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Applying triple collocation for verifying wind resource measurements and reanalysis data

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Overview

Agenda of this presentation

- Motivation – Applications of dual-collocation
- Introduction of triple collocation
- Case studies / datasets
- Results for triple collocation
- Discussion and conclusions

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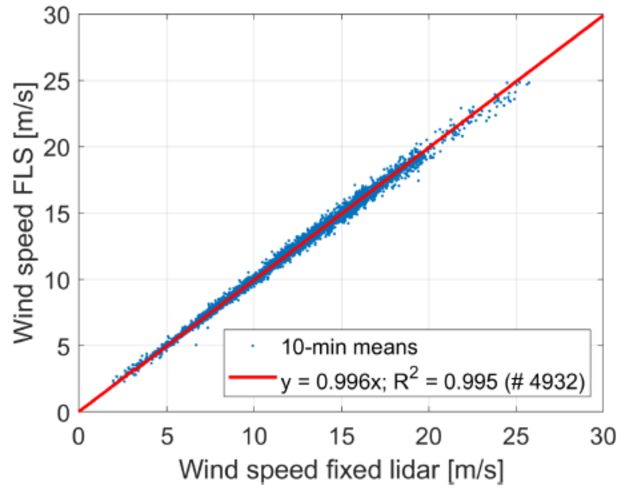
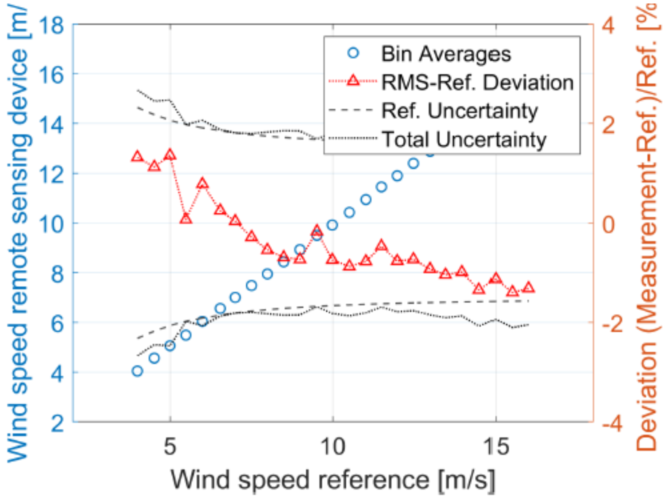
Motivation

Application of dual collocations

Example 1: Performance verification (PV) / calibration of Floating Lidar System (FLS) at offshore met. mast





Gerrit Wolken-Möhlmann et al 2022 J. Phys.: Conf. Ser. 2362 012042, doi:10.1088/1742-6596/2362/1/012042

- Met. mast is used as reference here; but FLS data can also be compared to fixed lidar profiler (at mast platform) or reanalysis data (e.g., ERA 5)

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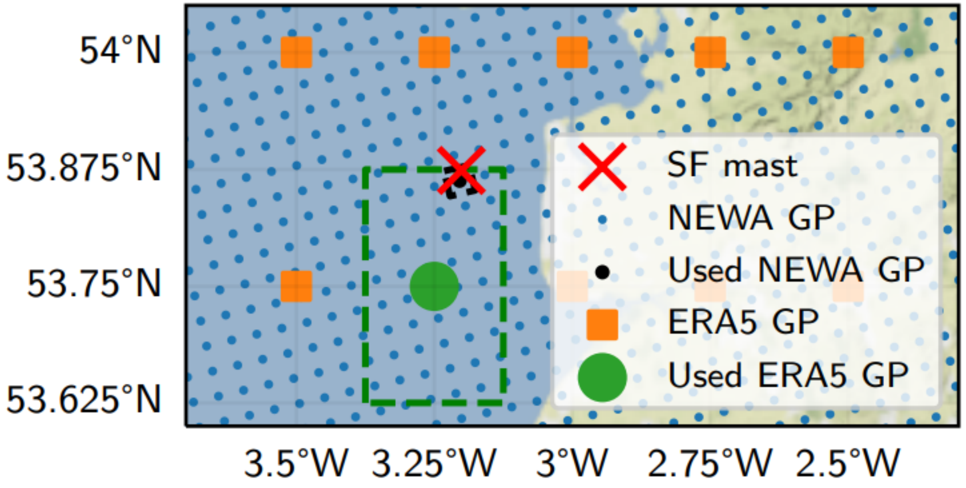
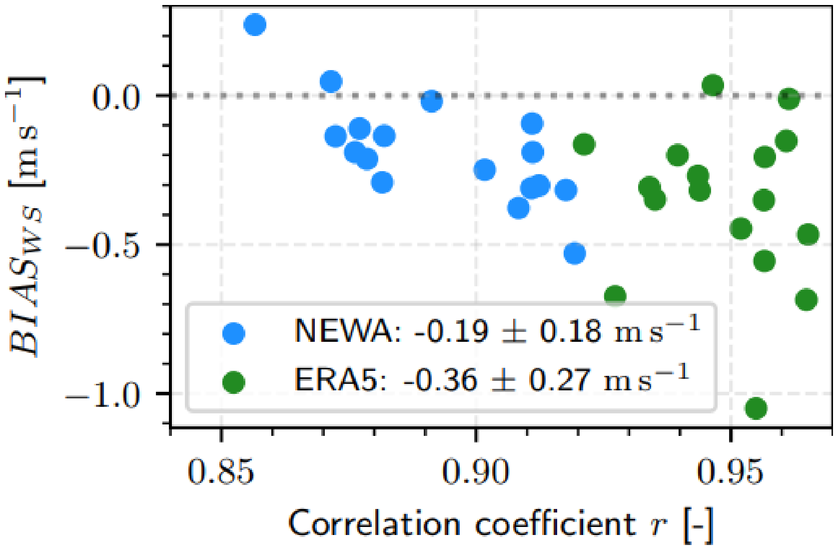
Motivation

Application of dual collocations

Example 2: Validating a mesoscale model (NEWA / WRF) and ERA5 for assessing offshore wind resources





P J Meyer and J Gottschall 2022 J. Phys.: Conf. Ser. 2151 012009, doi:10.1088/1742-6596/2151/1/012009

- (Downscaled) mesoscale model shows lower bias but also lower correlation to in-situ measurements .. what does qualify a numerical dataset as wind resource data source?

Motivation

Application of dual collocation (→ conventional 2D linear regression analysis)

- Implicit assumption in dual comparisons: all errors are due to the system that is being tested
- Reference system is assumed perfect (what if there are several possible references?)
- For PV / calibration, a reference uncertainty is defined but typically not considered in the regression analysis
- Is there a way to consider “scales“ of data sources as well (?)

Introduction of triple collocation

As an alternative method, proposed by Stoffelen [J. Geophys. Res. 103C3, 7755-7766 (1998), DOI:10.1029/97JC03180]

1. Start with three systems

$$x_1 = a_1 t + b_1 + e_1, \qquad x_2 = a_2 t + b_2 + e_2, \qquad x_3 = a_3 t + b_3 + e_3$$

2. Take one system (x_1) to be the reference system

$$a_1 = 1, \qquad b_1 = 0\,, \qquad \rightarrow x_1 = t + e_1$$

3. Calculate the calibration coefficients for the other two systems

$$a_2 = \frac{C_{23}}{C_{13}}, \qquad a_3 = \frac{C_{23}}{C_{12}}, \qquad b_2 = M_2 - a_2 M_1, \qquad b_3 = M_3 - a_3 M_1$$

4. Calculate the error variances

$$\sigma_1^2 = C_{11} - \frac{C_{13}C_{12}}{C_{23}}, \qquad \sigma_2^2 = C_{22} - \frac{C_{21}C_{23}}{C_{13}}, \qquad \sigma_3^2 = C_{33} - \frac{C_{13}C_{23}}{C_{12}}$$

TC output →

Estimates for ..	
a_1, b_1	w.r.t the reference system ← changes
a_2, b_2	
a_3, b_3	
σ_{e1}^2	w.r.t the truth
σ_{e2}^2	
σ_{e3}^2	

*M and C denote the mean and covariance, respectively;
Method is performed iteratively

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Introduction of triple collocation

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TC output →

Estimates for ..
a_1, b_1
a_2, b_2
a_3, b_3
σ_{e1}^2
σ_{e2}^2
σ_{e3}^2

a_1, b_1; a_2, b_2; a_3, b_3: w.r.t the reference system ← changes

σ_{e1}^2, σ_{e2}^2, σ_{e3}^2: w.r.t the truth

*M and C denote the mean and covariance, respectively;
Method is performed iteratively as outlined in [1]

Key assumptions
- Linear calibration is sufficient
- Reference system is calibrated and unbiased ($a_1 = 1,\ b_1 = 0$)
- Random error has a constant variance across the range of measurement values ($\langle e_\alpha^2 \rangle = \sigma_{e_\alpha}^2,\ \alpha = 1,2,3$)
- Random errors are uncorrelated ($\langle e_\alpha e_\beta \rangle = 0, \quad \alpha, \beta = 1,2,3$)

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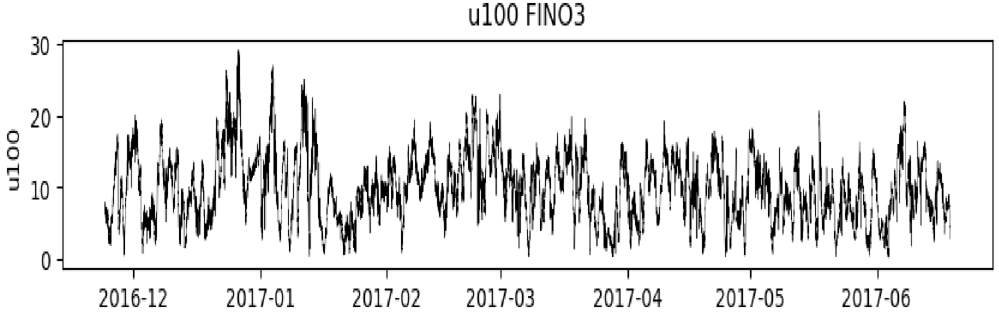
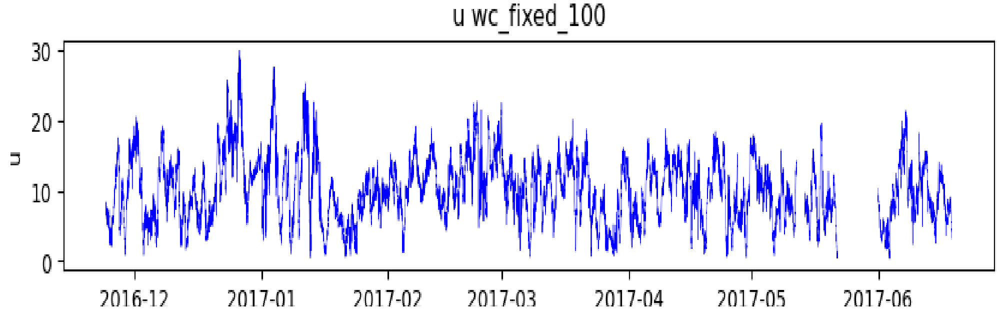
Case study #1

Description of datasets

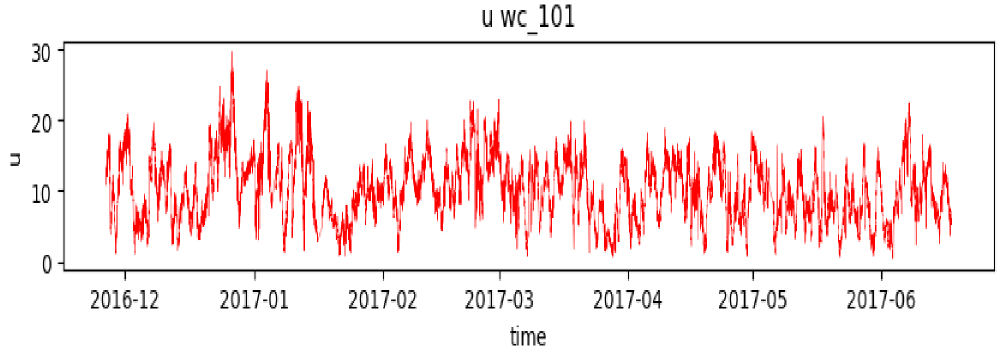
Met. mast



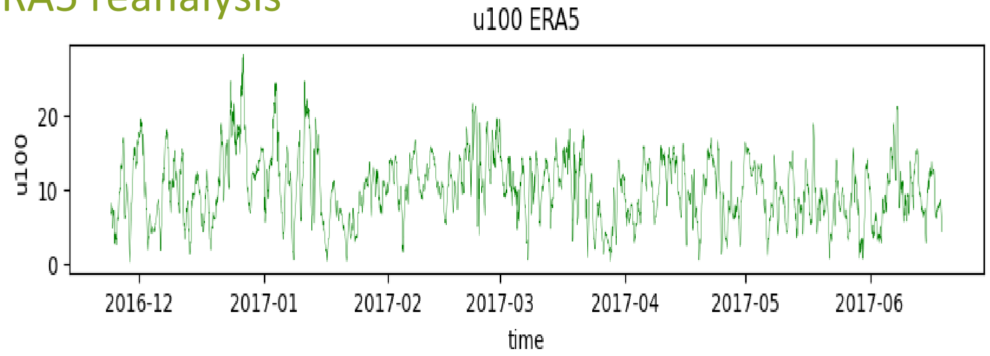
Fixed lidar



Floating lidar



ERA5 reanalysis



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Case study #1

Results for triple collocation

Model

Met. mast
Fixed lidar
Floating lidar
ERA5

1 parameter

$$X = \beta_X T + e_X,$$
$$X = \beta_Y T + e_Y,$$
$$Z = \beta_Z T + e_Z,$$

2 parameters

$$x = X + e_x \equiv T + e_x$$
$$y = Y + e_y \equiv \alpha_1 + \beta_1 T + e_y$$
$$z = Z + e_z \equiv \alpha_2 + \beta_2 T + e_z,$$

X
Y
Z

	1 param	2 param
α_Y	N/A	0.153
α_Z	N/A	0.301
β_Y	1.008	0.995
β_Z	1.015	0.991
$\sigma_{e_X}^2$	0.224	0.216
$\sigma_{e_Y}^2$	0.047	0.050
$\sigma_{e_Z}^2$	0.182	0.174

- Highest error variance found for met. mast (not FLS), lowest for fixed lidar

Case study #1

Results for triple collocation

X (blue), Y (red), Z (green):

	2 param
α_Y	0.106
α_Z	0.911
β_Y	1.000
β_Z	0.920
$\sigma^2_{e_X}$	0.136
$\sigma^2_{e_Y}$	0.090
$\sigma^2_{e_Z}$	1.430

X (black), Y (red), Z (green):

	2 param
α_Y	0.259
α_Z	1.052
β_Y	0.995
β_Z	0.915
$\sigma^2_{e_X}$	0.302
$\sigma^2_{e_Y}$	0.090
$\sigma^2_{e_Z}$	1.431

X (blue), Y (red), Z (green):

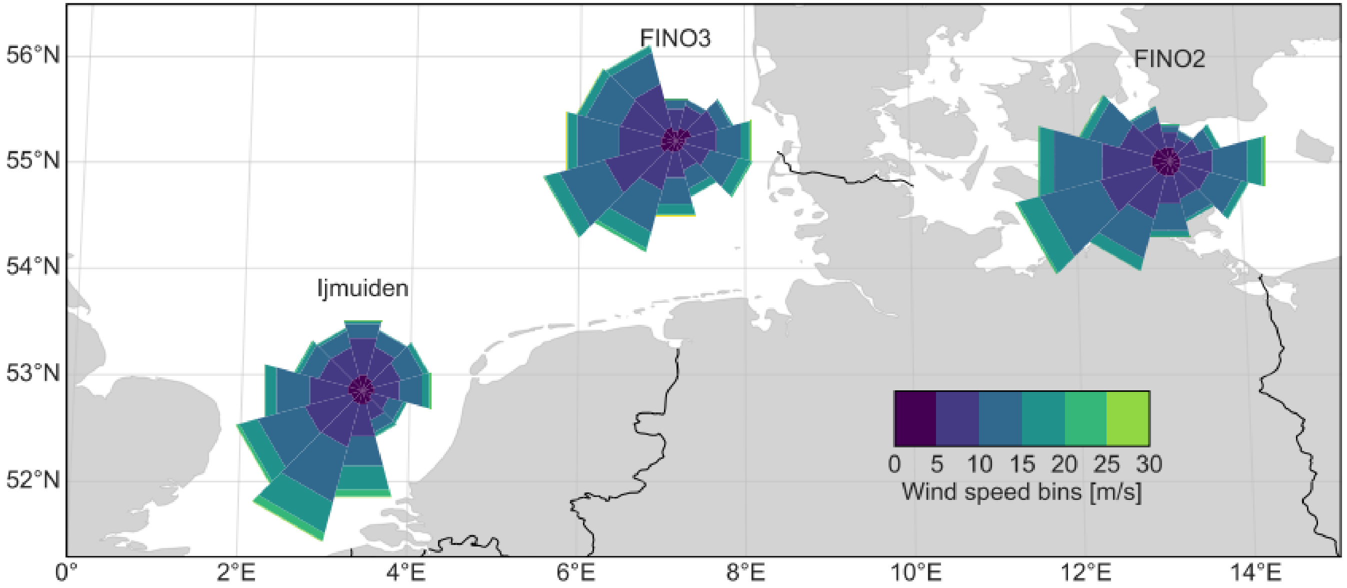
	2 param
α_Y	0.106
α_Z	0.911
β_Y	1.000
β_Z	0.920
$\sigma^2_{e_X}$	0.136
$\sigma^2_{e_Y}$	0.090
$\sigma^2_{e_Z}$	1.430

Met. mast
Fixed lidar
Floating lidar
ERA5

- Error variance for reanalysis data always highest, for FLS always lowest

Case study #2
Description of datasets

- Wind speed date from (3) met. masts



Jonietz Alvarez et al., Wind Energ. Sci. Discuss. [preprint], https://doi.org/10.5194/wes-2023-127, in review, 2023.

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X = met mast 92 m
Y = WRF model 100 m
Z = ERA5 model 100 m

FINO3

X = met mast 91 m
Y = WRF model 100 m
Z = ERA5 model 100 m

FINO2

X = met mast 92 m
Y = WRF model 100 m
Z = ERA5 model 100 m

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Case study #2

Results for triple collocation

Model:

1 parameter

$$X = \beta_X T + e_X,$$
$$X = \beta_Y T + e_Y,$$
$$Z = \beta_Z T + e_Z,$$

2 parameters

$$x = X + e_x \equiv T + e_x$$
$$y = Y + e_y \equiv \alpha_1 + \beta_1 T + e_y$$
$$z = Z + e_z \equiv \alpha_2 + \beta_2 T + e_z,$$

Ijmuiden

	1 param	2 parameter
α_Y	N/A	-0.158
α_Z	N/A	-0.170
β_Y	0.952	0.965
β_Z	0.953	0.967
$\sigma_{e_X}^2$	1.456	1.450
$\sigma_{e_Y}^2$	1.034	1.035
$\sigma_{e_Z}^2$	0.436	0.436

X = met mast 92 m
Y = WRF model 100 m
Z = ERA5 model 100 m

- Error variance for ERA5 lowest, for met. mast highest

Case study #2

Results for triple collocation

X = met mast
Y = WRF model
Z = ERA5 model

Ijmuiden

	2 parameter
α_Y	-0.158
α_Z	-0.170
β_Y	0.965
β_Z	0.967
$\sigma_{e_X}^2$	1.450
$\sigma_{e_Y}^2$	1.035
$\sigma_{e_Z}^2$	0.436

FINO3

	2 parameter
α_Y	-0.411
α_Z	-0.366
β_Y	1.061
β_Z	1.069
$\sigma_{e_X}^2$	1.597
$\sigma_{e_Y}^2$	1.047
$\sigma_{e_Z}^2$	0.386

FINO2

	2 parameter
α_Y	-0.282
α_Z	-0.024
β_Y	0.965
β_Z	0.953
$\sigma_{e_X}^2$	1.675
$\sigma_{e_Y}^2$	0.944
$\sigma_{e_Z}^2$	0.561

Discussion

- Can typical wind [energy] data applications (cf. examples) benefit from triple collocation?
- May obtained error variances be related to uncertainty estimates? ↔ Traceable uncertainty quantification requires well defined reference uncertainty.
- Possible (already tested) applications: Measure-Correlate-Predict (MCP) for long-term extrapolation and/or short-term data gap filling
- Quadrupole collocation as possible (but considerably more complex) extension

Summary

Conclusions of this study

- “Dual collocation“ as a standard instrument for wind [energy] data analysis .. with inherent flaws
- Triple collocation may allow for a more “objective“ evaluation → possibly helping to identify which datasets are most suited to represent the relevant offshore wind resource
- Most promising applications for

  .. combining different types of data and future resource assessment methods

  .. as well as measurement calibration standards

Thank you for your time!

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