Imaging and monitoring with industrial seismic noise.

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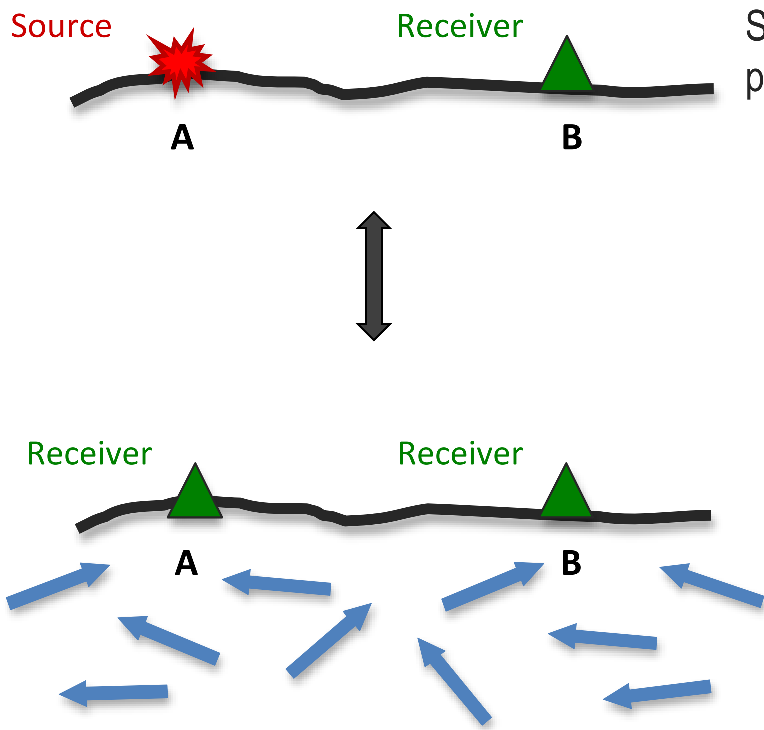
Boston, May 2016

Passive imaging: Long range correlations



Source in A $\Rightarrow$ the signal recorded in B characterizes the propagation between A and B.

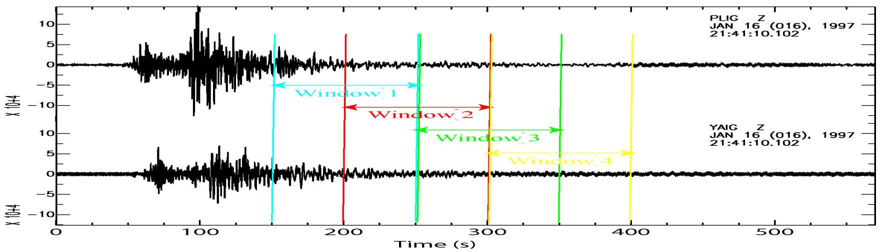
➡ **Green function** between A and B: G_{AB}

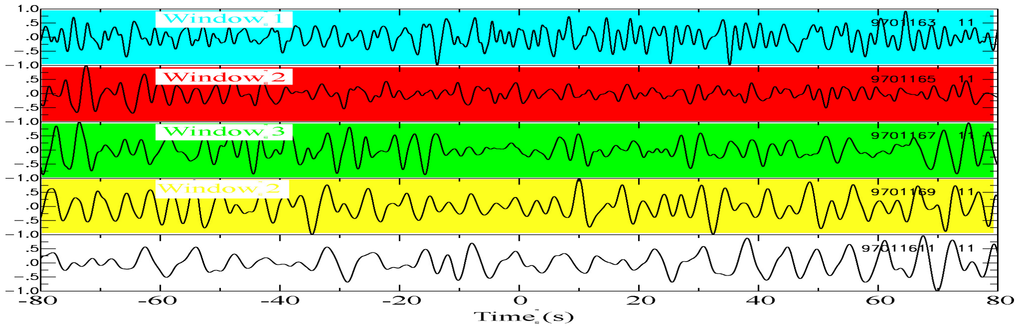
G_{AB} can be reconstructed by the correlation of noise or « diffuse » (equipartitioned) fields recorded at A and B (C_{AB})

A way to provide new data with control on source location and origin time

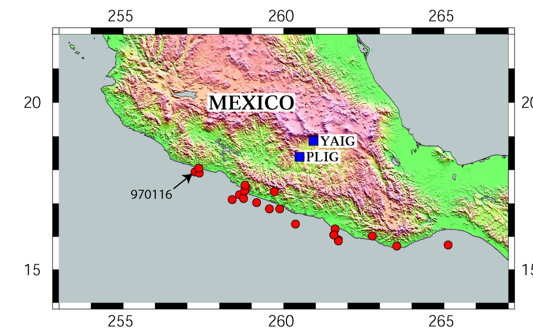
Seismological application: coda waves

Individual cross-correlations:fluctuations dominate.





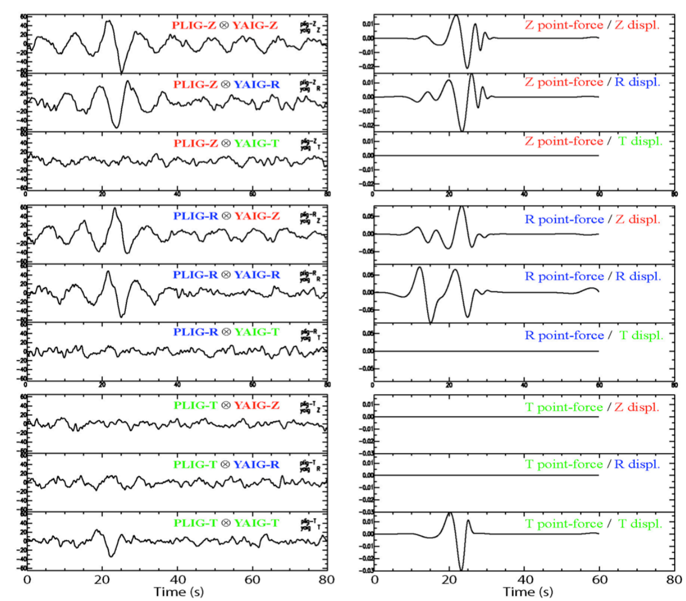
After averaging over 100 EQs➔



Emergence of the Green function

Stacks of 196 cross-correlations

Theoretical Green tensor at 69 km distance

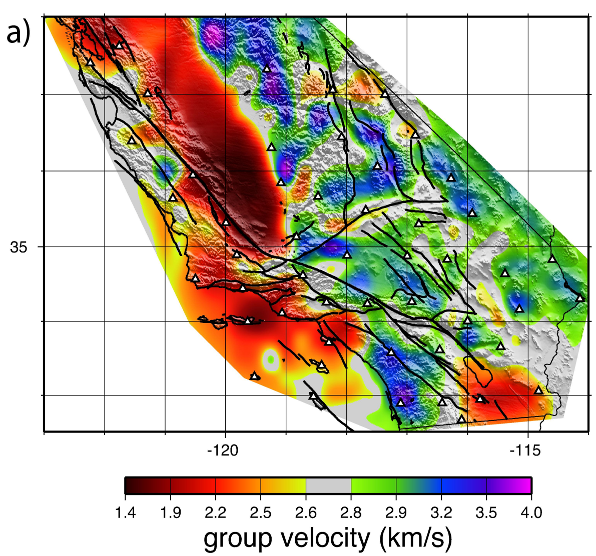


(Paul and Campillo, AGU 2001; Campillo and Paul, Science, 2003)

Cross-correlations of coda and noise records≈ Green functions = virtual seismograms

-demonstrated for the retrieval of surface waves (e.g. Paul and Campillo, 2001; Campillo and Paul, 2003; Shapiro and Campillo, 2004….) or body waves (e.g. Zhan et al., 2010 ; Poli et al., 2012).

High resolution velocity map of California obtained from ambient noise (Rayleigh)
(Shapiro, Campillo, Stehly and Ritzwoller, Science 2005)

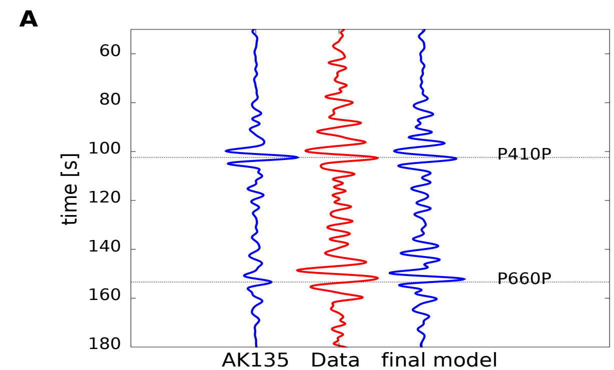


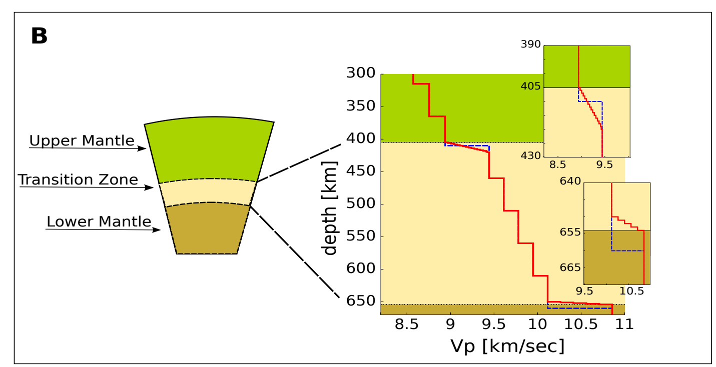
Large N sensor array =➔ $N^2/2$ correlations

Earth's mantle discontinuities from ambient noise (phase transition ➔ (P,T))

Body waves (Poli et al., 2012)

Poli, Campillo, Pedersen. Science 2012



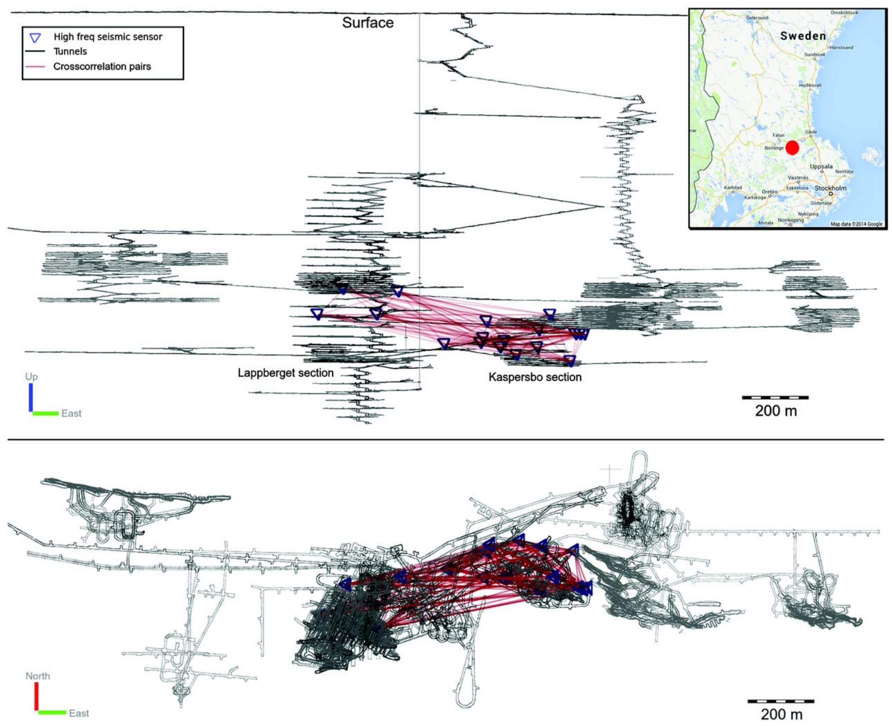


Smaller scale, industrial environment

Active mine: various sources of noise
tunnels (scattering)

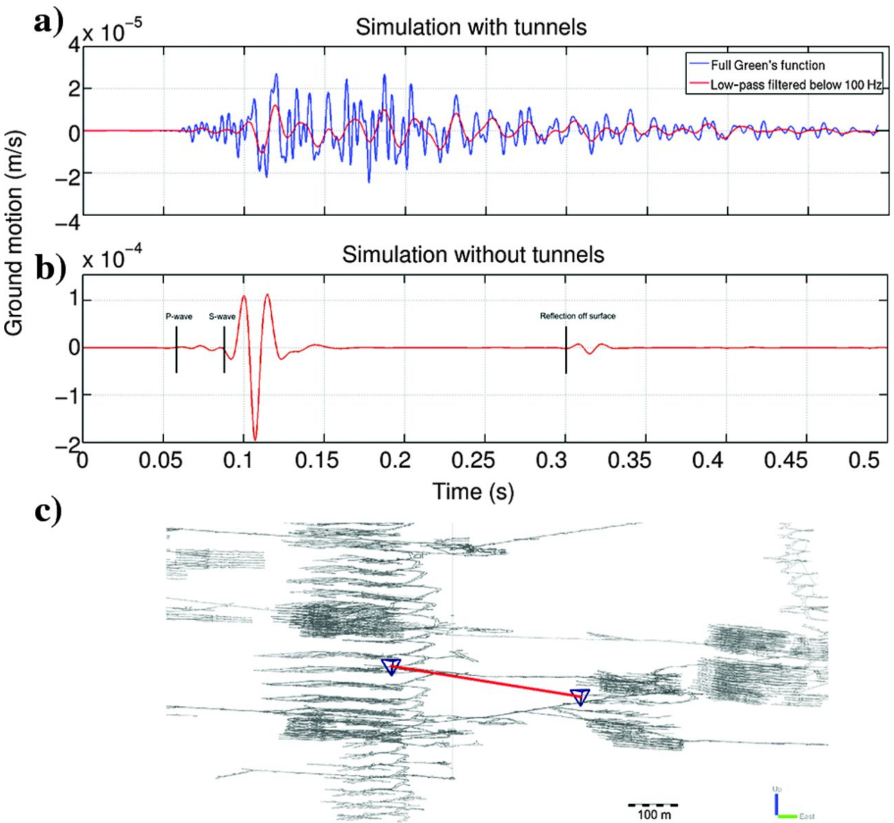
Section view

Plan view

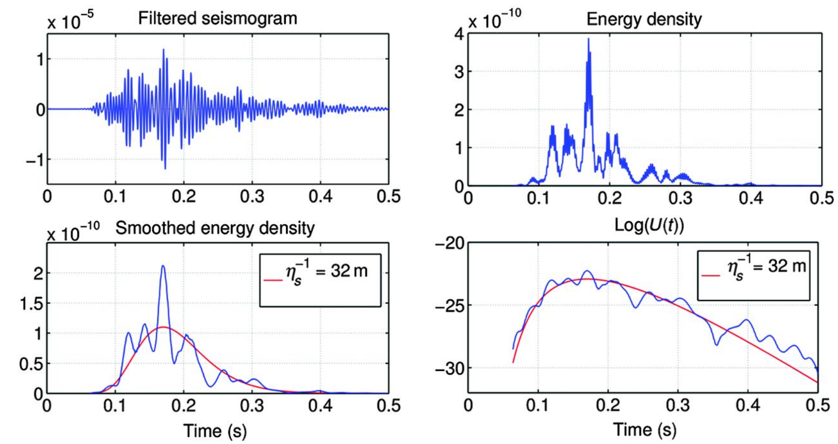


Results from Olivier, Brenguier, Campillo, Lynch and Roux, 2015
GEOPHYSICS, VOL. 80, NO. 3 (MAY-JUNE 2015); P. KS11–KS25

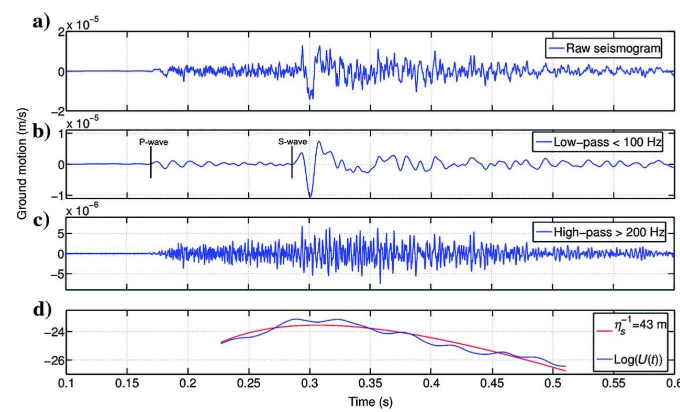
Numerical simulation in presence of the tunnels



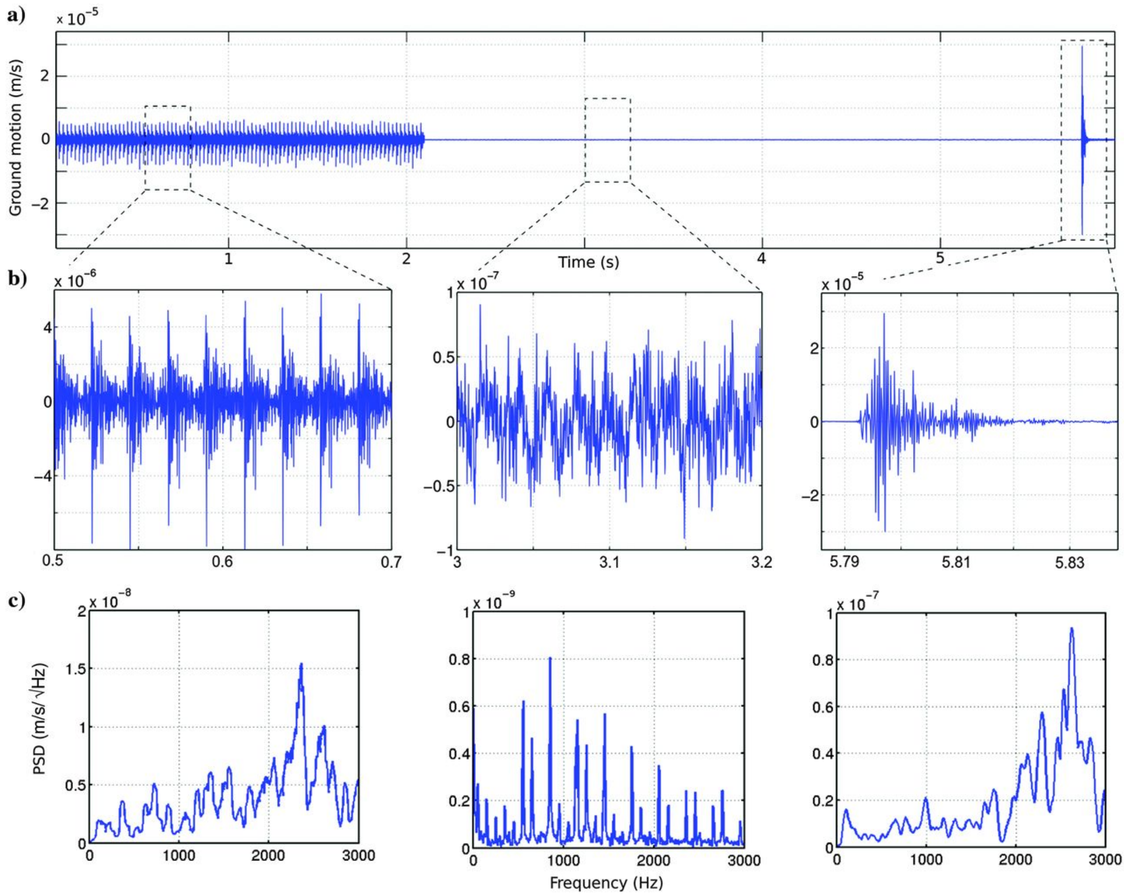
Synthetics vs Diffusion approximation



Actual event vs Diffusion approximation



Nature of the noise: example of a 5s record

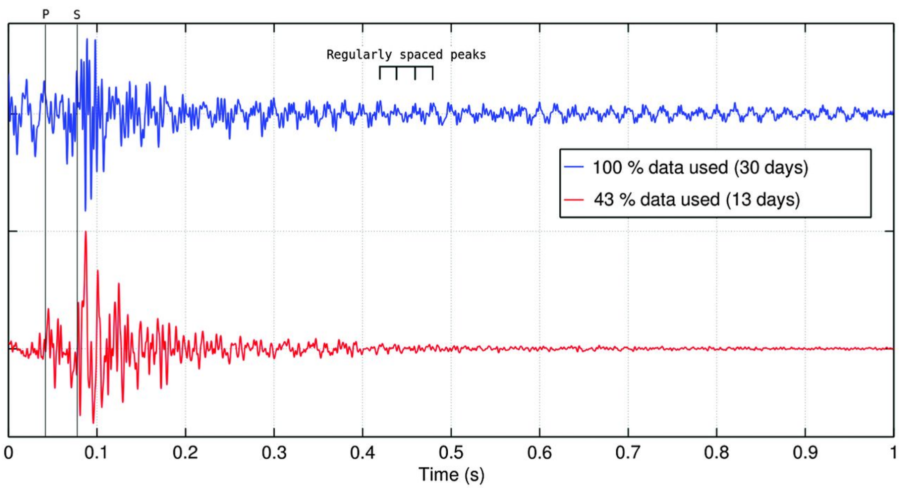


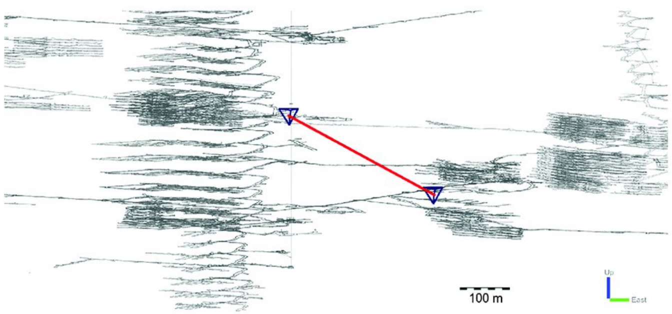
impacts of a hammer drill

microseismic event

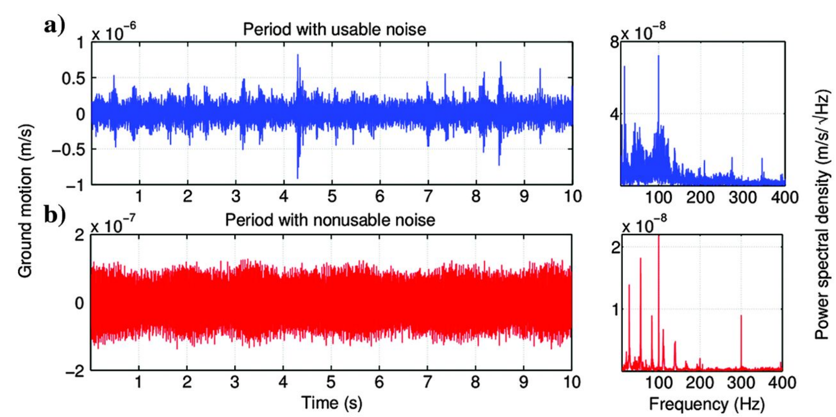
multiple sources
incl. (pumps, fans, etc.)

Correlation functions (ZZ)





Selective stacking: optimal time windows for body wave contributions:



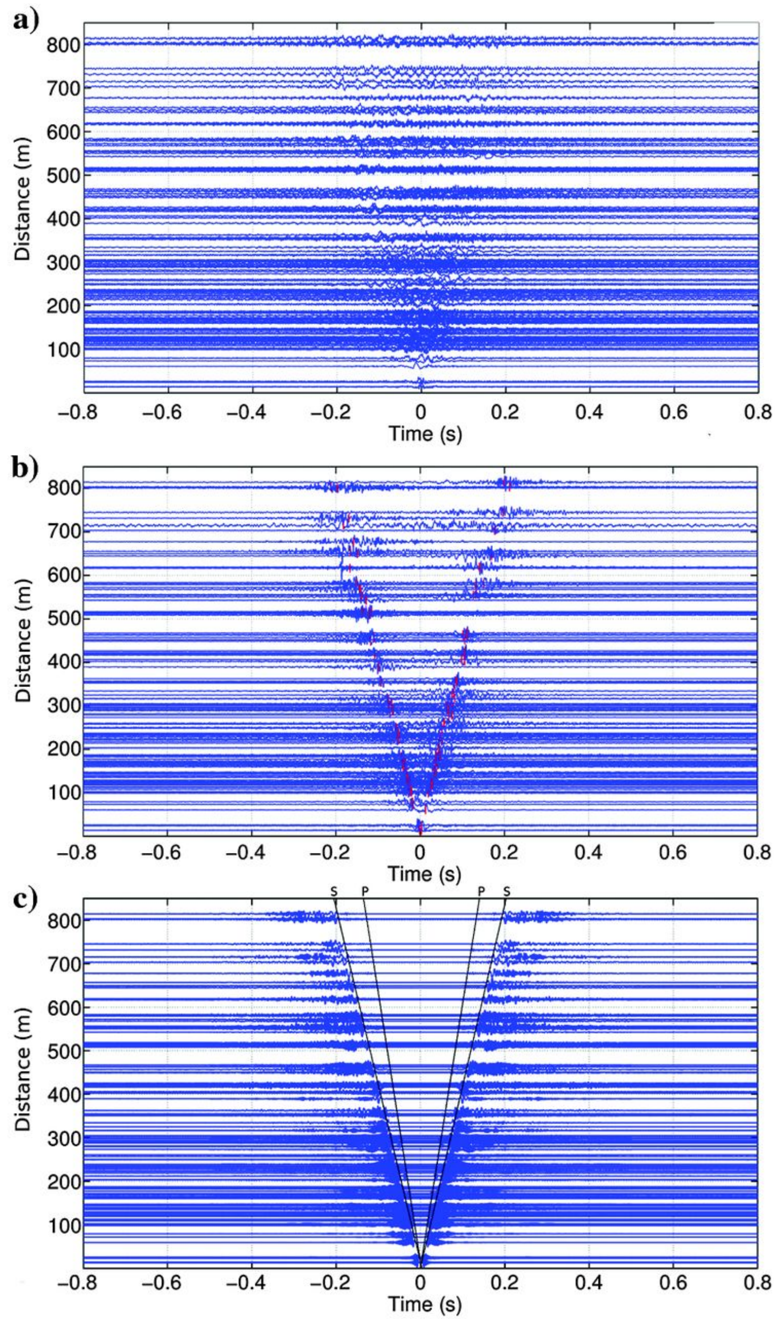
Removing of monochromatic sources

ZZ time-distance sections

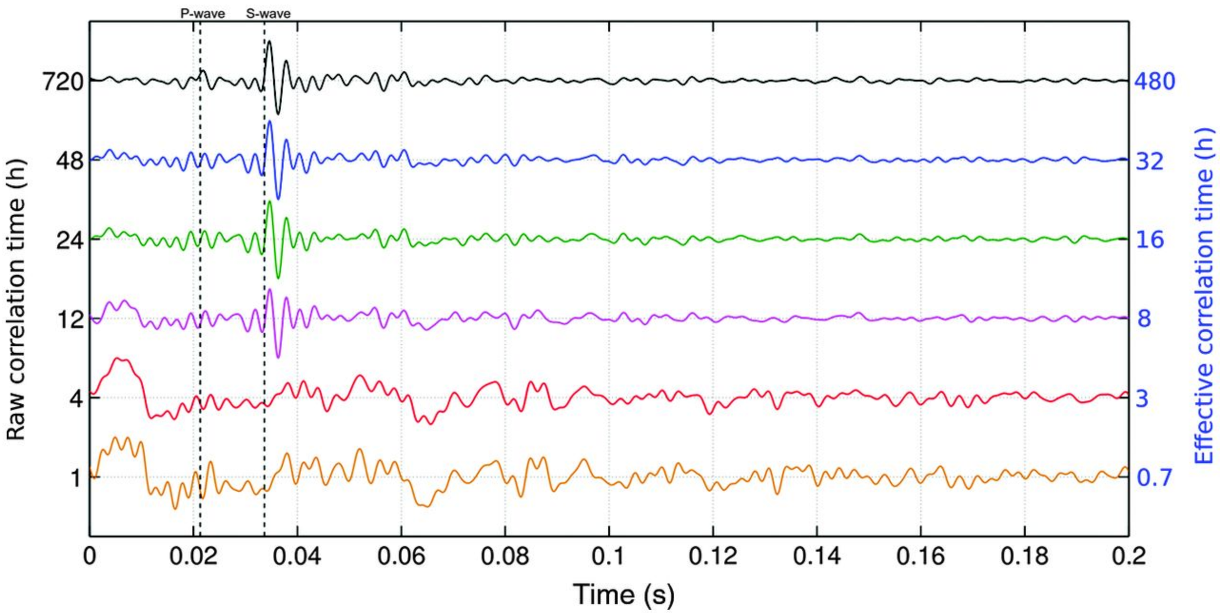
Noise correlations: blind stacking

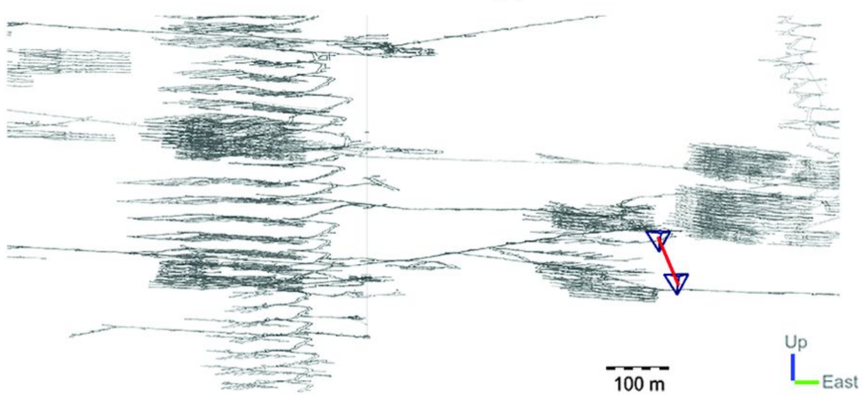
Noise correlations: optimal stacking

Synthetics

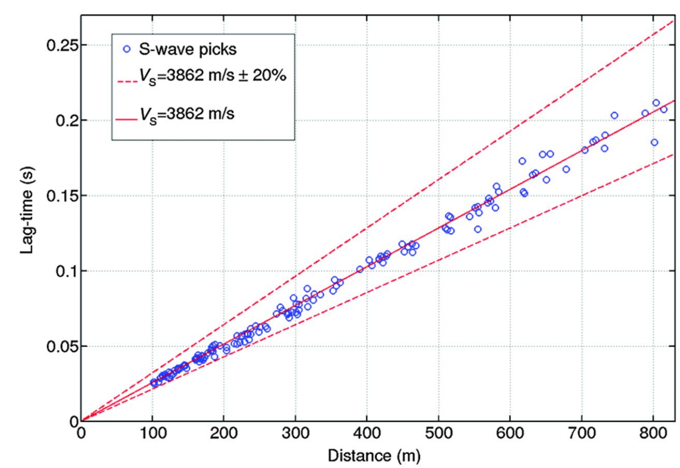


Convergence of the ZZ correlation function

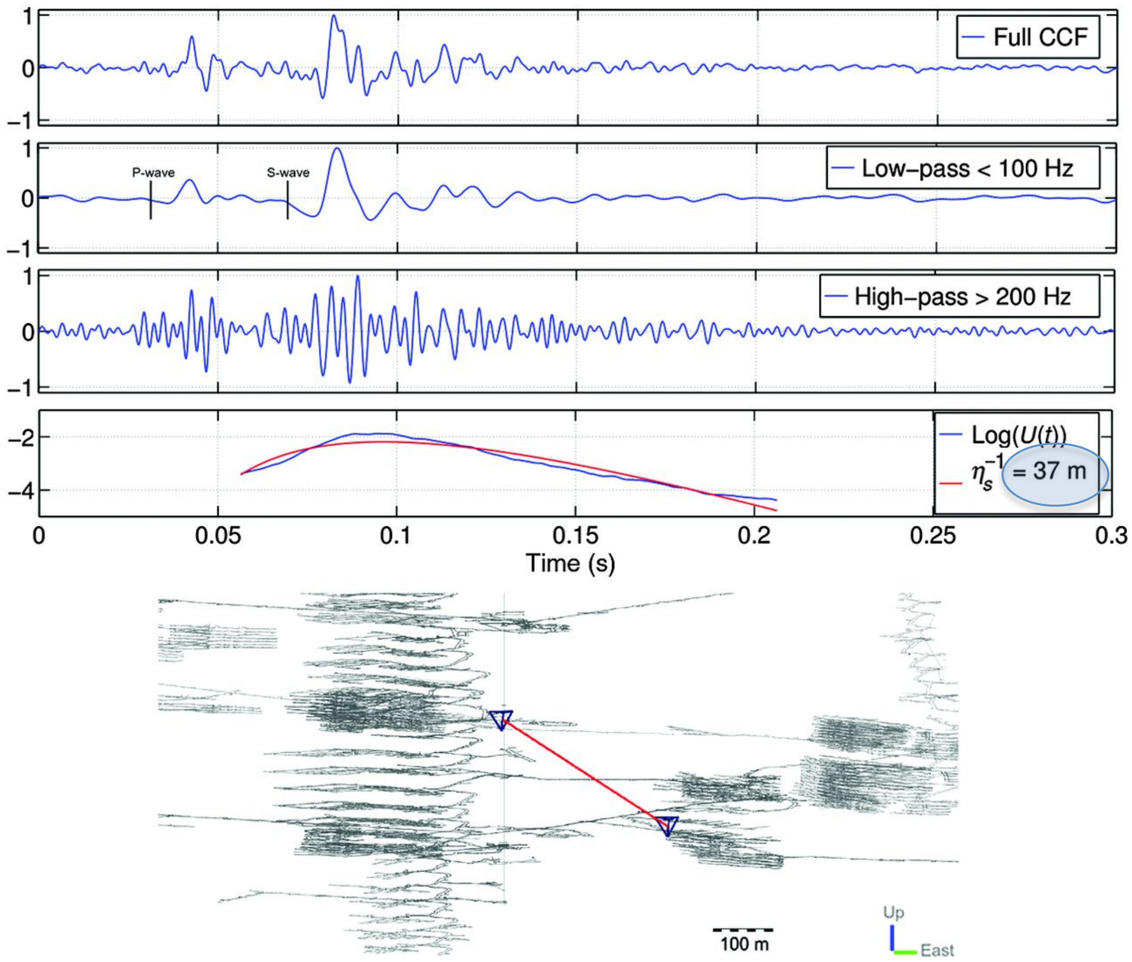




S wave velocity

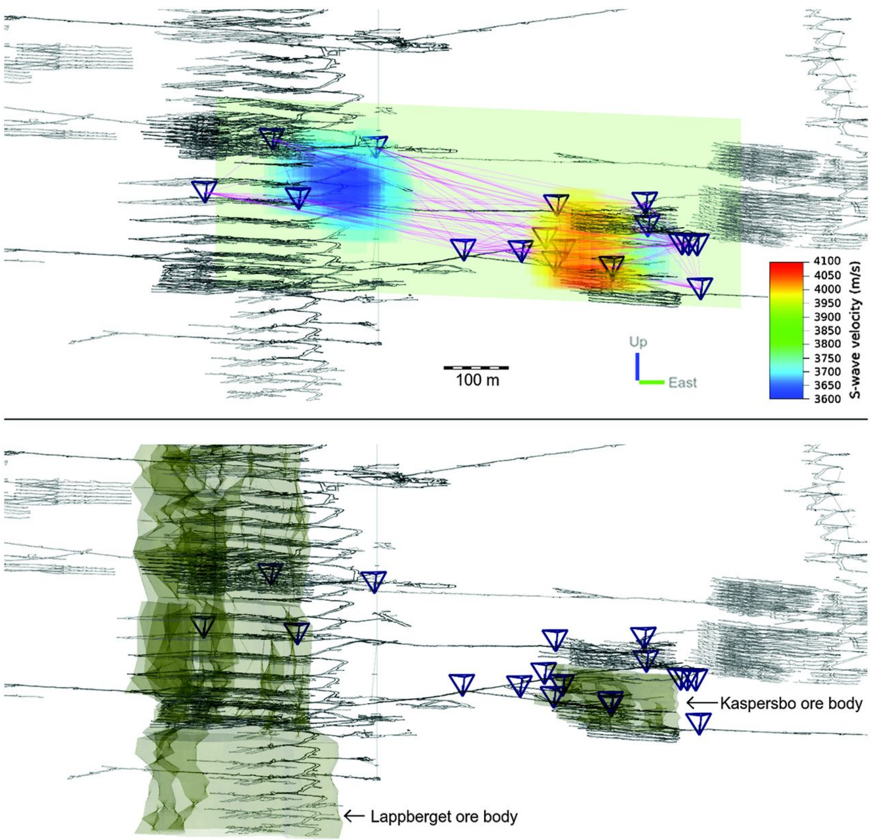


Scattering properties from noise correlations

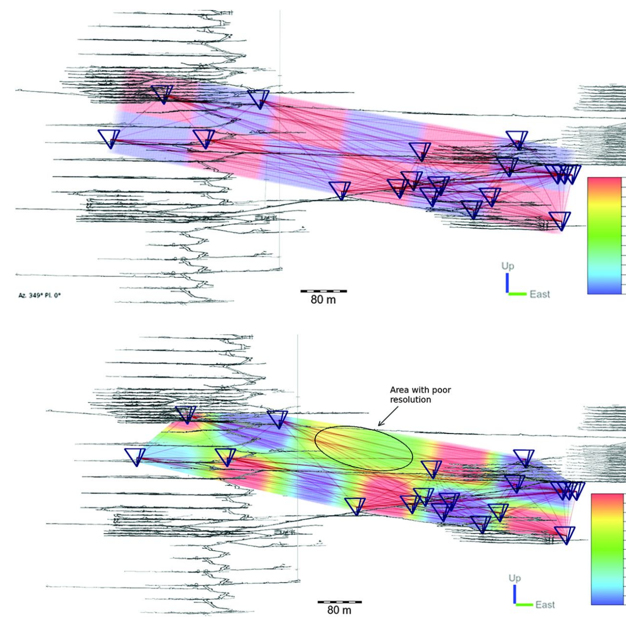


Diffusion approx.

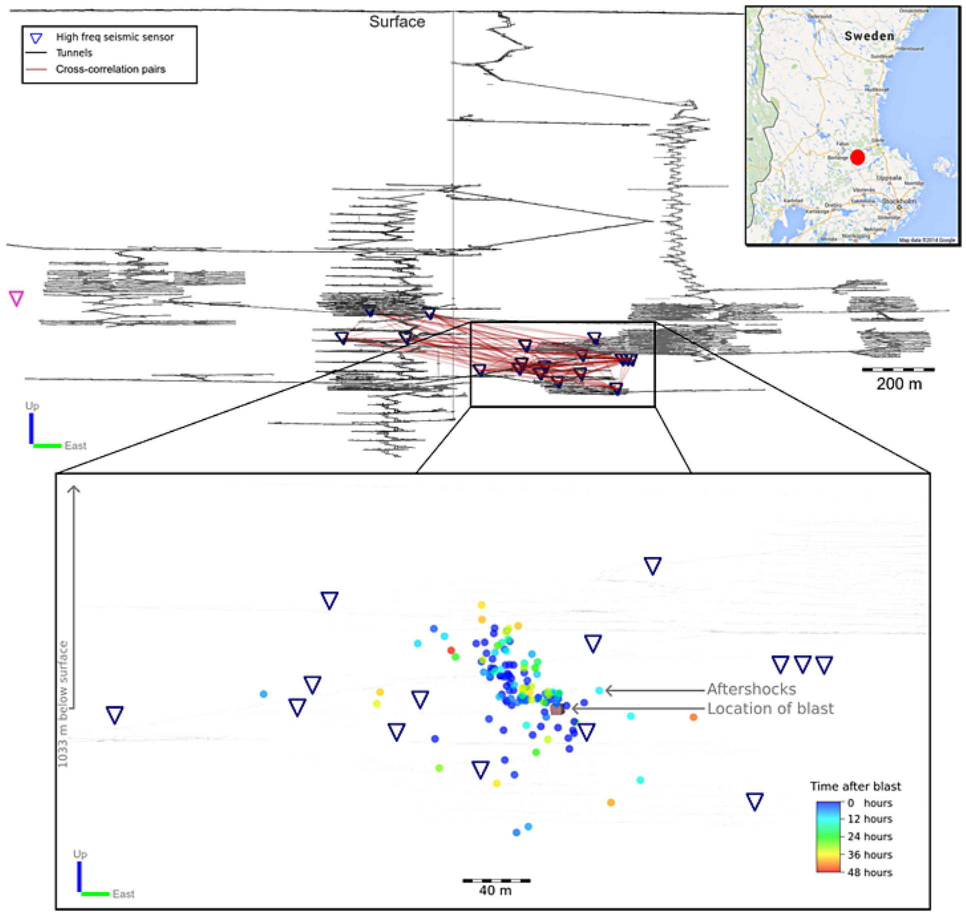
Travel time tomography from noise correlations



Checkboard test



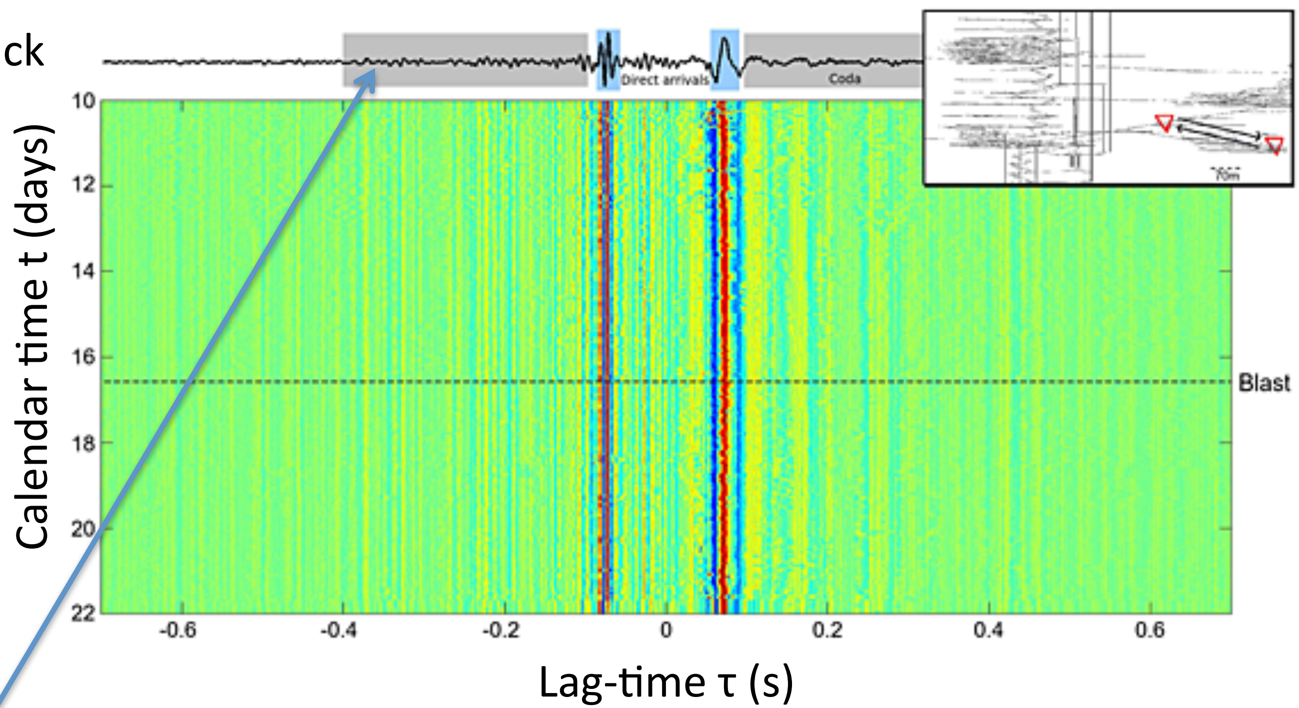
Investigation of coseismic and postseismic processes using in situ measurements of seismic velocity variations in an underground mine



Results from Olivier, Brenguier, Campillo, Roux, Shapiro and Lynch, 2015 **Geophysical Research Letters**
[Volume 42, Issue 21,](http://onlinelibrary.wiley.com/doi/10.1002/2015GL065975/full#grl53668-fig-0001) pages 9261-9269, 11 NOV 2015 DOI: 10.1002/2015GL065975
http://onlinelibrary.wiley.com/doi/10.1002/2015GL065975/full#grl53668-fig-0001

Investigation of coseismic and postseismic processes using in situ measurements of seismic velocity variations in an underground mine

12 day stack

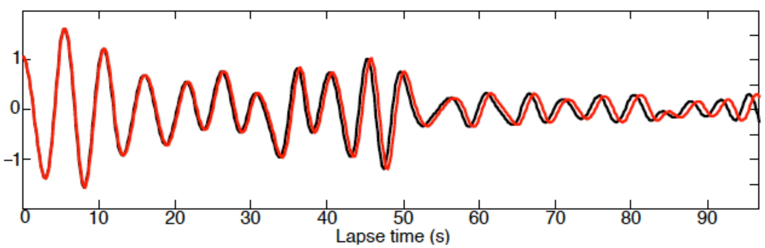


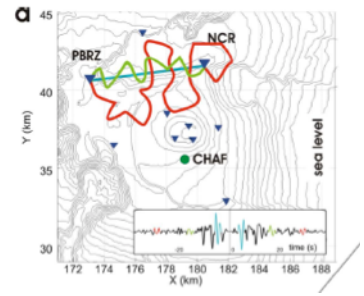
Hourly correlation functions for 12 days

Lag time window (scattered waves) for the delay analysis➔

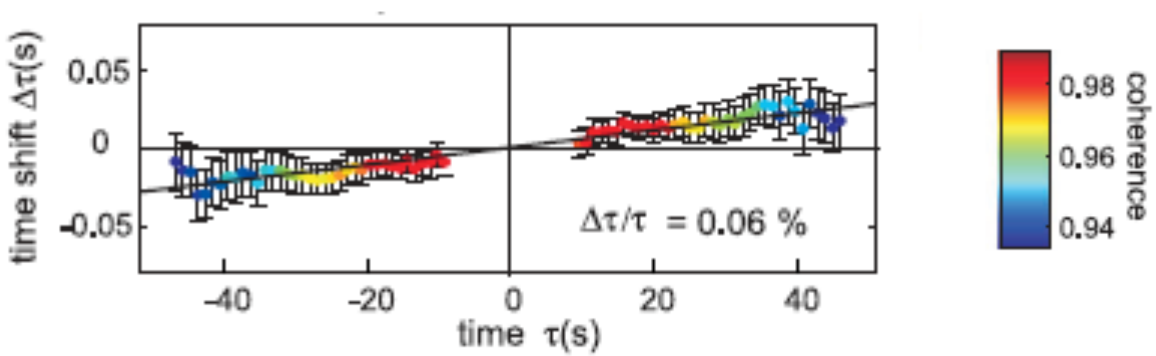
Detecting a small change of seismic speed: coda waves

Comparing a trace with a reference under the assumption of an homogeneous change



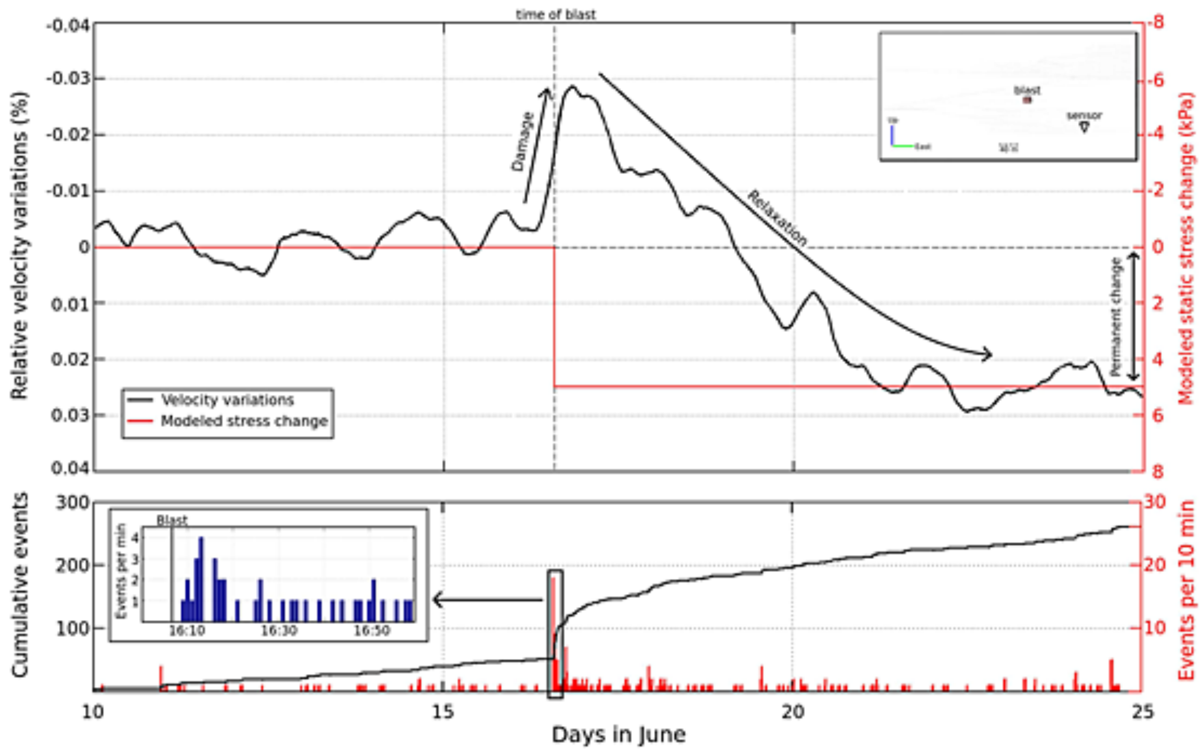


The ‘doublet’ method: moving window cross spectral analysis of the delays



Relative velocity change: $$\frac{dV}{V}(t) = -\frac{d\tau}{\tau}(t)$$

Temporal evolution of the seismic velocity measured from all correlations involving a particular sensor (4 hour window)

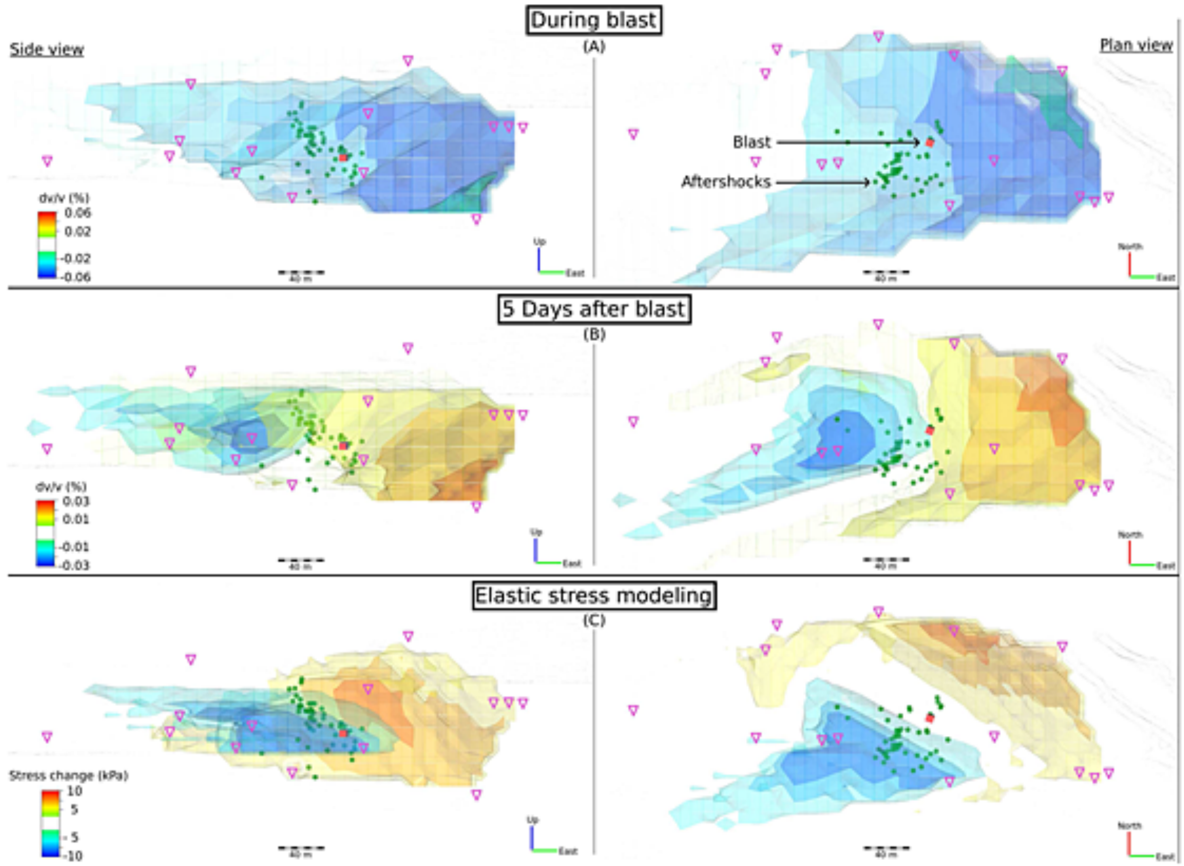


The relaxation time is larger than the one deduced from detected seismicity

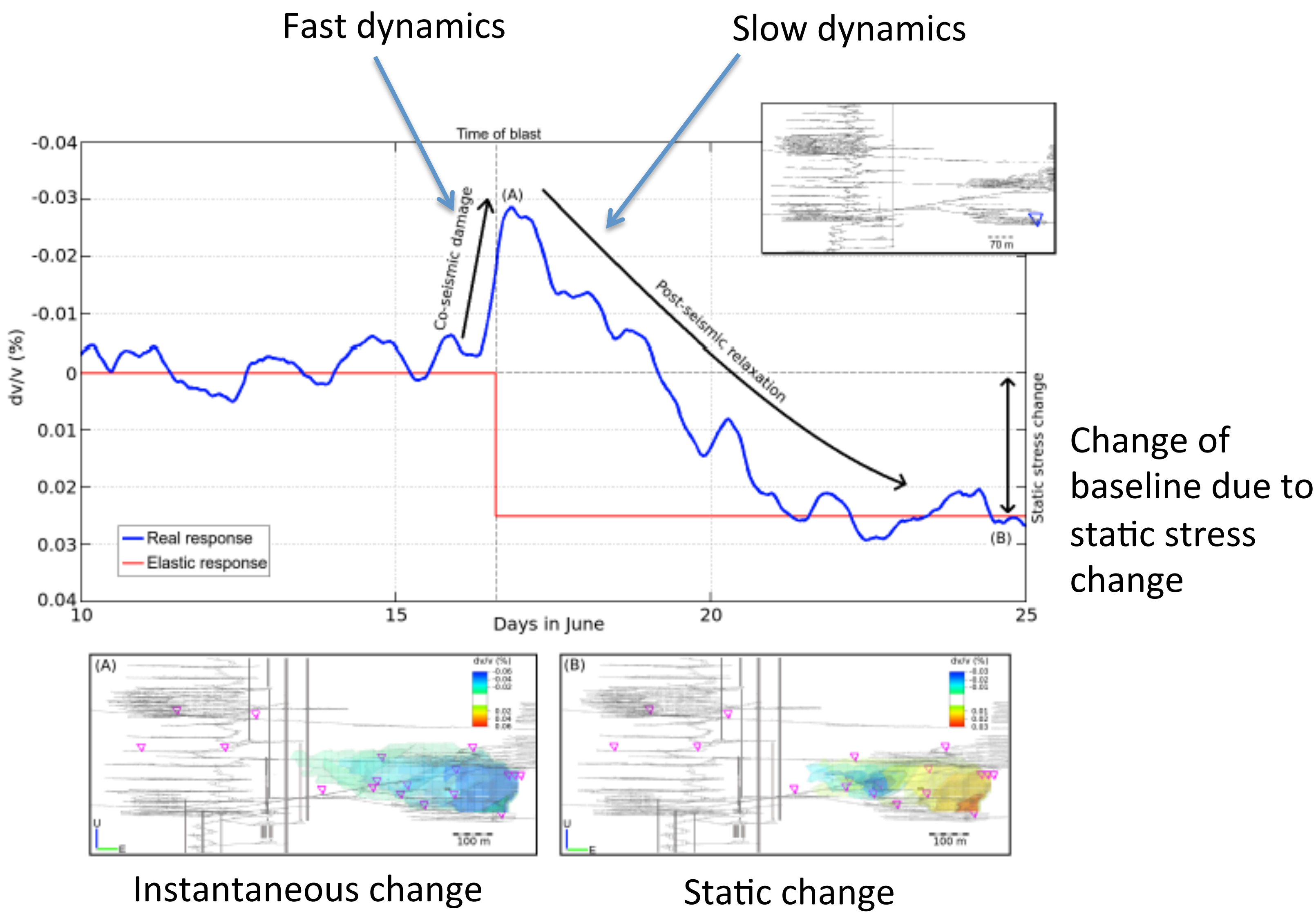
Comparison of velocity changes and volumetric stress changes

Instaneous velocity drop

'Static' change



Velocity change due to blast and excavation



Conclusions:

Passive (noise based) imaging is possible in industrial environment like mines.

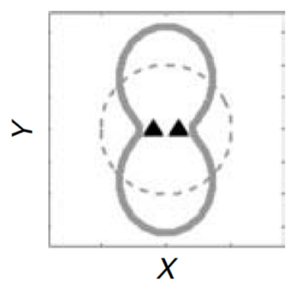
It requires a careful analysis of the noise properties

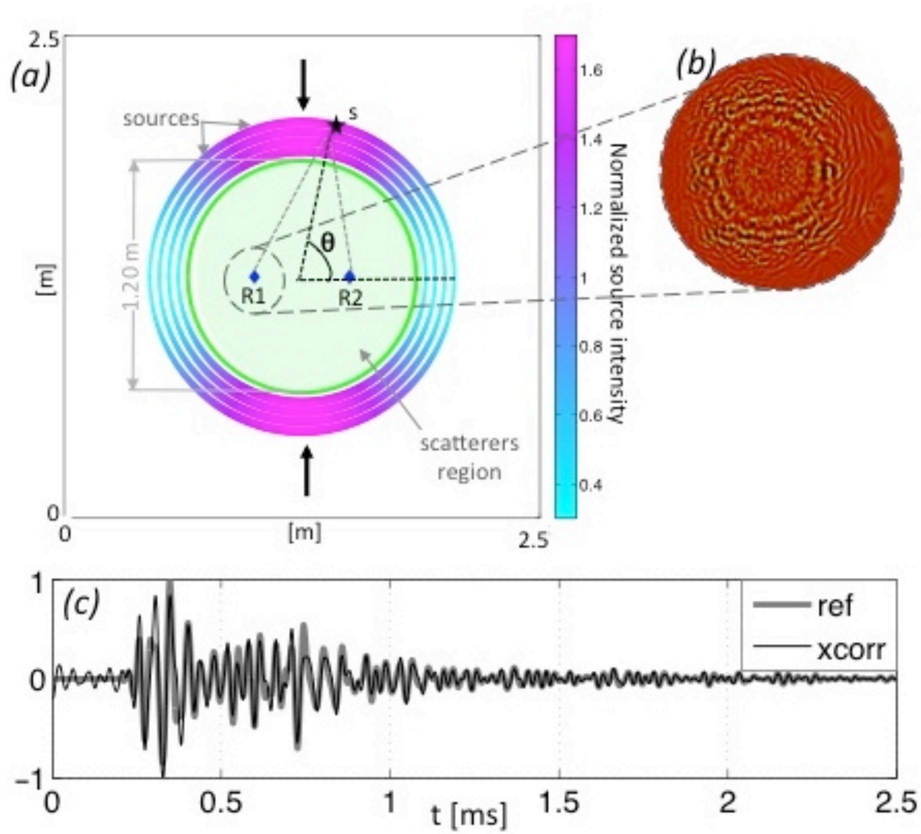
Body waves are retrieved and could be used for imaging

Time dependent elastic properties can be inferred giving new clues on the geomechanical evolution

Measuring slight changes of seismic velocity using coda waves (long travel time)
Numerical simulations in a scattering medium

2D spectral elements, anisotropic intensity of sources



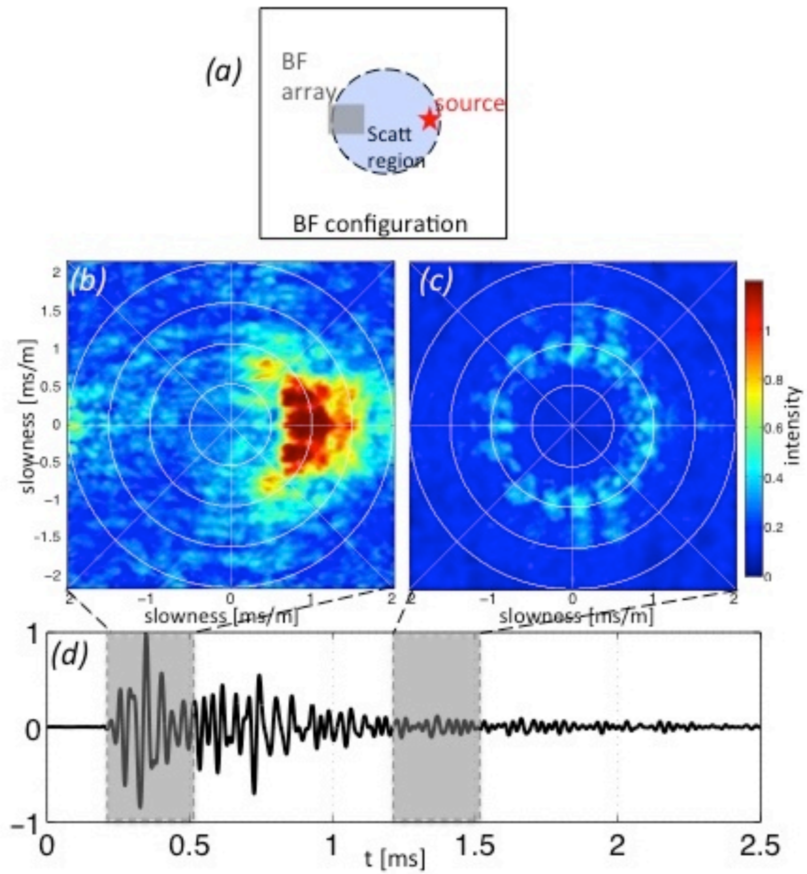


Comparison of correlations with Green function

Colombi, Chaput, Hillers et al., 2014 in press

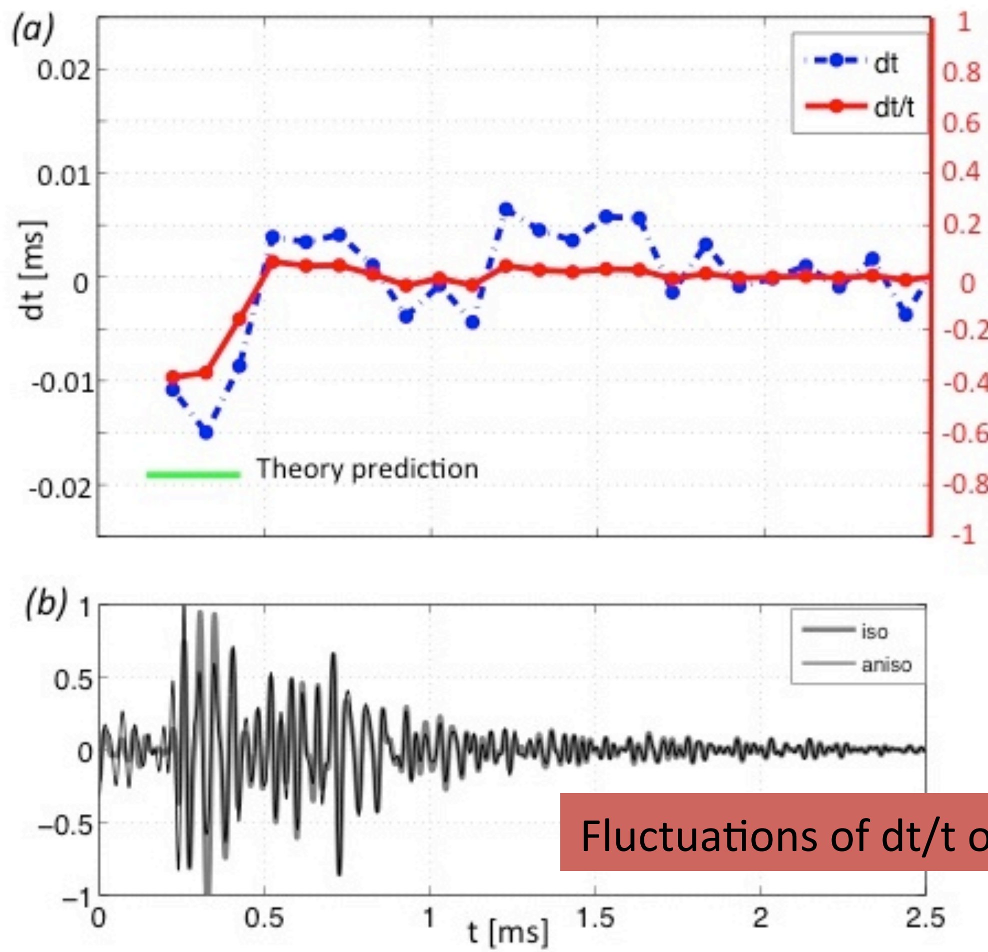
Effect of scattering   (single source)

Beam forming



Colombi, Chaput, Hillers et al., 2014 in press

Measure of the bias induced by a strong anisotropy of the wave field
(delay with respect to the Green function)



Blue: delay

Red: relative delay

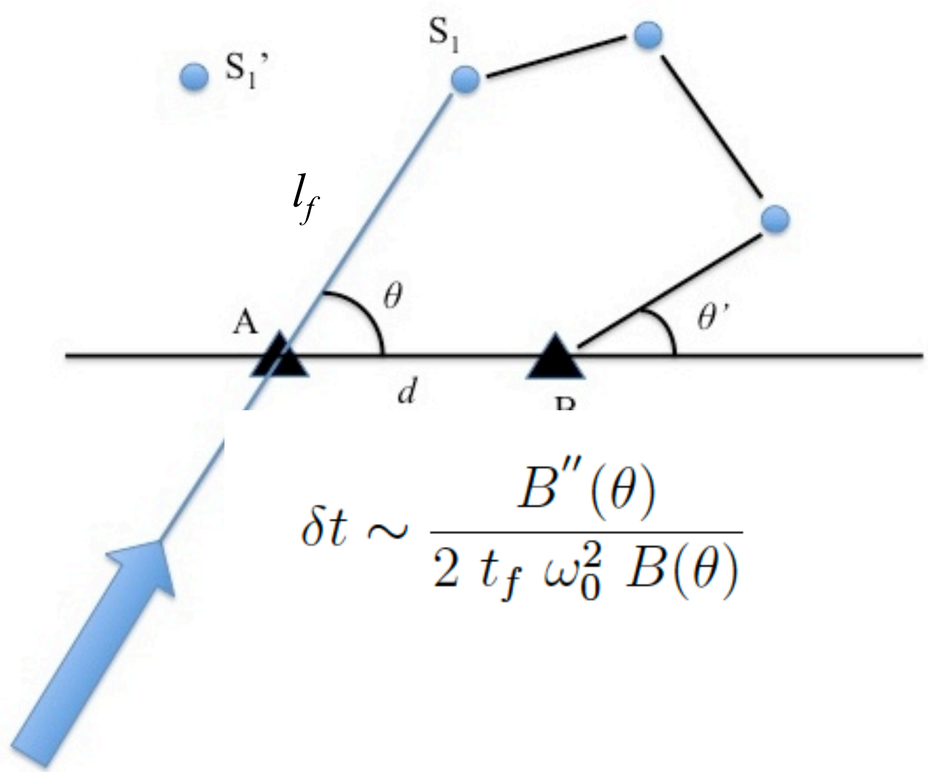
Fluctuations of dt/t of the order of 10^{-4}

Colombi, Chaput, Hillers et al., 2014

Representation of coda waves as the sum of contributions of numerous paths

For a single path:

$t_f = l_f / V$



$$\delta t \sim \frac{B''(\theta)}{2\, t_f\, \omega_0^2\, B(\theta)}$$

We have to compute the contributions of paths with first scatterers at all distances l_f and all azimuths θ

We have to consider that the distribution of distance between scattering events is exponential:

$$P(l_f) = \frac{1}{l} e^{-\frac{l_f}{l}}$$

where l is the mean free path

$$< l_f > = l \qquad t_f = l_f / V$$

We make use of

$$\delta t \sim \frac{B''(\theta)}{2\, t_f\, \omega_0^2\, B(\theta)}$$

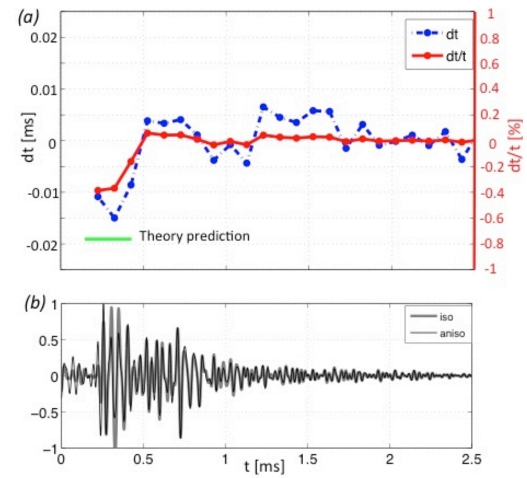
valid for $l_f > \lambda$

Applications

Numerical simulations

$$l = 0.5m,\ c = 2000\text{m/s},$$

$$f_0 = 30000\text{Hz},\ B_2 = -0.6 \text{ and } \tau_m = 0.002\text{s}$$



➔ fractional error $\frac{\delta t(\tau_m)}{\tau_m}$ of 10^{-4}.