Assessing Smoothing Effects of Wind-Power around Trondheim via Koopman Mode Decomposition

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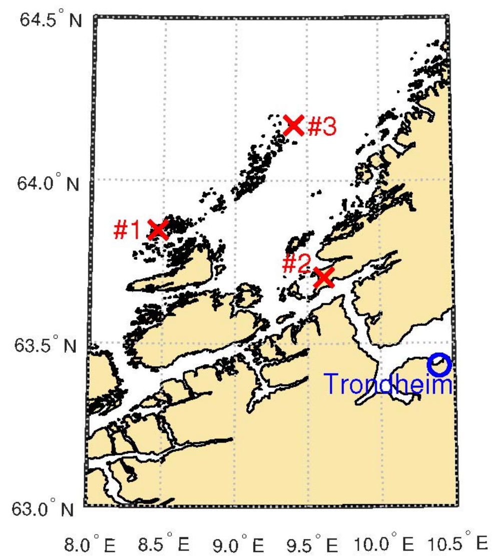
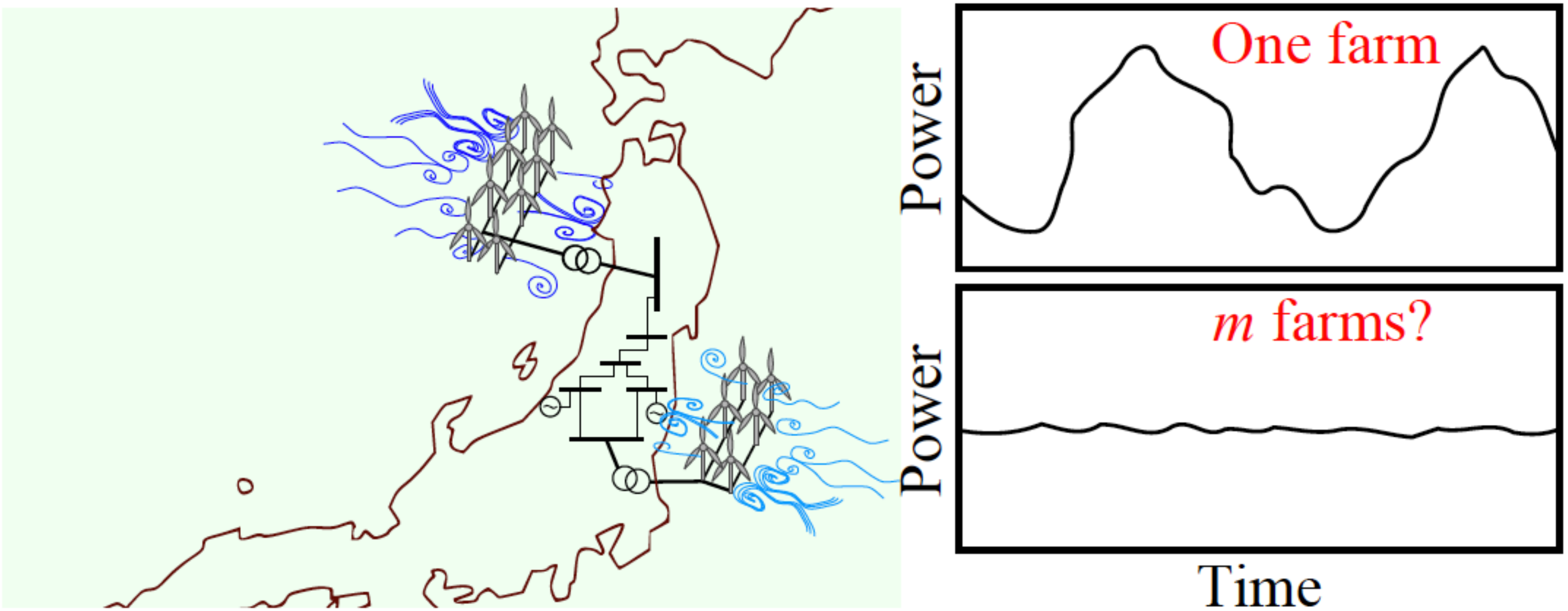
Outline of Presentation

- Introduction
  - About JST Project / Why Smoothing Effect?
- Koopman Mode Decomposition (KMD)
  - Brief summary of nonlinear time-series analysis
- KMD-based Quantification of Wind-Power Smoothing
  - F. Raak, Y. Susuki *et al.*, *NOLTA, IEICE*, vol.8, no.4, pp.342-357 (2017).
  - Definition and simple example
- Application to Wind-Data around Trondheim
  - Synthetic wind-power output
  - Quantification result
- Conclusion



Smoothing Effects of Wind-Power

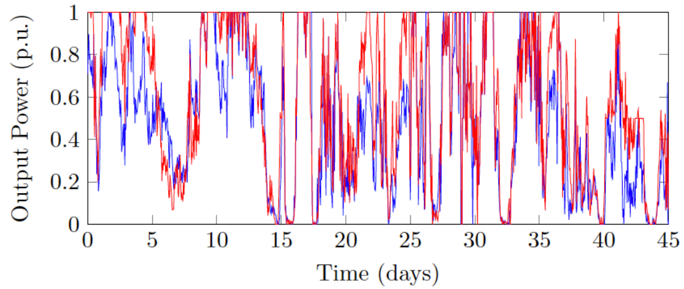
- Reduction of fluctuations in wind-power by aggregation
- Importance of its assessment (or quantification) for managing large-scale introduction of wind power:
  - *Large-term* use --- planning w/ use of **in-vehicle batteries**
  - *Short-term* use --- controlling turbines / maintaining power quality

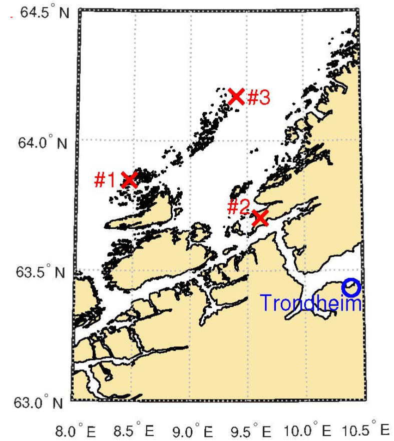


Purpose and Contents

Quantifying Smoothing Effects of Wind-Power around Trondheim via Koopman Mode Decomposition

1. Introduction of Koopman Mode Decomposition (KMD)
2. Review of KMD-based Quantification
   – F. Raak, Y. Susuki *et al.*, *NOLTA, IEICE*, vol.8, no.4, pp.342-357 (2017).
3. Application to Measured Data on Wind-Speed around Trondheim
   – Newly reported in this presentation





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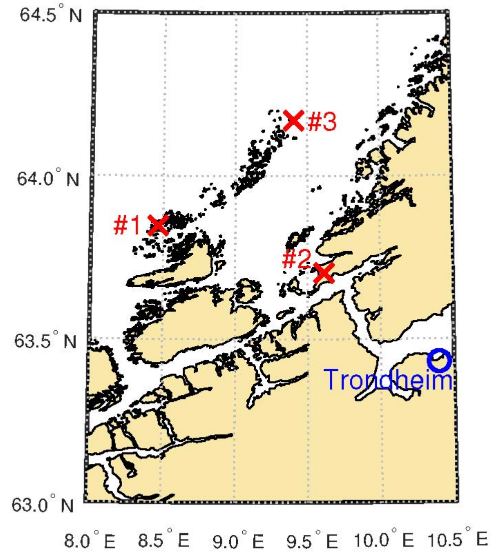


Koopman Mode Decomposition (KMD)

Novel technique to decompose multi-channel, complex time-series into **modes with single-frequencies,** conducted directly from ***data***

$\{g_0, \ldots, g_m\}$ Finite-time data obtained in experiments or simulations under uniform sampling

Koopman Eigenvalue, determining freq./damping

Koopman Mode, determining amplitude/phase

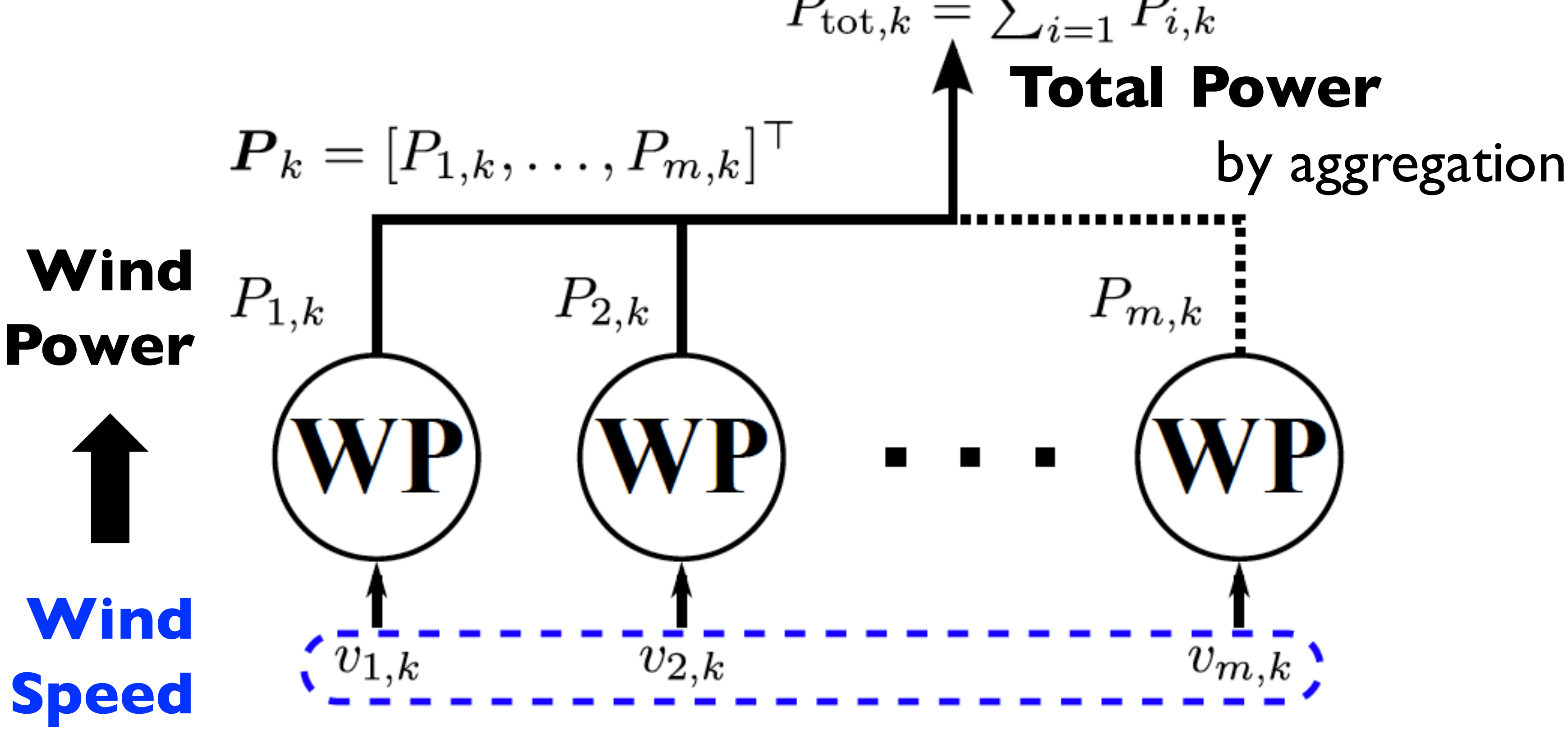
$$g_k = \sum_{j=1}^{m} \tilde{\lambda}_j^k \tilde{V}_j, \quad g_m = \sum_{j=1}^{m} \tilde{\lambda}_j^m \tilde{V}_j + \eta_m$$

$$k = 0, \ldots, m-1$$

For details, see the paper [C. Rowley, I. Mezic, *et al.*, *J. Fluid Mech.*, vol.641, pp.115-127 (2009)].

KMD-based Quantification (1/3) -- Derivation

Ref.) F. Raak, Y. Susuki *et al.*, *NOLTA, IEICE*, vol.8, no.4, pp.342-357 (2017).



$$\boldsymbol{P}_k = \sum_{i=1}^{N} \tilde{\lambda}_i^k \tilde{\boldsymbol{v}}_i, \quad k = 0, \ldots, N$$

KMD of Wind-Power

$$P_{\mathrm{tot},k} = \sum_{i=1}^{N} \tilde{\lambda}_i^k \sum_{j=1}^{m} [\tilde{\boldsymbol{v}}_i]_j =: \sum_{i=1}^{N} \tilde{\lambda}_i^k \overline{\boldsymbol{v}}_i$$

KMD-based Quantification (2/3) -- Definition

Ref.) F. Raak, Y. Susuki *et al.*, *NOLTA, IEICE*, vol.8, no.4, pp.342-357 (2017).

KMD of Wind-Power (again):

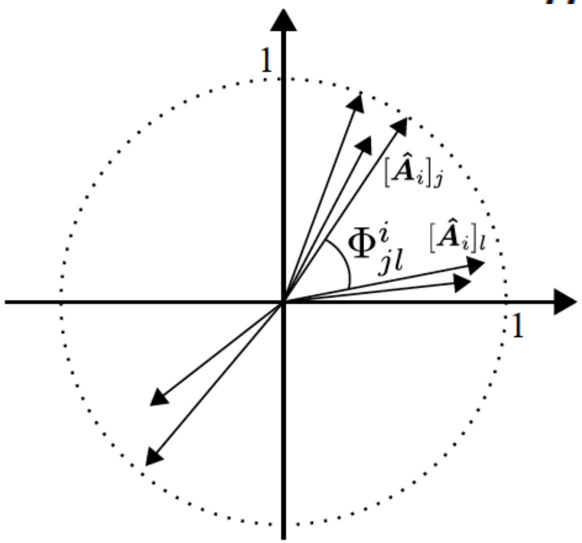
$$\boldsymbol{P}_k = \sum_{i=1}^{N} \tilde{\lambda}_i^k \tilde{\boldsymbol{v}}_i, \quad k = 0, \ldots, N \qquad \tilde{\boldsymbol{v}}_i = \boldsymbol{A}_i \angle \boldsymbol{\alpha}_i$$

Complex-valued vectors

Proposed Index:

$$\mathrm{coh}_{i,\mathrm{KMD}} = \frac{1}{m(m-1)} \sum_{j=1}^{m} \sum_{\substack{l=1 \\ l \neq j}}^{m} [\hat{\boldsymbol{A}}_i]_j [\hat{\boldsymbol{A}}_i]_l \cos(\Phi_{jl}^i)$$

Normalized Moduluses



- Total sum of **similarity** for every pair of components of a single Koopman mode
- Index computed for each **single** frequency
- Generalization of the conventional Power Spectrum Density (PSD)-based index

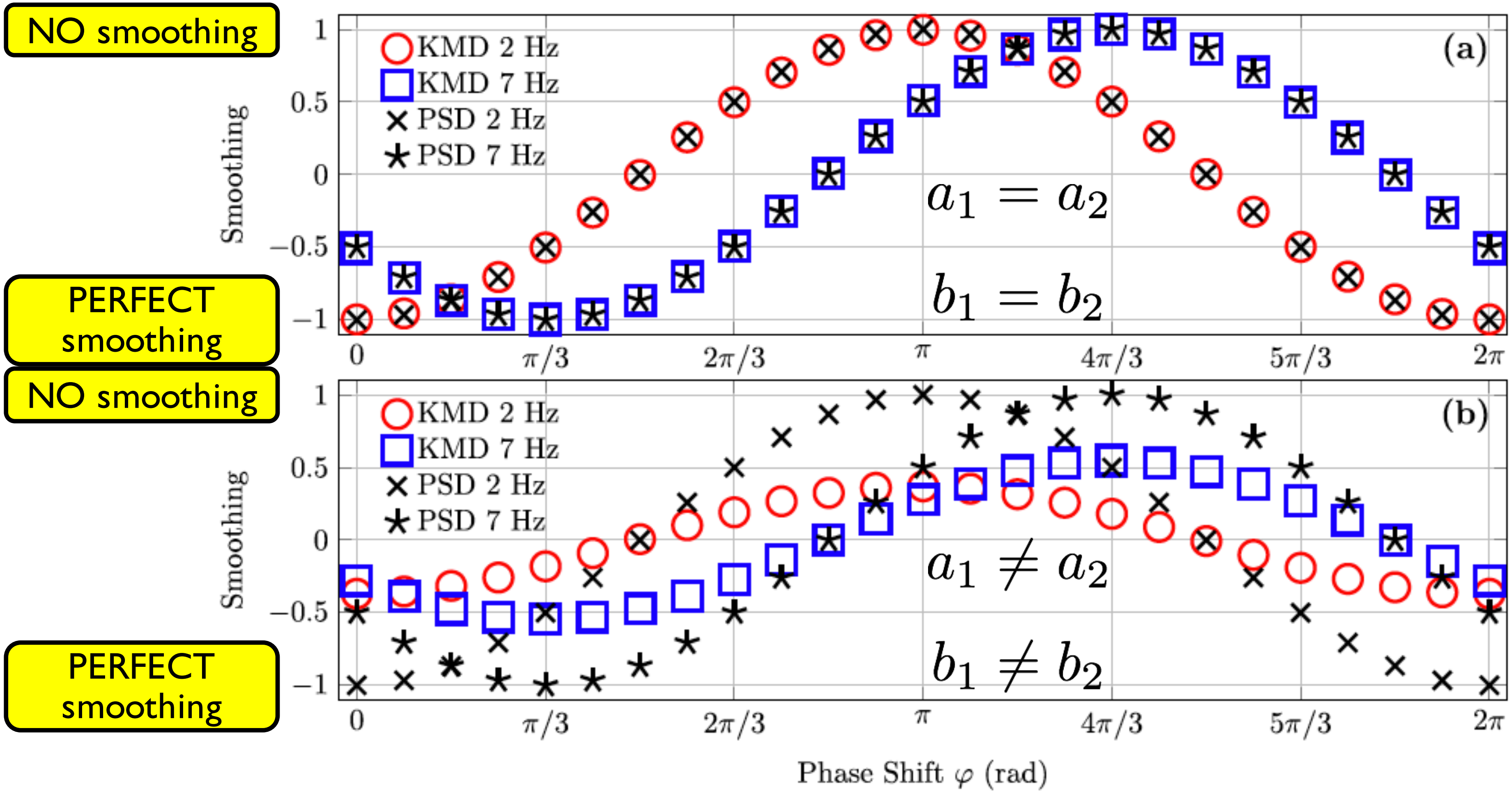
KMD-based Quantification (3/3) -- Example

Ref.) F. Raak, Y. Susuki *et al.*, *NOLTA, IEICE*, vol.8, no.4, pp.342-357 (2017).

$$x_1(t) = a_1 \cdot \sin(2\pi f_1 t) + b_1 \cdot \cos(2\pi f_2 t),$$

$$x_2(t) = -\left\{a_2 \cdot \sin(2\pi f_1 t + \varphi) + b_2 \cdot \cos\left(2\pi f_2 t - \frac{\pi}{3} + \varphi\right)\right\}$$

$$f_1 = 2\,\text{Hz}$$
$$f_2 = 7\,\text{Hz}$$



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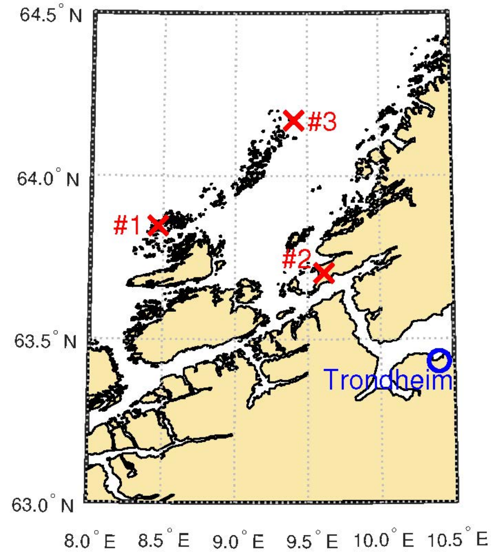
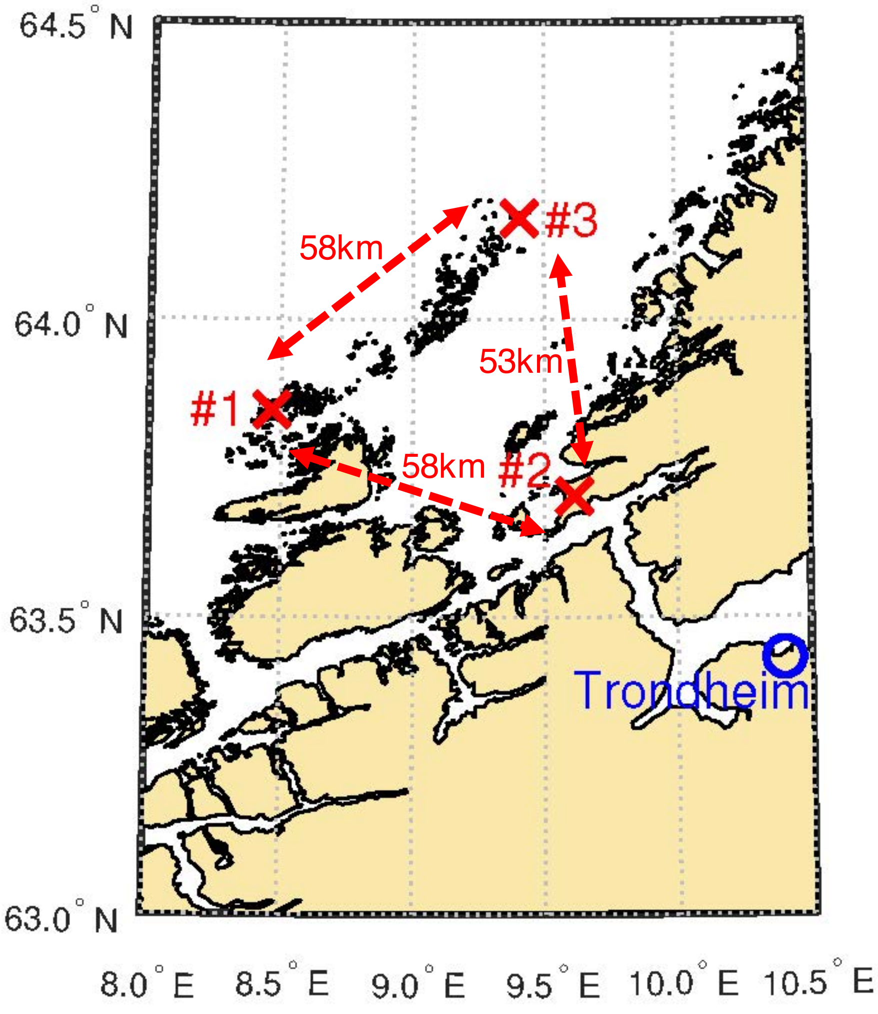
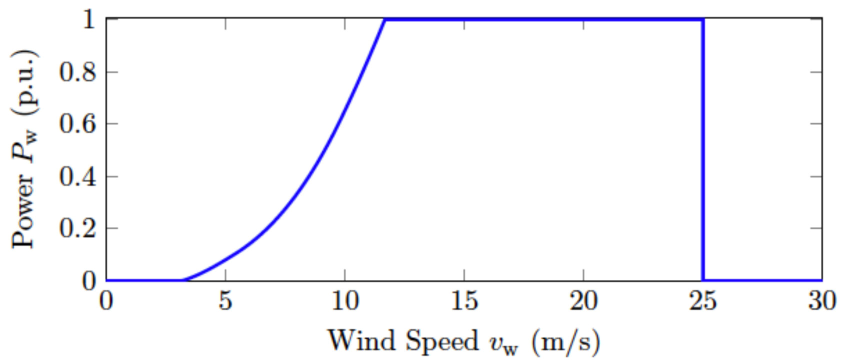


Measurement Data around Trondheim

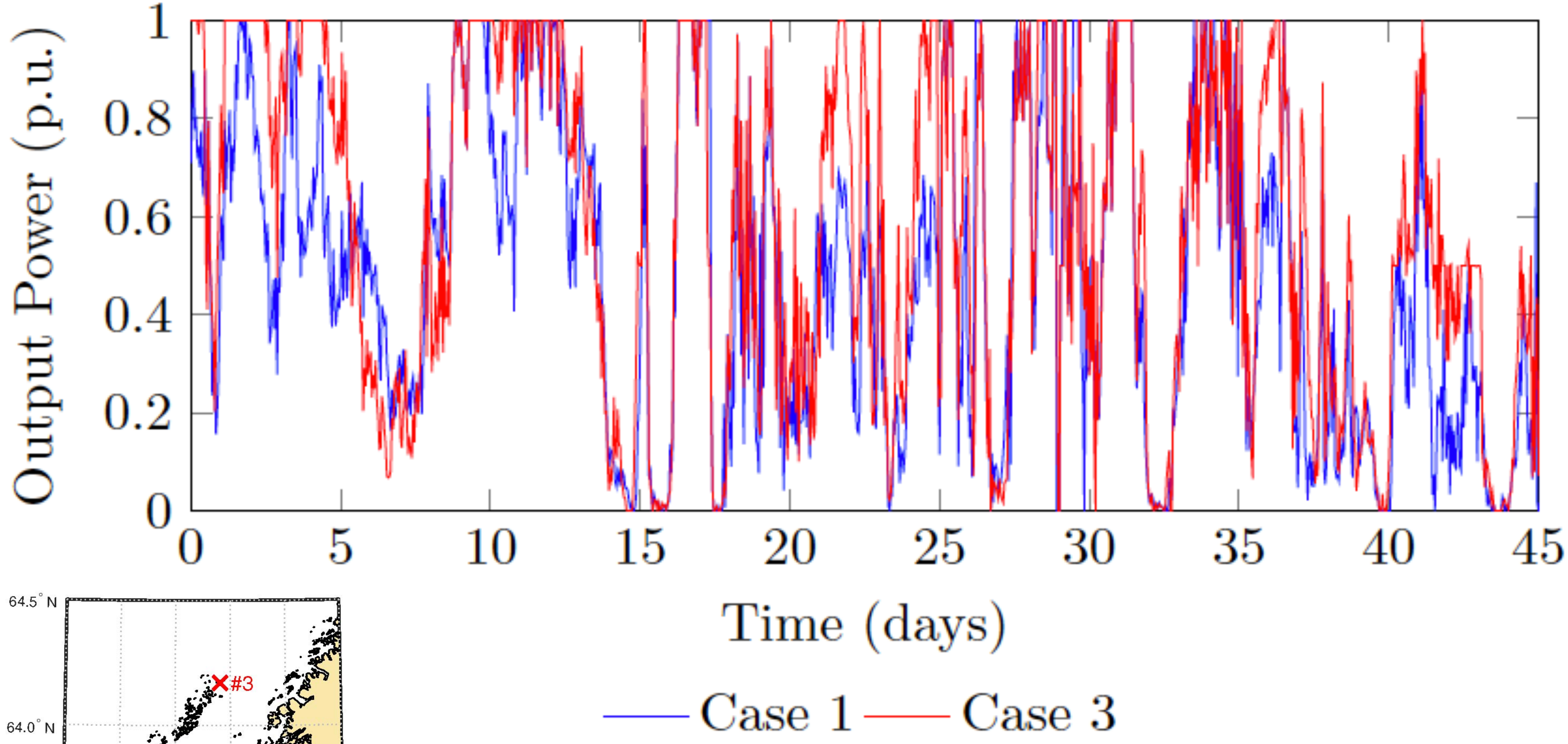


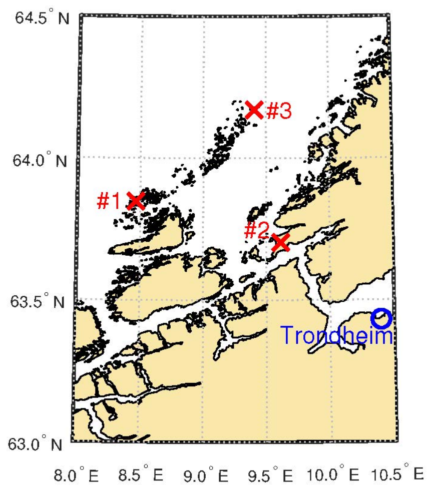
Three Hypothetical Wind-Farm Sites

- 92-days long time-series of hourly wind speeds
  - 10 meters above ground / Mmean value for last 10 minutes before time of observation
- Converted into wind-power (in per-unit) via the static nonlinear power curve below



Data on Aggregated Wind-Power





Aggregation of #1 and #2

Aggregation of #2 and #3

Original Data and Reconstructed Data via KMD

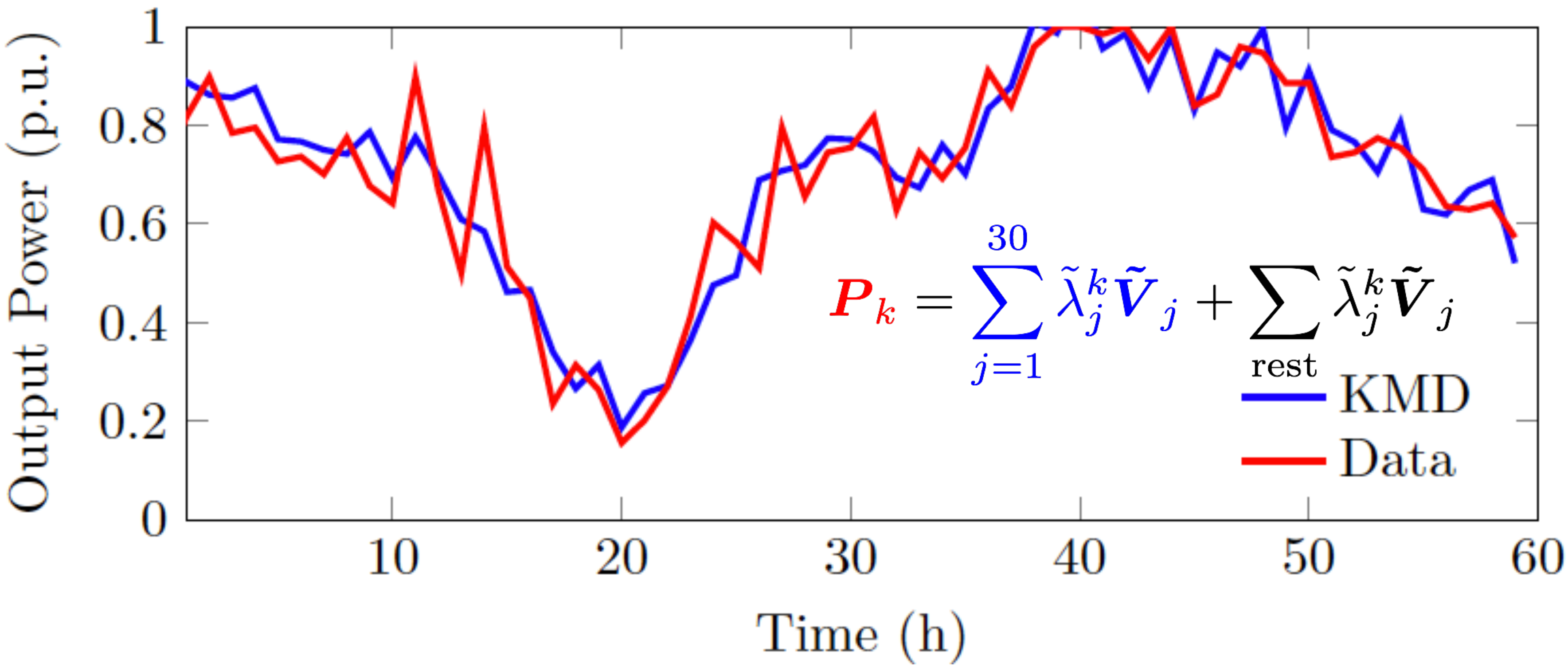
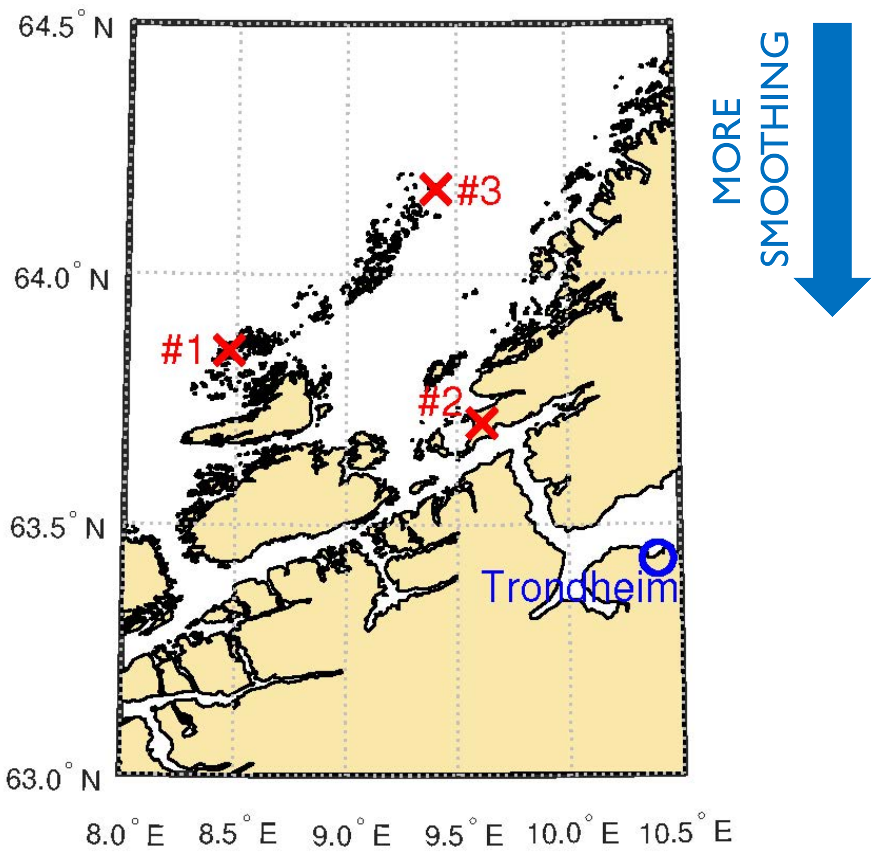


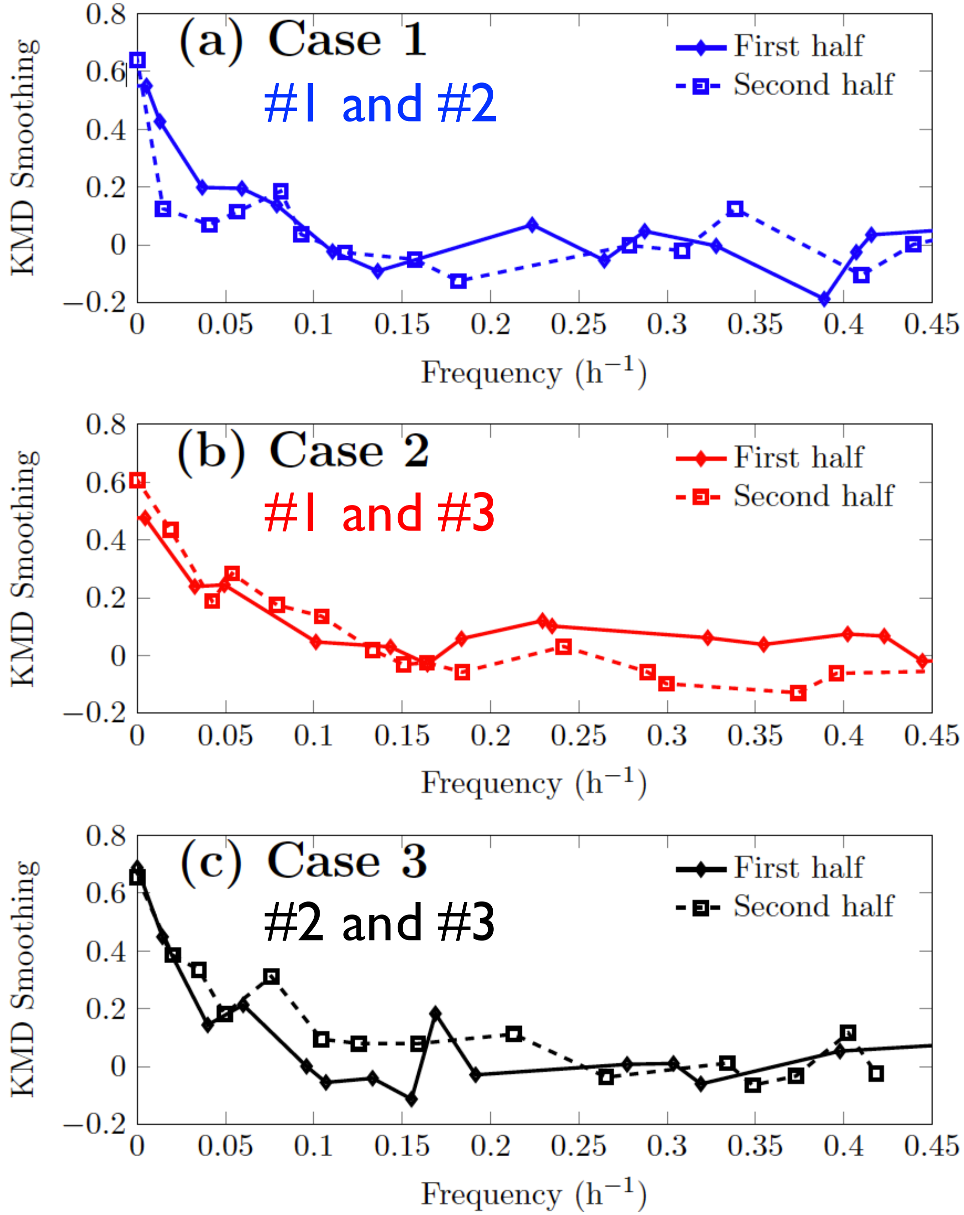
Table 1. Variances of total powers P and of reconstructed time-series via KMD $\tilde{P}$

Case	$P_{\text{tot,first}}$	$P_{\text{tot,last}}$	$\tilde{P}_{\text{tot,first}}$	$\tilde{P}_{\text{tot,last}}$
Case 1 #1 and #2	0.10	0.08	0.12	0.06
Case 2 #1 and #3	0.11	0.09	0.12	0.08
Case 3 #2 and #3	0.12	0.10	0.12	0.09

Lower Value of Variance!

Quantification Result





- More smoothing archived in high frequencies
- Better smoothing engineered in Case:1, consistent with the variance test

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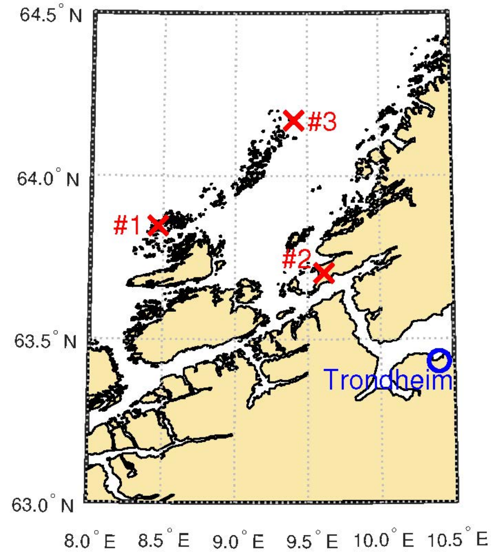
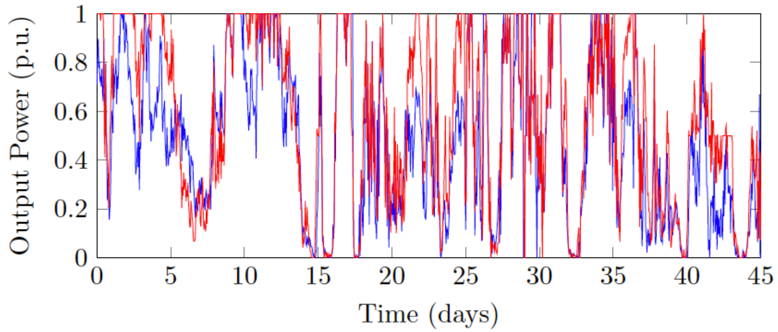
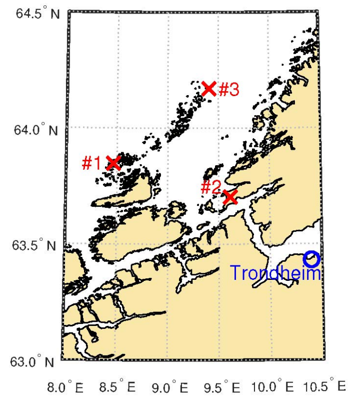


Summary and Take-Home Messages

Quantifying Smoothing Effects of Wind-Power around Trondheim via Koopman Mode Decomposition (KMD)

1. KMD enables an extraction of dominant feature w/ clear time-scale separation directly from complex wind-power data.
2. KMD enables a quantification of smoothing effects of wind-power around Trondheim
   ---*how the smoothing is engineered by the choice of locations.*





Thank You for Your Attention!

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