Constrained simulation of normal turbulence operation with embedded lidar measurements

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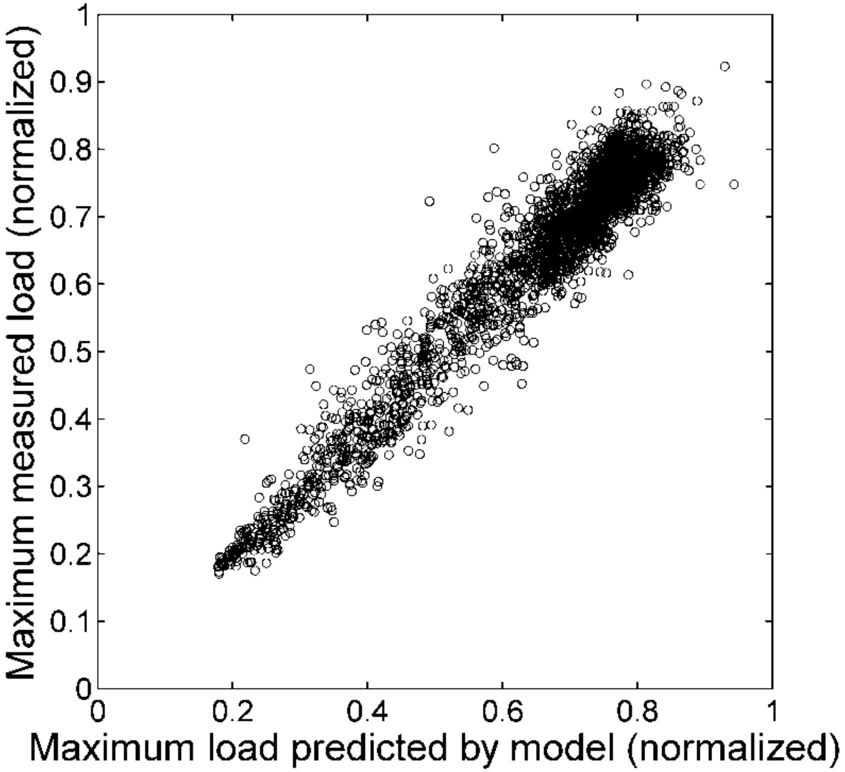
UniTTe: Unified Turbine Testing

Introduction

- Simulation of loads under operating conditions requires a turbulent wind field realization (so-called “Turbulence box”) as input

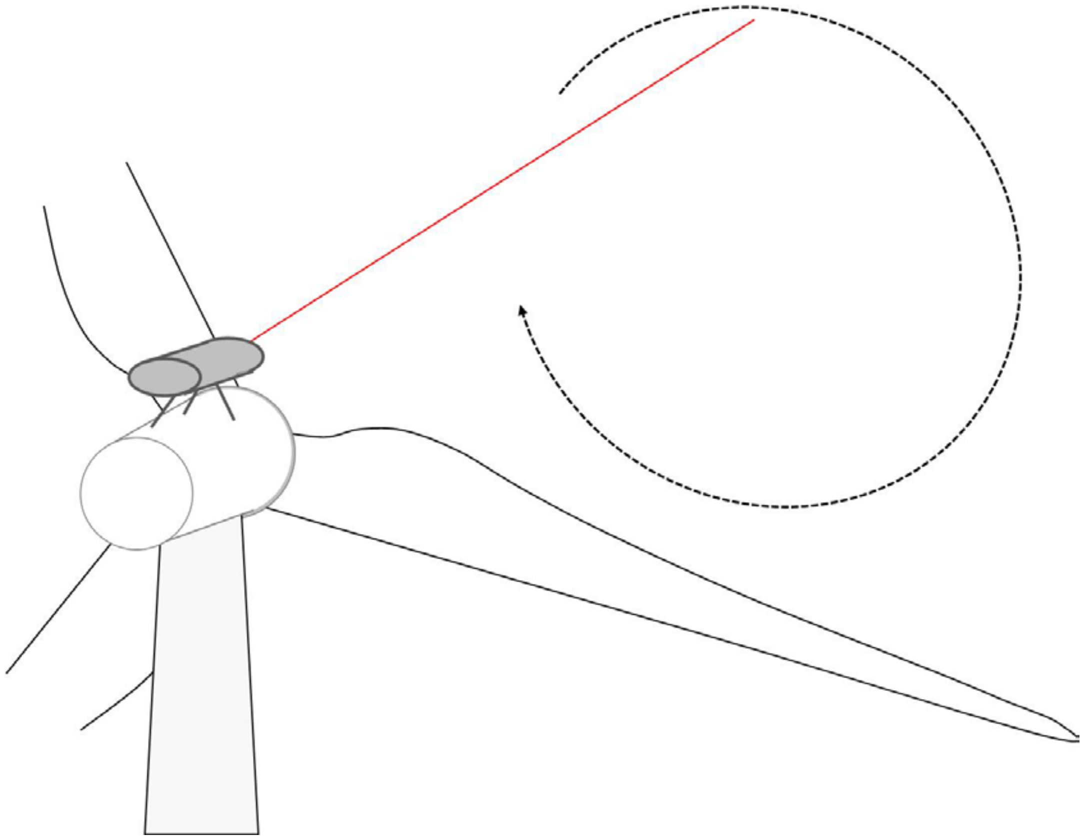
- The turbulent field is subject to several uncertainties:
  - Model uncertainties
  - Measurement uncertainties
  - Wind field inhomogeneity (e.g. differences between measurement and turbine location)
  - Statistical “realization-to-realization” uncertainty



Introduction

- Lidar (LIght Detection And Ranging): scanning of wind speeds at multiple locations upwind

- Can we use lidar measurements to reduce statistical uncertainty?



Constrained Gaussian fields

- A zero-mean, homogeneous, isotropic Gaussian field $\tilde{g}\,(\boldsymbol{r})$ is defined by its power spectrum $S_r(\boldsymbol{k})$
- Subject to a set of constraints, $\Gamma = \{C_i(\boldsymbol{r})|_{r_i} = c_i, \quad i = \ 1, \ldots, M\}$
- We define a constrained field as:

$$g(\boldsymbol{r}) = \tilde{g}(\boldsymbol{r}) + \boldsymbol{\zeta}(\boldsymbol{r})\mathbf{Z}^{-1}[\boldsymbol{C} - \tilde{g}_c(\boldsymbol{r})]$$

where

- $\langle . \rangle$ denotes ensemble averaging
- $\boldsymbol{\zeta}(\boldsymbol{r}) = [\langle g(\boldsymbol{r})C_1\rangle, \langle g(\boldsymbol{r})C_2\rangle, \ldots, \langle g(\boldsymbol{r})C_M\rangle]$ are the cross-correlations between the field and the constraints
- $\mathbf{Z}$ is the correlation matrix of constraints, $\mathrm{Z}_{ij} = \langle C_i C_j\rangle,\ i = 1 \ldots M, j = 1 \ldots M$
- $\boldsymbol{C} = [C_1, C_2, \ldots, C_M]^T$ is the vector with constraint values

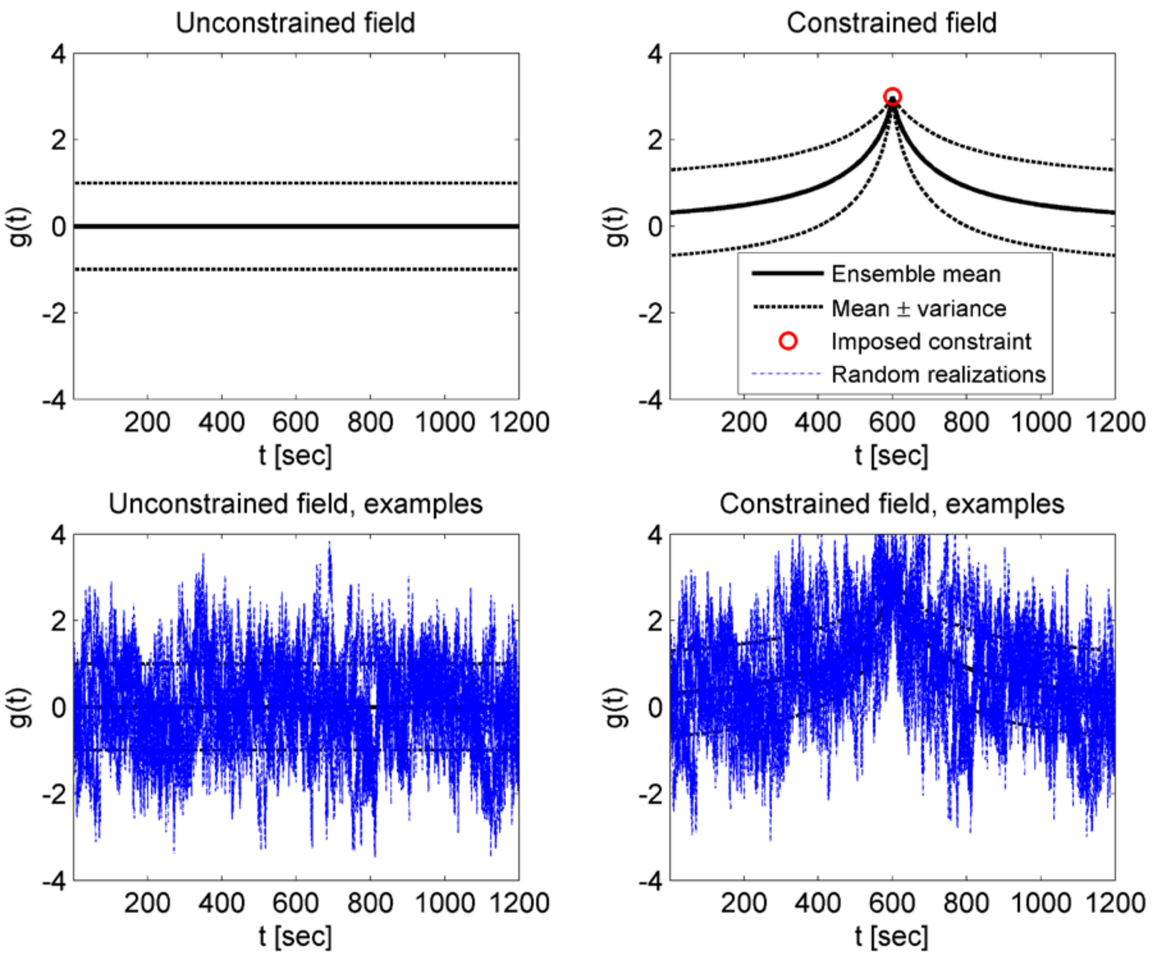
Constrained Gaussian fields

- The mean of the field is “shifted”:

$$\bar{g}(\boldsymbol{r}) = \langle g(\boldsymbol{r})|\Gamma\rangle = \boldsymbol{\zeta}(\boldsymbol{r})\mathbf{Z}^{-1}\boldsymbol{C}$$

- The variance “collapses” close to constraints

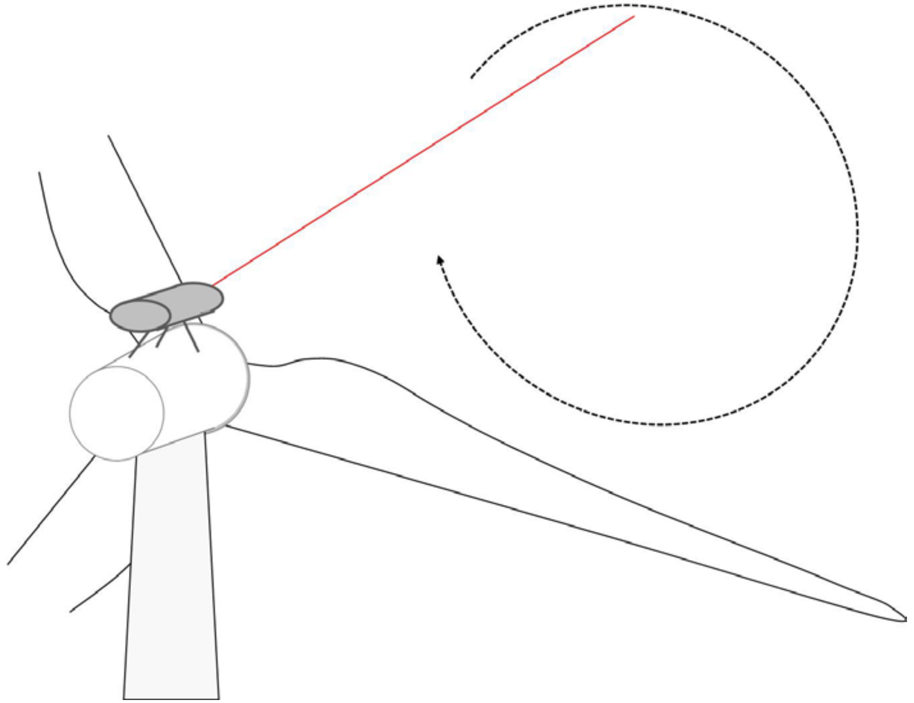
$$\sigma^2(\boldsymbol{r}|\Gamma) = \sigma^2 - \boldsymbol{\zeta}(\boldsymbol{r})\mathbf{Z}^{-1}\boldsymbol{\zeta}(\boldsymbol{r})^T$$



From lidar measurements to constrained fields

A number of uncertainties present:

- 1-direction measurements along the line-of-sight
- Large measurement volume
- Evolution of turbulence
- Turbine motion
- Spatial locations of measurements not falling on a rectangular grid
- Turbulence spectrum

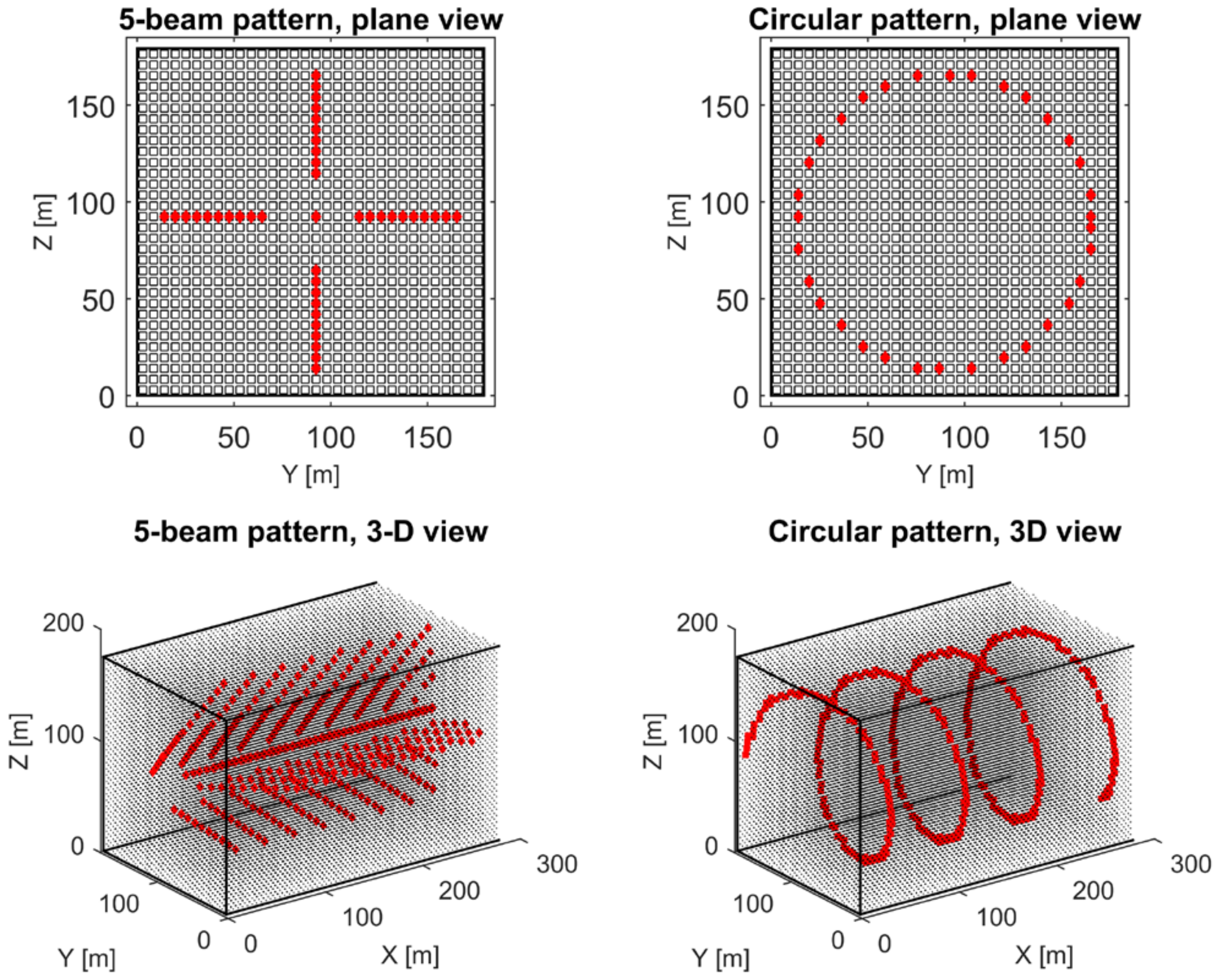


We want to assess the performance of the numerical method

⇒ we consider a case where the measurement uncertainty is eliminated.

Assumption: the lidar measurements have been used to calculate a known wind speed in longitudinal direction

Constrained turbulence box examples



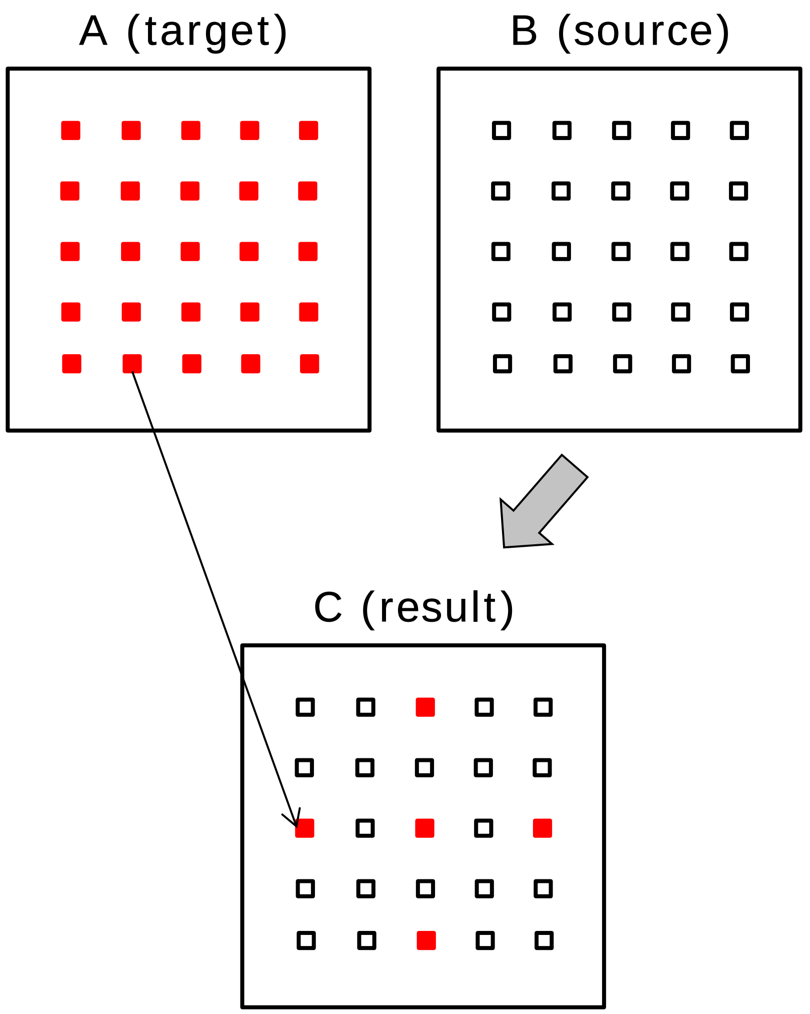
Constrained turbulence box examples

We have 3 different realizations:

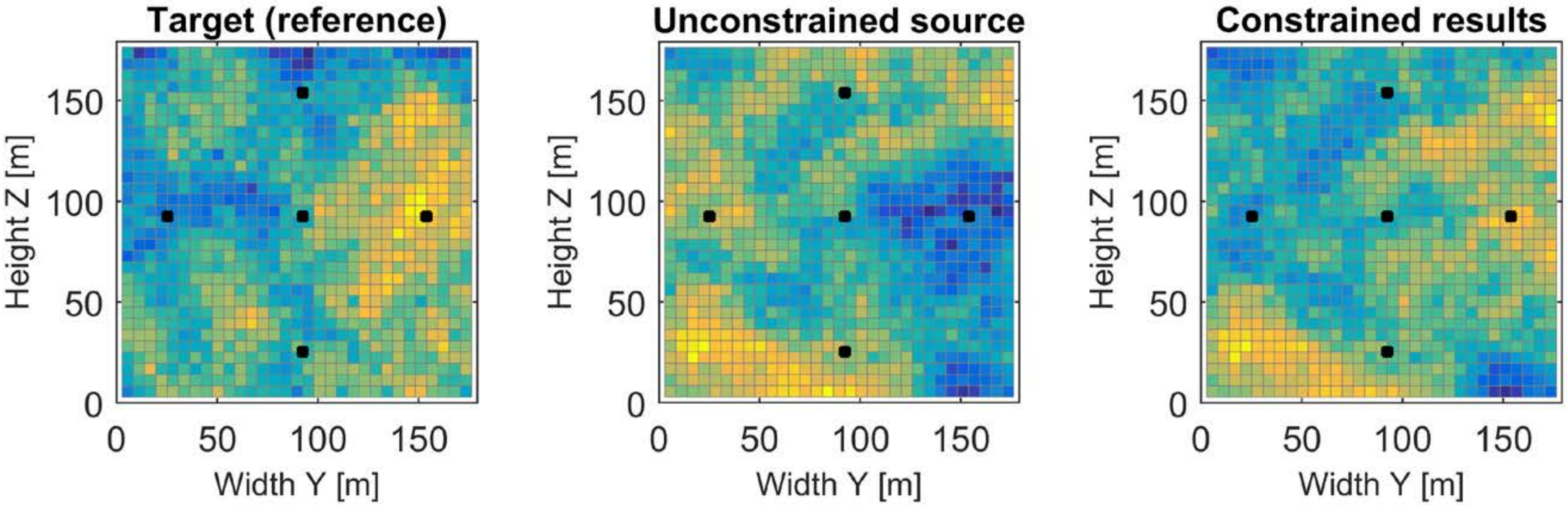
A) Reference random realization
(we take the constraints from it)

B) Unconstrained random realization (base)

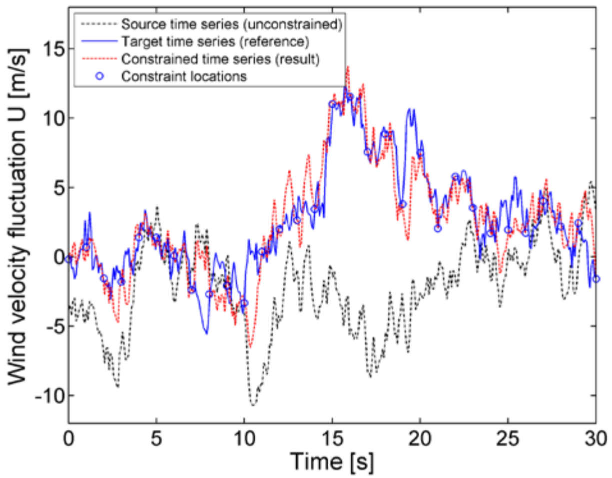
C) Resulting constrained random realization,
using B) as a base and taking constraints from A)



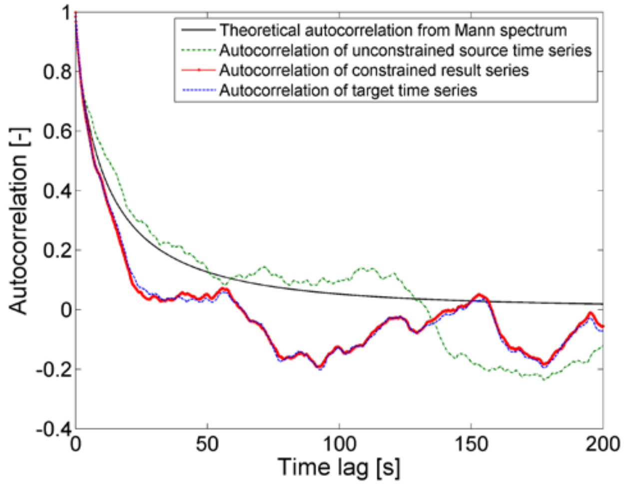
Constrained turbulence box examples



Time series comparison



Autocorrelation functions



Explained variance

- Explained variance: a measure of the proportion of the dispersion in the random field which is explained by the constraints imposed on it

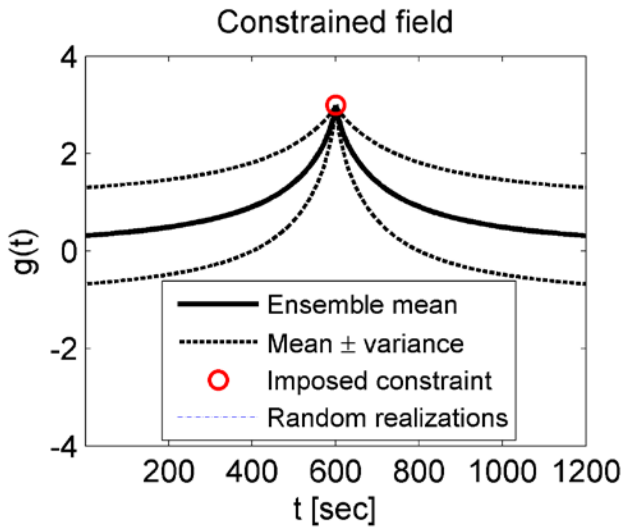
- The explained variance at a given point is defined as:

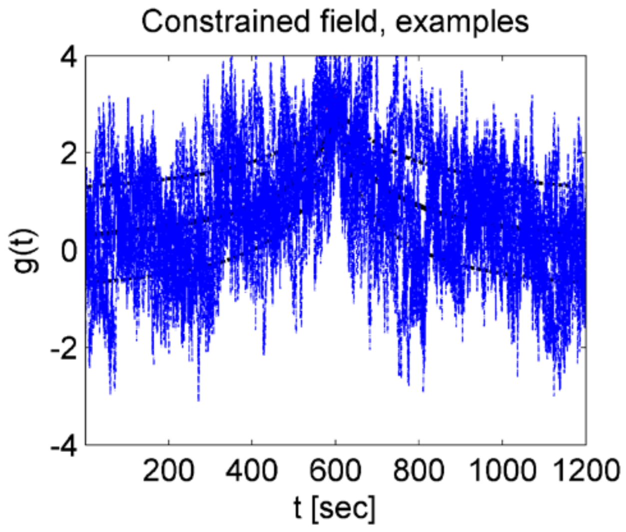
$$\sigma_{E,s}^2 = \boldsymbol{\zeta}(\boldsymbol{r})\mathbf{Z}^{-1}\boldsymbol{\zeta}(\boldsymbol{r})^T$$

- For the entire turbulence box:

$$\mu_{\sigma_E^2} = \frac{1}{V}\int_V \sigma_E^2(\boldsymbol{s})d\boldsymbol{s} = \frac{1}{V}\int_{-L_1/2}^{L_1/2}\int_{-L_2/2}^{L_2/2}\int_{-L_3/2}^{L_3/2}\sigma_E^2(t,y,z)\cdot dtdydz$$

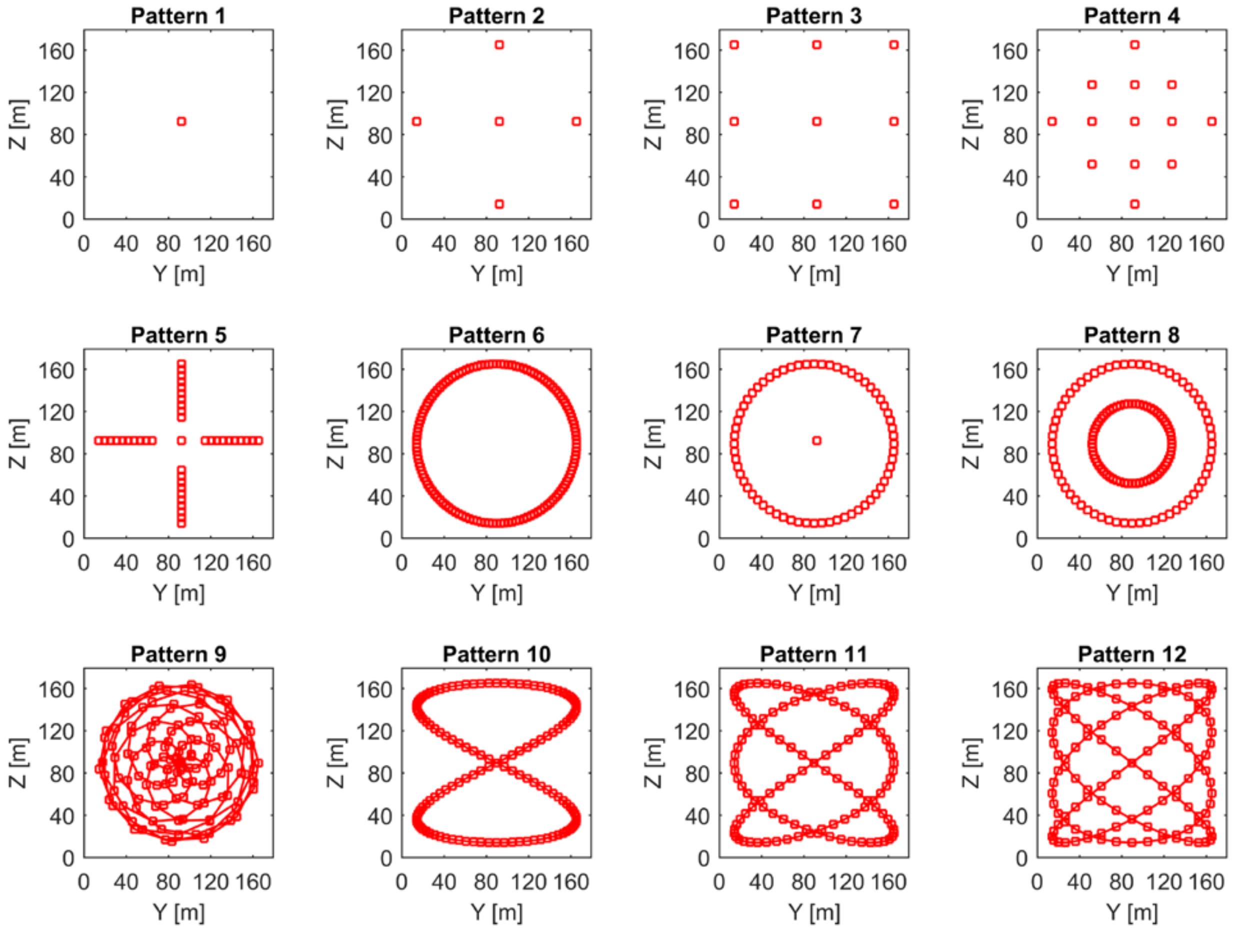
- Can we use the explained variance to assess the efficiency of different scanning patterns?





Parametric study on pattern choices

- We assess the explained variance and load uncertainties achieved with 12 different patterns
- Different pattern sizes and scanning periods are tested



Study on load and power uncertainty

- DTU 10MW turbine, HawC2 aeroelastic tool
- IEC61400, ed.3, class 1A, DLC 1.1
- Wind speed 4 to 25m/s
- 18 seeds per wind speed (396 per simulation set)
- Yaw error alternating between -10, 0, 10 deg.
- Two sets of turbulence seeds:

  $\boldsymbol{A} = [a_1, a_2, \dots, a_{396}]$ and $\boldsymbol{B} = [b_1, b_2, \dots, b_{396}]$

Study on load and power uncertainty

A number simulation sets are considered:

- A “target” reference case, unconstrained turbulence from set $\boldsymbol{A}$

- A baseline case, using unconstrained turbulence from set $\boldsymbol{B}$.

- Several constrained cases with different scanning patterns, using set $\boldsymbol{B}$ as base, and taking constraints from $\boldsymbol{A}$
  - Single-beam, single-range pattern (denoted set $\boldsymbol{C}$)
  - 5-beam, single-range pattern (set $\boldsymbol{D}$)
  - Pulsed-lidar pattern with 5 beams and 10 ranges (set $\boldsymbol{E}$)
  - Circular pattern with 30 points per revolution (set $\boldsymbol{F}$)
  - Higher-order curved patterns (Lissajous and double-co-rotating curves, sets $\boldsymbol{G}$ and $\boldsymbol{H}$)

- Each case is repeated with two turbulence length scales: $L = 29.4m$ and $L = 72m$

Load uncertainty

- Defining uncertainty variables:

$$X_B(i) = \frac{M(b_i)}{M(a_i)}$$

- Results (tables with mean and standard deviation of uncertainty variables)
  - X_B: reference
  - X_C: constrained, single-point pattern
  - X_D: constrained, 5-point pattern
  - X_E: constrained, 5-point, multi-range pattern
  - X_F: constrained, circular pattern
  - X_G: constrained, Lissajous curve pattern
  - X_H: constrained, double co-rotating pattern

Extremes

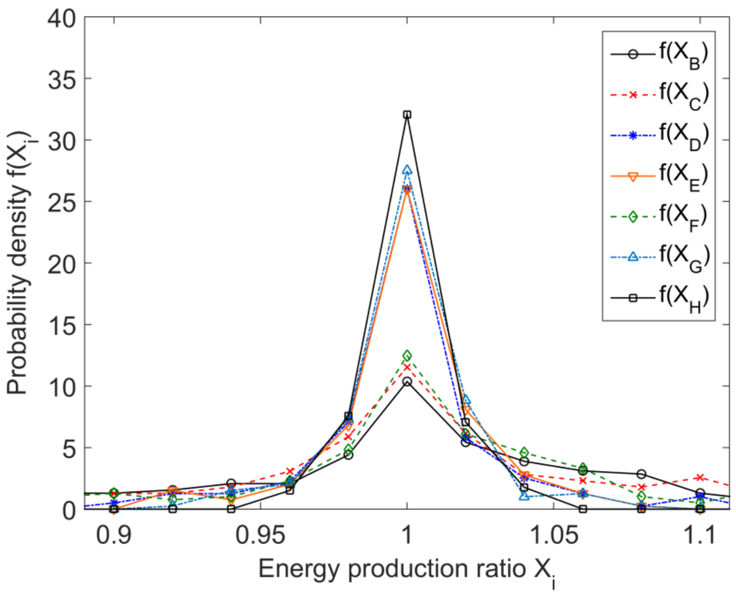
Channel	L	$\frac{Std(X_B)}{Std(X_B)}$	$\frac{Std(X_C)}{Std(X_B)}$	$\frac{Std(X_D)}{Std(X_B)}$	$\frac{Std(X_E)}{Std(X_B)}$	$\frac{Std(X_F)}{Std(X_B)}$	$\frac{Std(X_G)}{Std(X_B)}$	$\frac{Std(X_H)}{Std(X_B)}$
Units	m	%	%	%	%	%	%	%
Tower F-A	72	100	97	69	71	78	58	56
Tower S2S	72	100	88	80	79	86	77	73
Yaw	72	100	70	50	47	52	35	35
Shaft	72	100	100	42	34	70	33	26
Blade F	72	100	97	63	57	70	50	45
Blade E	72	100	105	63	58	61	53	52

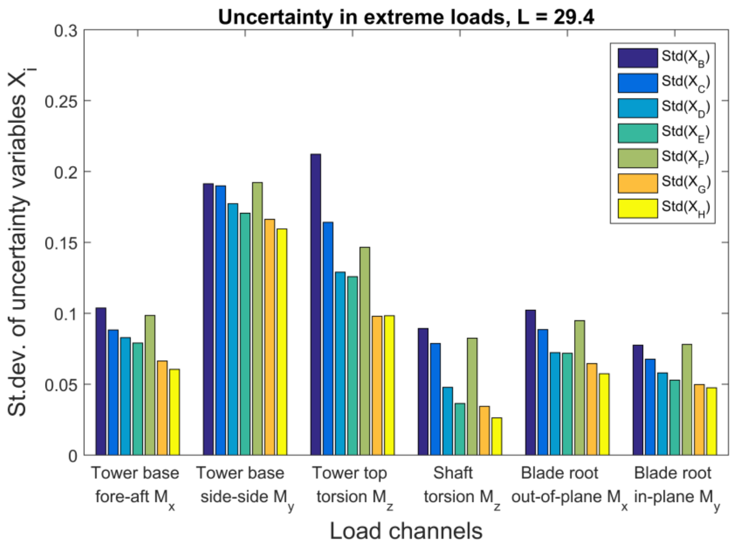
Fatigue (DEL)

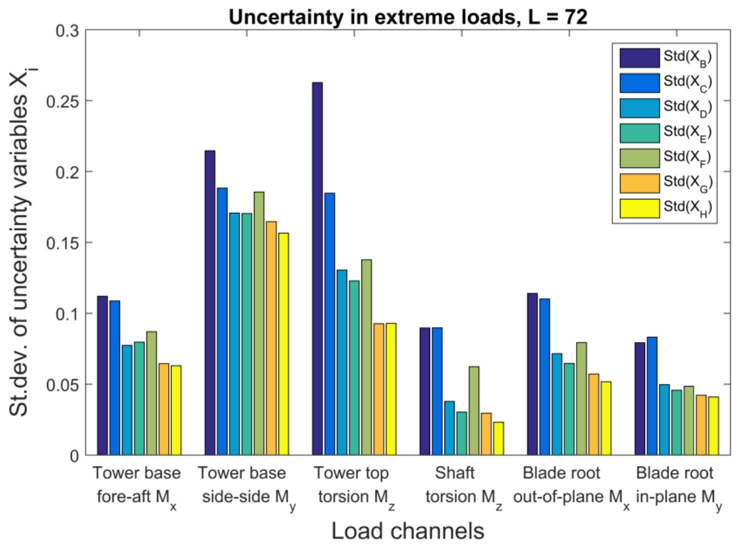
Channel	L	$\frac{Std(X_B)}{Std(X_B)}$	$\frac{Std(X_C)}{Std(X_B)}$	$\frac{Std(X_D)}{Std(X_B)}$	$\frac{Std(X_E)}{Std(X_B)}$	$\frac{Std(X_F)}{Std(X_B)}$	$\frac{Std(X_G)}{Std(X_B)}$	$\frac{Std(X_H)}{Std(X_B)}$
Units	M	%	%	%	%	%	%	%
Tower F-A	72	100	57	42	42	62	30	29
Tower S2S	72	100	86	81	80	89	80	81
Yaw	72	100	43	26	25	53	18	17
Shaft	72	100	74	34	27	54	22	20
Blade F	72	100	77	47	44	64	35	34
Blade E	72	100	136	37	34	48	32	30

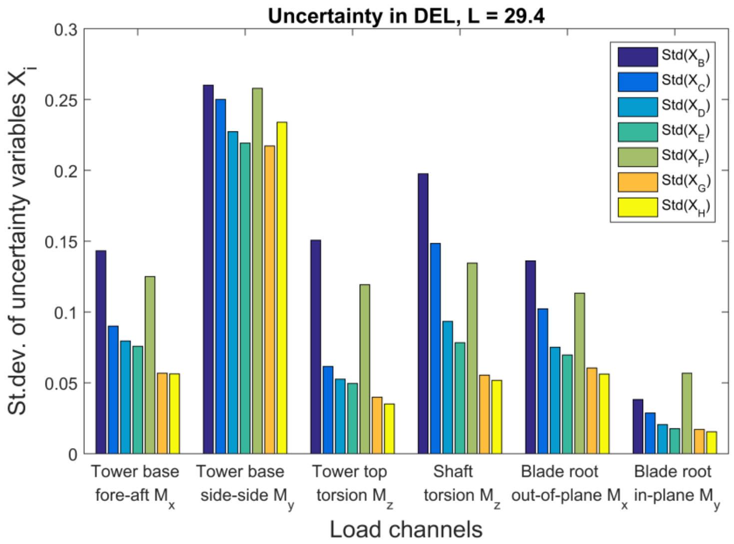
Study on load uncertainty

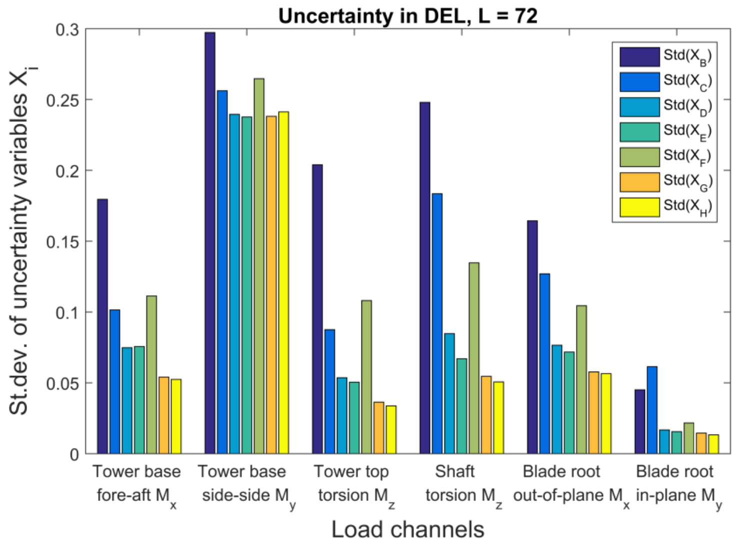
- Results
  (Probability distributions of uncertainty variables)











Conclusions

- Lidar measurements can be included in turbulence boxes by generation of constrained Gaussian random fields.

- The numerical study showed that the one-to-one uncertainty in load simulations can be reduced.

- The longitudinal component (u) is driving the load uncertainty, v and w have almost no effect

- The procedure allows the estimation of explained variance. However the explained variance is not fully correlated with pattern efficiency.

- The results presented are a “best-case scenario” as they only represent the statistical uncertainty due to seed-to-seed variations. Using real field-measurements will likely increase the overall uncertainty.

END

- To follow: NKE Load measurement campaign. From LOS measurements to u- time series