Scaling and spatio-temporal properties of power-grid frequency: An open database

Special Track: *Modelling Dynamics of Power Grids*

DLR Institute of Networked Energy Systems

Forschungszentrum Jülich - IEK-STE
Institute of Energy and Climate Research
Systems Analysis and Technology Evaluation

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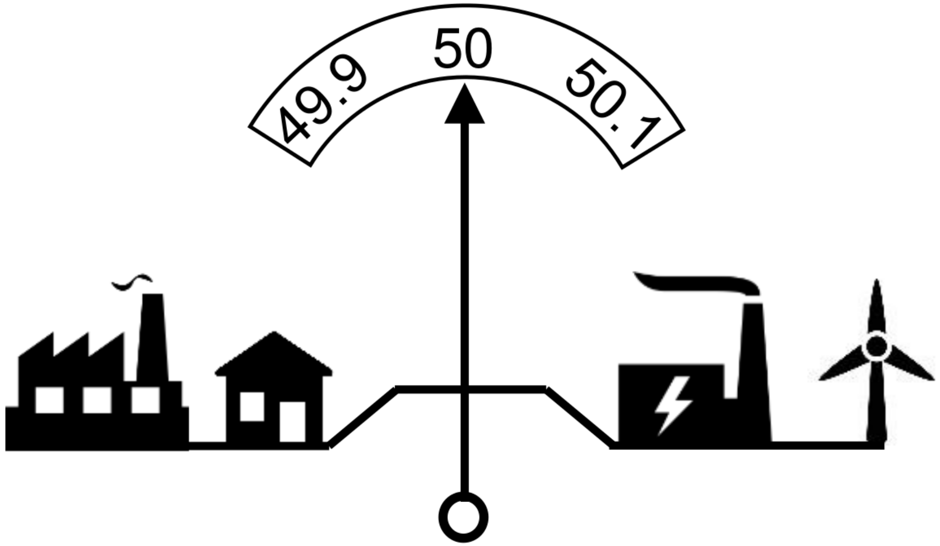
Power-grid frequency: The common indicator for stability



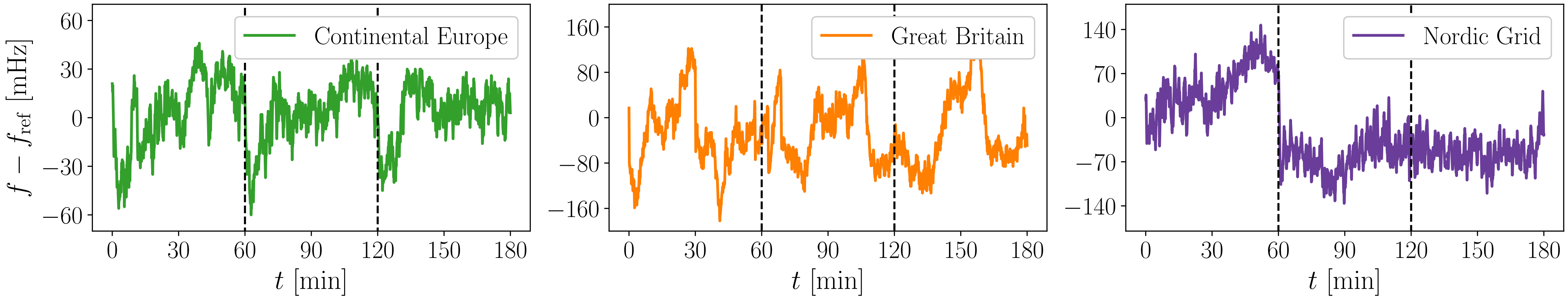
Power-grid frequency is the key indicator of stability in power-grid systems. It comprises the balance between generation and consumption, but much more is encoded in its physics.
In this presentation we will investigate:

- The nature of power-grid fluctuation.
- A scaling law relating inertia/generation and fluctuation amplitude.
- The finer structure of power-grid frequency fluctuations in real-world recordings.

Extant power-grid frequency recordings

Excerpts February 2019

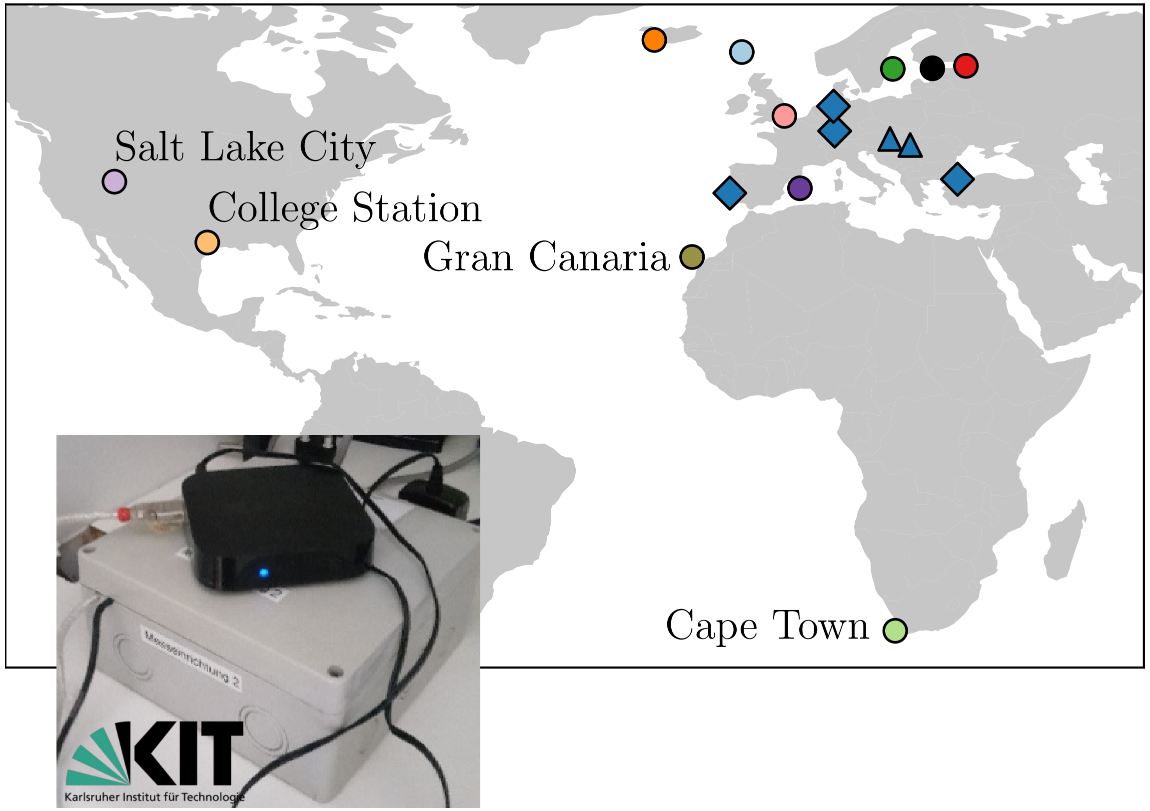
Three recordings from 11th of February 2019, from midnight.

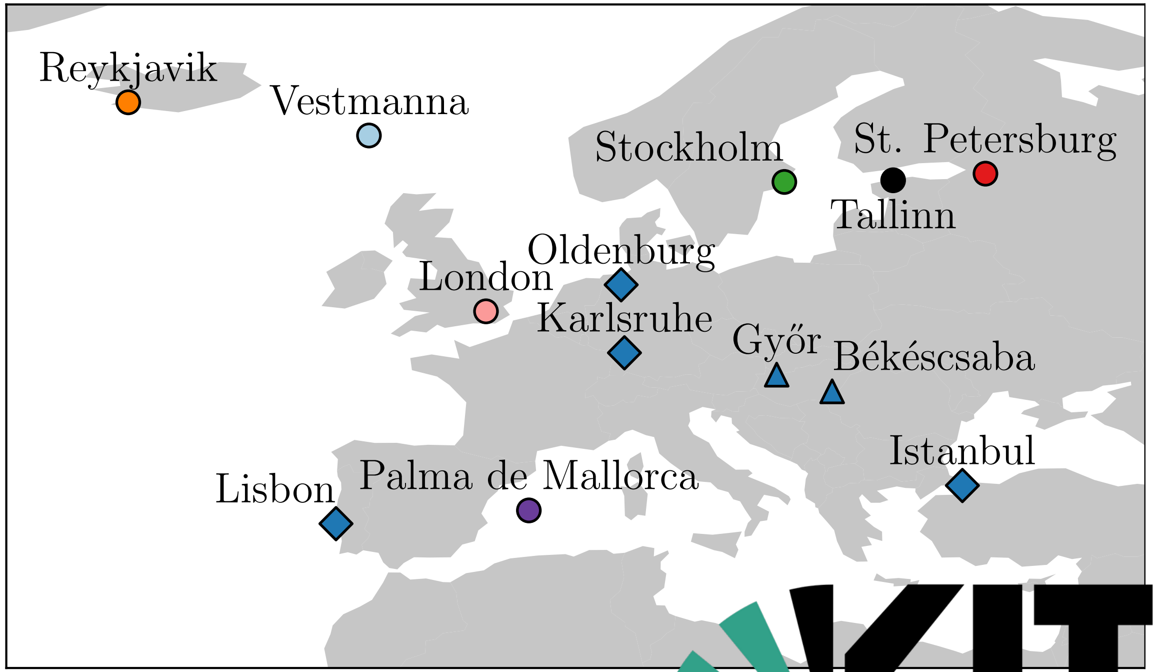


Continental Europe Great Britain Nordic Grid

Electrical Data Recorder (EDR) across the globe

There is a scarcity of power-grid frequency data freely available





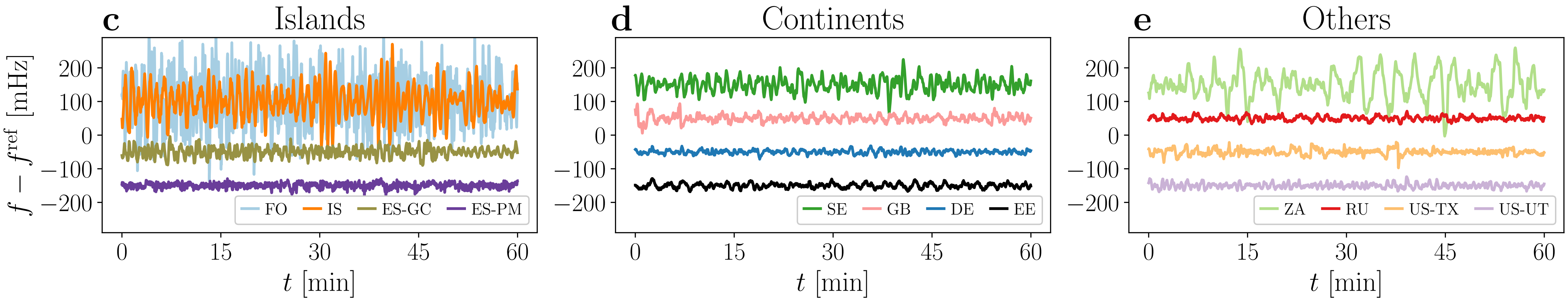
Karlsruher Institut für Technologie

Work by: Richard Jumar, Heiko Maass, Benjamin Schäfer, LRG, Veit Hagenmeyer
Location of data: https://power-grid-frequency.org/

Electrical Data Recorder (EDR) across the globe

Excerpts of the power-grid frequency recordings

17 recordings, over 12 synchronous areas



FO: Faroe Islands
IS: Iceland
ES-GC: Spain, Gran Canaria
ES-PM: Spain, Palma de Mallorca

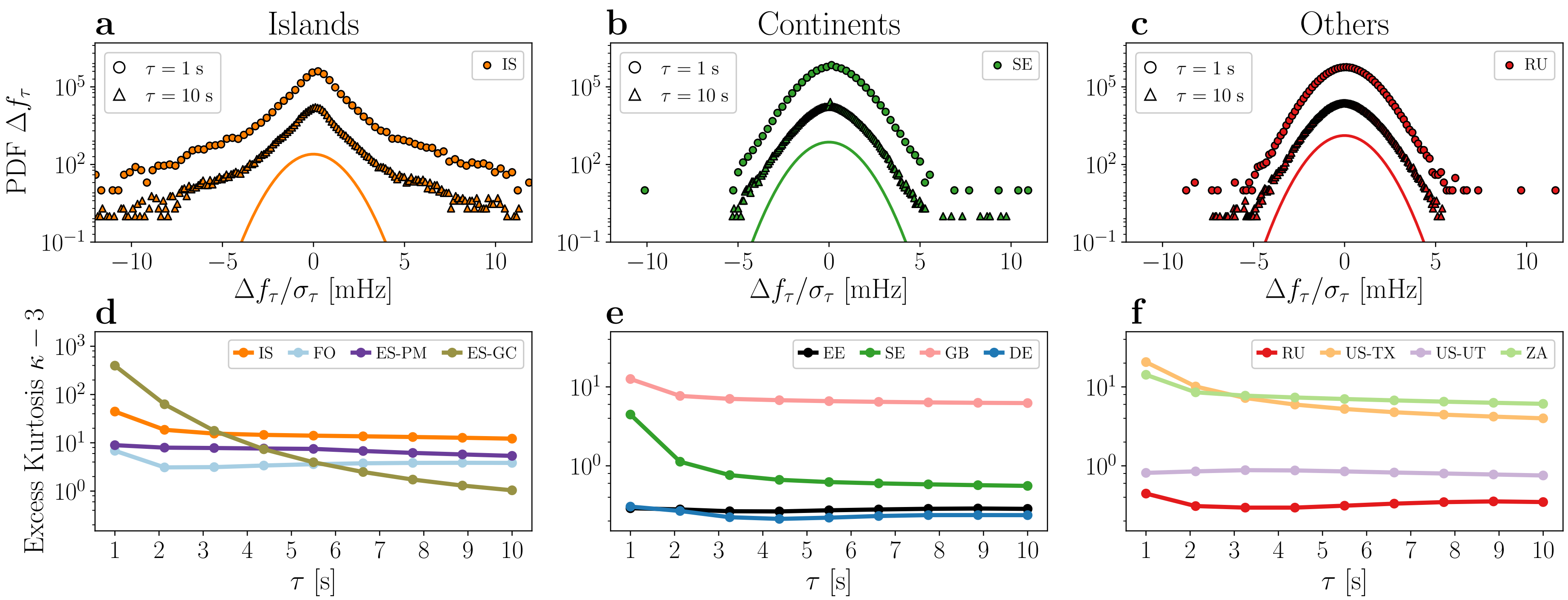
SE: Sweden
GB: Great Britain
DE: Germany
EE: Estonia

ZA: South Africa
RU: Russia
US-TX: USA, Texas
US-UT: USA, Utah

Electrical Data Recorder (EDR) across the globe

Statistical properties of the recordings

$$\Delta f_\tau(t) = f(t+\tau) - f(t)$$



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Kurtosis: $$\kappa(X) = \mathrm{E}\left[\left(\frac{X-\mu_X}{\sigma_X}\right)^4\right] = \frac{\mathrm{E}\left[(X-\mu_X)^4\right]}{\left(\mathrm{E}\left[(X-\mu_X)^2\right]\right)^2}$$

Power-grid frequency: A stochastic approach

We can precise an SDE for the “bulk” an $\theta(t)$ and “bulk” angular velocity $\omega(t)$

$$\mathrm{d}\theta = \omega\,\mathrm{d}t,$$

$$M\mathrm{d}\omega = -c_1\omega\,\mathrm{d}t - c_2\theta\,\mathrm{d}t + \Delta P\,\mathrm{d}t + \boxed{\epsilon\,\mathrm{d}W(t)},$$

where c_1 is the primary control, c_2 is the secondary control, ΔP is the power mismatch, and dW is an uncorrelated Gaussian noise with amplitude . We can write a Fokker–Planck equation (for ΔP = 0)

$$\frac{\partial p}{\partial t} = -\frac{\partial}{\partial\omega}(c_1\omega p) + \boxed{\frac{\epsilon^2}{2}}\frac{\partial^2 p}{\partial\omega^2}$$

$$= -\frac{\partial}{\partial\omega}\mathcal{D}^{(1)}p + \frac{\partial^2}{\partial\omega^2}\mathcal{D}^{(2)}p.$$

Power-grid frequency: A scaling law

Take that the stochastic noise present is a sum of i.i.d Gaussian distributed random variables

$$\frac{\partial p}{\partial t} = -\frac{\partial}{\partial \omega}(c_1 \omega p) + \boxed{\frac{\epsilon^2}{2}} \frac{\partial^2 p}{\partial \omega^2} = -\frac{\partial}{\partial \omega}(c_1 \omega p) + \boxed{\frac{1}{2}\frac{\sum_i^N \epsilon_i^2}{M^2}} \frac{\partial^2 p}{\partial \omega^2}$$

which results in a relation†

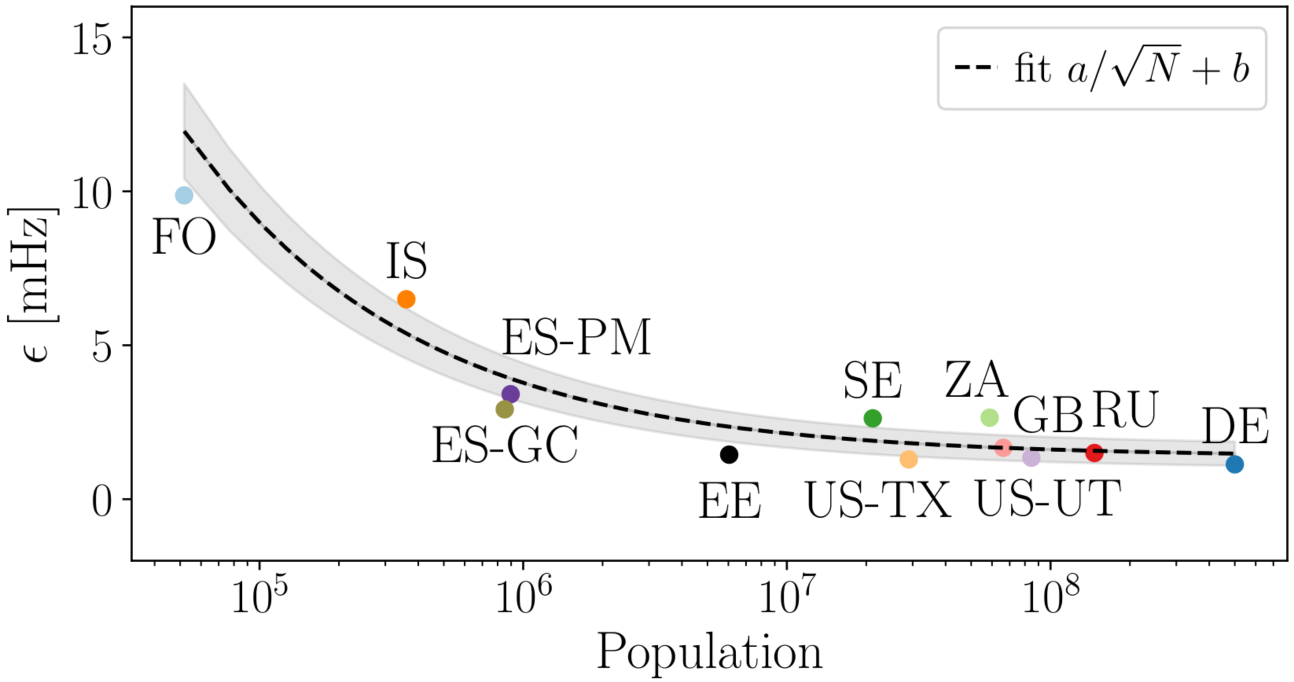
$$\sigma \sim \frac{1}{\sqrt{c_1 N}} \text{ or strictly from the diffusion: } \boxed{\epsilon \sim \frac{1}{\sqrt{N}}}$$

With N the number of nodes and an estimator $\hat{\epsilon} = \frac{1}{2} \lim_{\tau \to 0} \frac{1}{\tau} \langle (X(t+\tau) - X(t))^2 | X(t) = f \rangle$

†Schäfer, B., Beck, C., Aihara, K., Witthaut, D., Timme, M. *Non-Gaussian power grid frequency fluctuations characterized by Lévy-stable laws and superstatistics*, Nature Energy 3(2):119–126, 2018, doi:10.1038/s41560-017-0058-z

Power-grid frequency: A scaling law

This results in:



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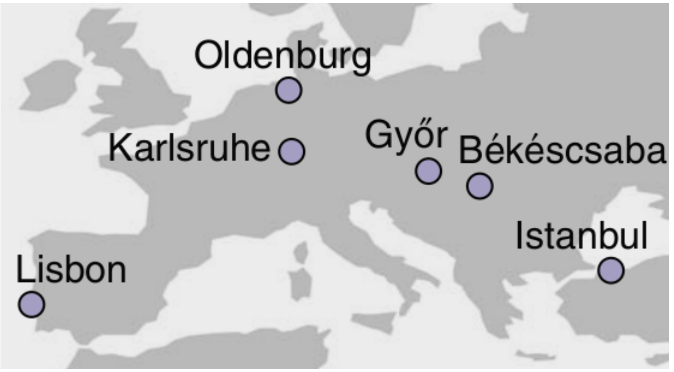
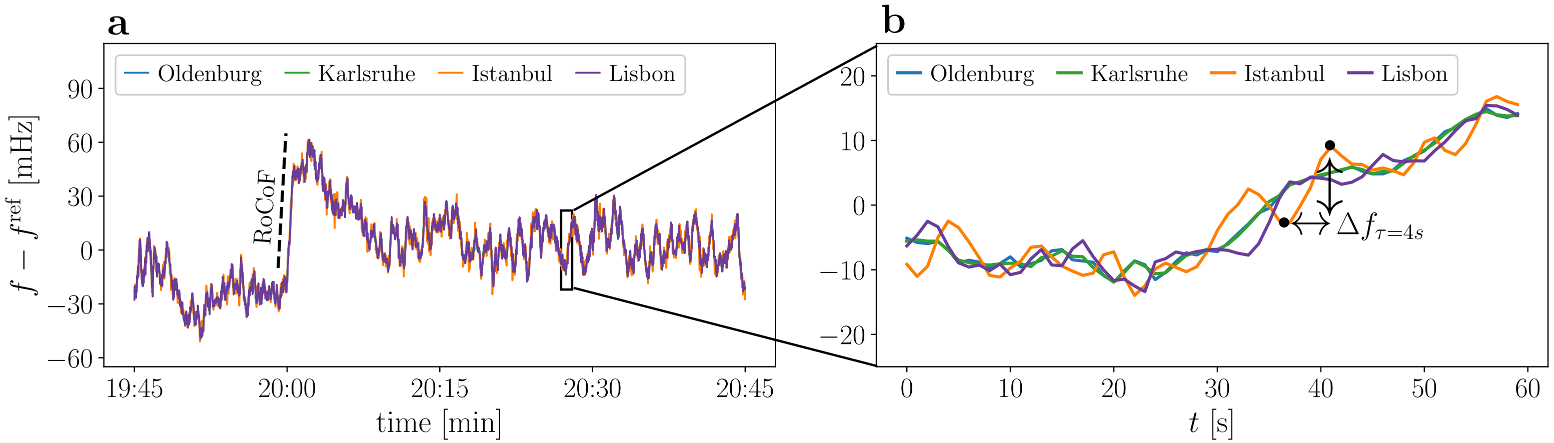
$$\sigma \sim \frac{1}{\sqrt{c_1 N}} + b$$ or strictly from the diffusion: $$\boxed{\epsilon \sim \frac{1}{\sqrt{N}}} + b$$

The finer details in the same synchronous area

Synchronised recordings in the Continental European grid

4 recordings with the EDR, +2 recording from the Hungarian TSO MAVIR.
From 2019-07-09 to 2019-07-15, with a 1 second sampling.

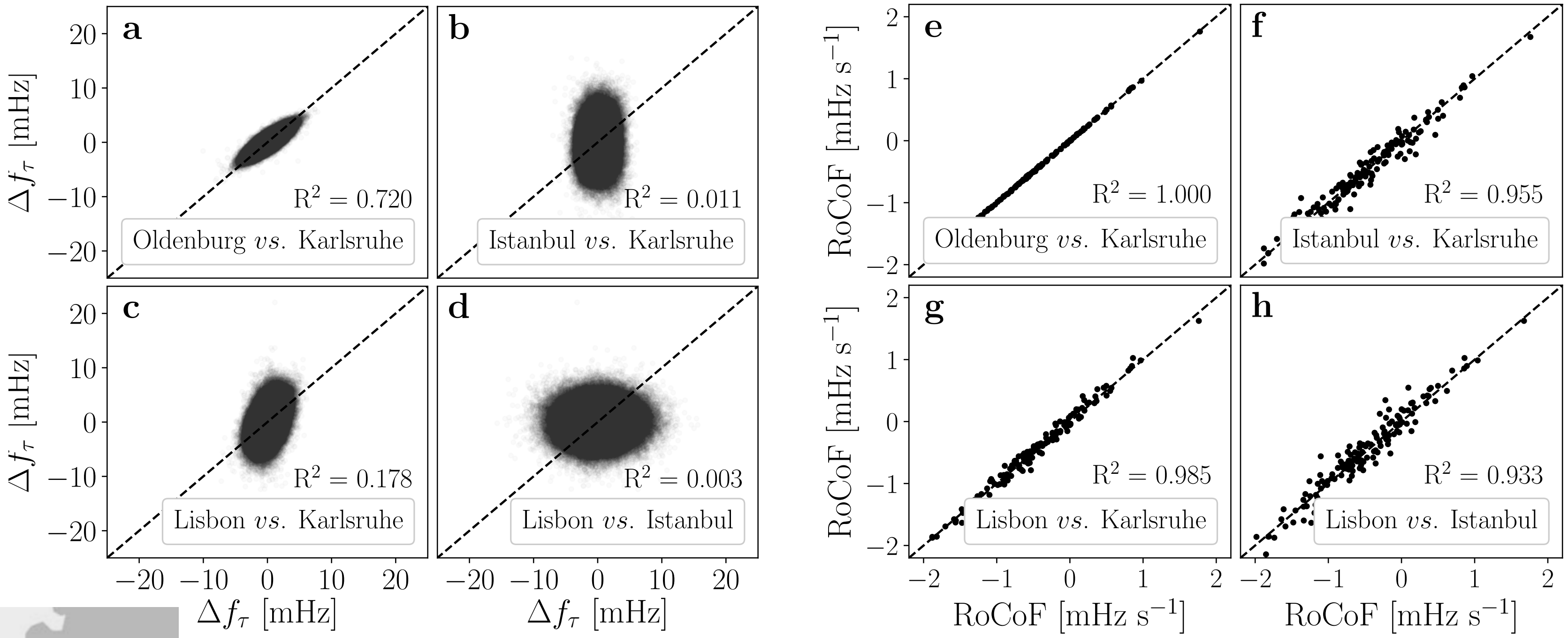


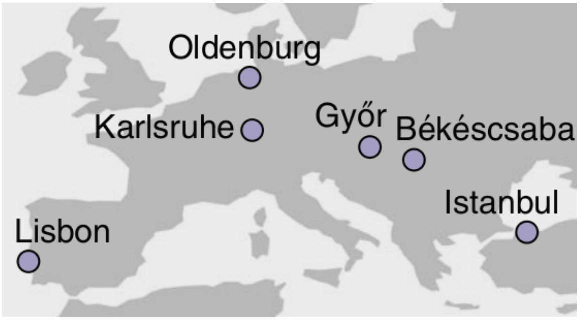


Increment statistics: $\Delta f_\tau(t) = f(t+\tau) - f(t)$

The finer details in the same synchronous area

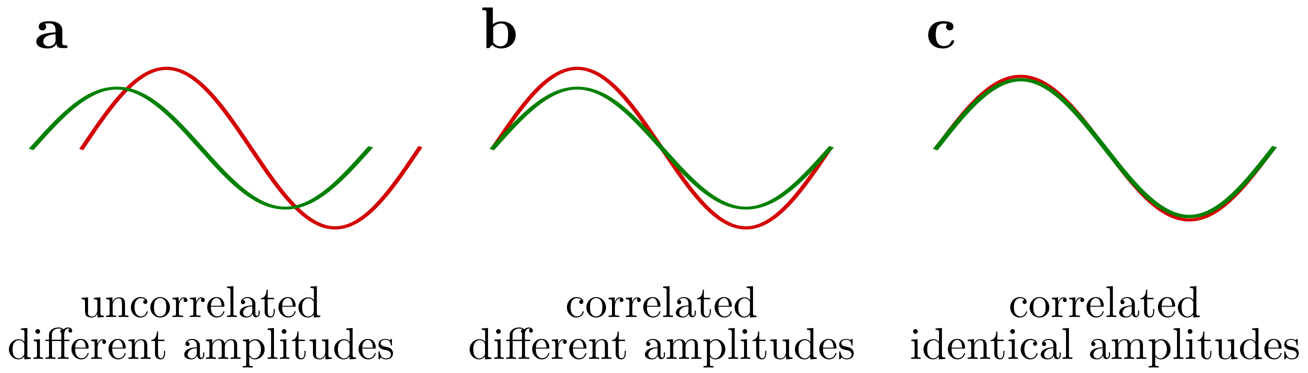
Synchronised recordings in the Continental European grid





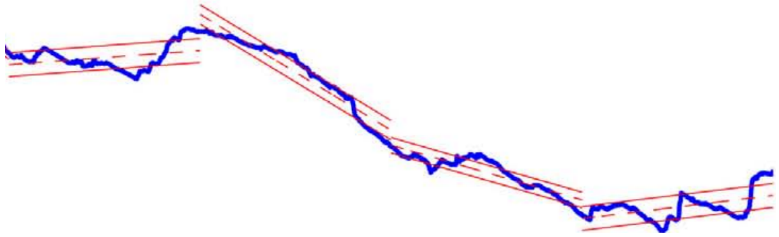
Is there more to the nature of stochastic fluctuation?

Quantifying fluctuations



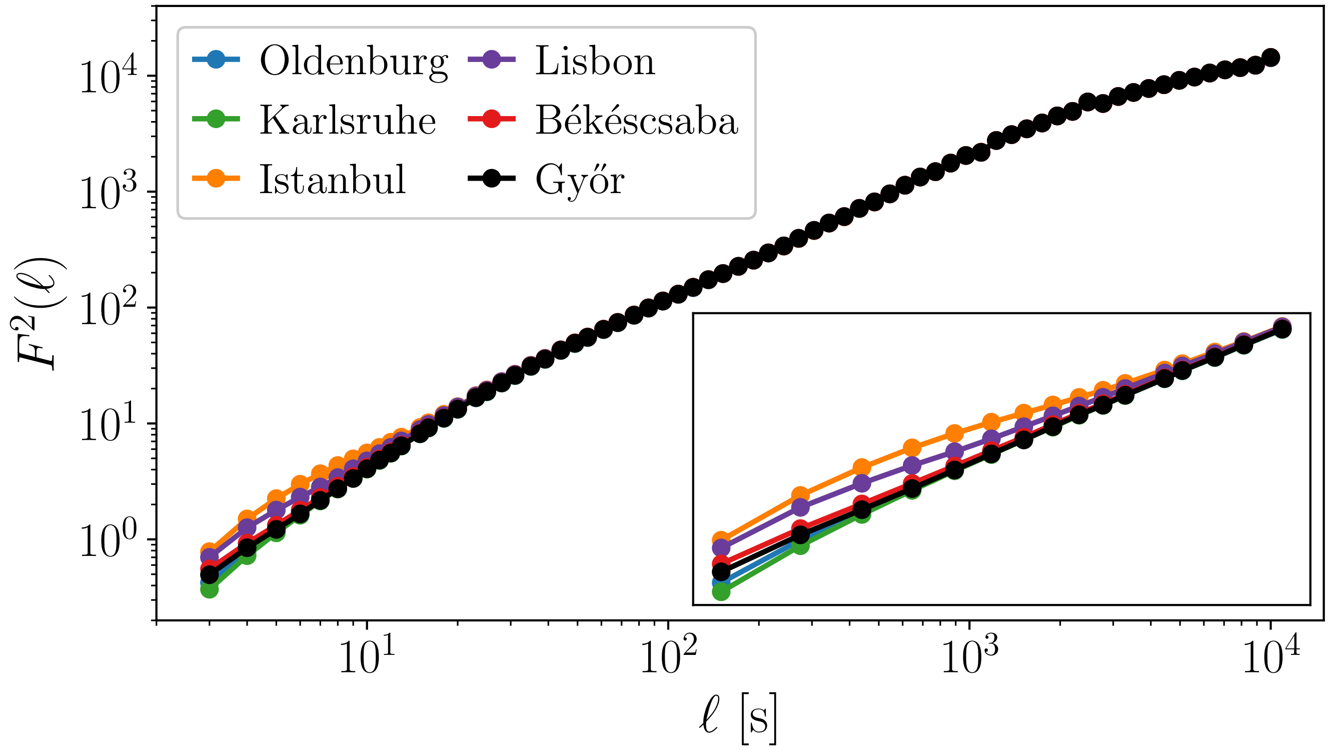
Applying Detrended Fluctuation Analysis (DFA): we can obtain a fluctuation function $F^2(\ell)$ for a segment with length ℓ:

$F^2(\ell)$ comprises solely the variance of the increments



Quantifying fluctuations

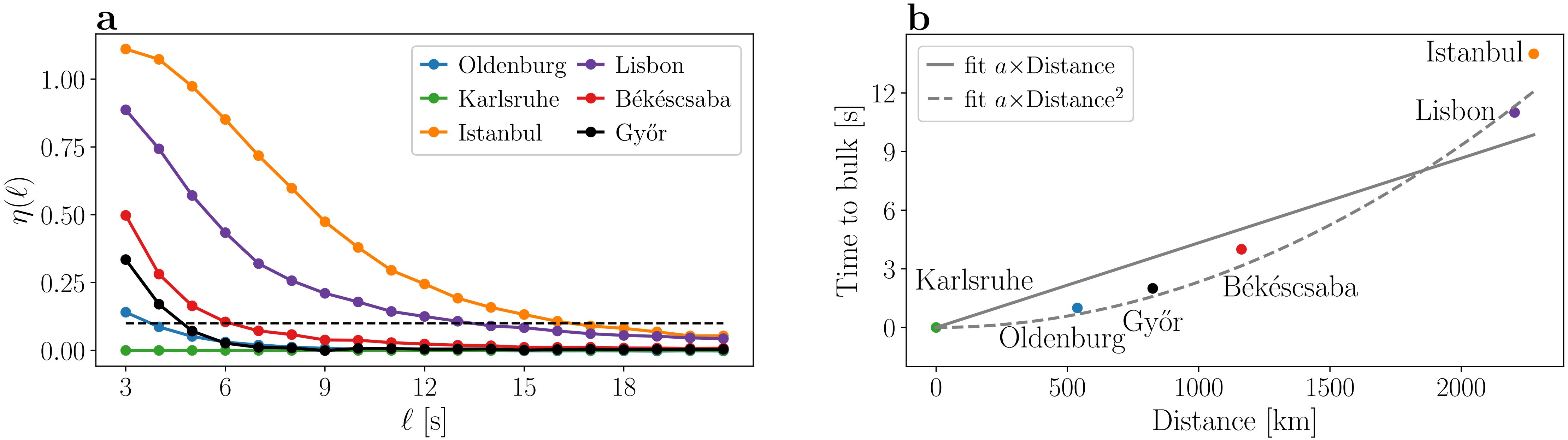
Regime of amplitude synchronisation

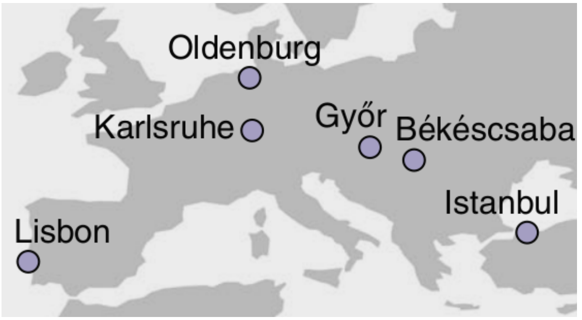


For a detailed analysis of DFA, see: Meyer, P. G., Anvari, M., Kantz, H. *Identifying characteristic time scales in power grid frequency fluctuations with DFA*, Chaos: An Interdisciplinary Journal of Nonlinear Science 30:013130, 2020, doi:10.1063/1.5123778

Quantifying fluctuations

Regime of amplitude synchronisation: “time-to-bulk” behaviour





$$\eta(\ell) = \frac{{F^2}^{\text{location}}(\ell) - {F^2}^{\text{Karlsruhe}}(\ell)}{{F^2}^{\text{Karlsruhe}}(\ell)},$$

Envoi: Space and time correlations

We have:

- Gathered a large dataset of power-grid frequency which is still growing.
- Identified characteristic scaling of the diffusion with the number of consumers.
- Devised a method to uncover a global synchronisation of fluctuations across a synchronous area.

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ARTICLE

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https://doi.org/10.1038/s41467-020-19732-7 OPEN

Open database analysis of scaling and spatio-temporal properties of power grid frequencies

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doi:10.1038/s41467-020-19732-7

Future work:

- Is the physics fluctuation amplitude universal? – What is the impact of the topology of power grids?
- What are the consequences for smaller (island) grids?

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