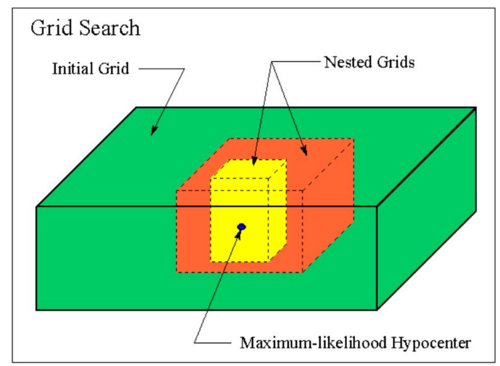
How to locate an earthquake with high-resolution?

Detect!



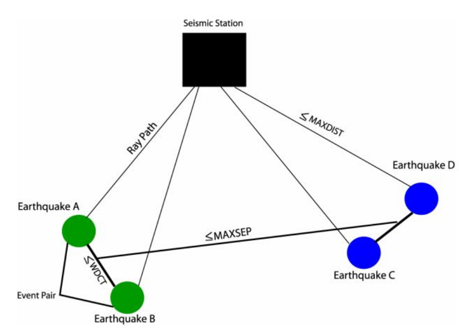
Locate!

(absolute)



Relocate!

(relative)



Origin time from Wadati diagram

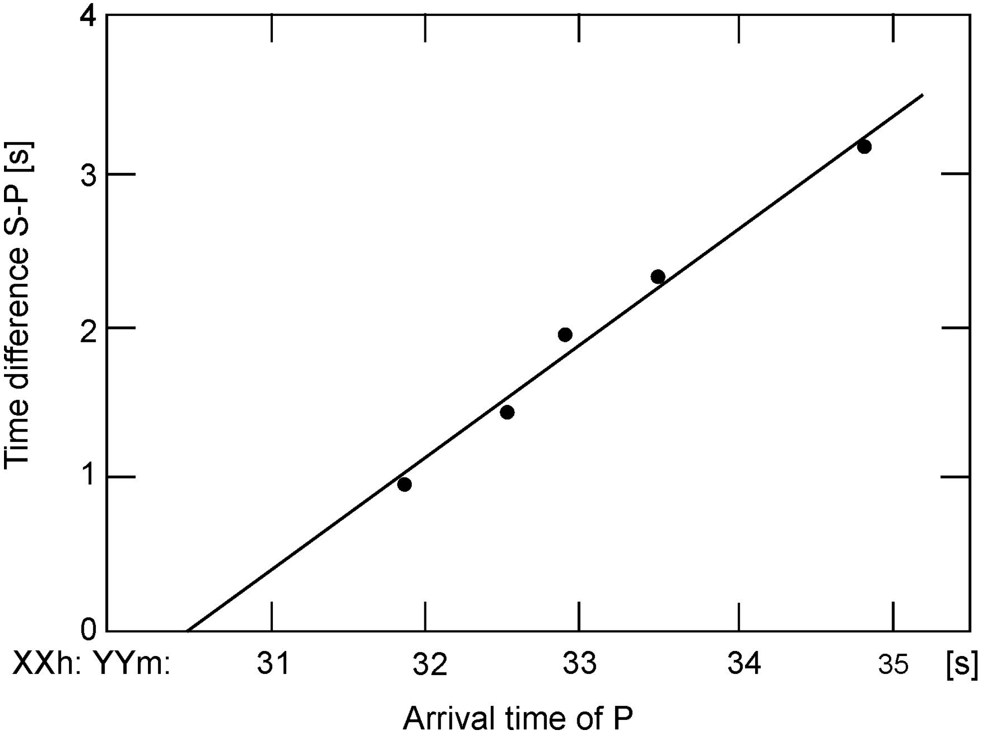
For single station:

$$t_p = t_o + \frac{D}{v_p}$$

t_o = origin time
t_p = P-arrival time
t_s = S-arrival time
v = velocity of homogeneous half space (v_p for P-wave, v_s for S-wave)
D = epicentral distance

For multiple station:

$$t_s - t_p = \left(\frac{v_p}{v_s} - 1\right)\left(t_p - t_o\right)$$



IS 11.1 by J. Havskov

Assumptions:
- v_p/v_s is constant
- P and S phases are of the same type (i.e. Pg and Sg)

But we have an overdetermined system...

Absolute Positioning

$$t_i^c = \frac{\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}}{v} + t_o$$

t_o = origin time
t = arrival time
v = velocity of homogeneous half space

In principle, the best location is determined where the residual is minimum.

$$r_i = t_i^{calc} - t_i^{obs}$$

NONLINEAR function

+

OVERDETERMINED systems

no simple way of finding the best solution

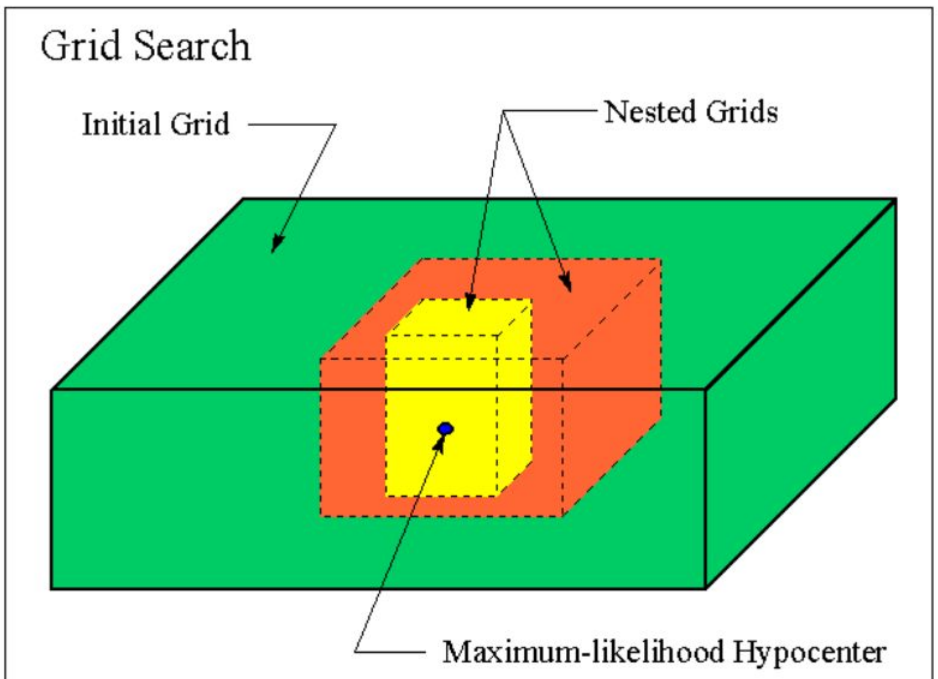
Least square method in locating earthquake

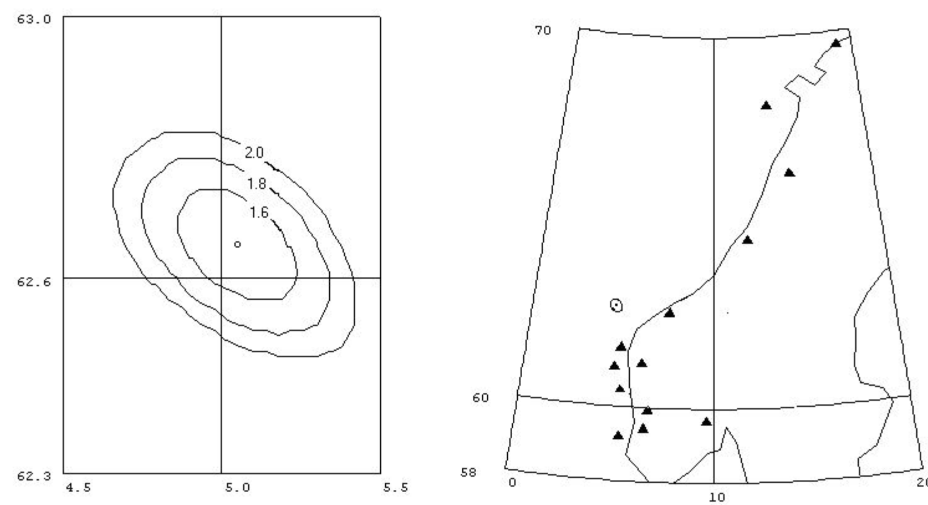
overdetermined system → **Least square method**

$$S=\sum_{i=1}^{n} r_i^2=\sum_{i=1}^{n}\left(t_i^{calc}-t_i^{obs}\right)^2$$

$$RMS=\sqrt{\frac{S}{n}}$$

Grid search





IS 11.1 by J. Havskov

Linearizing the inversion problem

"true hypocenter" is close enough to the "trial hypocenter"

$$r_i \alpha(\Delta x, \Delta y, \Delta z, \Delta t)$$

where
Δx, Δy, Δz, Δt= corrections on the model

$$t_i^c = \frac{\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}}{v} + t_o$$

Iterative method

Taylor's expansion

$$r_i = \frac{\delta t_i}{\delta x_i}\Delta x + \frac{\delta t_i}{\delta y_i}\Delta y + \frac{\delta t_i}{\delta z_i}\Delta z + \Delta t$$

In Matrix form

$$\boldsymbol{r} = \boldsymbol{G}\boldsymbol{X}$$

in linear form!

Trial 1 solution

X1 corrections

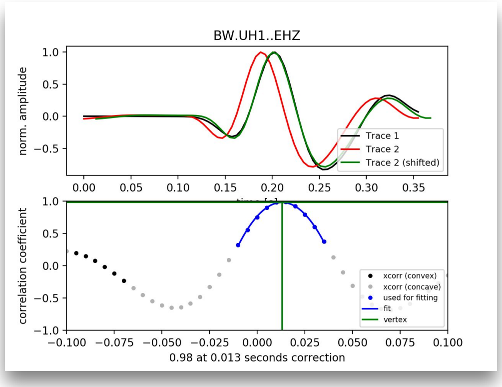
Trial 2 solution = Trial 1 solution + X1

X2 corrections

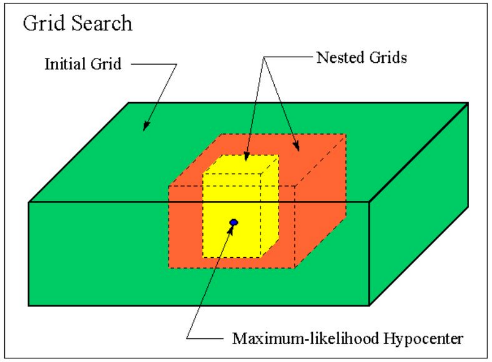
.
.
.

How to locate an earthquake with high-resolution?

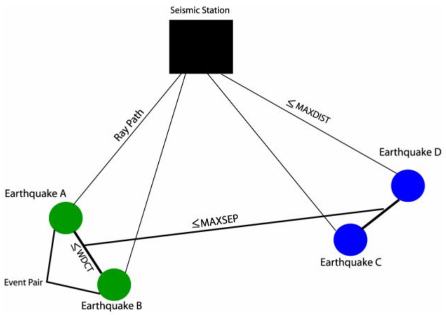
Detect!



Locate!
(absolute)



Relocate!
(relative)



Relative location method is robust

ABSOLUTE LOCATION METHOD

complete knowledge on the seismic velocities in the Earth?

RELATIVE LOCATION METHOD

solve for changes in the distance between pairs of events

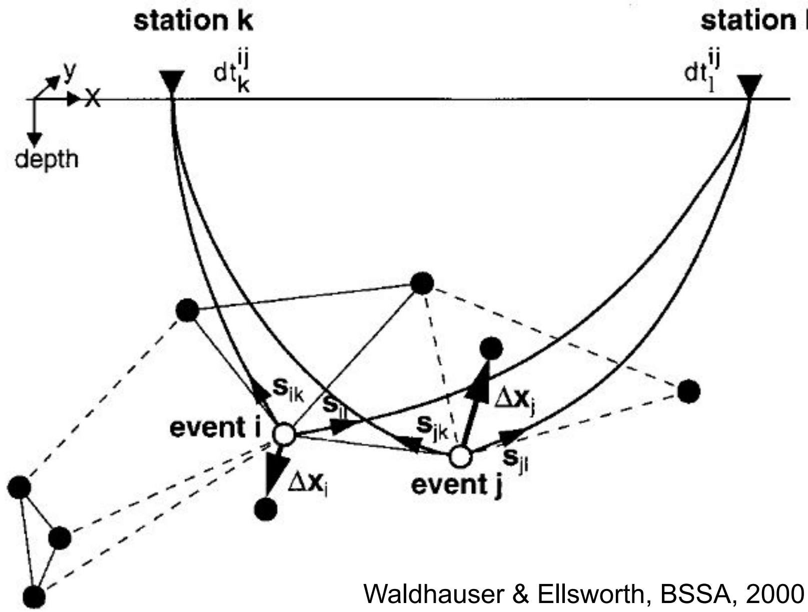
cancelling the travel time errors due to the unknown Earth structure

Double-difference algorithm eliminates the common errors

dr =double difference residual for 2 earthquakes i and j

$$dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal}$$

Δx, Δy, Δz, Δ$\boldsymbol{\tau}$ *changes required for better model*



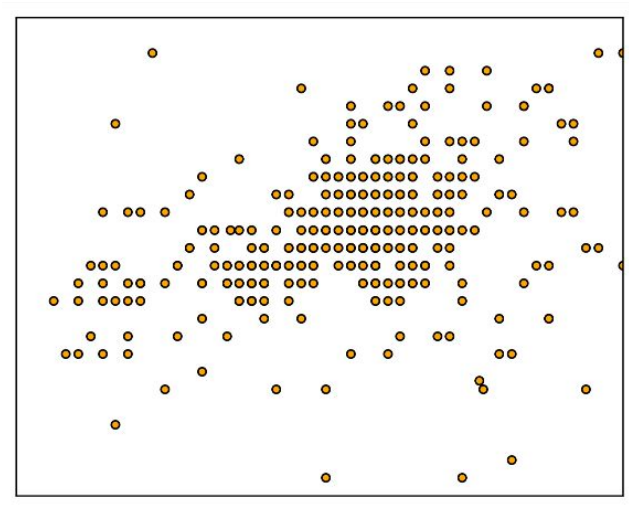
Waldhauser & Ellsworth, BSSA, 2000

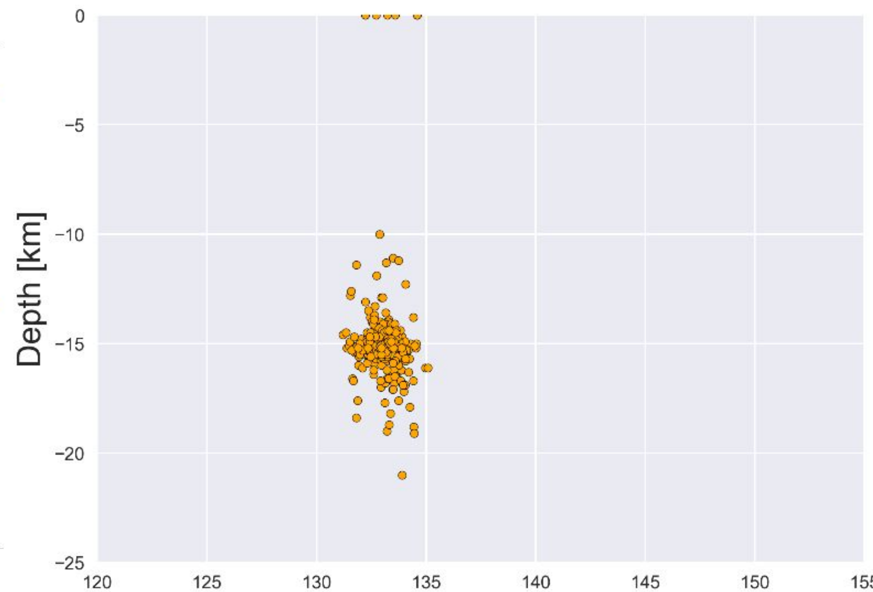
$$\frac{\delta t_k^i}{\delta x}\Delta x^i + \frac{\delta t_k^i}{\delta y}\Delta y^i + \frac{\delta t_k^i}{\delta z}\Delta z^i + \Delta\tau^i - \frac{\delta t_k^j}{\delta x}\Delta x^j - \frac{\delta t_k^j}{\delta y}\Delta y^j - \frac{\delta t_k^j}{\delta z}\Delta z^j - \Delta\tau^j = dr_k^{ij}$$

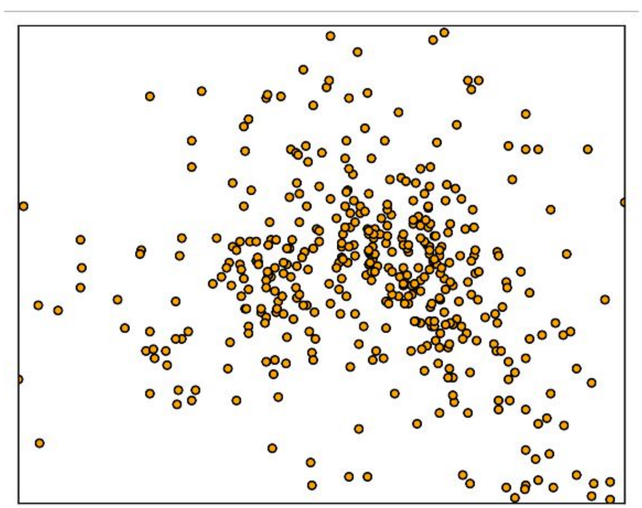
$$\mathbf{WGm} = \mathbf{Wd}$$

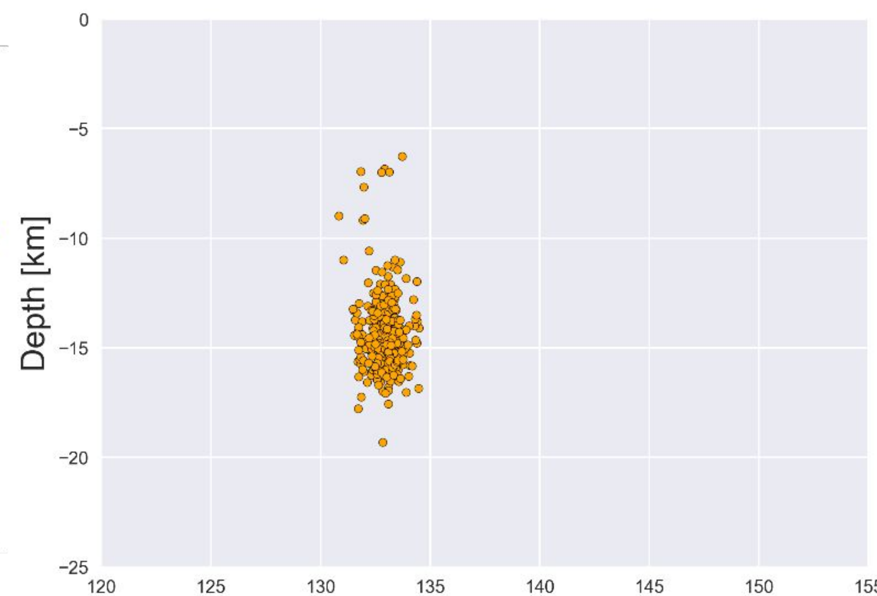
Obtained through linear, least square inversion, iterating through all the station-hypocentre pairs

Relocation of detections









The preparatory phase of the 2009 M_W 6.3 L'Aquila earthquake by improving the detection capability of low-magnitude foreshocks

Monica Sugan, Aitaro Kato, Hiroe Miyake, Shigeki Nakagawa, Alessandro Vuan

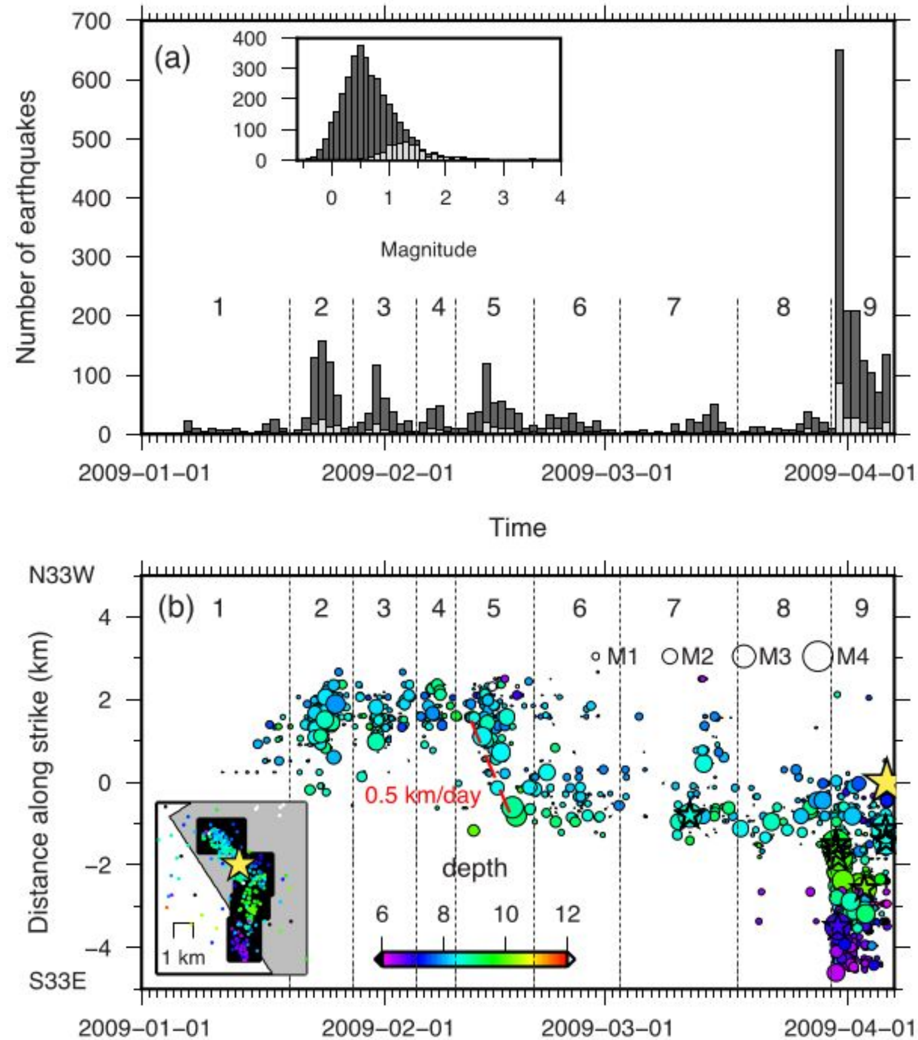
First published: 11 September 2014 Full publication history

DOI: 10.1002/2014GL061199 View/save citation

512 template earthquakes
3571 new earthquakes between -0.4 and 3.9

Highly stressed fault patch where the mainshock happened from multiple small earthquakes

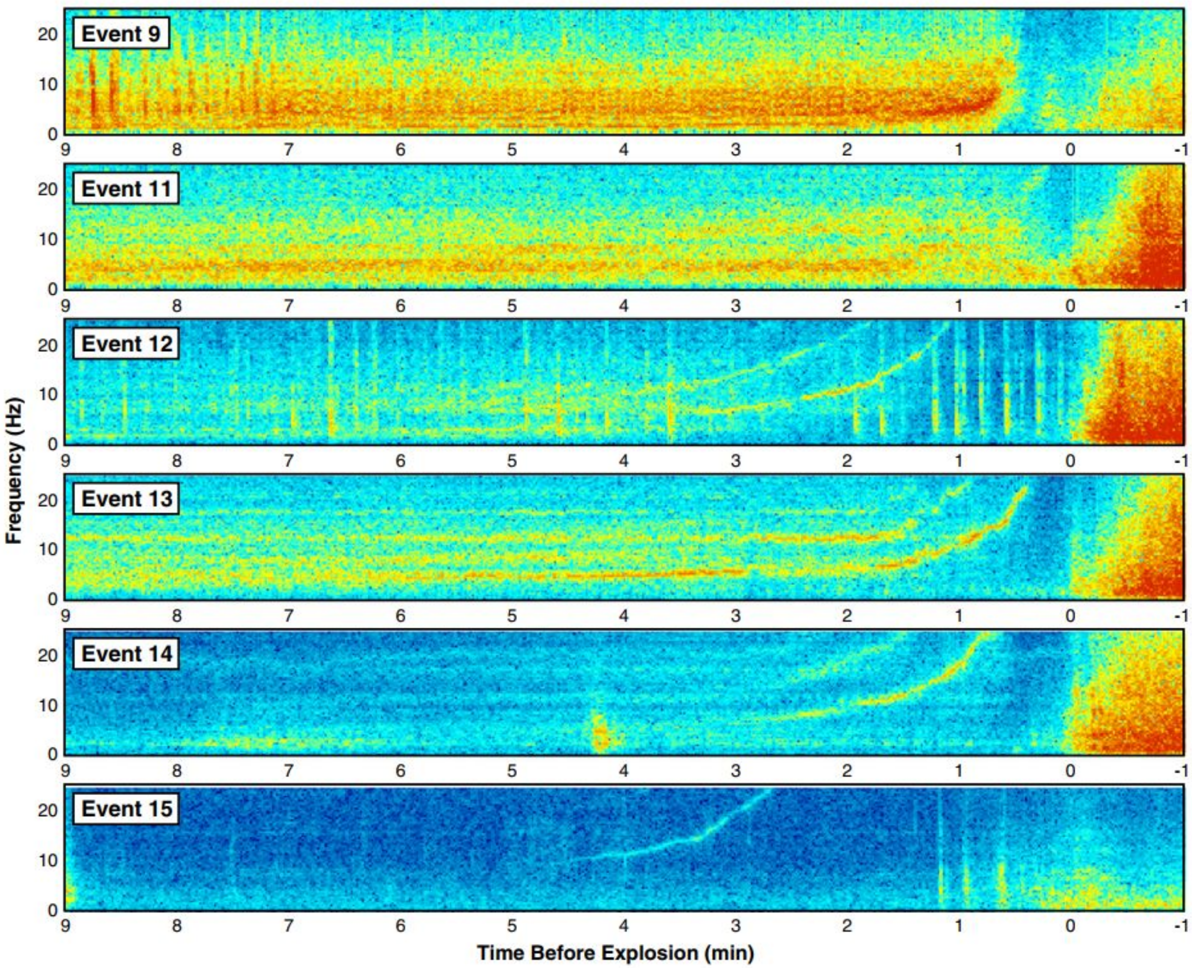
Migration with 0.5 km/day towards mainshock - slow slip transient



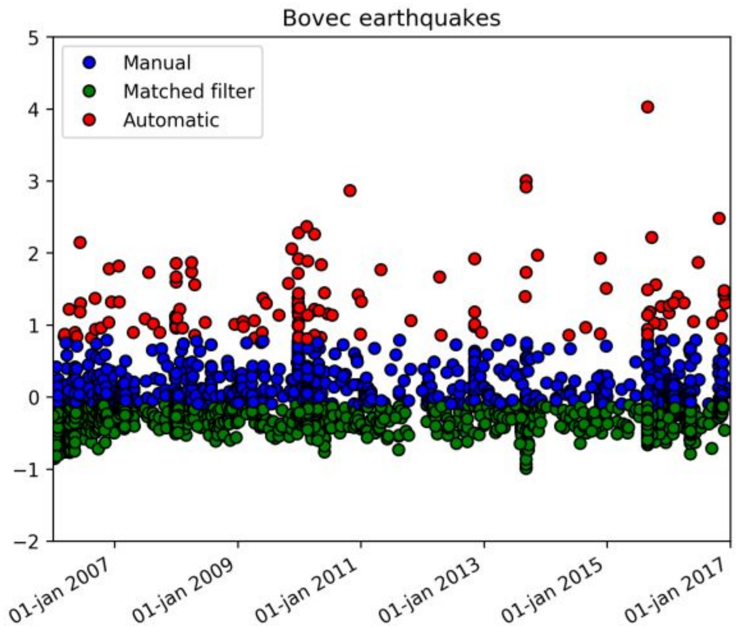
Strongly gliding harmonic tremor during the 2009 eruption of Redoubt Volcano

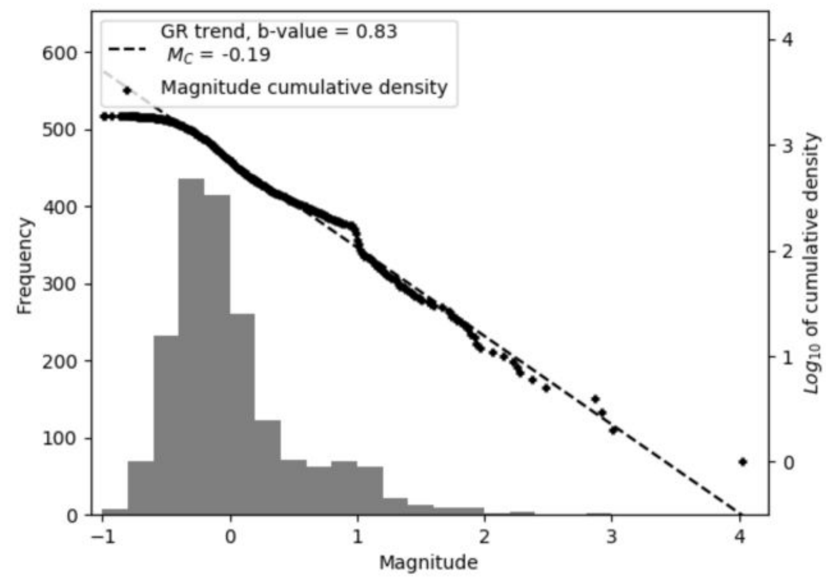
Alicia J. Hotovec [a,*], Stephanie G. Prejean [b], John E. Vidale [a], Joan Gomberg [c]

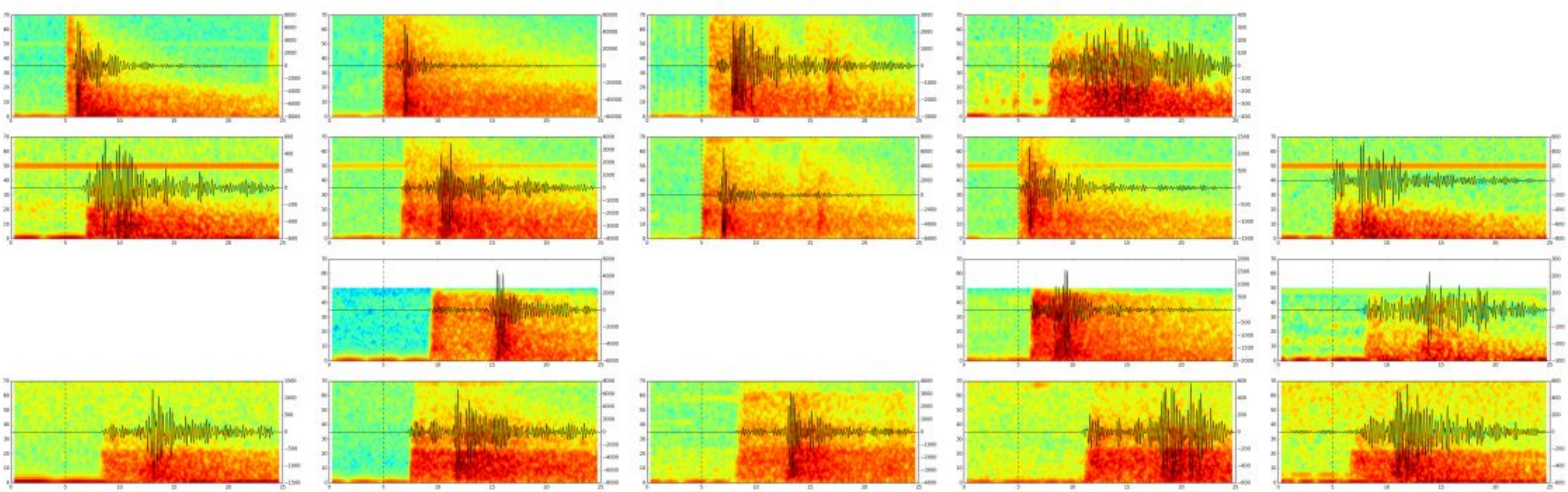
[a] University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195, USA
[b] United States Geological Survey, Volcano Science Center, 4210 University Dr., Anchorage, AK 99508, USA
[c] United States Geological Survey, University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195, USA



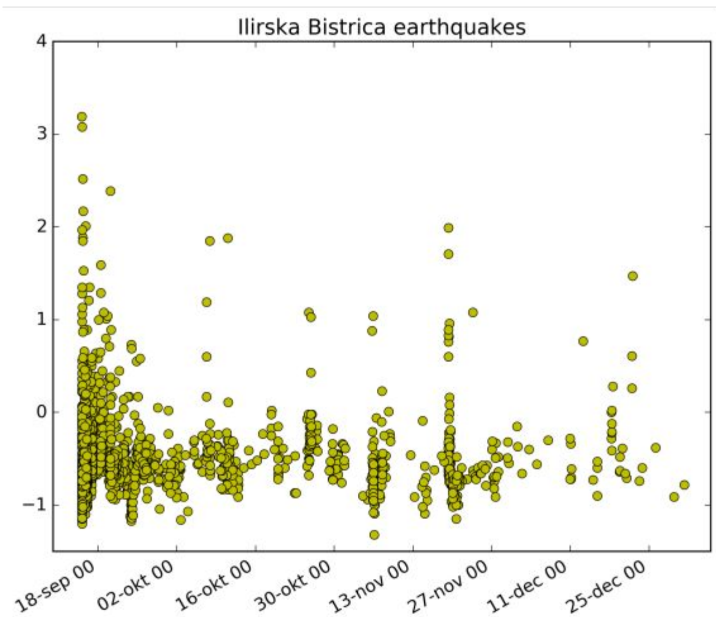
IFS: Ravne fault case

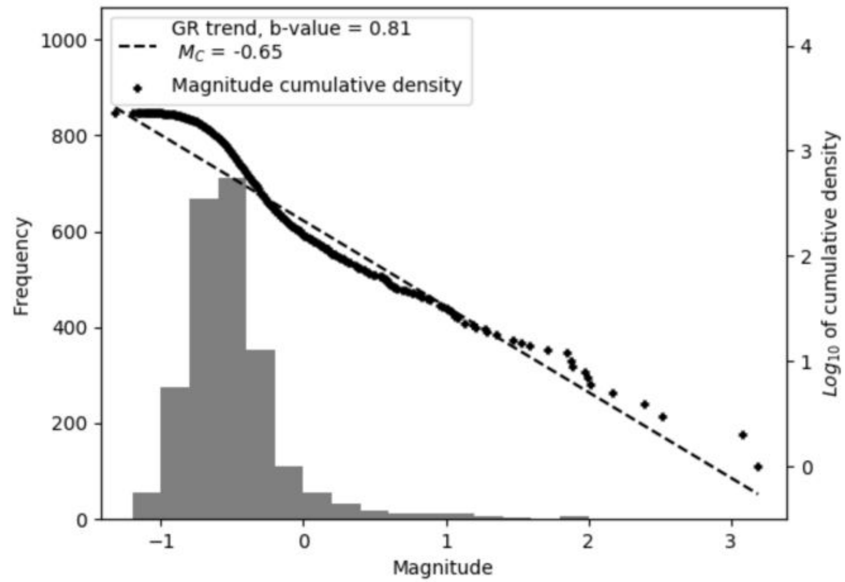


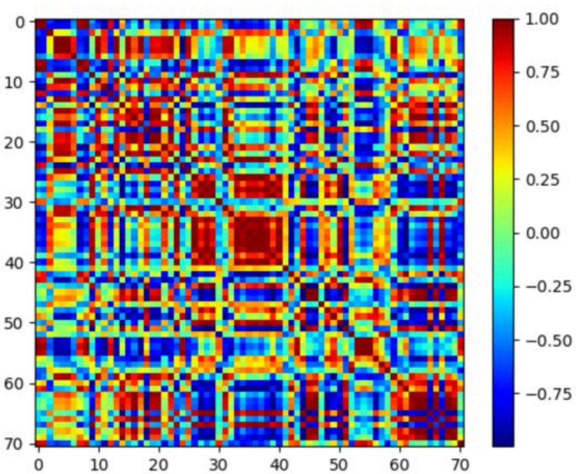


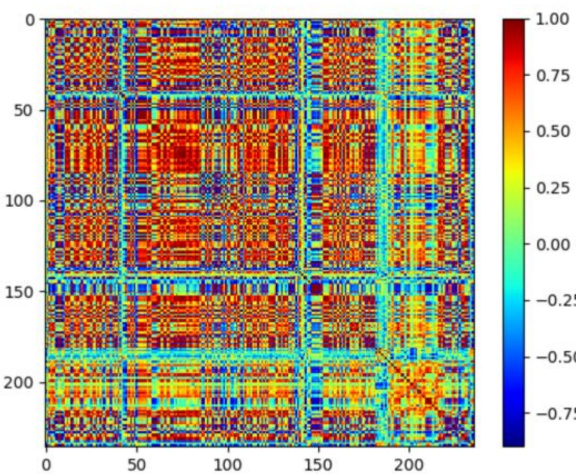


IFS: Ilirska Bistrica seqence









IFS: Ilirska Bistrica seqence