WIND POWER | WEATHER & CLIMATE | AVIATION WEATHER | AIR QUALITY & INDUSTRIAL RISK

Assessment of the repeatability and stability of Windcube performances

Paul Mazoyer, Clement Hermaszewski, Florian Rebeyrat
WindEurope Ressource Assessment 2017

Agenda

- Industry feedback - Why does the repeatability and stability of wind measurement sensors matter?
- Lidar manufacturing and factory validation process
- Study of repeatability and stability of Windcube performances and over 595 datasets

Industry feedback

Why does repeatability and stability in wind measurement sensors matter?

Definitions

Repeatability

The degree to which measurements from different units under unchanged conditions show the same results.

Stability

The degree to which a unit measures the same over time under unchanged conditions.

Industry feedback – Why does repeatability and stability in wind measurement sensors matter?

"The benefit of stable, precise and accurate measurements is that uncertainty in the power curve verification campaign and in the site assessment can be reduced and we will have more certainty in the site data and AEP calculations as well as the measure power curve." **Tue Hald, Senior Specialist, MHI-Vestas**

"In my opinion, repeatability and stability basically contribute to the uncertainty of measurements. If measurements are not repeatable or stable a measure of the drift or change has to be attributed as uncertainty to the first measurement. For example, if a power curve verification is repeated after some time with the purpose to assess whether the performance has changed repeatability is essential. Otherwise only the difference in the measurement device would be observed." - **Jochen Rainer Cleve, Senior Measurements Engineer, DONG Energy**

"In a first approach the repeatability and stability seem to will reduce the noise and improve the data quality, so it will [illegible] However, in my opinion, it pays a more relevant role on the power performance where the uncertainty is always on the equation to assess the AEP." **Joan Arnet-Orizeta, Wind Resource and wind turbine performance specialist - ALSTOM Wind**

"Repeatable and stable wind measurements result in low uncertainties in energy yield assessments with accurate P90 values as a result. Most confidence results in more attractive financing conditions. Similarly, [illegible] wind farm results in [illegible] power curves. As a result, [illegible] performance can be validated and also turbine improvements are better demonstrated. For these reasons, ECN is working hard on the acceleration and acceptation of all technologies that contribute to reduction in cost of wind energy." **Dr. Jan Willem Wagneer, Project Manager and Researcher, ECN**

"Stability of measurements is required to avoid misinterpreting an artificial drift as a natural evolution of wind conditions overtime; and raising P90 values for project financing by reducing uncertainties. Reducing uncertainties through proofs of repeatability increases reliability of wind sensors. This is essential for the use of multiple Lidars in parallel for complex or large sites; or replacing a sensor during a maintenance event. Both repeatability and stability are required to reduce uncertainties and increase acceptance of Lidars for contractual performance verification." **Philippe Loiseau, Engineering Manager, BORALEX**

"Stability is very relevant for every wind resource assessment campaign [illegible] of the measurement result. A good and proven stability is a condition that a LiDAR can be used for certain campaign without any [illegible]). A high repeatability is a good indication of the quality of a product. Furthermore, a poor repeatability could also put in question the results of sensitivity tests / classifications being representative for all units of the specific type of LiDAR." **Axel Albers, Managing Director, Deutsche WindGuard**

"The wind industry needs proofs of repeatability and stability of Lidars to further reduce uncertainty, and in turn risks in yield assessments and power performance verifications." **Edouard Rol, Wind Resource Engineer, ENGIE Green**

"One aspect of WRA is the capture of the variations of wind characteristics with time (diurnal, seasonal variations) – for this application the choice of the measurement equipment therefore relies a lot on the stability of the measurements over time and their repeatability. For power performance evaluation, measurements are used in comparison to other cases (measurements or simulations) with [illegible] site [illegible] important to ensure that the observed differences between the various cases are due to the variations in wind conditions and not to the degradation over time of one lidar signal or a difference between different lidar units." **Rozen Wagner, Senior Scientist, DTU Wind Energy**

"Proofs of repeatability and stability of wind measurements [illegible] is a must-have for taking full advantage of cost savings and knowledge bringing potential of a Lidar." **Peter Enevoldsen, Researcher - Global Siting, Siemens Wind Power**

"For us, when we analyze wind measurement data and produce bankable or power performance reports for our clients, the data reliability is always one of the key points we address. Knowing that an instrument's measurements are accurate and do not drift over time, or at least the limits of any such drift, directly affects the uncertainties put on the data source. This can have a major impact the resulting values, eg P50 values or power curve uncertainties. Proofs of repeatability and stability is needed for not having to send an instrument to post-measurement-campaign calibration/validation. It is not only cost effective but makes it possible to finalize and present the report to investors at an earlier stage." **Martin Sigurd Grønsleth, PhD. Physics, Kjeller Vindteknikk**

We've asked ~20 developers, operators, consultants, OEMs, research institutes

3 main reasons emerge

Thanks to all who participated!

(see all answers in appendices)

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"Proofs of repeatability [illegible] cost savings and knowledge sharing potential." **[illegible], Research [illegible], Siemens Wind Power**

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1. Reduces uncertainties for power performance measurements and yield energy assessment

2. Fosters the development of "advanced" applications

3. Increases general confidence within the industry

Lidar manufacturing and factory verification process

Every Lidar follows the same process to ensure repeatability and stability

LEOSPHERE FACTORY

MANUFACTURING

Independent of environmental conditions

FAIL?

VALIDATION (pass/fail test)

Measure of accuracy and precision against the reference Lidar

PASS?

CUSTOMER

Measurement campaign with optional third party /on-site verification depending on applications

MAINTENANCE / REPAIR

The systematic validation of all Lidar provides Accuracy and Precision measurements

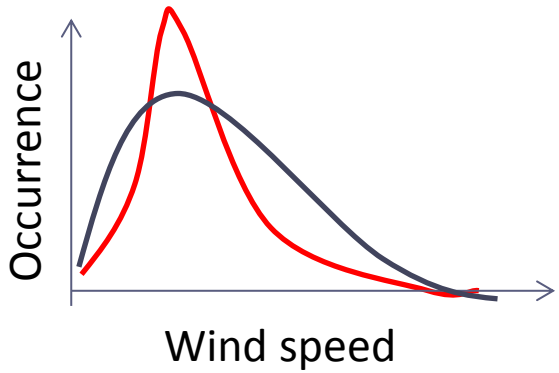
Accuracy

refers to the closeness of a measured value to a reference or known value.

Precision

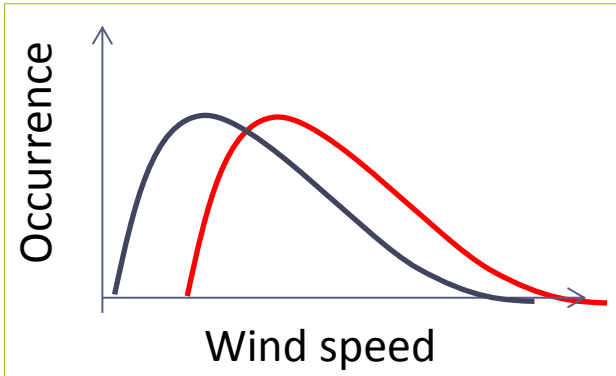
refers to the closeness of two or more measurements to each other.

The systematic validation of all Lidar provides Accuracy and Precision measurements



➔ High accuracy
➔ Low precision

Real
Measured



➔ Low accuracy
➔ High precision

Study over 595 datasets
Repeatability of measurements

06/2012 to 02/2017
448 systems – Windcube ground-based Lidar
Factory validations at Orsay Facility (France) only

Accuracy and Precision are measured for each system for each pairing {wind parameter;height}

ACCURACY

	HWS @ Height
System 1	0,01 m/s
System 2	-0,01 m/s
System 3	0,02 m/s
…	
…	
…	
System 595	0,01 m/s

PRECISION

	HWS @ Height
System 1	0,05 m/s
System 2	0,03 m/s
System 3	0,04 m/s
…	
…	
…	
System 595	0,02 m/s

Mean deviation and Standard deviation of Accuracy and Precision are then computed

ACCURACY

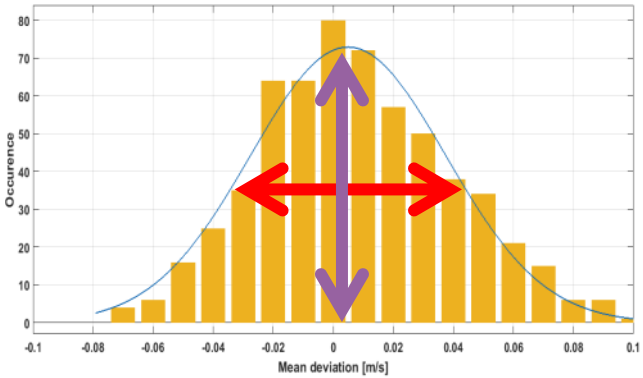
	HWS @ Height
System 1	0,01 m/s
System 2	-0,01 m/s
System 3	0,02 m/s
…	
…	
…	
System 595	0,01 m/s

Mean Deviation of Accuracy
**Or Accuracy of Precision*

0,01 m/s

Standard Deviation of Accuracy
**Or Precision of Accuracy*

+/-0,03m/s



In the end…

For each pairing {Wind parameter;Height}

We compute Mean and Standard deviation

Of Accuracy and Precision

For each pairing we compute Mean and Standard deviation for Accuracy and Precision

Statistics for all 595 systems			40m	80m	120m	160m	200m
Parameter	Unit						
Wind speed	m/s	Accuracy	-0,01 ±0,03	0,00±0,02	0,00±0,03	0,01±0,03	0,02±0,04
		Precision	0,07±0,02	0,05±0,02	0,05±0,02	0,06±0,03	0,07±0,03
Wind direction	°	Accuracy	0,17±1,47	0,17±1,46	0,18±1,46	0,17±1,47	0,16±1,48
		Precision	1,37±1,12	0,84±0,80	0,82±1,01	0,84±1,02	0,86±1,16
TI	%	Accuracy	-0,1±0,6	-0,1±0,3	-0,1±0,3	-0,1±0,3	-0,1±0,5
		Precision	1,6±0,7	1,0±0,8	0,9±0,6	1,0±0,7	1,1±0,8

For each couple {Parameter;Height} we compute Mean and Standard deviation for Accuracy and Precision

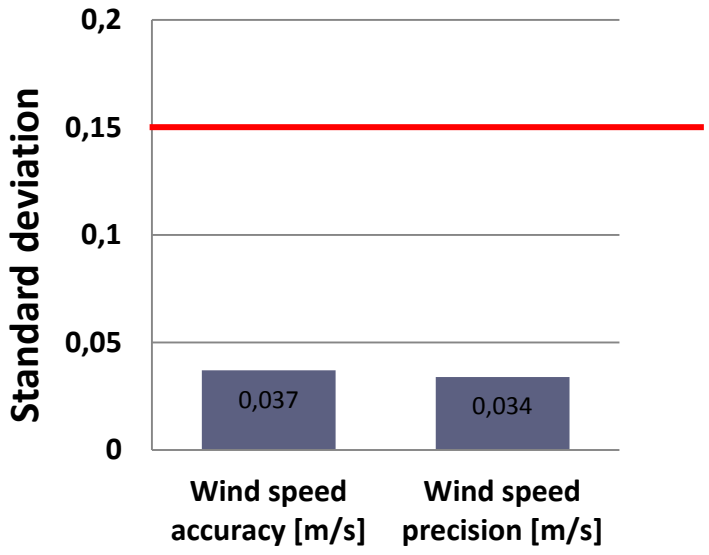
Statistics for all 595 systems			40m	80m	120m	160m	200m
Parameter	Unit						
Wind speed	m/s	Accuracy	-0,01 ±0,03	0,00±0,02	0,00±0,03	0,01±0,03	0,02±0,04
		Precision	0,07±0,02	0,05±0,02	0,05±0,02	0,06±0,03	0,07±0,03
Wind direction	°	Accuracy	0,17±1,47	0,17±1,46	0,18±1,46	0,21±1,47	0,16±1,48
		Precision	1,37±1,12	0,84±0,80	0,82±1,01	0,84±1,02	0,86±1,16
TI	%	Accuracy	-0,1±0,6	-0,1±0,3	-0,1±0,3	-0,1±0,3	-0,1±0,5
		Precision	1,6±0,7	1,0±0,8	0,9±0,6	1,0±0,7	1,1±0,8

Our analysis shows high accuracy and precision

For all wind parameters at all heights

With high repeatability

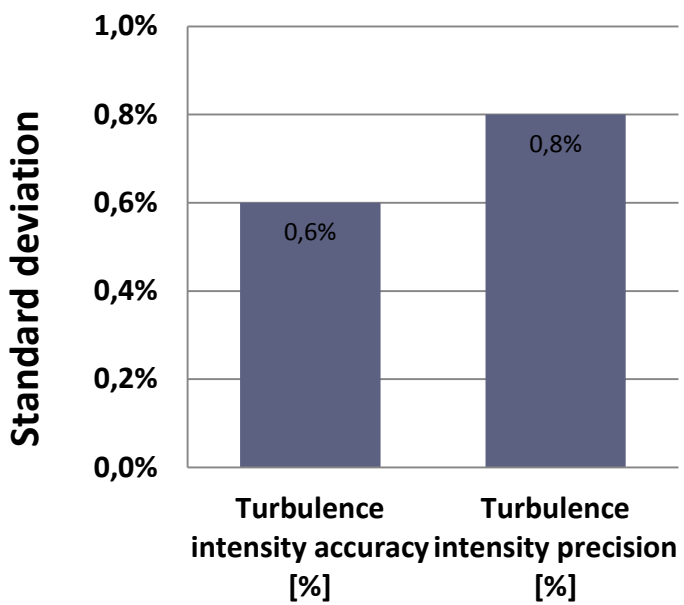
Maximum variability of wind speed is in line with industry standards requirements



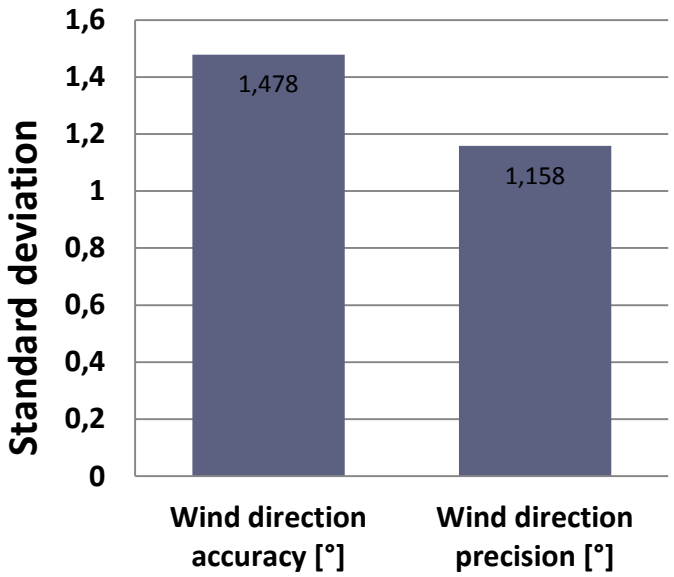
Maximum variability of wind speed at all heights

Typical third party acceptance criteria when comparing a Lidar to a mast

Equivalent conclusion could be held for TI and Direction, although no standard exists for comparison



Maximum variability of Turbulence intensity at all heights



Maximum variability of wind direction at all heights

Study over 595 datasets
Stability of measurements

06/2012 to 02/2017
448 systems – Windcube ground-based Lidar
Factory validations at Orsay Facility (France) only

We evaluate stability of systems which did not go through any major repair

We identify systems for which we have:

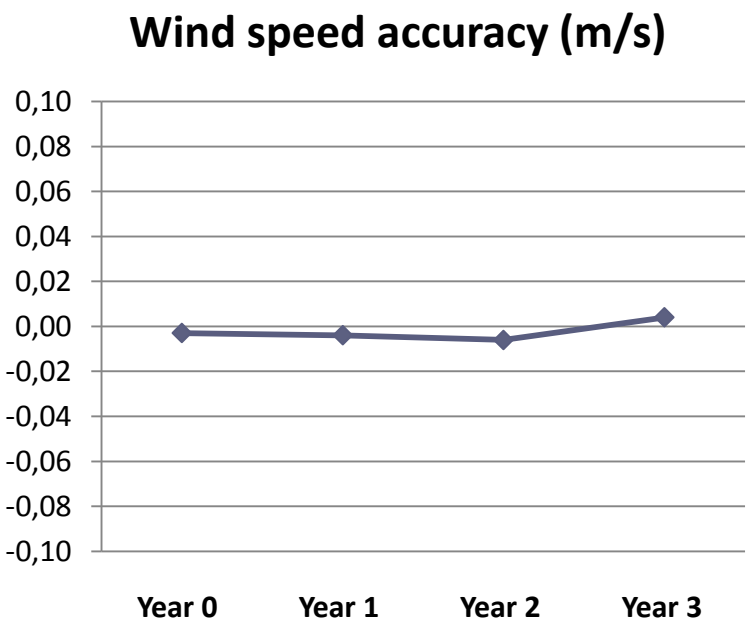
1. Validations dataset after 1, 2 or 3 years after initial validation (year 0)

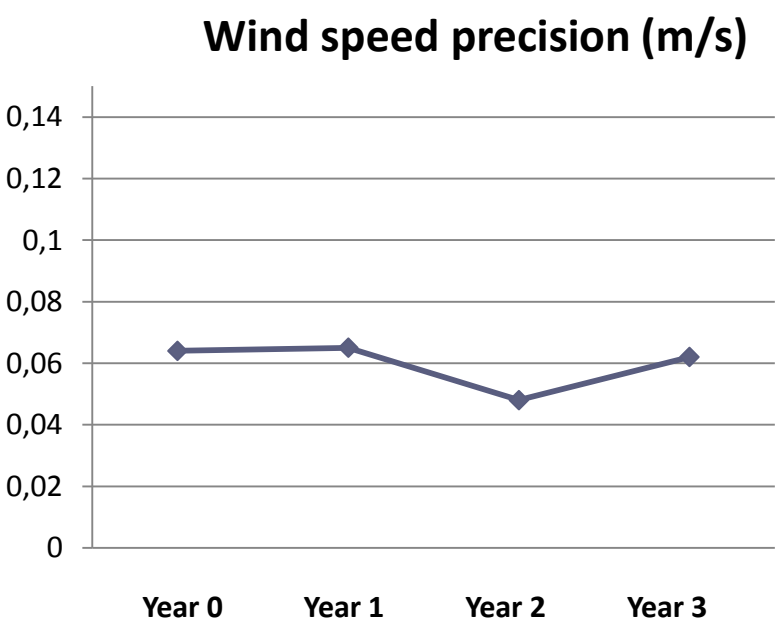
2. And no changes impacting metrology in between

For each duration an analysis of accuracy and precision is carried out

@120m			Year 0 (20 units)	Year 1 (11 units)	Year 2 (9 units)	Year 3 (3 units)
Parameter	Unit	Statistic				
Wind speed	m/s	Accuracy	-0,00 ± 0,02	-0,00 ± 0,02	-0,01 ± 0,02	0,00 ± 0,03
		Precision	0,06 ± 0,03	0,07 ± 0,03	0,05 ± 0,02	0,06 ± 0,01
Wind direction	Degrees	Accuracy	0,10 ± 1,03	0,79 ± 0,86	0,35 ± 0,82	0,71 ± 0,80
		Precision	1,20 ± 1,70	0,81 ± 0,65	0,45 ± 0,21	0,54 ± 0,15
TI	%	Accuracy	-0,09 ± 0,19	-0,14 ± 0,29	-0,11 ± 0,30	0,05 ± 0,18
		Precision	1,09 ± 0,73	1,14 ± 0,86	0,73 ± 0,57	0,52 ± 0,06

With a year on year average variation of <0.02 m/s we observe a good stability of wind speed

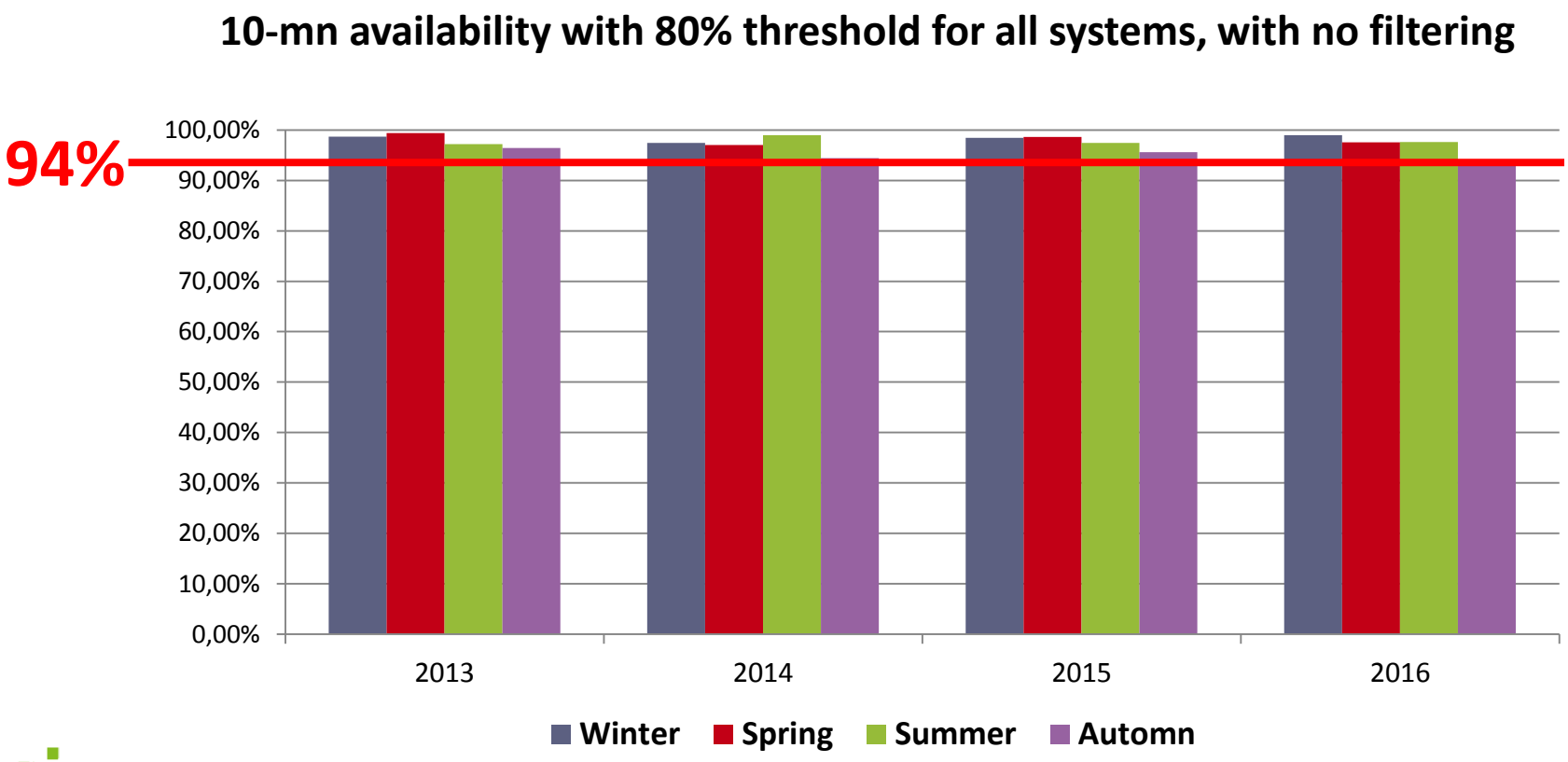




Study over 595 datasets
Focus on data availability

448 systems
06/2012 to 20/2017
Factory validations at Orsay Facility (France) only

10-mn availability in Leosphere facility (France) is observed to be stable and repeatable



Conclusion

- Repeatability and stability of wind sensors is key
- Every Lidar goes through the same industrial process to ensure repeatability
- 595 Lidar validations have been analyzed with respect to stability and repeatability
- We observe high repeatability of accuracy and precision for all wind measurements
- A good stability of wind measurements over time is observed

Appendices

Dataset

- Number of validation datasets: 595
- Mean duration: 5 days
- Location: Leosphere factory, Orsay, France
- Overall number of different systems: 448
- Validation data from 06/2012 to 02/2017
- > 16 cumulated years of observation

Lidar manufacturing and factory verification process

Factory validation process

- Every Lidar going out of Leosphere's factory (new unit, after a maintenance of repairs) follows the same validation process against a reference Lidar

- The objective is to assess Accuracy and Precision without any filtering except threshold on quality factor (% of availability)

- The reference Lidar is verified every 2 years against a mast in order to assess its accuracy and precision against a mast following national standards

Results example of a reference Lidar verification against a mast at DTU test site

DTU Wind Energy
Department of Wind Energy

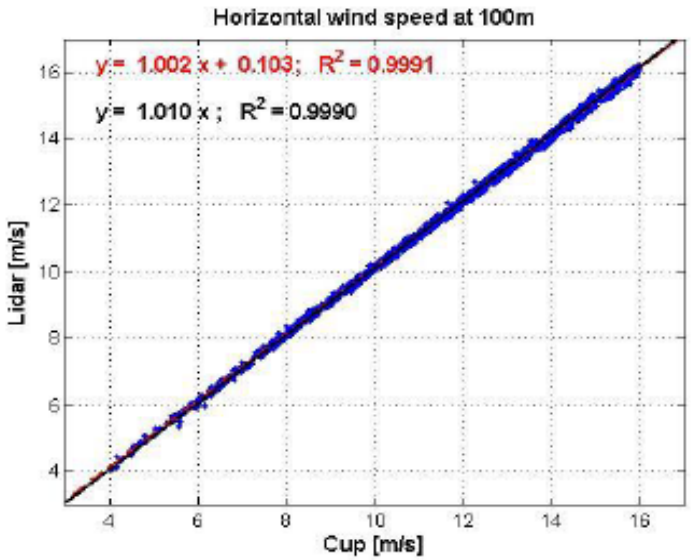


Figure 14.a 1-parametric regression between the 10 minute mean wind speed measurements from the Windcube at 100m and the cup anemometer at 100m.

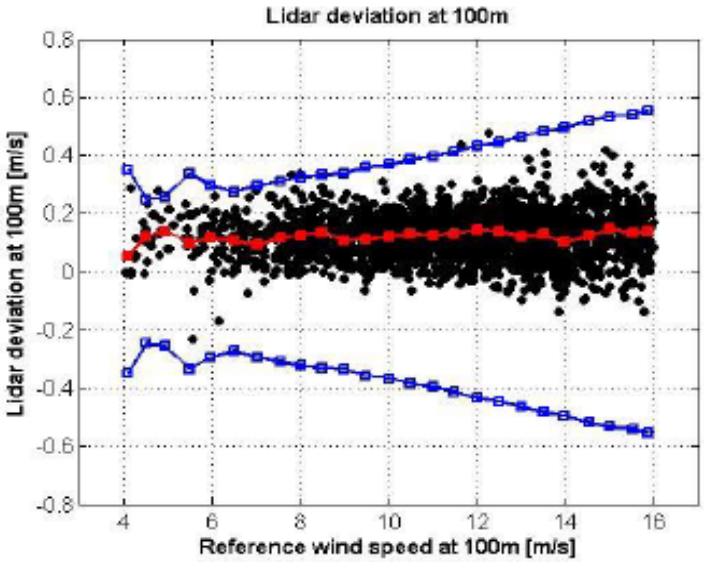


Figure 14.c Deviation at 100m versus wind speed. Each black dot represents a 10 min value; the red dots are the wind speed bin averages and the blue squares show $\pm 2u_{lidar}^{(2)}$ *. The lines result from linear interpolation.*

Industry feedback

Why does repeatability and stability in wind measurement sensors matter?

Verbatims from the panel
(when agreement was given)

Why does repeatability and stability in wind measurement sensors matter? (1/4)

"Stability is very relevant for every wind resource assessment or wind turbine power curve test, as any instability causes a bias of the measurement result. A good and proven stability is a condition that a LiDAR can be used for a certain campaign without any control anemometer (stand-alone operation). A high repeatability is a good indication of the quality of a product. Furthermore, a poor repeatability could also put in question the results of sensitivity tests / classifications being representative for all units of the specific type of LiDAR."

Axel Albers, Managing Director, Deutsche WindGuard, Germany

"The wind industry needs proofs of repeatability and stability of Lidars to further reduce uncertainty, and in turn risks in yield assessments and power performance verifications."

Edouard Rol, Wind Resource Engineer, ENGIE Green, France

"Ecofys WTTS is of the opinion that a high level of repeatability is crucial to allow for new applications of LiDAR such as the first ever all-LiDAR Site Calibration done by us last year at our Test Site."

Erik Holstag, Chief Operations, Ecofys WTTS, The Netherlands

"Knowledge and understanding about input and efficiency of a wind turbine is the key to avoid expensive surprises, e.g. regarding energy yield or with respect to the results of a power performance verification test. One of the most important aspects in that regard is the ability to measure the wind speed in a reliable way, with the lowest possible uncertainty and maximum repeatability."

Erik Tüxen, Global Excellence Team Leader – Power Performance, DNV GL, Germany

Why does repeatability and stability in wind measurement sensors matter? (2/4)

"Repeatable and stable wind measurements result in low uncertainties in wind resource assessments with accurate P90 value as a result. More confidence results in more attractive financing conditions. Similarly, repeatable and stable wind measurements result in more accurate power curves. As a result turbine performance can be validated and also turbine improvements are better demonstrated. For these reasons, ECN is working hard on the acceleration and acceptation of all technologies that contribute to reduction in cost of wind energy."

Dr. Jan Willem Wagneer, Project Manager and Researcher, ECN, The Netherlands

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Jochen Rainer Cleve, Senior Measurements Engineer, DONG Energy, Denmark

"In a first approach the repeatability and stability of the device will reduce the uncertainty of the wind measurement so it will be interesting for both. However, in my opinion, it pays a more relevant role on the power performance where the uncertainty is always on the equation to assess the AEP."

Jordi Armet-Unzeta, Wind resource and wind turbine performance specialist - ALSTOM Wind, Spain

Why does repeatability and stability in wind measurement sensors matter? (3/4)

"For us, when we analyze wind measurement data and produce bankable or power performance reports for our clients, the data reliability is always one of the key points we address. Knowing that an instrument's measurements are accurate and do not drift over time, or at least the limits of any such drift, directly affects the uncertainties put on the data source. This can have a major impact the resulting values, eg P50 values or power curve uncertainties. Proofs of repeatability and stability is needed for not having to send an instrument to post-measurement-campaign calibration/validation. It is not only cost effective but makes it possible to finalize and present the report to investors at an earlier stage."

Martin Sigurd Grønsleth, PhD. Physics, Kjeller Vindteknikk, Norway

"Proofs of repeatability and stability of wind measurements systems is very much needed for our daily tasks. In addition to mobility, it is a must-have for taking full advantage of cost savings and knowledge bringing potential of a Lidar."

Peter Enevoldsen, Researcher – Global Siting, Siemens Wind Power, Denmark

"Stability of measurements is required to avoid misinterpreting an artificial drift as a natural evolution of wind conditions overtime; and raising P90 values for project financing by reducing uncertainties. Reducing uncertainties through proofs of repeatability increases reliability of wind sensors. This is essential for the use of multiple Lidars in parallel for complex or large sites; or replacing a sensor during a maintenance event. Both repeatability and stability are required to reduce uncertainties and increase acceptance of Lidars for contractual performance verification."

- Philippe Loiseau, Engineering Manager, BORALEX, France

Why does repeatability and stability in wind measurement sensors matter? (4/4)

"One aspect of WRA is the capture of the variations of wind characteristics with time (diurnal, seasonal variations) – for this application the choice of the measurement equipment therefore relies a lot on the stability of the measurements over time and their repeatability. For power performance evaluation, measurements are used in comparison to other cases (measurements or simulations) with different wind conditions (e.g. other sites, other times of year). Repeatability is therefore very important to ensure that the observed differences between the various cases are due to the variations in wind conditions and not to the degradation over time of one lidar signal or a difference between different lidar units."

Rozen Wagner, Senior Scientist, DTU Wind Energy

"There are many characteristics that determine the quality of measurements and instruments, of which repeatability and stability are two very important ones."

Stefan Goossens, Wind analyst, Nuon/Vattenfall, The Netherlands

"Stable, repeatable, and highly accurate wind speed measurements are mandatory to reduce the uncertainty calculation of our energy production reports and power curves measurements. Stable and repeatable measurements give us great confidence in the validation of our modeled wind flows."

Sven Huneke, Meteorologist – Senior Manager CFD/LIDAR – Site Assessment, juwi, Germany

"The benefit of stable, precise and accurate measurements is that uncertainty in the power curve verification campaign and in the site assessment can be reduced and we will have more certainty in the site data and AEP calculations as well as the measure power curve."

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