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Locating the Source of Forced Oscillations in Transmission Power Grids

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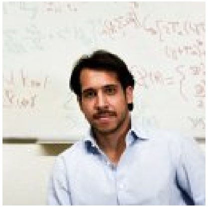
People

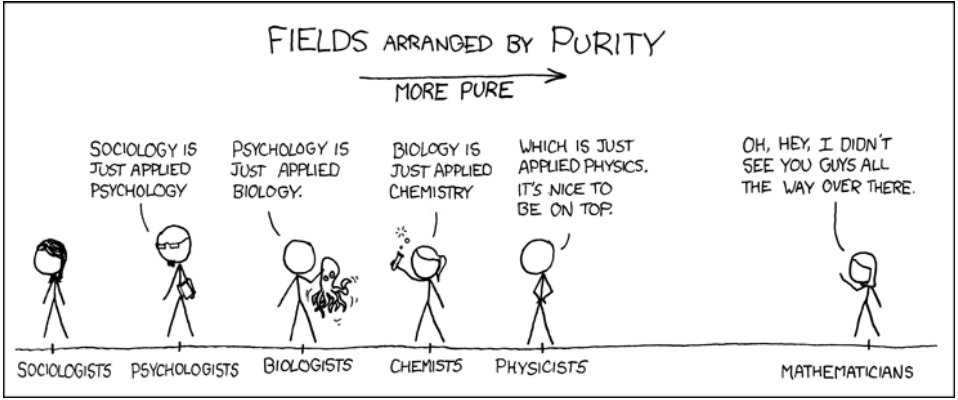
Andrey Lokhov (LANL)



Melvyn Tyloo (LANL)

Marc Vuffray (LANL)

Disclaimer

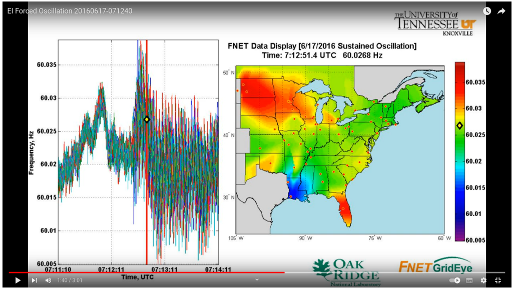


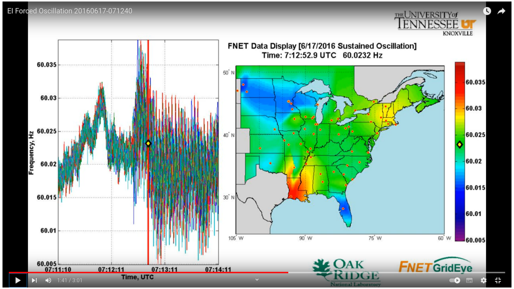
https://xkcd.com/435/

V. Sekara *et al.*, *PNAS* **115** (2018), https://doi.org/10.1073/pnas.1800471115

Sustained and forced oscillations

- Underdamped eigenmodes,
- Malfunctioning device.





https://www.youtube.com/watch?v=1vuxZJitEJg

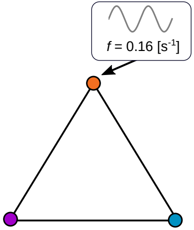
Model and assumptions

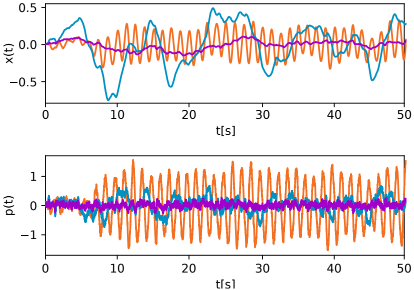
Voltage dynamics:

$$\dot{\theta}_i = \omega_i \,,$$
$$m_i \dot{\omega}_i = -d_i \omega_i + \sum_j V_i V_j \left(B_{ij} \sin(\theta_i - \theta_j) + G_{ij} \cos(\theta_i - \theta_j)\right) \,.$$

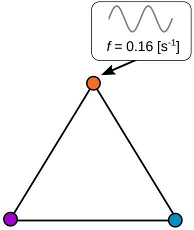
- Steady state operation;
- Forced oscillations:
  - Sufficiently low amplitude;
  - Sufficiently low frequency.

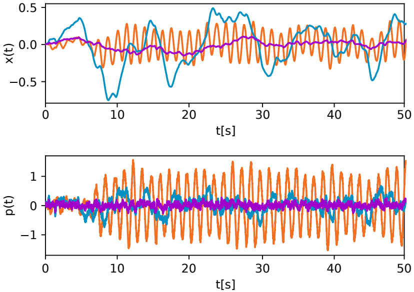
Intuitive (but a bit naive) approach: ...

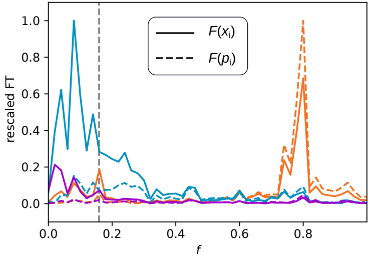




Intuitive (but a bit naive) approach: the Fourier Transform







SALO: System-Agnostic Location of Oscillations

Dynamics: $M\dot{\boldsymbol{\omega}} = D\boldsymbol{\omega} + B\mathbf{x} + \gamma\mathbf{e}_\ell \cos(2\pi f t + \phi) + \boldsymbol{\xi}$.

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Discretized: $\mathbf{X}_{t_j} = (\mathbf{x}_{t_j}, \boldsymbol{\omega}_{t_j})$ and $\boldsymbol{\Delta}_{t_j} = (\mathbf{X}_{t_{j+1}} - \mathbf{X}_{t_j})/\tau$,

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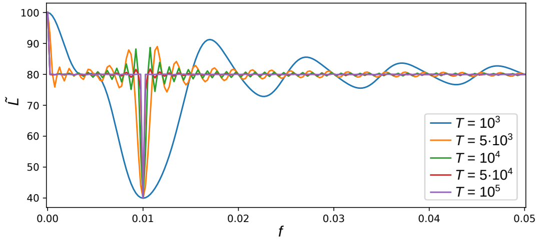
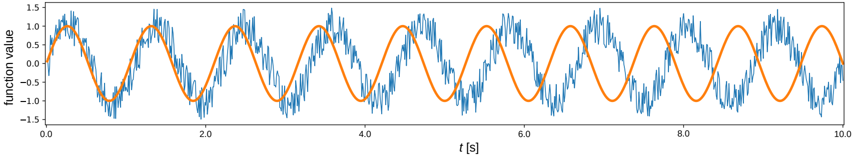
Least square error:

$$\text{SALO:} \qquad \underset{A,\gamma,k,\ell,\phi}{\arg\min} \sum_{j=0}^{T-1} \left\| \boldsymbol{\Delta}_{t_j} - A\mathbf{X}_{t_j} - \gamma\mathbf{e}_\ell\cos(2\pi k t_j/T + \phi) \right\|^2\,.$$

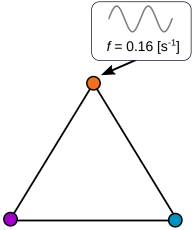
... and a bit of work.

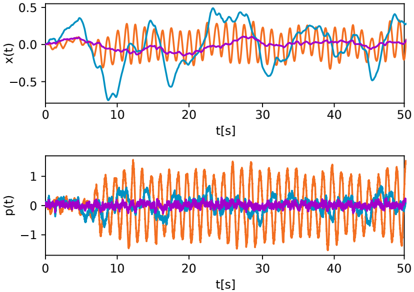
Opimization landscape

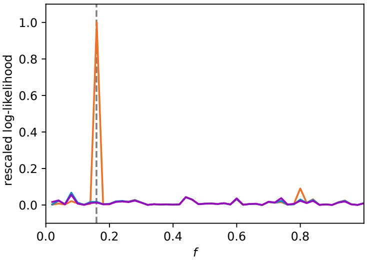




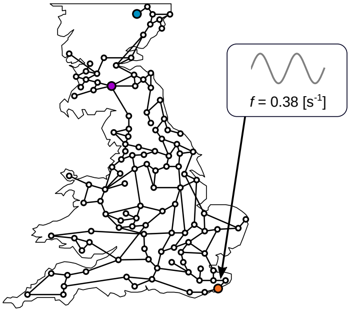
Using the *System-Agnostic Location of Oscillations (SALO)* algorithm

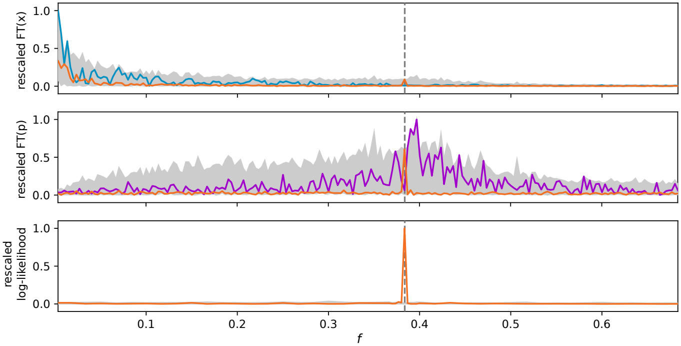




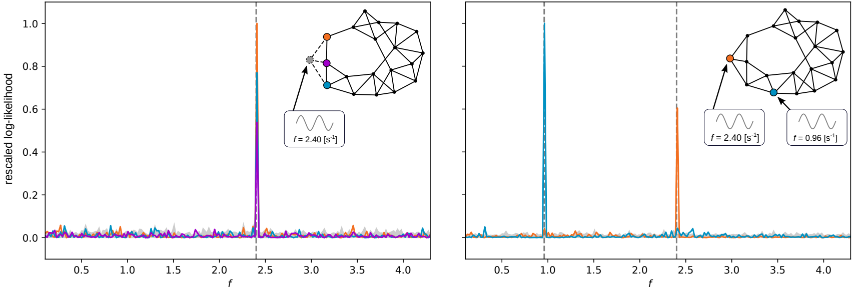


Synthetic data





Multiple or hidden sources



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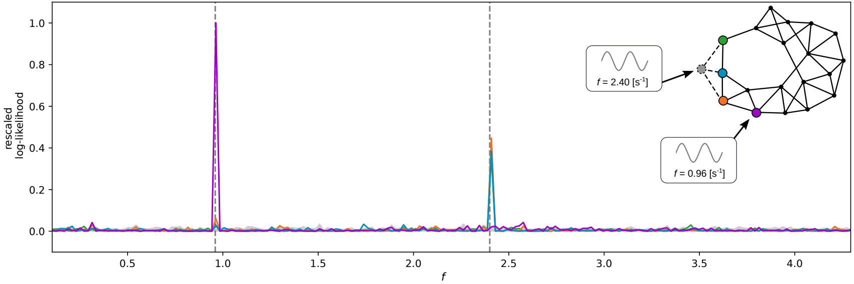
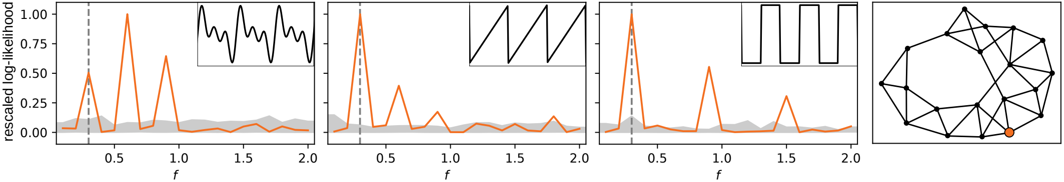


Other disturbances



Prior information

Curiosity: The inferred matrix $\hat{\mathbf{A}}$ has nothing to do with the actual system.

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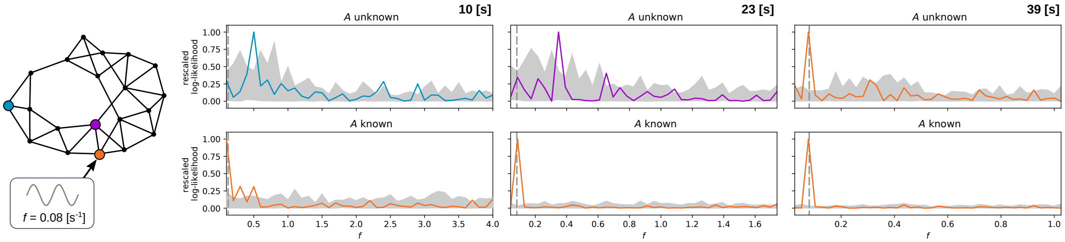


SALO-relax

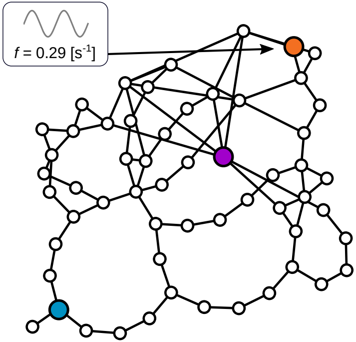
Relaxation of the amplitude vector:

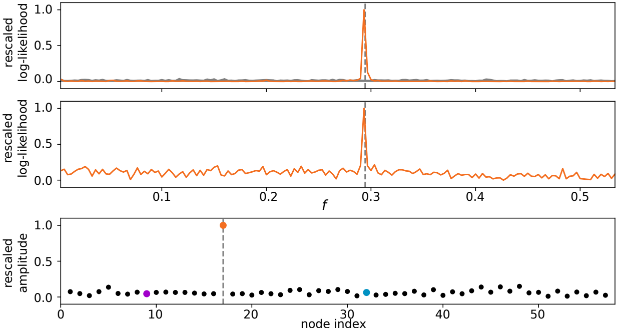
$$\text{SALO:} \qquad \operatorname*{arg\,min}_{A,\gamma,k,\ell,\phi} \sum_{j=0}^{T-1} \left\| \boldsymbol{\Delta}_{t_j} - A\mathbf{X}_{t_j} - \gamma \mathbf{e}_\ell \cos(2\pi k t_j / T + \phi) \right\|^2 .$$

$$\text{SALO-relax:} \qquad \operatorname*{arg\,min}_{A,\gamma,k,\phi} \sum_{j=0}^{T-1} \left\| \boldsymbol{\Delta}_{t_j} - A\mathbf{X}_{t_j} - \boldsymbol{\gamma} \cos(2\pi k t_j / T + \phi) \right\|^2 .$$

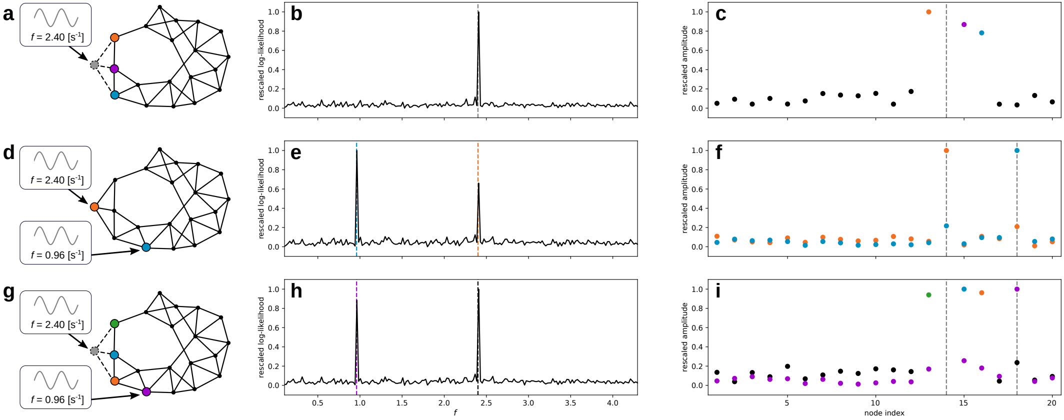
- Gain in computation time;
- Less parallelizable.

SALO-relax (bis)

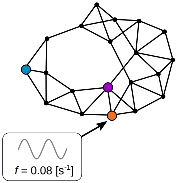


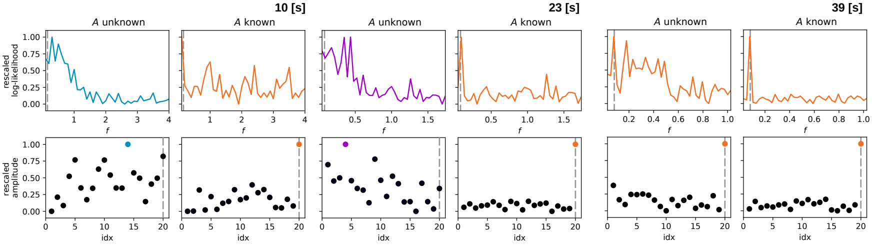


SALO-relax: Complex cases

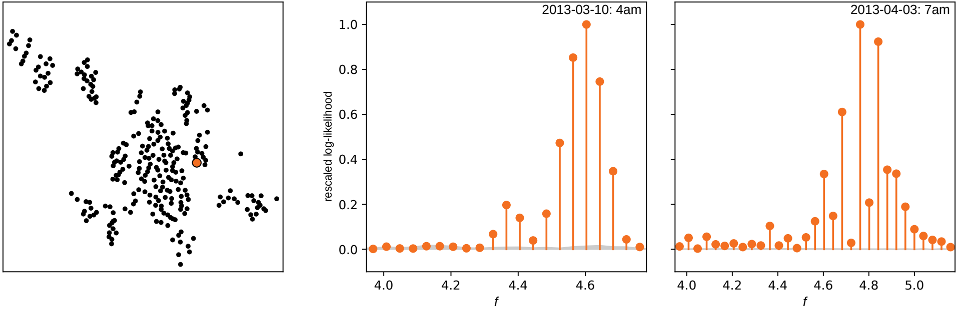


Informed SALO-relax



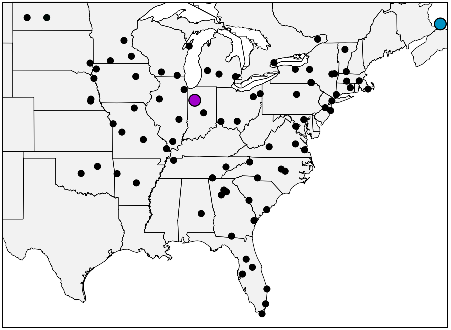


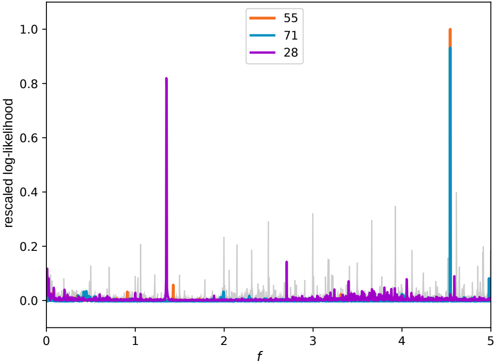
Measurement data



M. Escobar, D. Bienstock, and M. Chertkov, in *Proc. of the IEEE PowerTech* (IEEE, Milano, Italy, 2019).

Measurement data (bis)





The University of Tennessee, Knoxville FNET Server Web Display, https://fnetpublic.utk.edu, accessed: 2022-11-6.

The elephant in the room...

Measurements + Ground Truth

The elephant in the room...

Measurements + Ground Truth

Thank you!

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Least square error

$$
\begin{aligned}
&L_{\mathrm{SALO}}(\mathbf{A}, \gamma, \ell, k \mid \{\mathbf{X}_{t_j}\}) \\
&= \mathrm{Tr}(\mathbf{A}^\top \mathbf{A}\Sigma_0) - 2\mathrm{Tr}(\mathbf{A}\Sigma_1) - \frac{\gamma^2}{2} - \frac{2\gamma}{\sqrt{N}} \sqrt{\mathrm{Tr}(\mathbf{A}_{l,.}^\top \mathbf{A}_{l,.} F(k)) - 2 f_l(k) \mathbf{A}_{l,.} + g_l(k)} \\
&\Sigma_0 = \frac{1}{N} \sum_{j=0}^{N-1} \mathbf{X}_{t_j} \mathbf{X}_{t_j}^\top \\
&\Sigma_1 = \frac{1}{N} \sum_{j=0}^{N-1} \mathbf{X}_{t_j} \mathbf{\Delta}_{t_j}^\top .
\end{aligned}
$$