Locating the source of forced oscillations in transmission grids

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Forced oscillations in power grids

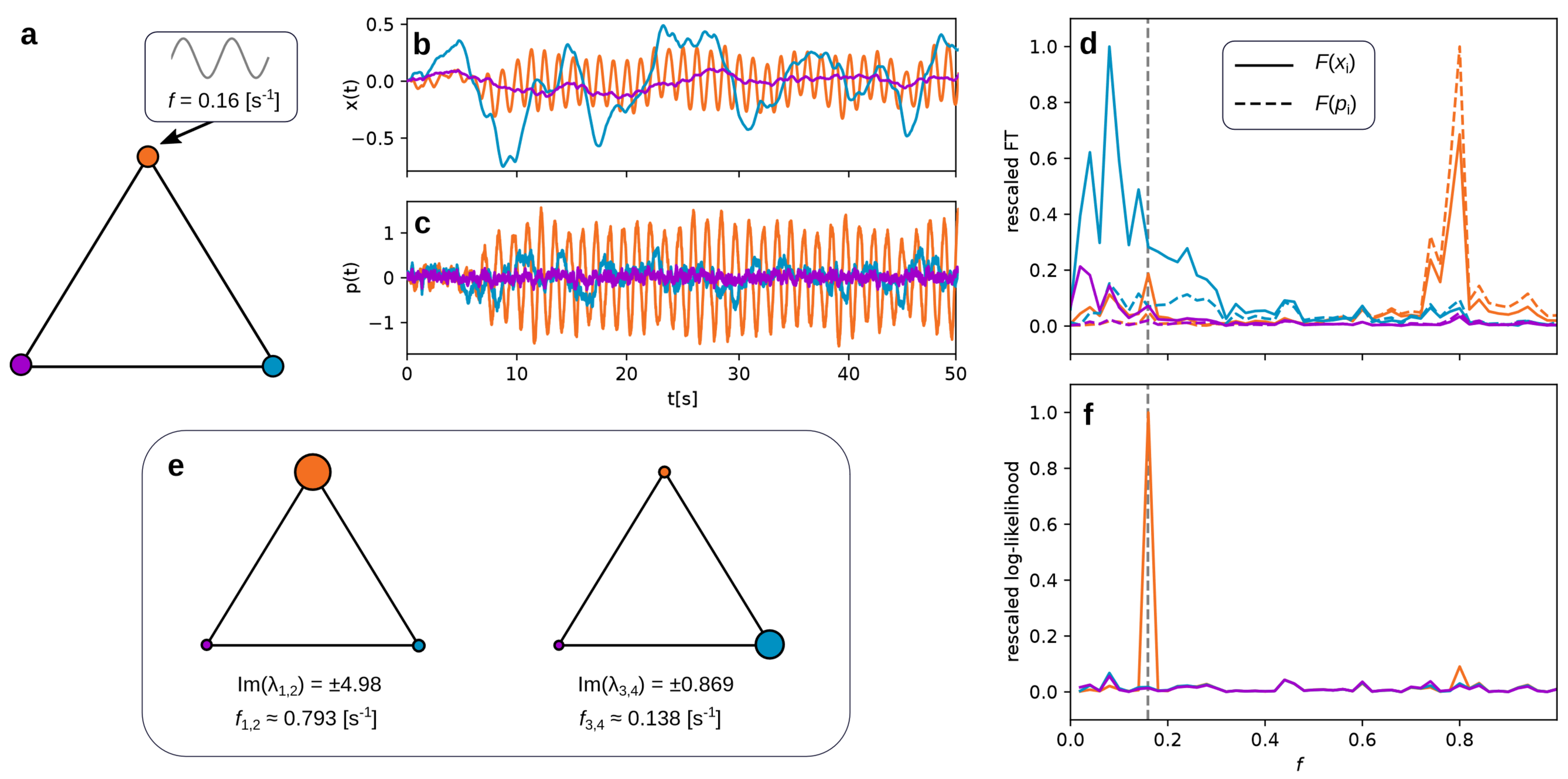
Swing dynamics

$$\boldsymbol{M} d\boldsymbol{p}_t = \boldsymbol{D}\boldsymbol{p}_t dt + \boldsymbol{L}\boldsymbol{x}_t dt + \gamma \boldsymbol{e}_l \cos(2\pi(ft+\phi))dt + d\boldsymbol{W}_t$$

Based on time-series measurements:

- Identify the forcing frequency.
- Locate the source of the forcing.

Illustration of the challenges:



Log-Likelihood optimization

Discretization:

$$\boldsymbol{\Delta}_{t_j} = \boldsymbol{A}\boldsymbol{X}_{t_j} + \gamma \boldsymbol{e}_l \mathrm{Re}\left(e^{2\pi i (k\frac{j}{N}+\phi)}\right) + \boldsymbol{\xi}_j$$

$$\boldsymbol{\Delta}_{t_j} = (\boldsymbol{X}_{t_{j+1}} - \boldsymbol{X}_{t_j})/\tau \qquad \tau = T/N \qquad t_j = j\tau \qquad \boldsymbol{A} = \begin{pmatrix} 0 & \mathbb{I} \\ \boldsymbol{M}^{-1}\boldsymbol{L} & -\boldsymbol{M}^{-1}\boldsymbol{D} \end{pmatrix}$$

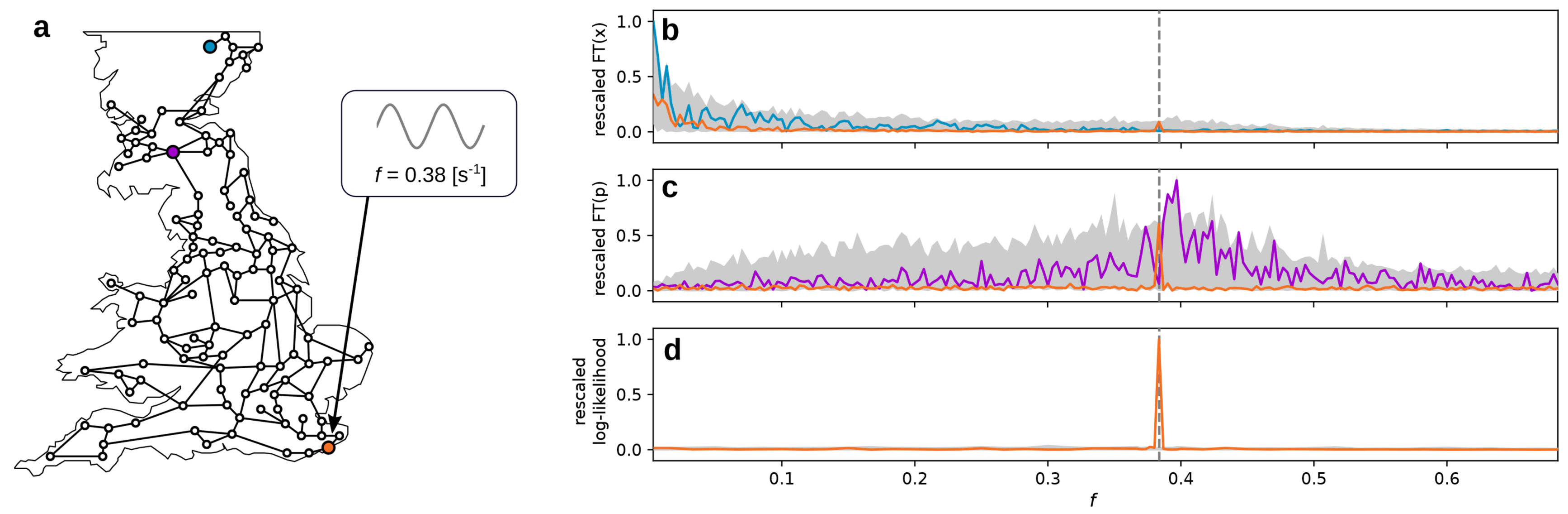
Objective function:

$$L\left(\boldsymbol{A}, \gamma, l, k, \phi \mid \{\boldsymbol{X}_{t_j}\}_{j=1}^N\right) = \frac{1}{N}\sum_{j=0}^{N-1}\left\|\boldsymbol{\Delta}_{t_j} - \boldsymbol{A}\boldsymbol{X}_{t_j} - \gamma \boldsymbol{e}_l \mathrm{Re}\left(e^{2\pi i (\frac{k}{N}j+\phi)}\right)\right\|^2$$

- Independent optimization on ϕ
- Recover parameters: $\boldsymbol{A}, \gamma, l, k$

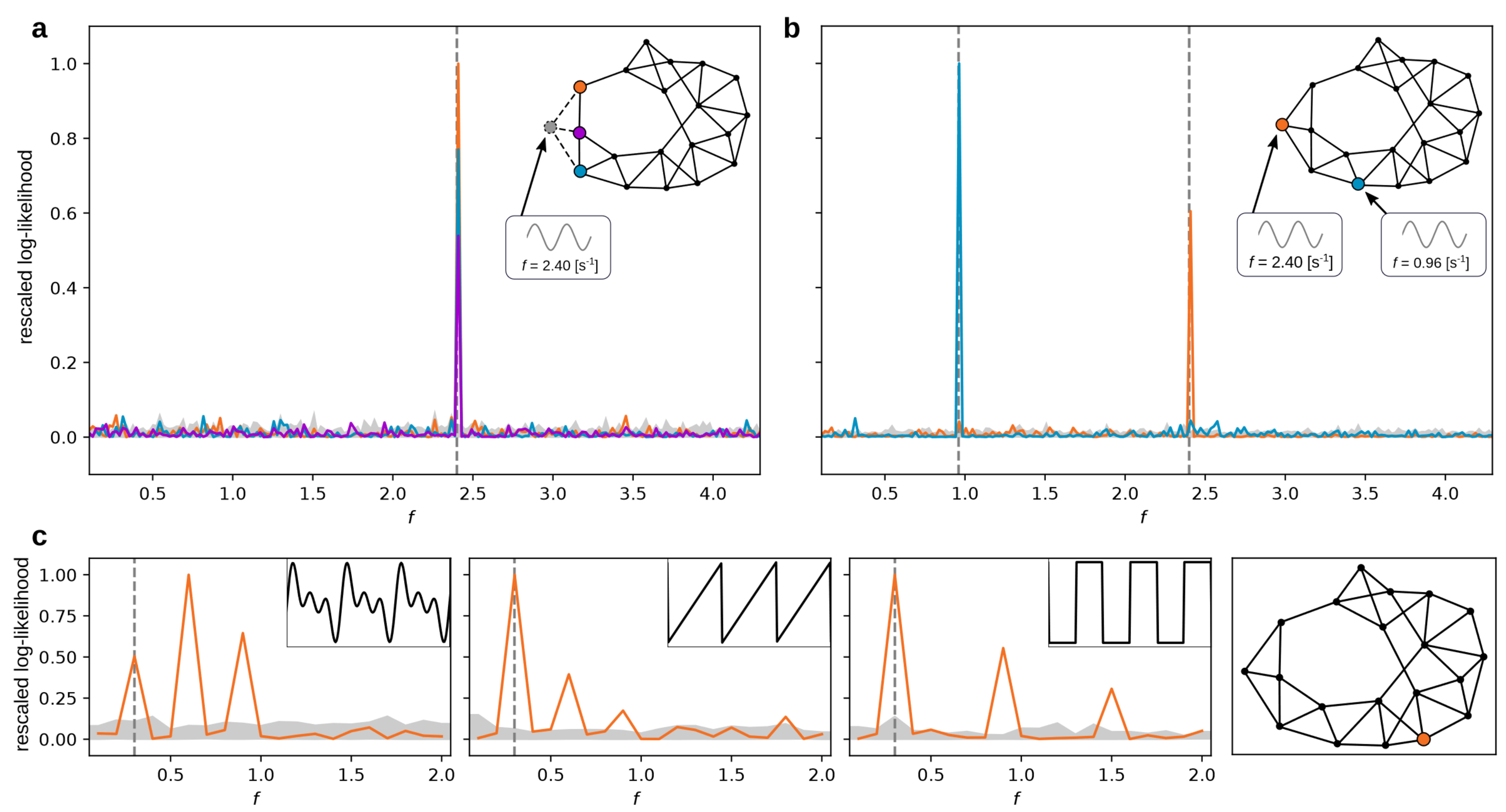
Synthetic data

Model of the UK grid:



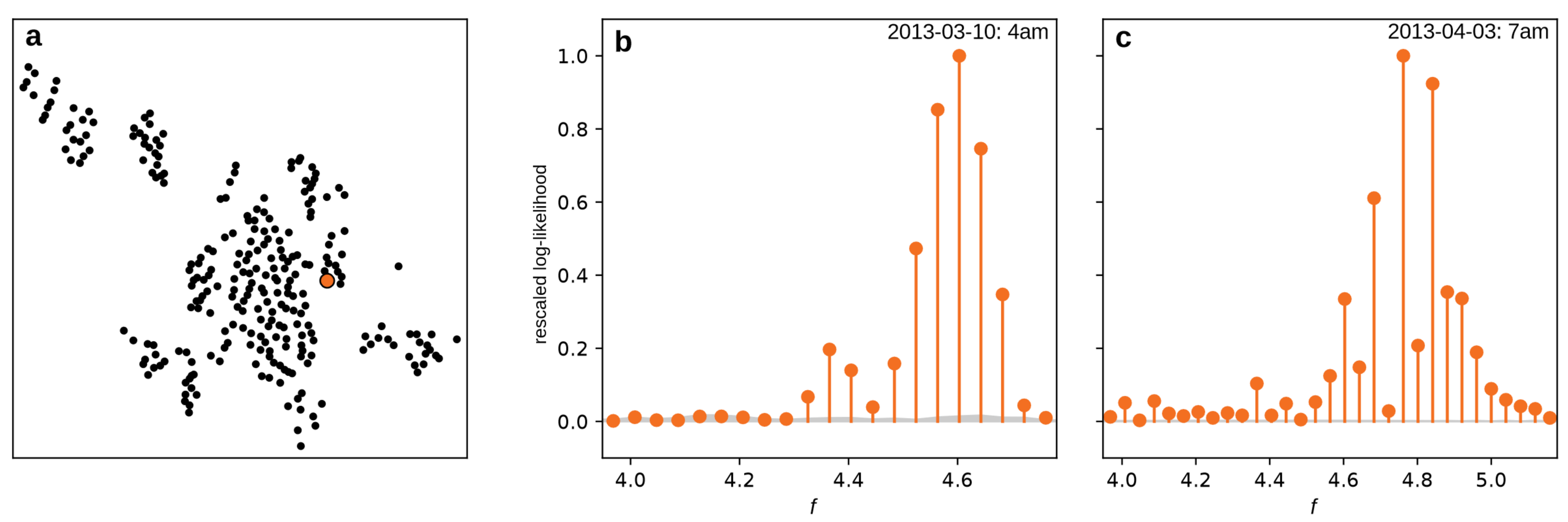
Outcome of the Fourier transform of the positions and velocities at each bus and of the optimization of the log-likelihood for a model of the UK power grid.

Algorithm robustness:



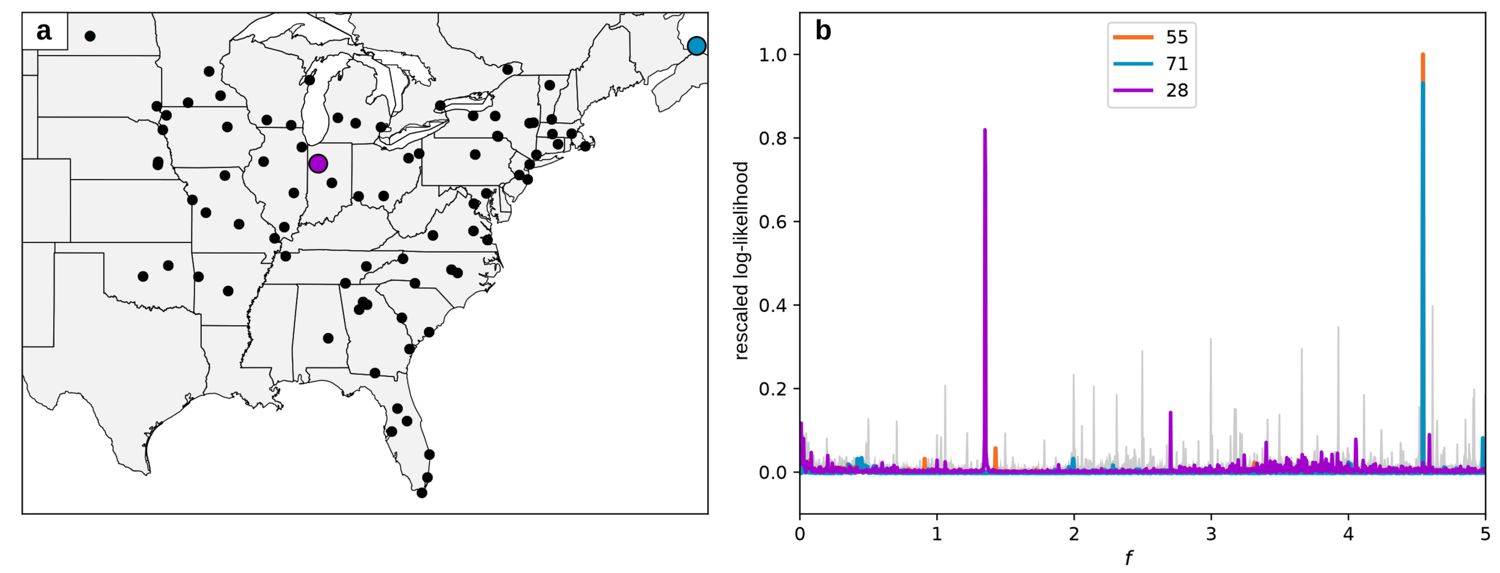
Measurement data

US operator:



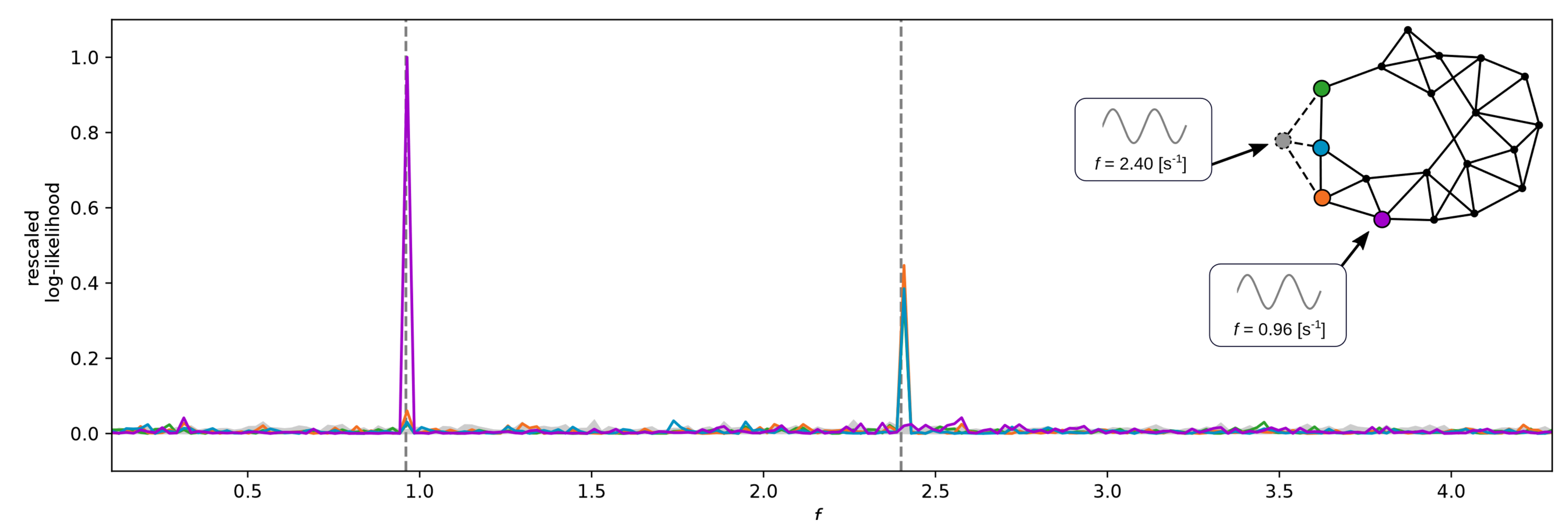
The algorithm consistently points to the same candidate source in a similar frequency range even for time series collected over two time periods separated by almost a month (March 2013 vs. April 2013).

U.S. Eastern Interconnection:



Known locations of FNET/GridEye measurement devices that recorded the data under an oscillatory event in the U.S. Eastern Interconnection area [2], along with the location of the most likely sources identified by SALO The location of the orange node is not available.

Source not recorded:



Conclusions

✓ **Solely based on time-series measurements of voltage angles and frequencies our algorithm is able to identify the forcing frequency and locate the source.**

✓ **A relaxed version of the algorithm makes it scalable to large systems (see Ref.[1]).**

References:

1. R. Delabays, A. Y Lokhov, M. Tyloo, M. Vuffray arXiv:2211.16064, submitted (2022)
2. The University of Tennessee, Knoxville FNET Server Web Display. https://fnetpublic.utk.edu. Accessed: 2022-11-6.

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