

# Analysis of time delay data and clock drift in a network of seismic monitors

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# Problem statement

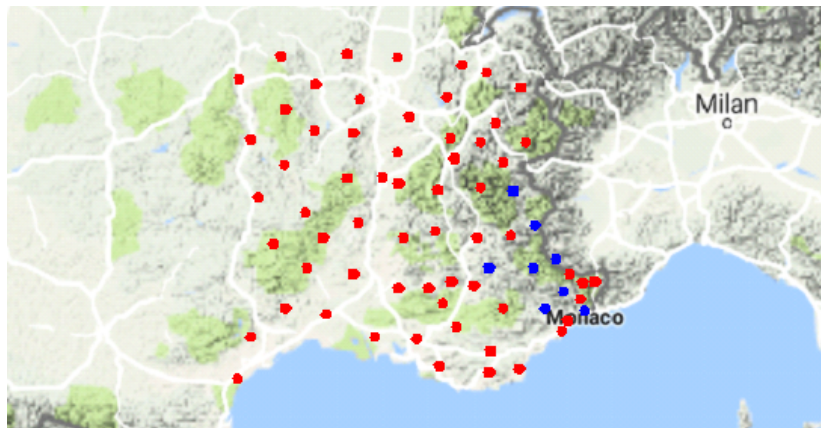
- ▶ Seismic monitoring is used to study the behaviour and composition of the underground floor
- ▶ There is a time drift in the monitors' clocks, causing inaccuracies in analysis
- ▶ Continuous synchronisation to the Global Positioning System for accurate timing is not possible
- ▶ A reliable method to correct the time drift of the clocks is required

# The network of seismic monitors

- ▶ The network consists of 73 seismic monitors
- ▶ For initial analysis, 8 stations are selected

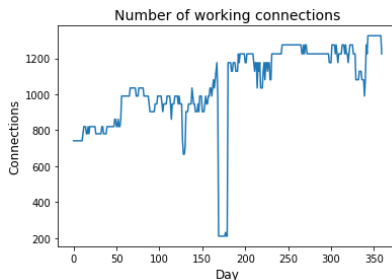
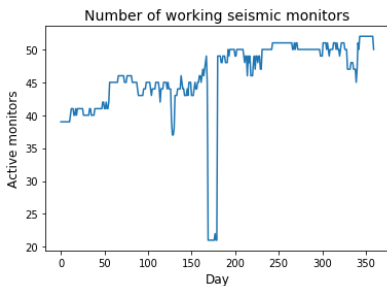


# The network of seismic monitors



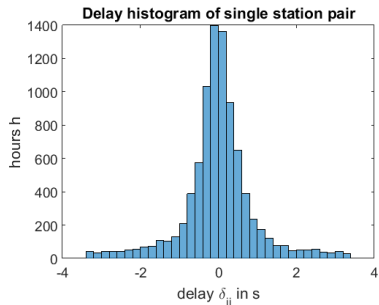
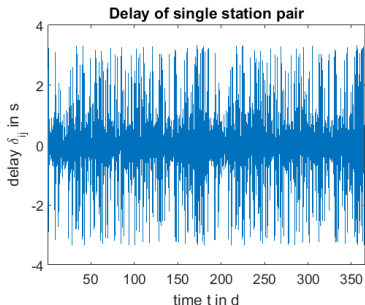
# Numbers of working stations and connections to stations during one year

- ▶ The maximum number of simultaneously working stations is 52 out of 73
- ▶ The maximum number of active connections is 1326
- ▶ If two monitors are working simultaneously, they are connected

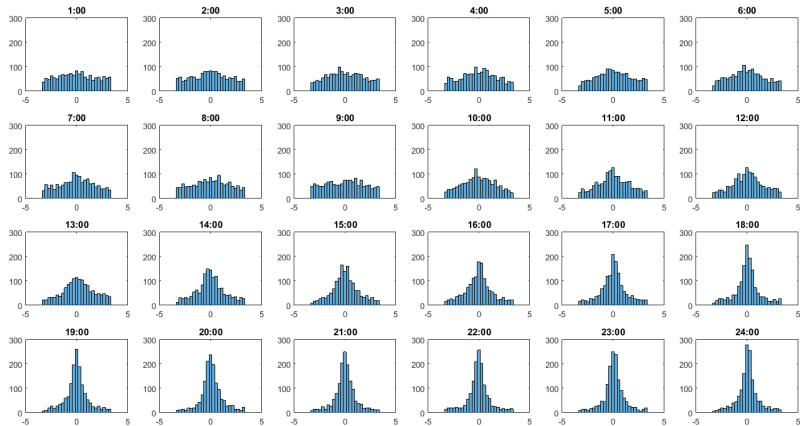


# Time-delay signal characteristics

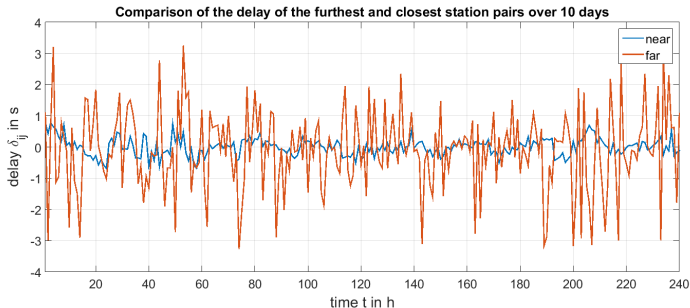
- ▶ Data is recorded in one second intervals
- ▶ Time-delay cross-correlation is computed in one-hour intervals
- ▶ Recording period is one year



# Histograms showing time delays recorded by all active stations over 24 hours



# Comparison of time delay of the furthest and the closest station pairs



- Time delays are smaller between stations which are close to each other



# Graph approach to model the data

- ▶ Measured time delays  $\hat{\delta}(t)$  between stations:

$$\hat{\delta}(t) = \delta(t) + \varepsilon(t) \quad (1)$$

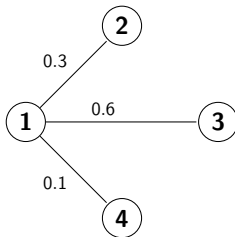
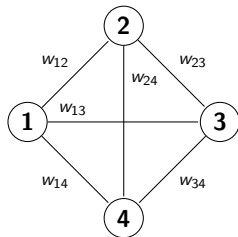
- ▶ Graphs:  $\mathcal{G}_{\delta} = (\mathcal{V}, \mathcal{E}, \hat{\delta})$ ,  $\mathcal{G}_r = (\mathcal{V}, \mathcal{E}, \mathbf{W})$

- ▶ Metric:

$$f_i(\mathbf{X}) = K_i \quad (2)$$

with

$$f_i(\hat{\delta}) = \sum_j \hat{\delta}_{ij} \quad \text{and} \quad K_i = f_i(\mathbf{W}) = \sum_j w_{ij} \quad (3)$$



normalised weights  
between  $[0, 1]$

# Signal denoising and extracting clock drift

- ▶ We specify a cost function  $c(\hat{\delta})$  measuring the deviation of the metric:

$$c(\hat{\delta}) = \sum_i e_i^2(\hat{\delta}) = \sum_i (f_i(\hat{\delta}) - K_i)^2 \quad (4)$$

- ▶ Error is minimized with gradient descent updates on  $\hat{\delta}$ :

$$\hat{\delta}^{(k+1)} = \hat{\delta}^k - \mu \sum_i E_i(\hat{\delta}^k) \frac{df_i(\hat{\delta}^k)}{d\hat{\delta}^k} \quad (5)$$

- ▶ The noise  $\varepsilon_{ij}$  between each pair of two stations is caused by clock drifts  $\Delta_i$  and  $\Delta_j$ , and other errors  $E_{ij}$ :

$$\varepsilon_{ij} = \Delta_i - \Delta_j + e_{ij} \quad (6)$$

## Solving individual clock drifts (1/2)

- We have overdetermined inverse problem of the form

$$\mathbf{G}\mathbf{s} = \mathbf{m} \quad (7)$$

$$\begin{bmatrix} 1 & -1 & 0 & 0 & \dots & 0 \\ 1 & 0 & -1 & 0 & \dots & 0 \\ 1 & 0 & 0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & 0 & \dots & -1 \\ 0 & 1 & -1 & 0 & \dots & 0 \\ 0 & 1 & 0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 1 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \\ \Delta_4 \\ \vdots \\ \Delta_k \\ \vdots \\ \Delta_{n-1} \\ \Delta_n \end{bmatrix} = \begin{bmatrix} \Delta_1 - \Delta_2 \\ \Delta_1 - \Delta_3 \\ \Delta_1 - \Delta_4 \\ \vdots \\ \Delta_1 - \Delta_n \\ \Delta_2 - \Delta_3 \\ \Delta_2 - \Delta_4 \\ \vdots \\ \Delta_2 - \Delta_k \\ \vdots \\ \Delta_{n-1} - \Delta_n \end{bmatrix} = \begin{bmatrix} \Delta_{12} \\ \Delta_{13} \\ \Delta_{14} \\ \vdots \\ \Delta_{1n} \\ \Delta_{23} \\ \Delta_{24} \\ \vdots \\ \Delta_{2k} \\ \vdots \\ \Delta_{(n-1)n} \end{bmatrix}$$

- The rank of matrix  $\mathbf{G}$  is  $n - 1$

## Solving individual clock drifts (2/2)

- ▶ Ordinary least squares regression

$$\|\mathbf{G}\mathbf{s} - \mathbf{m}\|_2^2. \quad (8)$$

- ▶ Tikhonov regularization is employed

$$\|\mathbf{G}\mathbf{s} - \mathbf{m}\|_2^2 + \|\mathbf{\Gamma}\mathbf{s}\|_2^2, \quad (9)$$

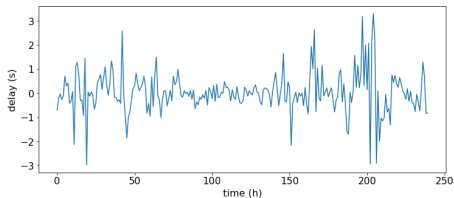
for some suitable Tikhonov matrix  $\mathbf{\Gamma} = \alpha \mathbf{I}$

- ▶ The explicit solution is hence given by

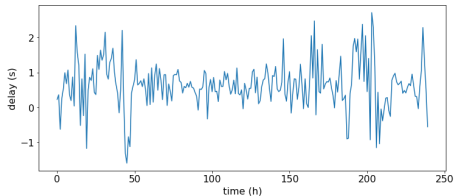
$$\hat{\mathbf{s}} = (\mathbf{G}^T \mathbf{G} + \mathbf{\Gamma}^T \mathbf{\Gamma})^{-1} \mathbf{G}^T \mathbf{m}. \quad (10)$$

# Signal - denoised signal - noise

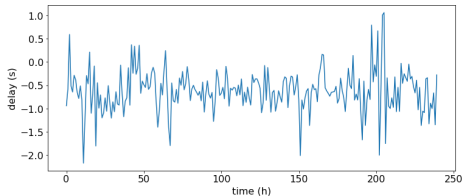
Delay signal  $\hat{\delta}$  of  
one connection for  
10 days



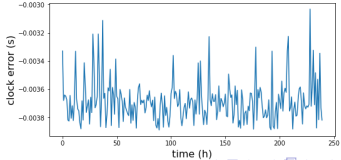
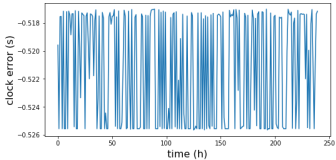
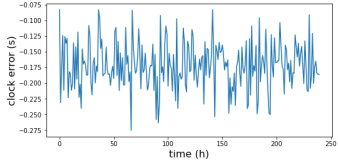
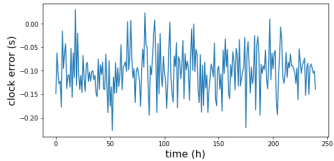
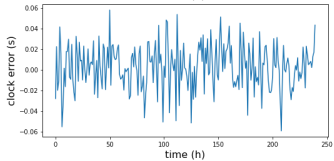
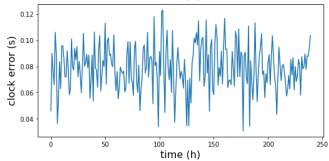
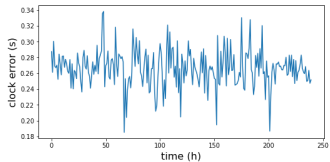
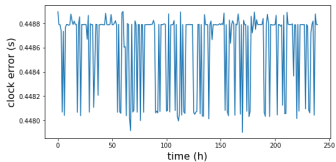
Denoised signal  $\delta$   
of the connection



Signal noise  $\epsilon$



# Clock drifts



# Conclusion

- ▶ A graph method to recover clock drift in large time-delay network was developed
- ▶ Clock drifts for the three most influential monitors and five others close-by were computed
- ▶ The drift varies over time
- ▶ Clock drift may account for up to 1 % inaccuracy in timing at each time point

## **Future work:**

- ▶ A synthetic dataset to verify the effectiveness of the method
- ▶ Analyse the complete network of monitors
- ▶ Develop and test other metrics
- ▶ Carry out sensitivity analysis