Passive monitoring of the bedrock response to the 2018 Helsinki/Espoo geothermal stimulation

George Taylor and Gregor Hillers

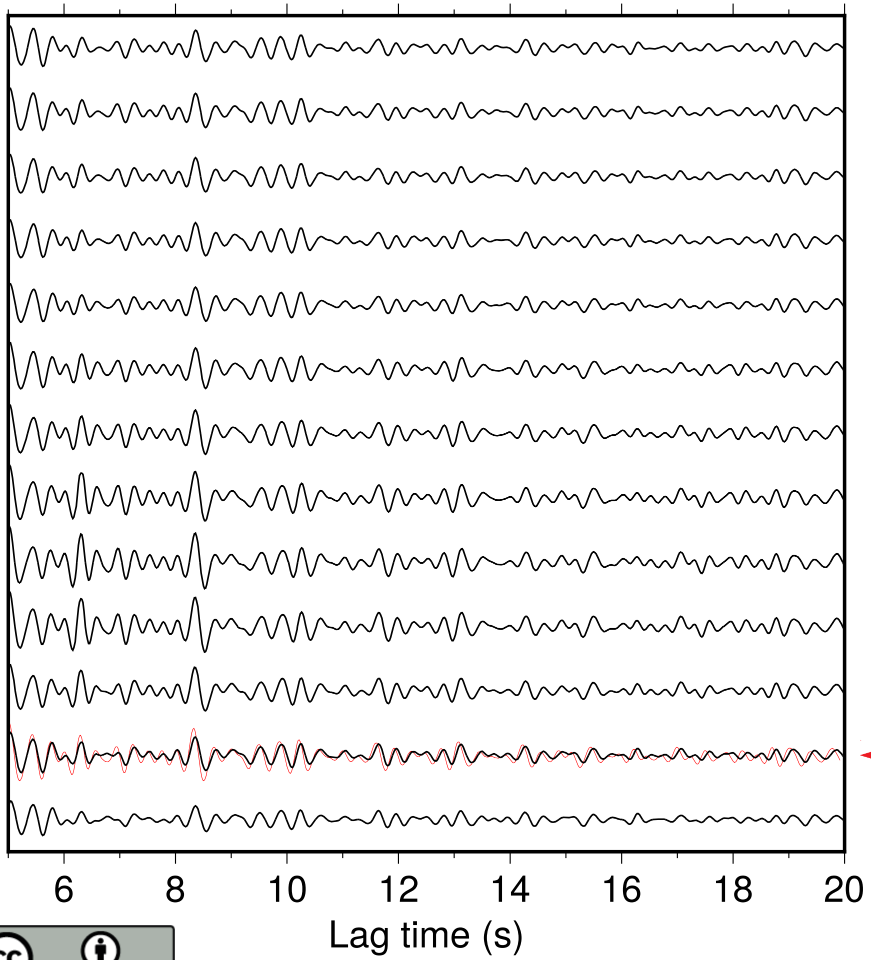
Institute of Seismology, University of Helsinki

UNIVERSITY OF HELSINKI

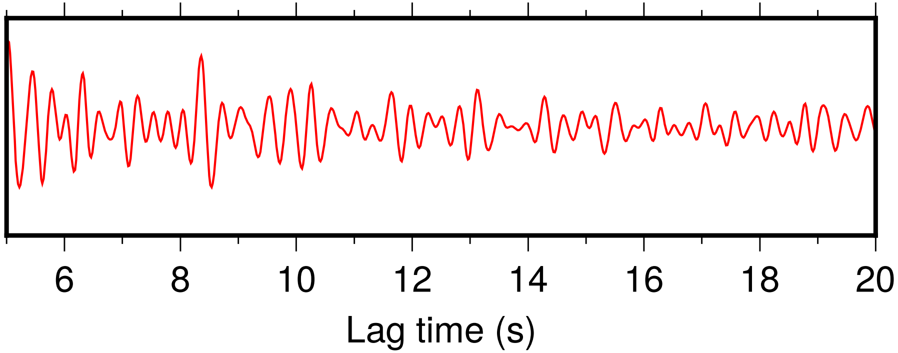
george.taylor@helsinki.fi

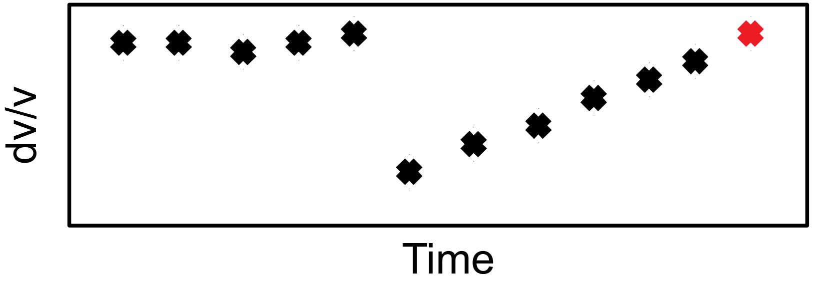
Monitoring – The reference approach is common, but often unreliable

Take your correlation gather



Calculate a stack – your “reference”



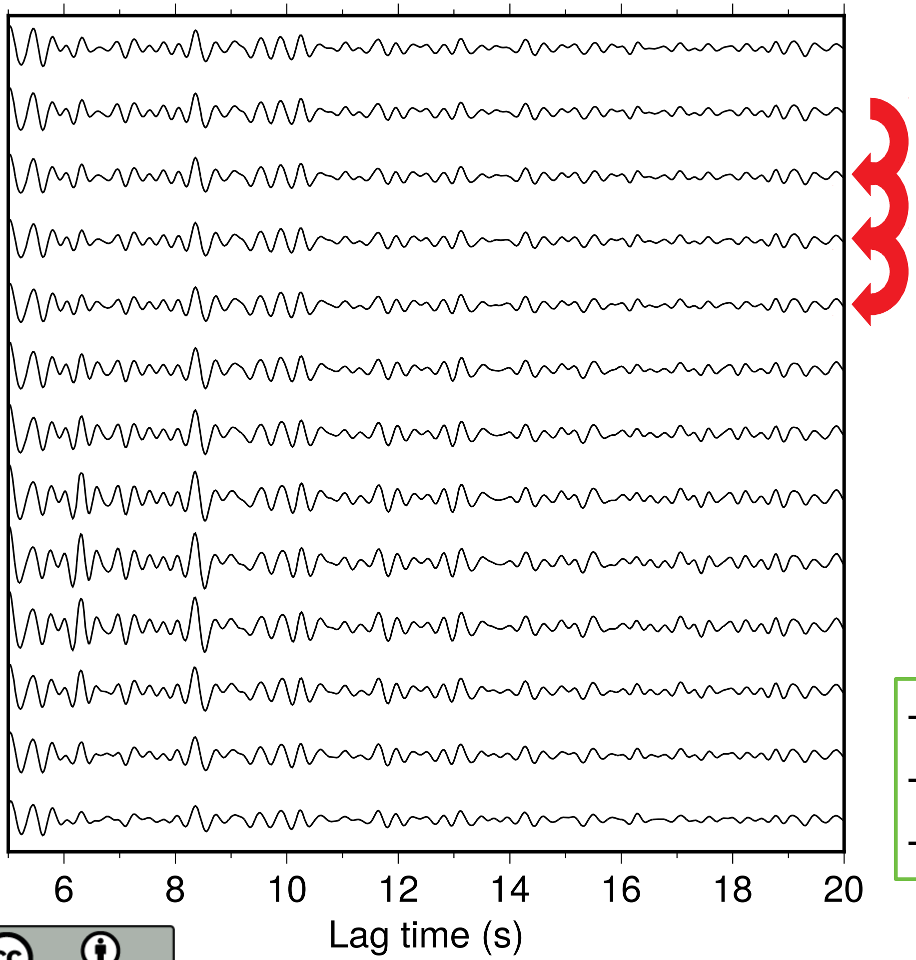


- Is the reference suitable?
- Variations in the noise field?
- Uncertainties?

Reference Independent Velocity Variation Estimator: RIVV-E

Brenguier et al. *Science* (2014)

Take your correlation gather



Compute velocity change between ALL correlations

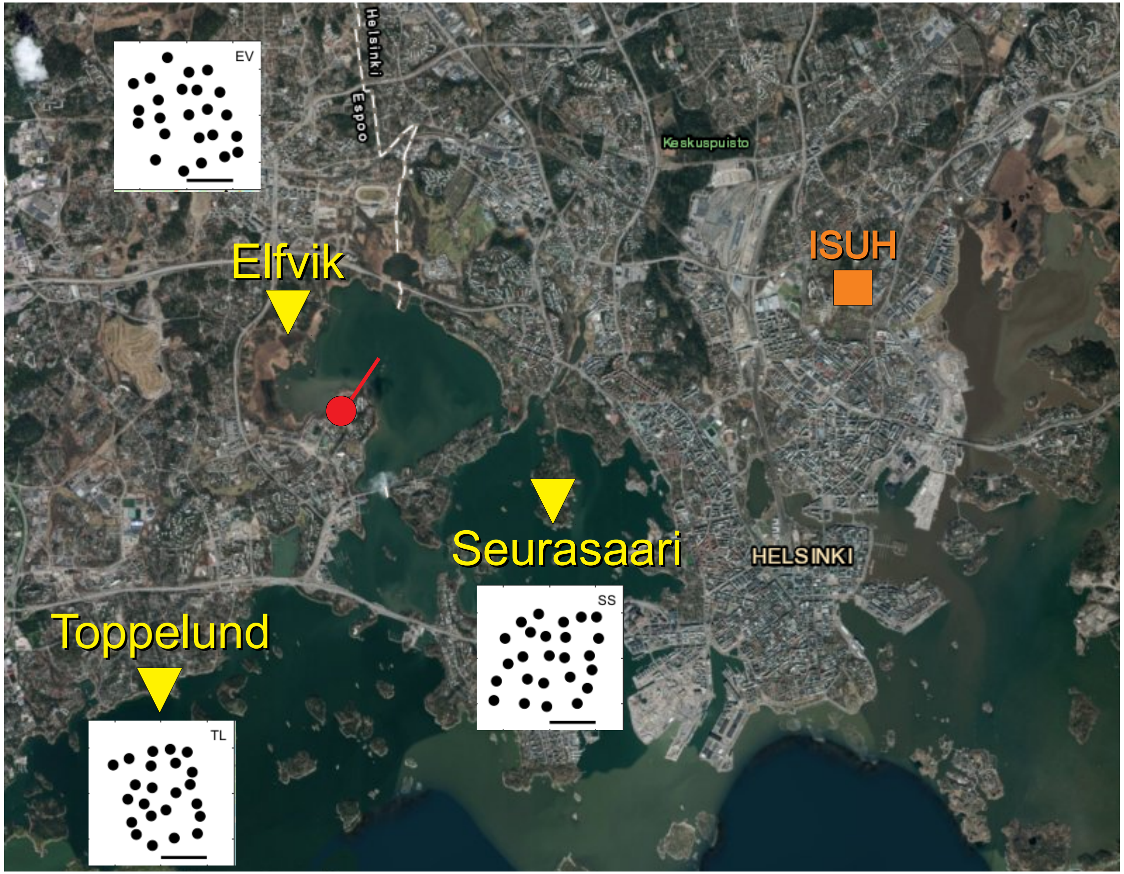
$$\mathbf{d}\begin{bmatrix} 0.002 \\ 0.005 \\ 0.001 \\ \vdots \\ 0.007 \\ 0.003 \\ 0.003 \end{bmatrix} = \mathbf{G}\begin{bmatrix} -1 & 1 & 0 & \cdots & 0 \\ -1 & 0 & 1 & \cdots & 0 \\ \vdots & & \cdots & & \vdots \\ \vdots & & \cdots & & \vdots \\ \vdots & & \cdots & & \vdots \\ 0 & \cdots & -1 & 0 & 1 \\ 0 & \cdots & 0 & -1 & 1 \end{bmatrix} \mathbf{m}\begin{bmatrix} dv_1 \\ dv_2 \\ dv_3 \\ \vdots \\ dv_{13} \end{bmatrix}$$

$$m = \left(G^T C_d^{-1} G + \alpha C_m^{-1} G\right)^{-1} G^T C_d^{-1} d$$

- No need for a reference
- Uses more data = more robust
- Small data gaps accounted for

- Need to solve large linear system
- Smoothing required (arbitrary)
- Uncertainty not easily obtained

Aside: Modern seismology trending towards large sensor deployments



The problem scales <u>quadratically</u>....

75 stations = 2775 station pairs

ZZ only, 100 days of data = 4950 corr. pairs

13,736,250 dv/v calculations for **d**.

Multiply for more motion components, etc...

A lot of number crunching!

Aside: Modern seismology trending towards large sensor deployments

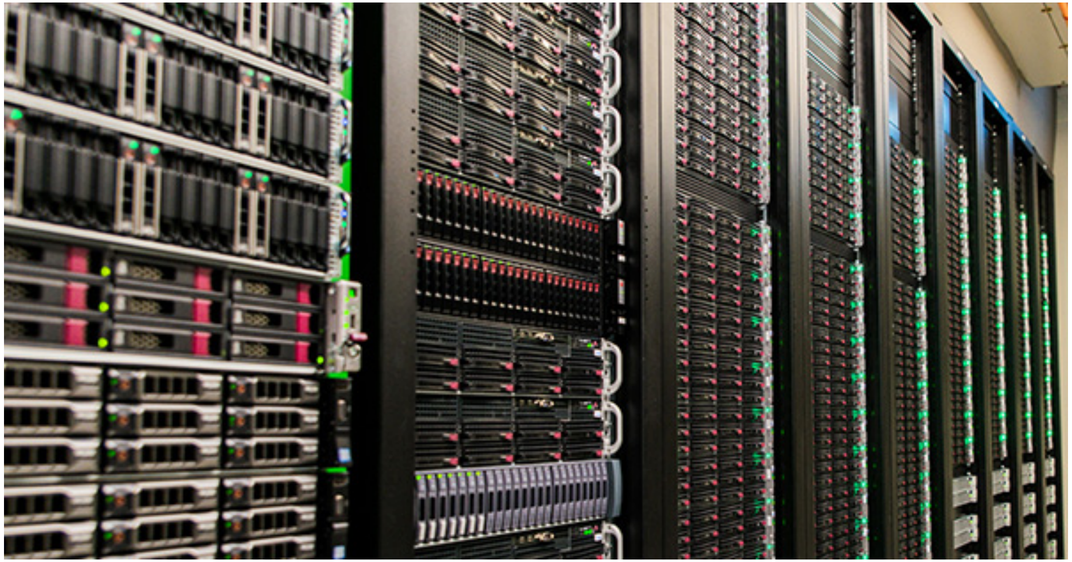
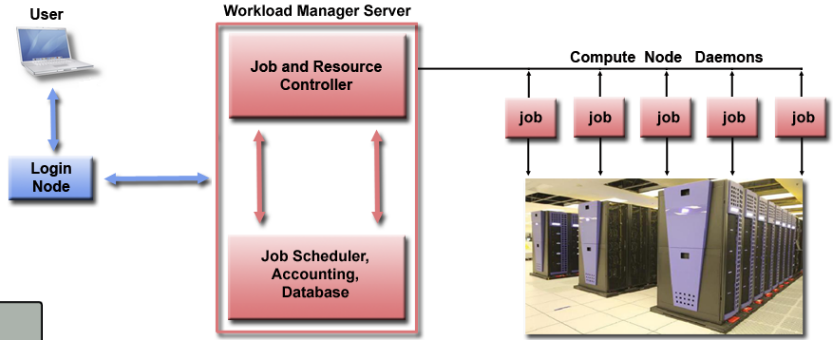


Image: CSC / Mikael Kanerva



A lot of number crunching!

Exploitable:
Each dv/v calculation is independent

Parallelisation reduces computation time.

With 200 cores:

Per station pair: < 5 minutes

Entire data set ready in ~ 1 week.

Markov chain Monte Carlo inversion – RIVV MCMC

Taylor and Hillers. *Geophys. J. Int.* (2019)

Compute velocity change between ALL correlations

$$\mathbf{d}\begin{bmatrix} 0.002 \\ 0.005 \\ 0.001 \\ \vdots \\ 0.007 \\ 0.003 \\ 0.003 \end{bmatrix} = \mathbf{G} \quad \mathbf{m}\begin{bmatrix} dv_1 \\ dv_2 \\ dv_3 \\ \vdots \\ dv_{13} \end{bmatrix}$$

- Produces a full probability distribution
- Only vector multiplication required – memory efficient
- No arbitrary smoothing

Use an MCMC framework

Start with a guess of **m**

↓

Randomly perturb **m** → **m'**

↓

How well does **m'** fit the data?
(Include data uncertainties)

↓

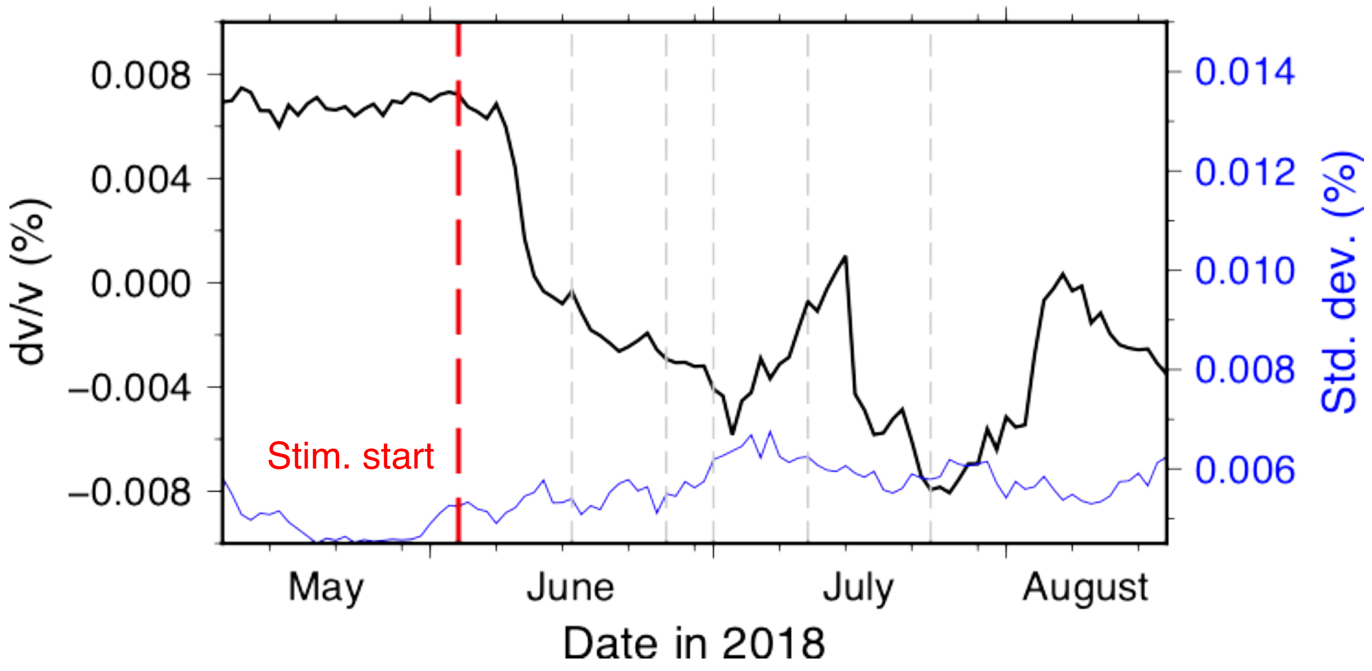
Metropolis rule

m' fits better than **m**?
Save **m'**, **m** → **m'**

m' fits worse than **m**?
Maybe save **m'**, **m** → **m'**
Else, discard **m'**

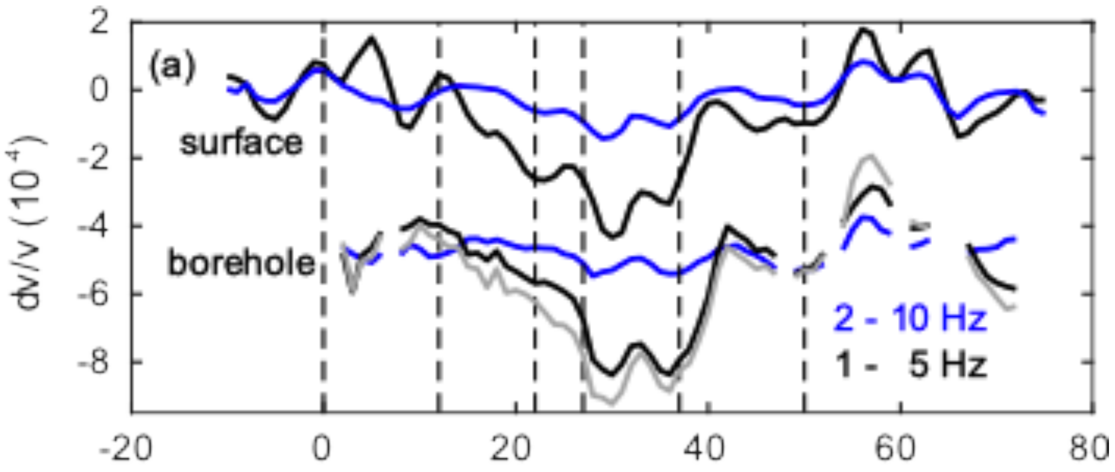
$$\frac{p(\mathbf{d}|\mathbf{m}')}{p(\mathbf{d}|\mathbf{m})}$$

Array-average response to borehole stimulation



MCMC approach:

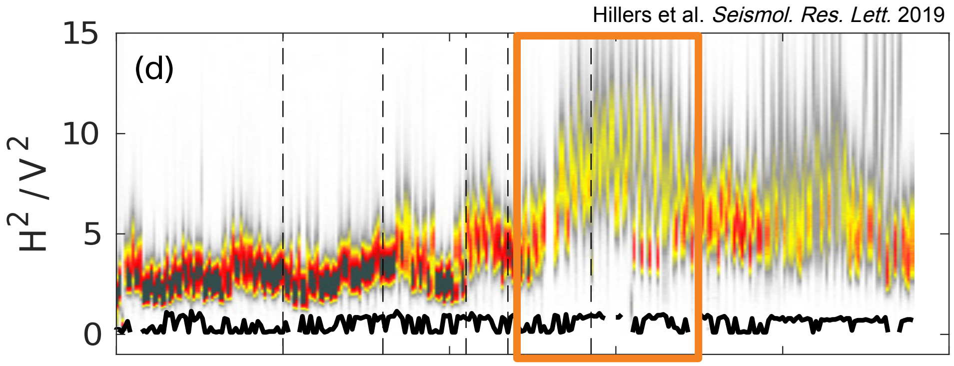
- Stable dv/v pre-stimulation.
- Immediate medium response.
- Evidence of a recover in seismic velocity.
- Information on uncertainty.



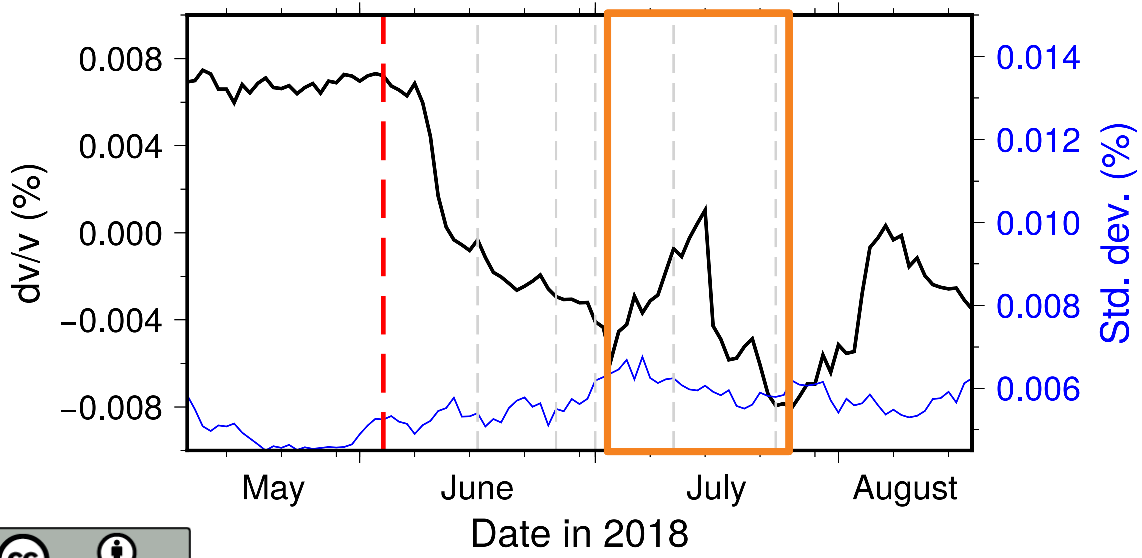
Reference approach:

- Variable dv/v pre-stimulation.
- Delayed medium response.
- Response contaminated by weekly periodicity.

Intermediate velocity recovery may be related to water content

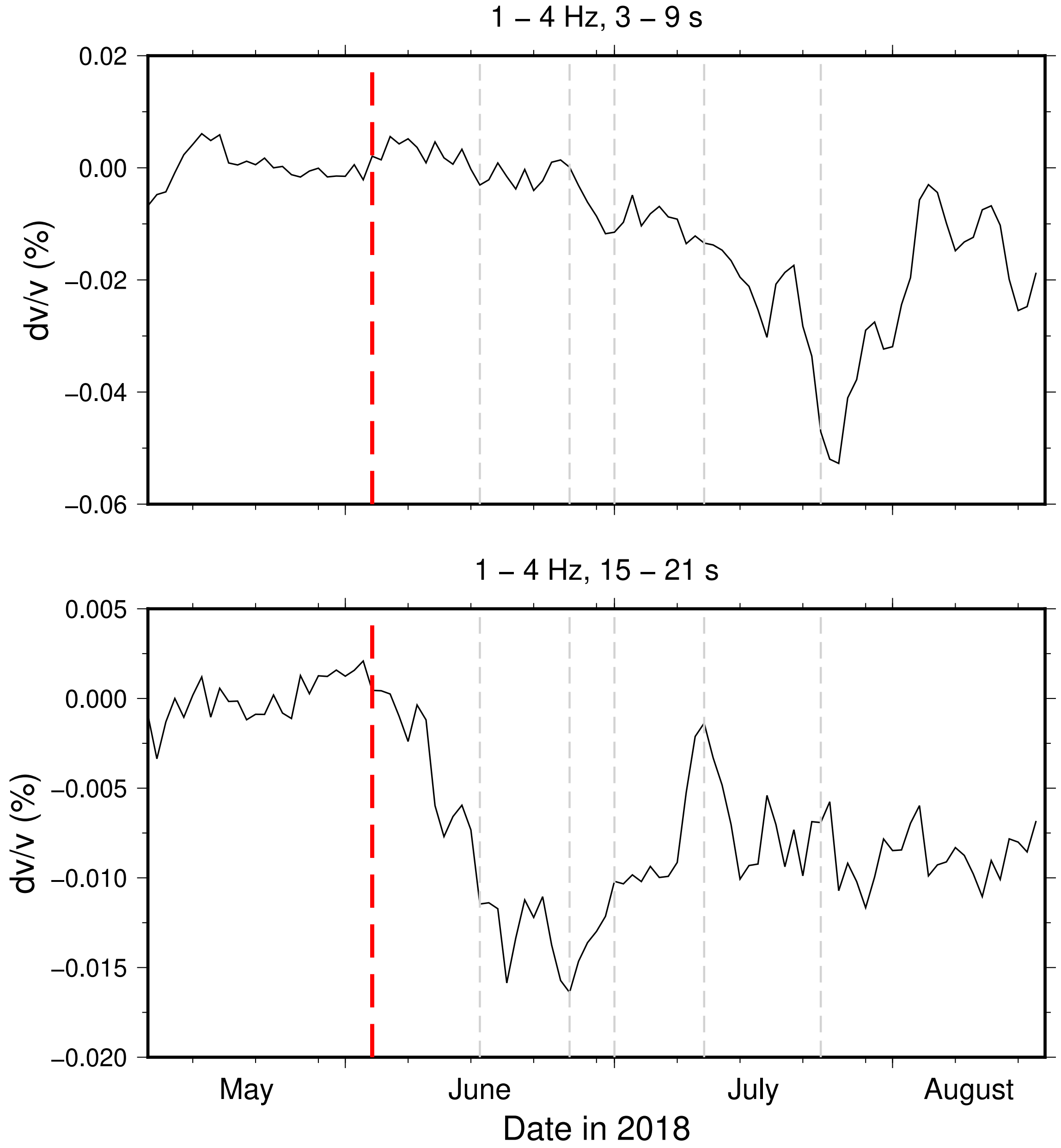


- Increase in H^2/V^2 ratio at the borehole in July.
- H^2/V^2 is a proxy for water content.



Intermediate increase in seismic velocity may be a response to increased pore fluid pressure at depth.

The response in not homogenous



The phases contained in the coda vary with time:

- Early coda windows are dominated by surface waves, which are sensitive to shallow structure.

- Late coda windows contain body waves, and deeper sensitivity.

- Shallow response to the stimulation is gradual, with no immediate effect.

- At depth, there is an immediate decrease in seismic velocity associated with pumping.

Use this to invert for spatial distribution!

Conclusions

- Markov chain Monte Carlo methods provide robust estimates seismic velocity variations.
- Advantages include:
  - Ability to include more data to constrain the velocity changes vs. reference method.
  - Estimates of uncertainty on the dv/v values.
  - More efficient computation than other inversion methods.

- Exploiting coda sensitivity will allow us to monitor spatial variations seismic velocity in 3D.

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GJI Seismology

Estimating temporal changes in seismic velocity using a Markov Chain Monte Carlo approach

G. Taylor and G. Hillers

Institute of Seismology, University of Helsinki, Finland. E-mail: george.taylor@helsinki.fi

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MCMC Python code available:

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