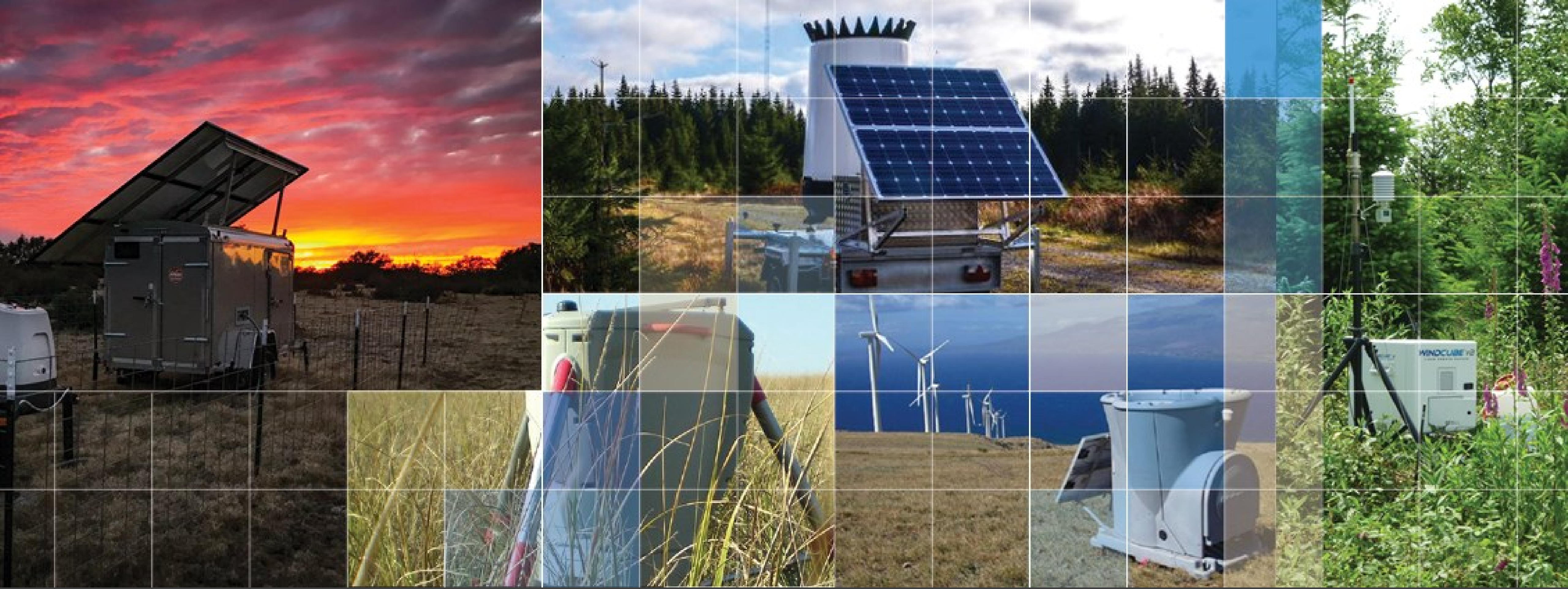

Survey of Correction Techniques for Remote Sensing Devices in Complex Flow

A. Black, M. Debnath, A. Lammers, P. Mazoyer, R. Schultz, T. Spalding, S. Wylie

DOI 10.5281/zenodo.4302363

IEA Task 32 - 8th December 2020 - Webinar

Consortium for the Advancement of Remote Sensing (CFARS)

Mission

- **Increase acceptance** of Remote Sensing Devices (RSD) by sharing information and involving the broad industry
- **Reduce project development costs** by supporting/enabling standardization and acceptance of RSDs
- **Reduce uncertainty** of pre-construction estimates by demonstrating and leveraging the value of RSDs

Vision

- Significantly contribute to the competitiveness of the wind industry by 2021 through broader acceptance/validation of RSDs

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CFARS Complex Flow Science Sub-Group

Team Members

- Andrew Black, Vaisala (lead), OEM
- Mithu Debnath, NREL, Academic Research
- Andrew Lammers, Pattern Energy, Developer-Operator
- Paul Mazoyer, Leosphere, OEM
- Robert Schultz, RWE, Developer-Operator
- Taurin Spalding, Natural Power, Consultant/IE
- Scott Wylie, ZX Lidars, OEM
- **Interested in contributing? Email: andrew.hastingsblack@vaisala.com**

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CFARS Industry Survey Results
Complex Flow

Question	Response	Count
How do you know whether to perform flow curvature correction on RSD wind speed data?	It remains a total mystery	5
	Only if there's noticeable bias in site data	5
	Use 3rd party tools to determine wither correction will be necessary	4
	Following specific guidelines/standards	4
	Based on experience and intuition	1
What would help you understand better whether to perform flow curvature correction on RSD wind speed data?	More guidelines and best practices	11
	Validation studies	9
	Specific standards (IEC) covering the use remote sensors in complex terrain	9
	Specific standards covering correction of flow curvature bias in RS data	8
	Bankability statements	5
	In-house experience gained from tower comparison studies using corrected data	4

CFARS Industry Survey. Conducted 2019.
Responses from Consultant/IE, Developer-Operator, OEM-Turbine, OEM-RSD, and Finance/Investment

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CFARS Complex Flow Sub-group Goals

Support increased use of RSDs in complex terrain by:

- Showing typical flow curvature biases for different terrains
- Validating commercially available bias correction methods
- Exploring limitations in correction technology, with focus on atmospheric stability, surface roughness, and detached flow
- Evaluating correction uncertainty as a function of site and measurement height
- Demonstrating value in corrected RSD measurements in complex flow

What is Complex Flow?

- **Complex flow** is a wind vector field with high spatial variability
- This spatial variability is generally caused by terrain and vegetation
- RSDs wind retrieval algorithms assume that wind vector fields above the sensors are homogeneous in the measurement volume, at each height
- In complex flow, this assumption is broken, and the wind retrieval algorithms generate biased measurements compared to cups
- Using Computational Fluid Dynamics (CFD), the wind vector fields above RSDs can be modeled with good skill
- Using these models, better estimates of the wind vector orientations can be used in the RSDs wind retrieval algorithms, greatly reducing the biases
- Combinations of RSD data and CFD models are called complex flow correction (CFC) techniques in this presentation

Survey Data and Information

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RSDs and Flow Models in the Literature

- There are many combinations of CFD and RSDs for CFC in the literature:

Model	Sensor	Title	Author	Publisher	Publication Type	Year	Sites
OpenFoam	ZX300	Lidar uncertainty in complex terrain development of a bias correction methodology	Fernando Adrián Borbón Guillén	Universidad Politécnica de Madrid	PhD Diss	2015	1
OpenFoam	WindCube	Guillén (2015)			PhD Diss	2015	1
Meteodyn	WindCube	LiDAR-mast deviations in complex terrain and their simulation using CFD	Klaas, Tobias, Lukas Pauscher, and Doron Callies	Meteorologische Zeitschrift	Journal Article	2015	2
Meteodyn	ZX300	The use of Meteodyn WT to post-process ZephIR 300 wind speed data in complex terrain	Meteodyn WT & ZX	Meteodyn WT & ZX	White Paper	2017	11
WAsP	WindCube	Klaas et al (2015)			Journal Article	2015	1
WAsP	ZX300	Validated adjustment of remote sensing bias in complex terrain using CFD	Harris, Michael, et al	European Wind Energy Conference Proceedings	Conference Paper	2010	6
WindSim	WindCube	Klaas et al (2015)			Journal Article	2015	1
WindSim	Triton	Validation of Triton Wind Profiler Measurements in Complex Terrain, Using WindSim CFD-Based Flow Curvature Correction	Stoelinga, M. and N. LaWhite	Vaisala, Inc.	White Paper	2018	26
FCR	WindCube	Case studies of WINDCUBE measurement uncertainty for complex terrain using Flow Complexity Recognition (FCR)	Krishnamurthy, R. and M. Boquet	EWEA Annual Event	Conference Poster	2014	6
FCR	WindCube	Windcube + FCR test at Hrgud, Bosnia and Herzegovina	Wagner, R., and J. Bejdic	DTU	Technical Report	2014	1
FCR	WindCube	Operation of the Windcube V2 lidar at CRES Test Station	Foussekis, D., N. Stefanatos, and F. Mouzakis	CRES	Technical Report	2011	1
FCR	WindCube	Measuring Wind Profiles in Complex Terrain using Doppler Wind LiDAR Systems with FCR and CFD Implementations	Schmitt, C., Wagner, L., and M. Boquet	EWEA Annual Event	Conference Poster	2013	2
FCR	WindCube	WindCube V2+FCR validation on complex site and application for resource assessment analysis	Ortiz, D., R. Martinez, and R. Zubiaur	Barlovento Recursos Naturales, S.L.	Technical Report	2012	1
ZephyScience	ZX300	The use of CFD to increase the acceptance of wind data from lidars in complex terrain	Wylie, S., M. Smith and A. Woodward	WindEurope RA 2020	Conference Poster	2020	11

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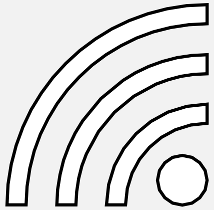
RSDs and Flow Models in this Study

remote sensor



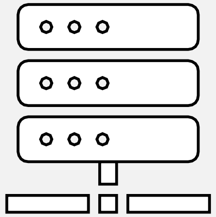
Triton Sonic Wind Profiler

26 sites

ZX300

WindCube

6 sites



wind flow model

WindSim

Meteodyn WT

Flow Complexity Recognition

RSDs and Flow Models in this Study

Sensor	Triton Sonic Wind Profiler	ZX300	WindCube
Measurement type	DBS sodar	VAD lidar	DBS lidar
Beams	3 beam orientations	1 beam, 360° scan	5 beam orientations
Beam angles	11.4° beam angle	30° beam angle	28° & 0° beam angles
Sample Rate	0.5 Hz sample rate	50 Hz sample rate	1 Hz sample rate
Averaging	10-min vector averaging	10-min scalar averaging	10-min scalar or vector averaging
Model type	RANS (mass + momentum)	RANS (mass + momentum)	SWIFT (mass conservation)
Horizontal mesh	5m	25m (finer near sensor)	10m
Vertical mesh	20m	4m	5m
Elevation database	SRTM + ASTER	SRTM	SRTM + ASTER
Land use database	CORINE	CORINE	Fixed value
Sectors	16	36	Continuous
Stability	Fixed, neutral	Fixed, neutral	Empirical, horiz./vert. WS
Location	Postprocessing, by sector	Postprocessing, by sector	Onboard Sensor CPU, continuous
CFD	WindSim Express	Meteodyn	Flow Complexity Recognition

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RSDs and Flow Models in this Study

These sensors all rely on detecting Doppler backscatter excited by focused beams of energy along fixed orientations in the air above them. Complex flow creates biases in these three, monostatic RSDs in the same way: incorrect angles in the wind retrieval algorithms.

Model type	RANS (mass + momentum)	RANS (mass + momentum)	SWIFT (mass conservation)
Location	Postprocessing, by sector	Postprocessing, by sector	Onboard sensor CPU, continuous
CFD	**WindSim Express**	**Meteodyn**	**Flow Complexity Recognition**

These correction models are all based on solving the Navier-Stokes equations for a fluid flowing above the sensor and deriving the likely angles of the flow in the beam directions. They differ in certain physical assumptions, like mass or mass and momentum conservation, and model configurations, such as topographic maps, meshing, roughness, atmospheric stability, et al

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Definitions of Complex Terrain

Used in WindCube study:

Terrain Classification	Std Dev of Elevation (m)	Slope (deg.)	Terrain Ruggedness Index	z0
Moderately complex	< 30	< 30	< 1.5	< 1.0
Forested moderately complex	< 30	< 30	< 1.5	[1.0, 1.5]
Highly complex	> 50	> 30	> 1.8	[1.5, 2.0]

Used in ZX300 study (Bingöl, 2009):

Terrain Classification	Class 0, z0 < 0.01m	Class 1, z0 in [0.01, 0.05]	Class 2, z0 in [0.05, 0.4]	Class 3, z0 > 0.4
Flat and low roughness	Simple	Simple		
Hilly: hill height < 100m, slope in [5°, 10°]	Moderately complex	Moderately complex	Moderately complex	Complex
Vegetated flat sites: canopy height in [5m, 10m]		Moderately complex	Moderately complex	
Mountains w/o forest, slope > 10°	Complex	Complex	Complex	
Flat, forests canopy height > 10m				Complex
Mountains and forests				Highly complex

Used in Triton study:

Terrain Classification	Flat	Rolling	Hilly	Complex

(Niels LaWhite and Dr. Mark Stoelinga)

- Each dataset has a different method to classify terrain
- **There is a need for a generalized method to classify terrain complexity.**

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Definitions of Complex Terrain

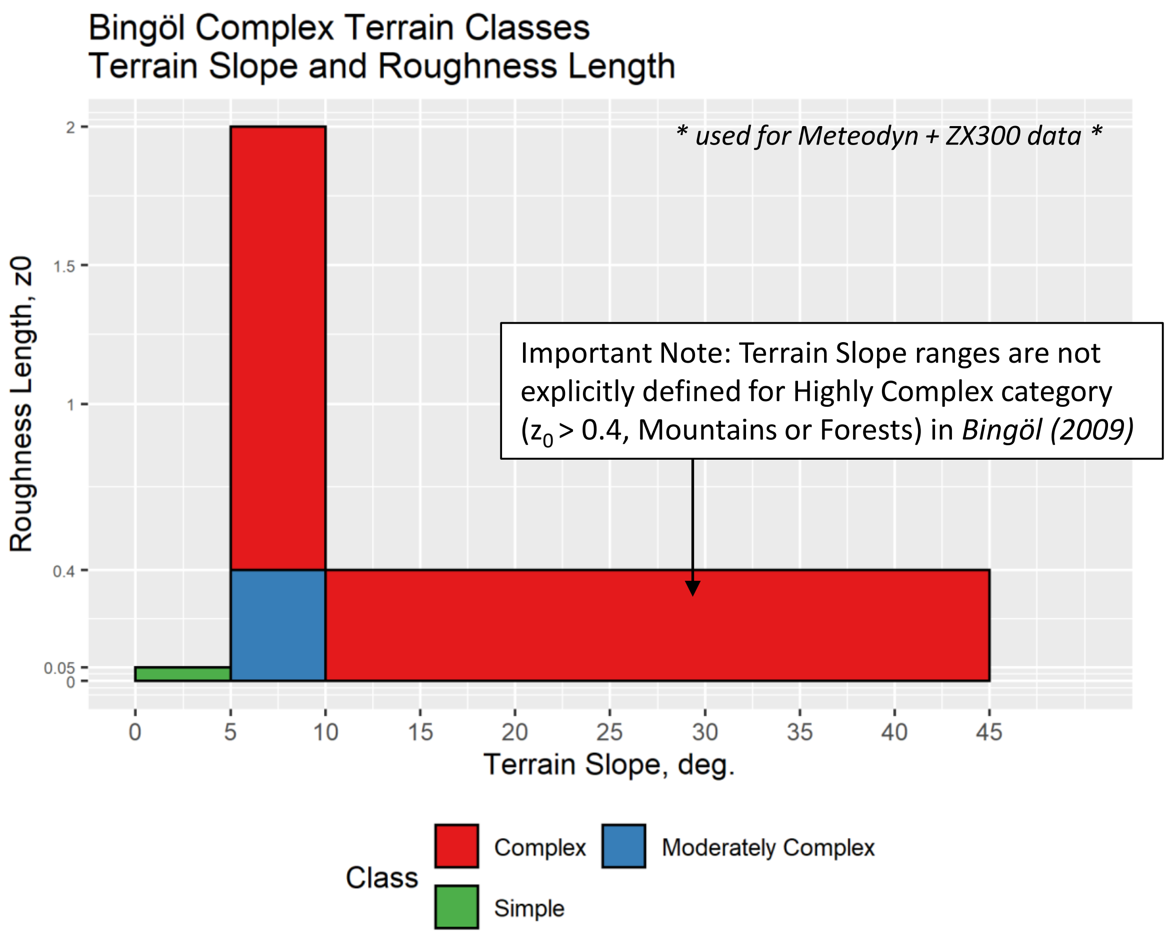
Variables Used in Classifying Terrain:

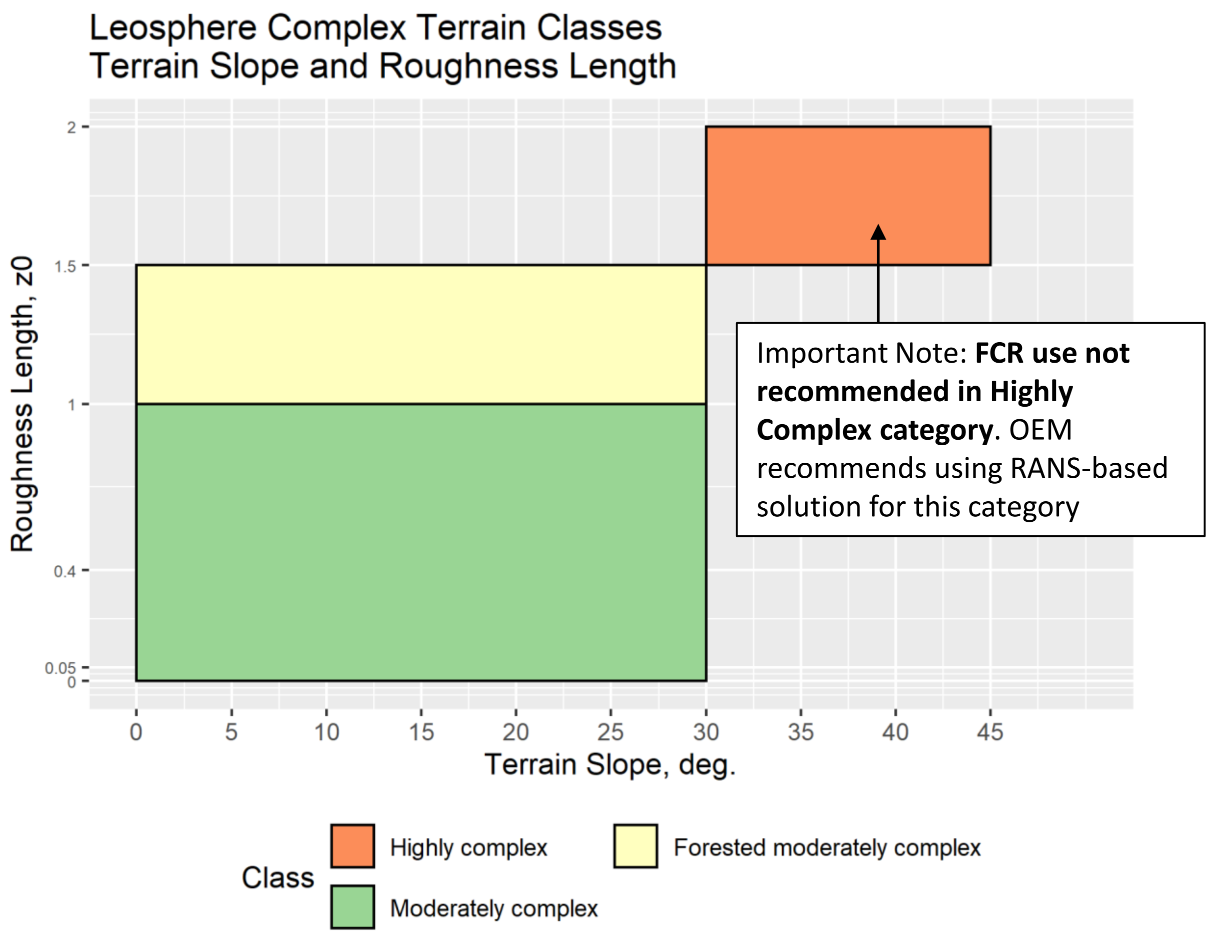
- Roughness Length (RIX)
- Slope of terrain (degrees)
- Standard deviation of elevation (meters)
- Terrain Ruggedness Index (TRI)
- Forest Canopy Height (meters)

Purposes:

- **Determining whether CFC is necessary**
- **Setting expectations for CFC performance**
- **Determining where to site RSD to avoid extreme terrain where CFD codes would have limitations**

Definitions of Complex Terrain





- z_0 and Terrain Slope are common to both rubrics, but not the only parameters

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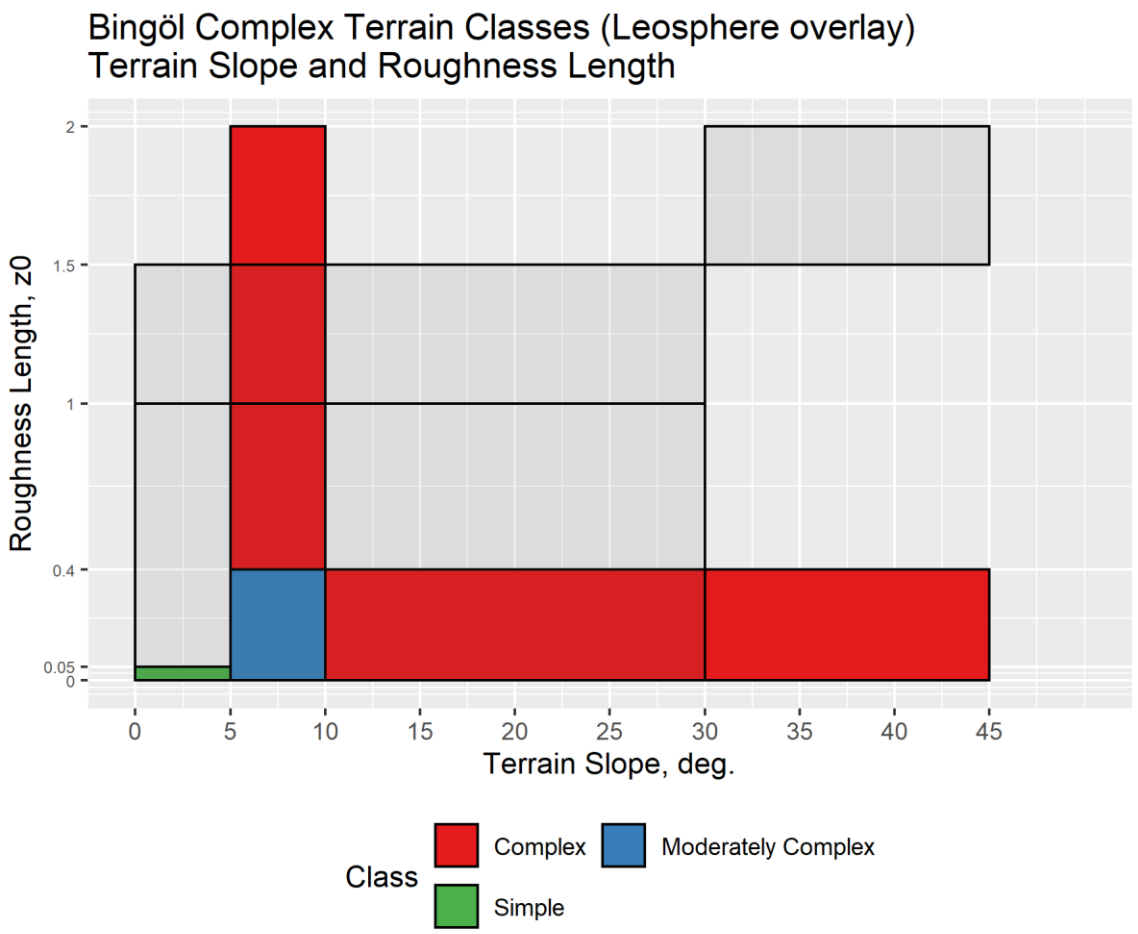
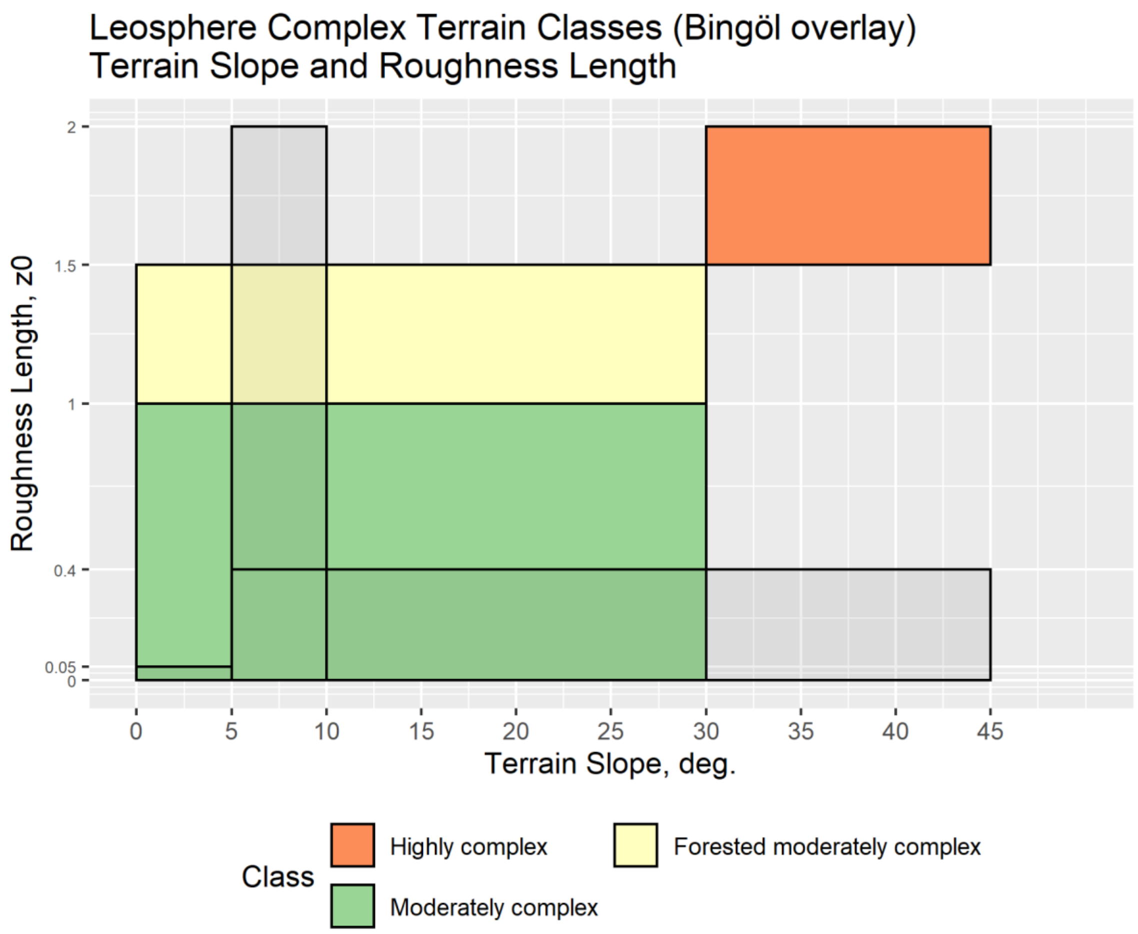
Definitions of Complex Terrain





- Parameter space is not fully defined, and classifications use confusingly similar terms

Survey Data

Triton + WindSim (26 sites)

- Stoelinga, M. and N. LaWhite. *Validation of Triton Wind Profiler Measurements in Complex Terrain, Using WindSim CFD-Based Flow Curvature Correction.* White Paper, February 2018

ZX300 + Meteodyn WT (11 sites)

- Meteodyn & ZX. *The use of Meteodyn WT to post-process ZephIR 300 wind speed data in complex terrain.* White paper, April 2017

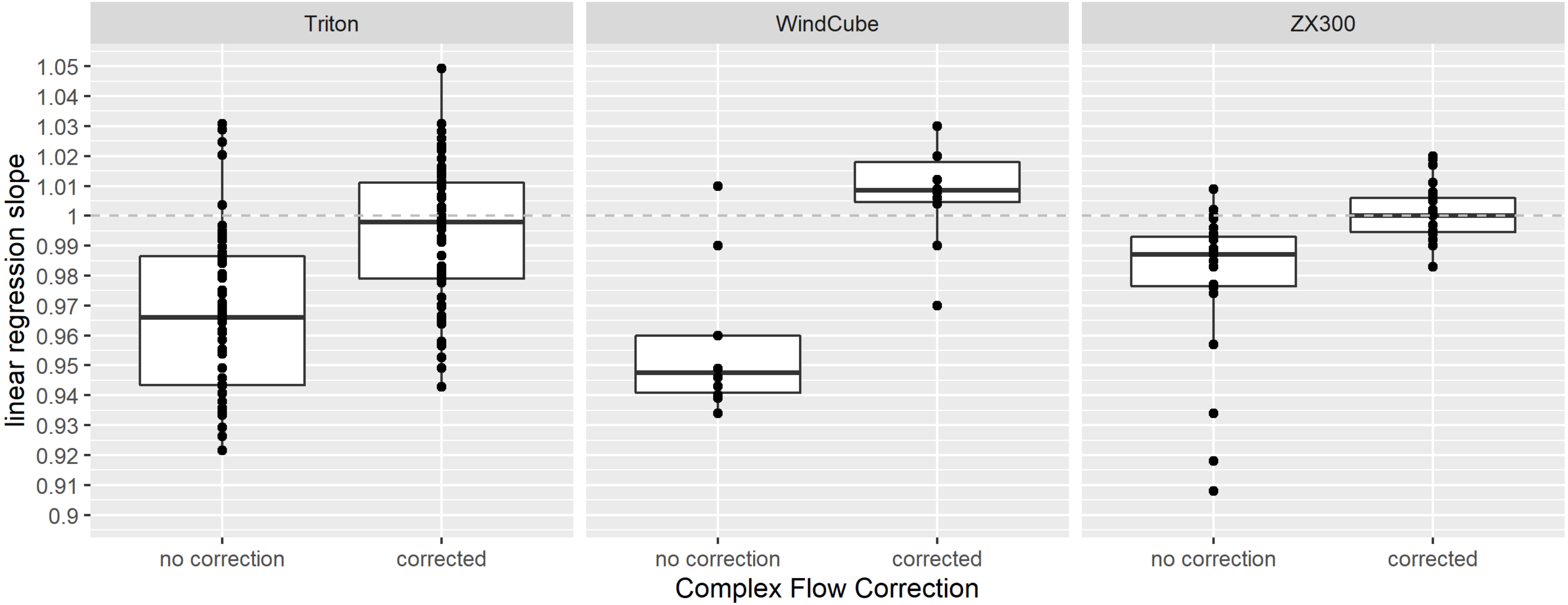
WindCube + FCR (6 sites)

- Krishnamurthy, R. and M. Boquet. *Case studies of WINDCUBE™ measurement uncertainty for complex terrain using Flow Complexity Recognition (FCR ®).* EWEA Annual Event, 2014.
- Wagner, R., and J. Bejdic. *Windcube + FCR test at Hrgud, Bosnia and Herzegovina.* DTU Wind Energy Technical Report, 2014
- Foussekis, D., N. Stefanatos, and F. Mouzakis. *Operation of the Windcube V2 lidar at CRES Test Station*. CRES Technical Report, 2011
- Schmitt, C., Wagner, L., and M. Boquet. *Measuring Wind Profiles in Complex Terrain using Doppler Wind LiDAR Systems with FCR™ and CFD Implementations.* EWEA Annual Event, 2013

Apples, Oranges, and Bananas

- There are many similarities between these CFC techniques, but…
- The survey data are taken from different sites
- The terrain classification rubrics are different
- Many of the RSDs and flow models in this study are outdated:
  - Triton data uses algorithms Sodar 2.2/2.5 → now Sodar 3.0
  - WindCube data is from v2.0 → now WindCube v2.1, FCR is standard
- ZX300 data in this study uses Meteodyn, but ZX300 CFC techniques also exist using Dynamics, WindSim, and ZephyScience.
- The survey should not be interpreted as a direct comparison between the techniques due to the differences in site and classification rubric

Complex Flow Correction Techniques
Boxplots of Linear Regression Slopes, RSD vs. Mast



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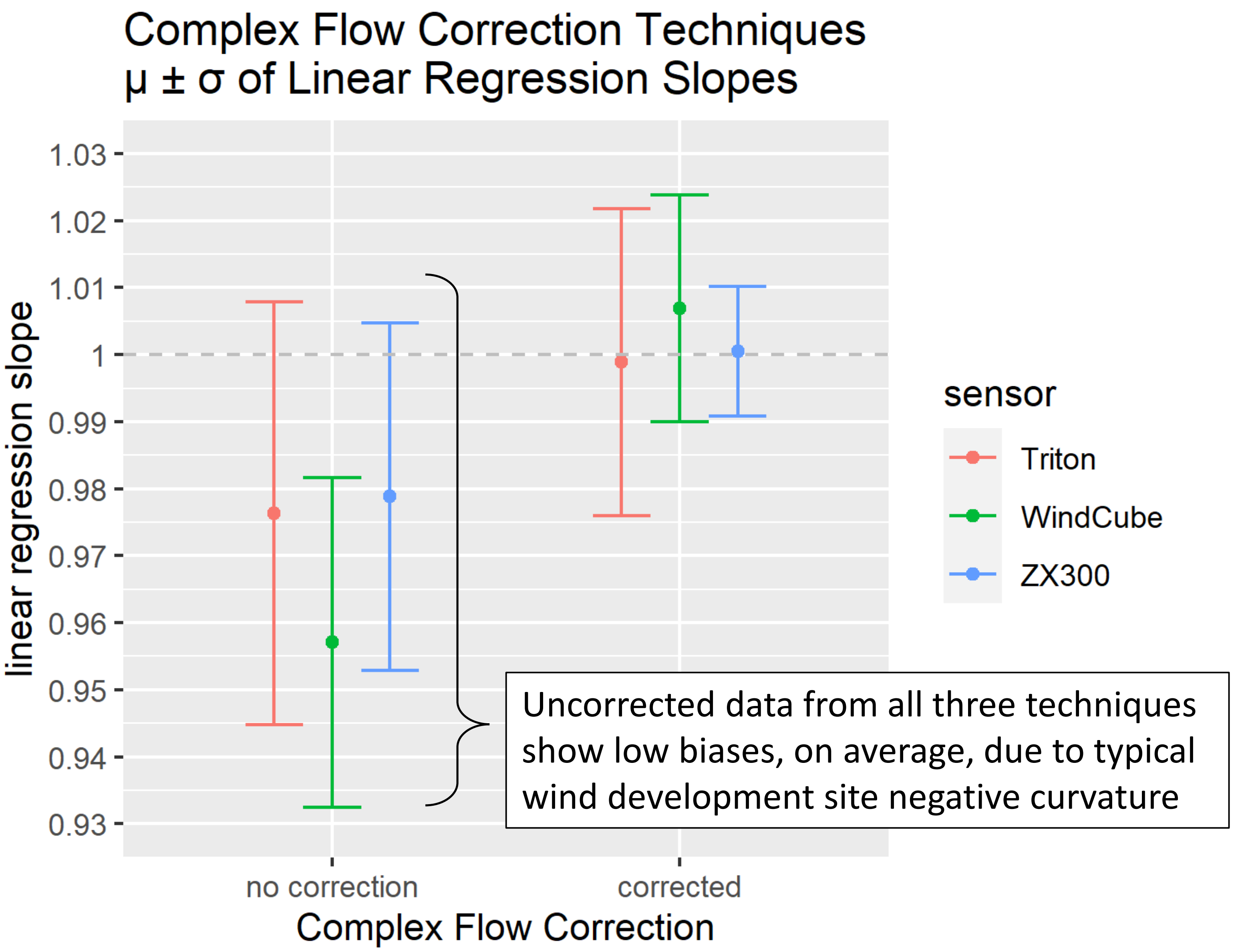

- The average slopes for all three techniques are within ±1% of unity

Slope Mean		
sensor	uncorrected	corrected
Triton	0.976	0.999
WindCube	0.957	1.007
ZX300	0.979	1.001

- The standard deviations of the slope distributions are reduced in all three techniques:

Slope Std Dev		
sensor	uncorrected	corrected
Triton	0.032	0.023
WindCube	0.025	0.017
ZX300	0.026	0.010

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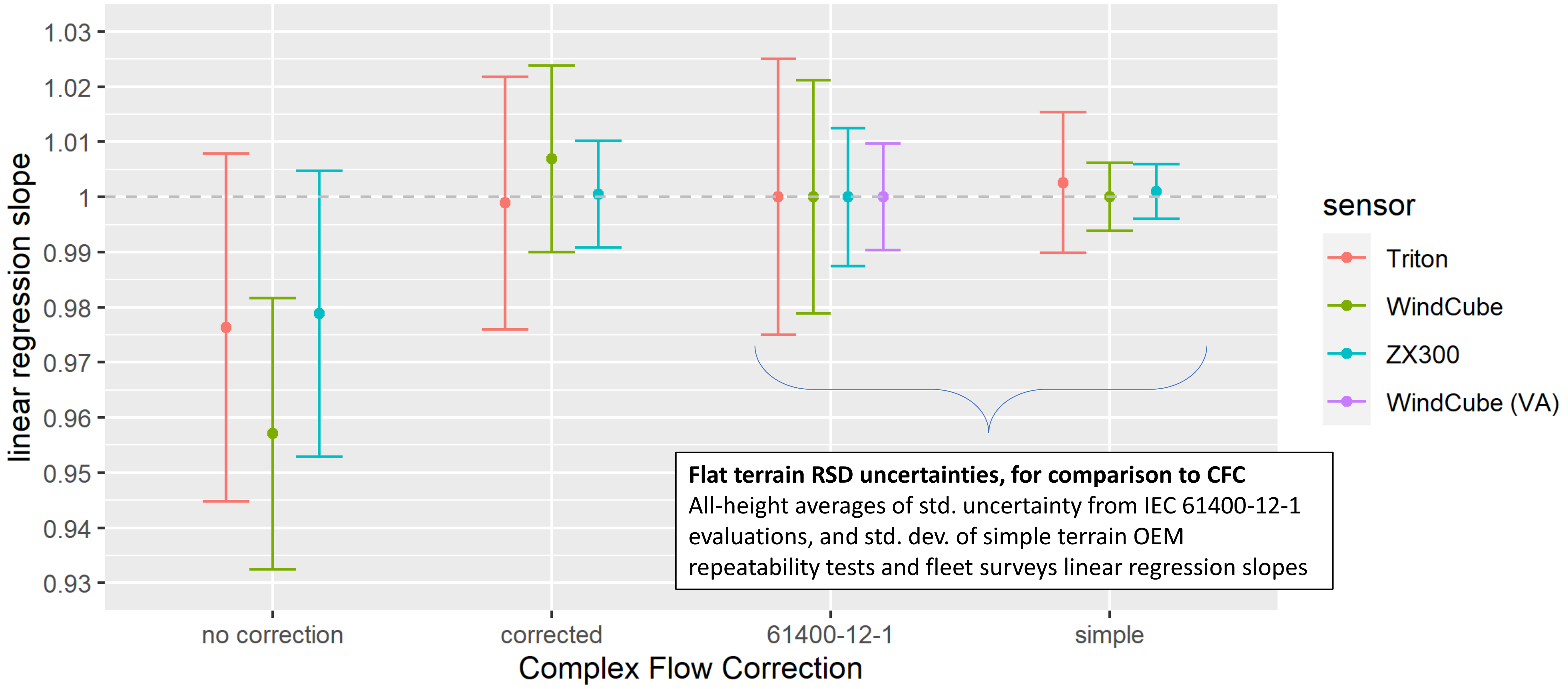
Complex Flow Correction and Simple Techniques
Various Uncertainty Metrics



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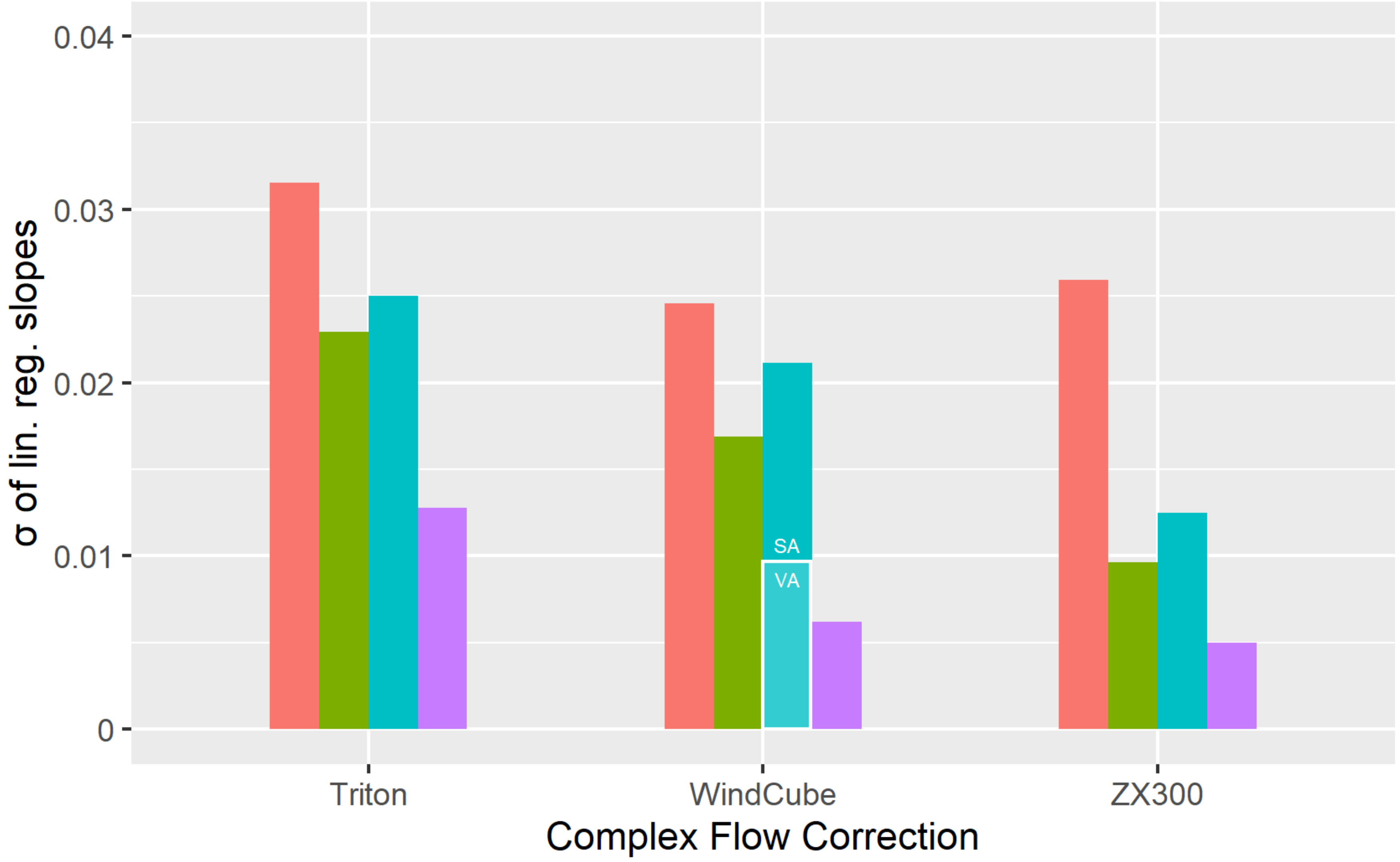
Complex Flow Correction and Simple Techniques Comparison of Uncertainty Estimates



For all three techniques, the uncertainty estimate of the CFC-corrected sites is *in between* the uncertainty estimates of the 61400-12 and the repeatability tests

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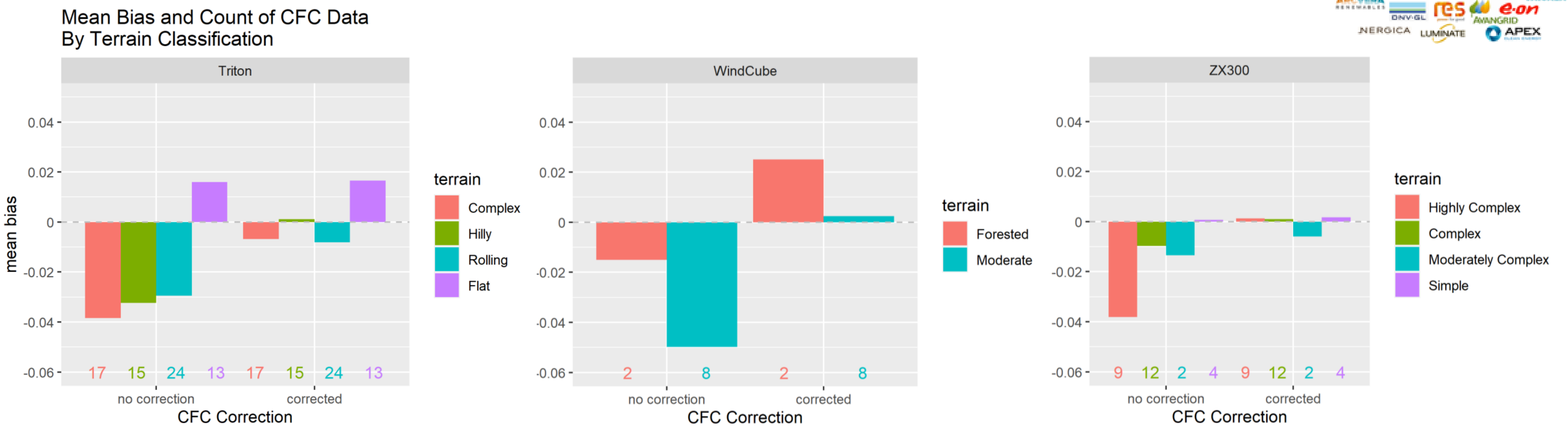

- For Triton and ZX300, the highest complexity categories show the largest biases in uncorrected data
- In all three datasets, the largest uncorrected bias categories are corrected to <1% bias compared to the collocated masts
- In the Simple / Flat categories, included in Triton and ZX300 data, there is no change from CFC
- WindCube's "Forested" and ZX300's "Moderately complex" categories only have two data points, not enough data to draw meaningful conclusions

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Complex Flow Correction Technique Uncertainties

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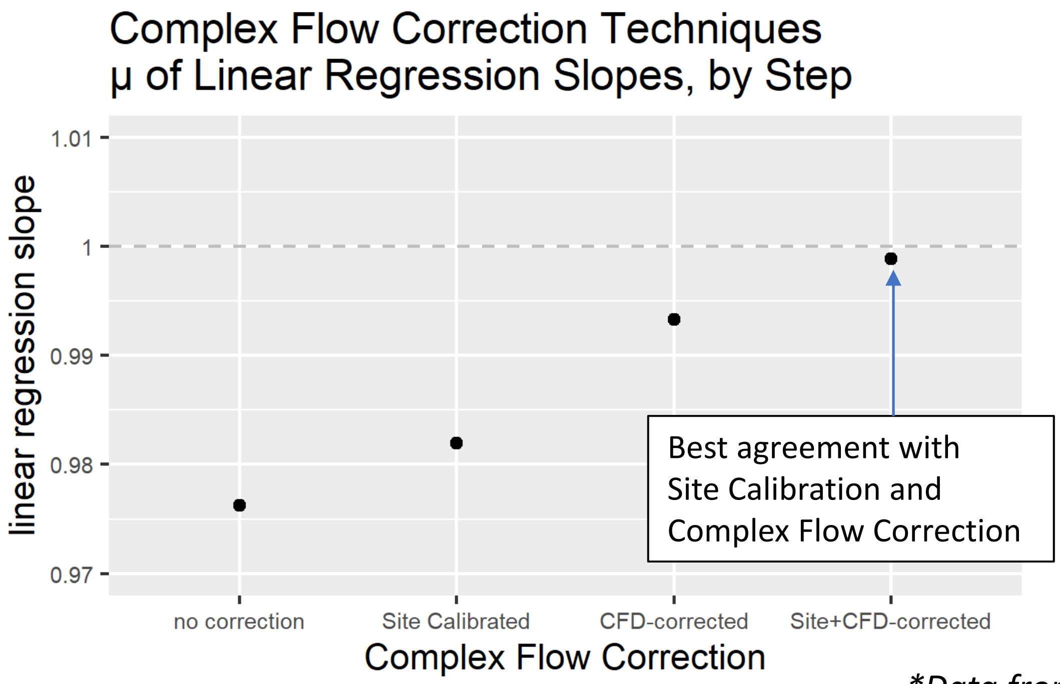
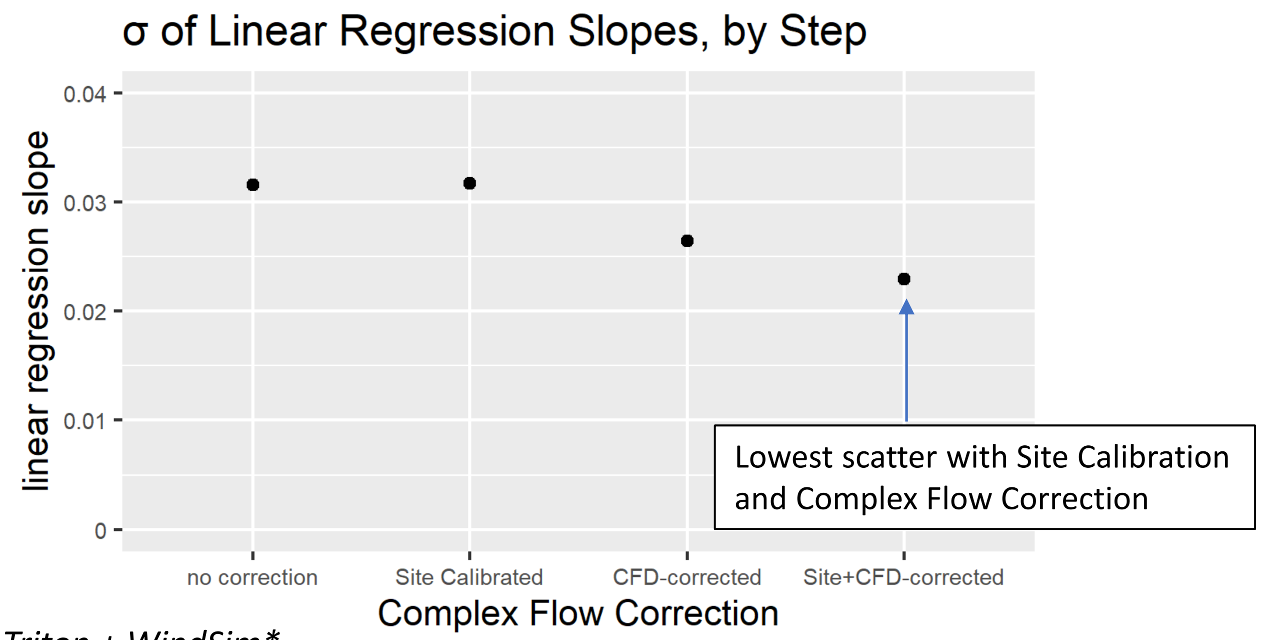
Uncertainties in CFC Techniques

- In CFC, three uncertainties are more important than in flat terrain:
  1. Site calibration uncertainty
     - IEC 61400-12-1: 2017, Annex C.6: *Site Calibration Uncertainty*
  2. Complex flow correction uncertainty
     - IEC 61400-12-1: 2017, Annex E.7.1, part (e): *the uncertainty related to flow variation in the different probe volumes*
  3. Anemometer biases due to off-axis flow
     - IEC 61400-12-1: 2017, Annex J.2.1: *Measurements in a wind tunnel for tilt angular response characteristics of cup anemometers*
     - This has not yet been robustly incorporated to CFC analysis

Site Calibration and Complex Flow Correction

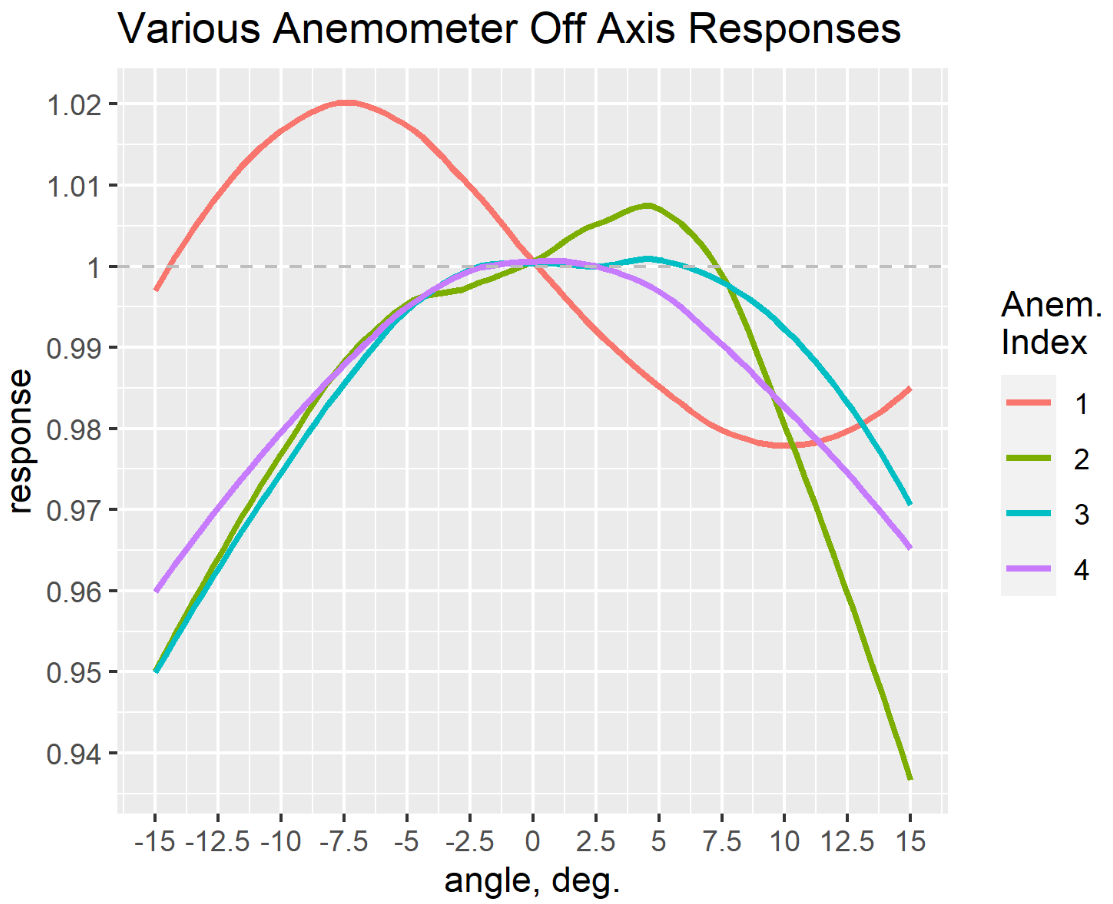




Data from Triton + WindSim

- Site Calibration adjustment to the RSD data or mast data should only be performed to verify performance of RSD + CFC compared to a mast
- Only Complex Flow Correction should be performed to generate the final, corrected RSD dataset

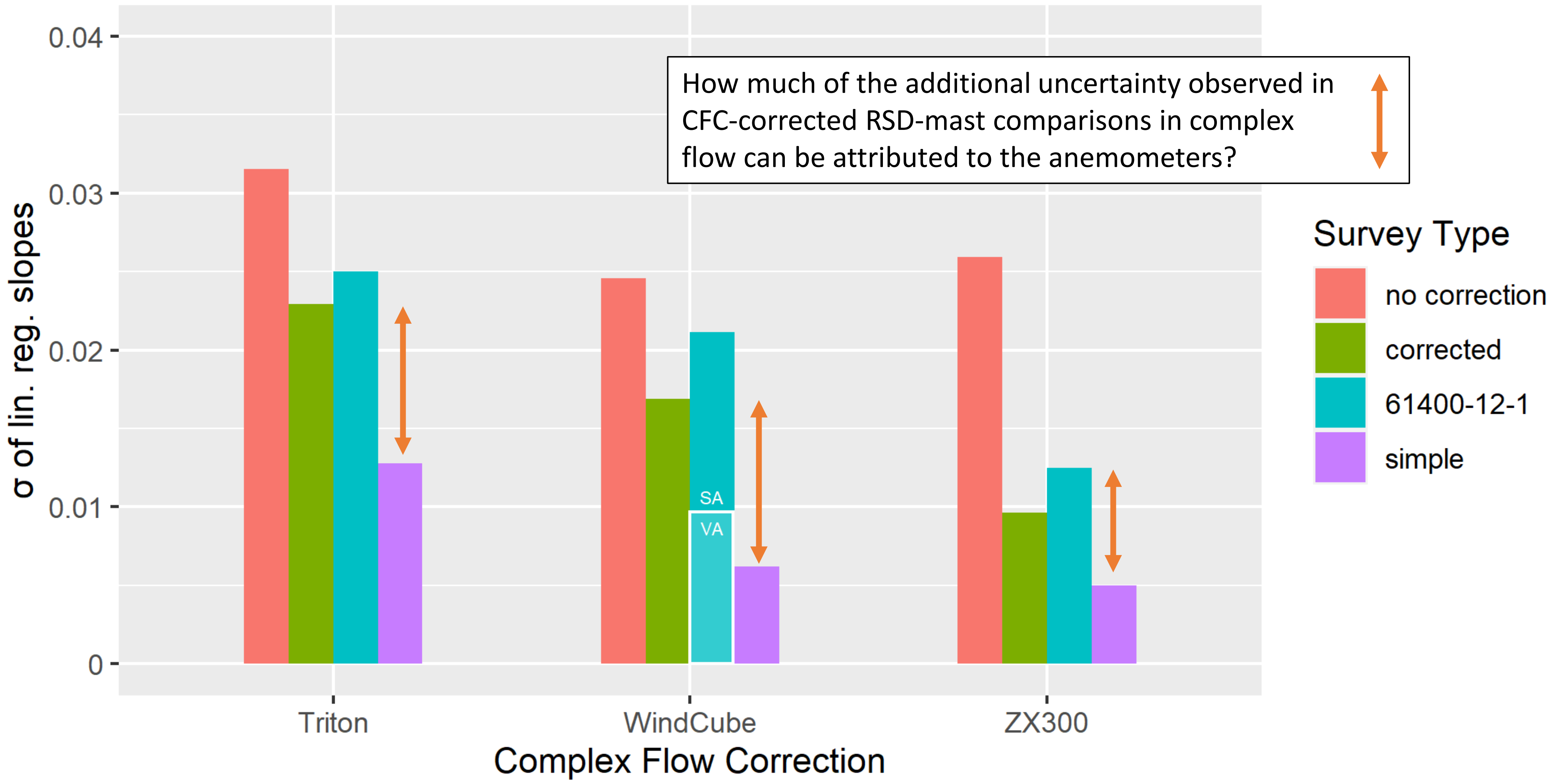
Anemometer Biases in Complex Flow



Graph generated from data in anemometer spec sheets and publications in References

- Filippelli, M., et al. *Adjustment of Anemometer Readings for Energy Production Estimates.* AWEA Windpower, June 2008
- Using the off-axis responses and measured inflow angles, *Filippelli et al* found **direction-dependent wind speed biases ranging from -1.51% to +3.7% in anemometer wind speeds in complex flow**

Complex Flow Correction and Simple Techniques Comparison of Uncertainty Estimates



Conclusions + Next Steps

- All the commercially-available CFC techniques show good skill in eliminating wind speed biases from RSDs when compared to collocated masts.
- CFC techniques have been validated at sites with a wide range of terrains, encompassing those found at typical complex development sites.
- Terrain classifications need more work, with a focus on explicit, quantifiable parameter boundaries for the different classes
- Uncertainties particular to complex terrain in the RSDs, the anemometers, and the CFC techniques are quantifiable, and are comparable to the uncertainties of RSDs in flat terrain, across various uncertainty metrics
- CFARS research into CFC and complex flow best practices is ongoing, with participation from key OEMs and developers, and in close coordination with IEA Task 32

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Remote Sensing + Complex Flow Resource Assessment “Framework”

CFARS
Consortium For Advancing Remote Sensing

Siting → Measurements → Modeling → Verification

Siting

- What is the terrain type at your site?
- **Choose a terrain classification rubric**
- Where is the best place to site your RSD and mast?
- **Follow manufacturer guidelines and use CFD software ahead of time**

Measurements

- Do you expect seasonal changes to surface roughness or forest canopies?
- **Photo documentation at all site visits**
- What is the expected flat terrain uncertainty of the RSD model?
- **This is a rough baseline for RSD + CFC performance**

Modeling

- Familiarize yourself with modeling tools before RSD measurement campaign begins
- **Understand uncertainties of model and correction methodology**
- There may be a new version between the start and end of your campaign
- **Understand how to use different or new features to maximize value**

Verification

- Do the mast and RSD require site calibration?
- **This will increase agreement between the RSD and mast**
- Is the mast experiencing off-axis flow?
- **Correct mast data with anemometer response, or include uncertainty in validation criteria**

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References

General References

- Consortium For the Advancement of Remote Sensing. CFARS Industry Survey. Conducted 2019
- Clifton, Andrew, et al. “Remote sensing of complex flows by Doppler wind lidar: issues and preliminary recommendations. No. NREL/TP-5000-64634.” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2015

Terrain Definitions

- Bingöl, F, Mann, J., and D. Foussekis. "Conically scanning lidar error in complex terrain." Meteorologische Zeitschrift 18.2 (2009): 189-195.
- Bingöl, F, “Complex Terrain and Wind Lidars.” PhD. diss. Risø National Laboratory, DTU, 2009
- Riley, Shawn J., Stephen D. DeGloria, and Robert Elliot. "Index that quantifies topographic heterogeneity." intermountain Journal of sciences 5.1-4 (1999): 23-27.

Uncertainties

- IEC 61400-12-1:2017 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines. Geneva: International Electrotechnical Commission, 2017.

DOI 10.5281/zenodo.4302363

References

Survey Data

- Stoelinga, M. and N. LaWhite. “Validation of Triton Wind Profiler Measurements in Complex Terrain, Using WindSim CFD-Based Flow Curvature Correction.” White Paper. Louisville, CO: Vaisala, Inc, 2018
- Meteodyn & ZX. “The use of Meteodyn WT to post-process ZephIR 300 wind speed data in complex terrain.” White paper. April 2017
- Krishnamurthy, R. and M. Boquet. “Case studies of WINDCUBE™ measurement uncertainty for complex terrain using Flow Complexity Recognition (FCR ®).” *European Wind Energy Conference Proceedings*. Barcelona: WindEurope, 2014.
- Wagner, R., and J. Bejdic. “Windcube + FCR test at Hrgud, Bosnia and Herzegovina.” Risø National Laboratory, DTU, 2014
- Schmitt, C., Wagner, L., and M. Boquet. “Measuring Wind Profiles in Complex Terrain using Doppler Wind LiDAR Systems with FCR™ and CFD Implementations.” *European Wind Energy Conference Proceedings*, Vienna: Wind Europe, 2013
- Foussekis, D., N. Stefanatos, and F. Mouzakis. “Operation of the Windcube V2 lidar at CRES Test Station.” Technical Report. Pikermi, Greece: CRES, 2011

DOI 10.5281/zenodo.4302363

References

IEC Classification Analyses

- Franke, K. “Summary of Classification of Remote Sensing Device Type: WindCube V2.0 (Vector Averaging).” Technical Report. Varel, DE: Deutsche WindGuard, 2020
- Tavares, R. “Remote Sensing Device Type-specific Classification Summary Type: ZX300 Lidar.” Technical Report. Kaiser-Wilhelm-Koog, DE: DNV-GL, 2018
- Black, A. and Niels LaWhite. “Field Results of New Sodar Algorithms.” *Wind Resource Assessment 2019*. Renton, WA: American Wind Energy Association, 2019

Flat Terrain Repeatability Studies

- Mangat, M. “Repeatability of ZephIR 300 performance” White Paper. Ledbury, England: ZX Lidars, 2016
- LaWhite, N. and M. Stoelinga. “Triton Remote Sensing Systems: Comparing Accuracy with Collocated Met Towers.” White Paper. Louisville, CO: Vaisala, Inc, 2015
- Mazoyer, P., Hermaszewski, C., and F. Rebeyrat. “Assessment of the repeatability and stability of Windcube performances.” *Resource Assessment 2017*. Edinburgh: WindEurope, 2017

DOI 10.5281/zenodo.4302363

References

Anemometer Behavior in Complex Flow

- Filippelli, Matthew, et al. "Adjustment of anemometer readings for energy production estimates." *Windpower Conference and Exhibition Proceedings*. Houston: American Wind Energy Association, 2008.
- Pedersen, T. “Characterization and Classification of the NRG Class 1 Anemometer for IEC 61400-12-1 Compliance.” Technical Report. Hinesburg, VT: NRG Systems, 2012
- Westermann, D. “Summary report VT121244 – Version 1.0 3 D Sonic Anemometer Classification.” Technical Report. Varel, DE: Deutsche WindGuard, 2017
- Westermann, D. “Summary report AK151023-1.3 Cup Anemometer Classification.” Technical Report. Varel, DE: Deutsche WindGuard, 2017
- “Wind tunnel calibration of cup anemometers” *Windpower Conference and Exhibition Proceedings*. Atlanta: American Wind Energy Association, 2012.

Correcting Anemometers in Complex Flow

- Meissner, C., Fontaine, A., and V. Vandale. “Inflow angles in complex terrain: is it possible to accurately predict them in a wind farm site?” *European Wind Energy Conference Proceedings*. Brussels: WindEurope, 2011.

References

Other CFD + RSD Combinations

- Klaas, Tobias, Lukas Pauscher, and Doron Callies. "LiDAR-mast deviations in complex terrain and their simulation using CFD." Meteorol. Z 24.6 (2015): 591-603.
- Harris, Michael, et al. "Validated adjustment of remote sensing bias in complex terrain using CFD." *European Wind Energy Conference Proceedings*. Warsaw: WindEurope, 2010.
- Guillén, Fernando Adrián Borbón. Lidar uncertainty in complex terrain development of a bias correction methodology. Diss. Universidad Politécnica de Madrid, 2015.
- Wylie, S., M. Smith and A. Woodward. “The use of CFD to increase the acceptance of wind data from lidars in complex terrain”. WindEurope Resource Assessment, 2020

DOI 10.5281/zenodo.4302363