#16245

Verification of nacelle-mounted LiDAR systems

A comparison of black and white box methodology

Jens Riechert, Joachim Schaeffer, Rafael Tavares (all DNV GL)

DNV·GL

Abstract

Especially for offshore measurements, the use of nacelle-mounted LiDAR systems becomes more and more important in the wind industry. For traceable field measurements it is recommended to assess the performance of the LiDAR system against a well known reference sensor, e.g. cup anemometer. For nacelle-mounted LiDAR systems two verification methodologies are discussed:

- White box approach
- Black box approach

The results of several verification campaigns for both the black and white box methodology are summarized. The campaigns were conducted at two different test sites, whereby two different LiDAR types were verified. The methodologies are compared and the pros and cons are discussed.

Methods

White Box (WB):

The WB methodology is based on the assessment of different input quantities which are used by the LiDAR to reconstruct the wind field characteristics. In general, the WB approach includes the verification of the following parameter:

- Scan geometry
- Measurement range
- Uncertainty assessment
- Inclinometers
- Line-of-sight velocity

Black Box (BB):

The BB methodology is based on the assumption that the total functionality of the LiDAR system is represented by the output quantities provided by the LiDAR system (e.g. horizontal wind speed). Therefore, a separate consideration of single input quantities, e.g. scan geometry or measurement position, which are used by the LiDAR algorithm, is not done.

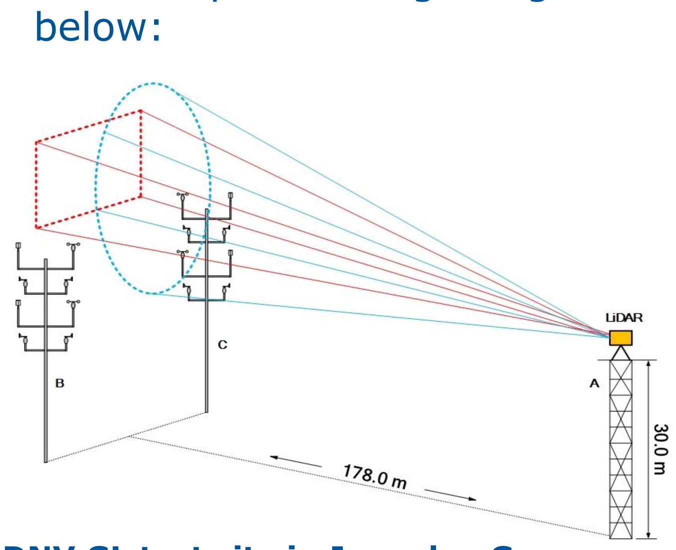
Illustration of white and black box methodology [1].

Test specifications

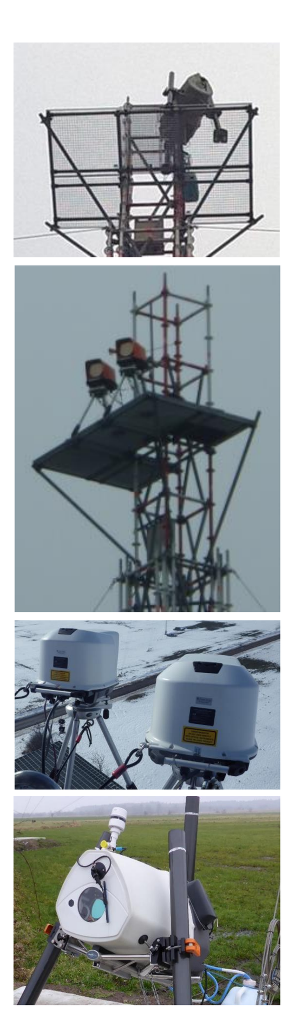
The comparison between black and white box approach is based on six verification campaigns. The campaigns were conducted at two different test sites, whereby two different LiDAR types (CW and pulsed) were verified. For the six tests, the following test configuration were applied:

Unit 1-4

- Horizontal setup (platform test)
- Test setup according to figure below:



DNV GL test site in Janneby, Germany



Unit 5-6

- Inclined test setup (slant test)
- Inclination angles: 12-25°
- Comparison against 100m mast
- Measurement range: 130-180m

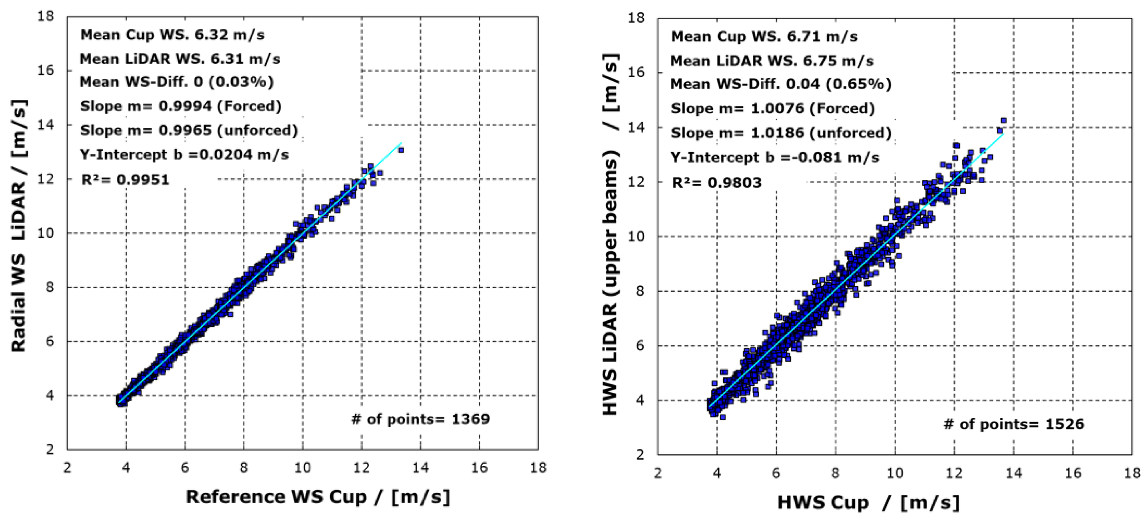
Results of linear regression analysis

Unit	# values	slope (forced)	R^2	HWS-avg Cup	HWS-avg Lidar	Mean HWS Diff.	Rel. Mean HWS Diff.
	-	-	-	[m/s]	[m/s]	[m/s]	%
Unit 1	1526	1.008	0.980	6.71	6.75	0.04	0.65%
Unit 2	1528	1.008	0.981	6.71	6.75	0.05	0.71%
Unit 3	1053	1.002	0.980	6.12	6.13	0.01	0.20%
Unit 4	943	0.998	0.967	6.52	6.51	0.01	0.18%
Unit 5	2044	0.993	0.989	8.47	8.41	-0.06	-0.72%
Unit 6	1041	1.009	0.988	7.49	7.55	0.06	0.82%

Summary of Black Box results

Unit	# values	slope (forced)	R^2	RWS-avg Cup	RWS-avg Lidar	Mean RWS Diff.	Rel. Mean RWS Diff.
	-	-	-	[m/s]	[m/s]	[m/s]	%
Unit 1	1369	0.999	0.995	6.32	6.31	0.00	0.03%
Unit 2	1361	0.999	0.997	6.30	6.29	0.01	0.10%
Unit 3	783	1.002	0.996	5.70	5.72	-0.01	-0.26%
Unit 4	754	0.998	0.995	5.60	5.58	0.01	0.21%
Unit 5	3779	0.997	0.991	7.10	7.08	-0.02	-0.32%
Unit 6	1384	1.001	0.993	6.52	6.54	0.01	0.21%

Summary of White Box results

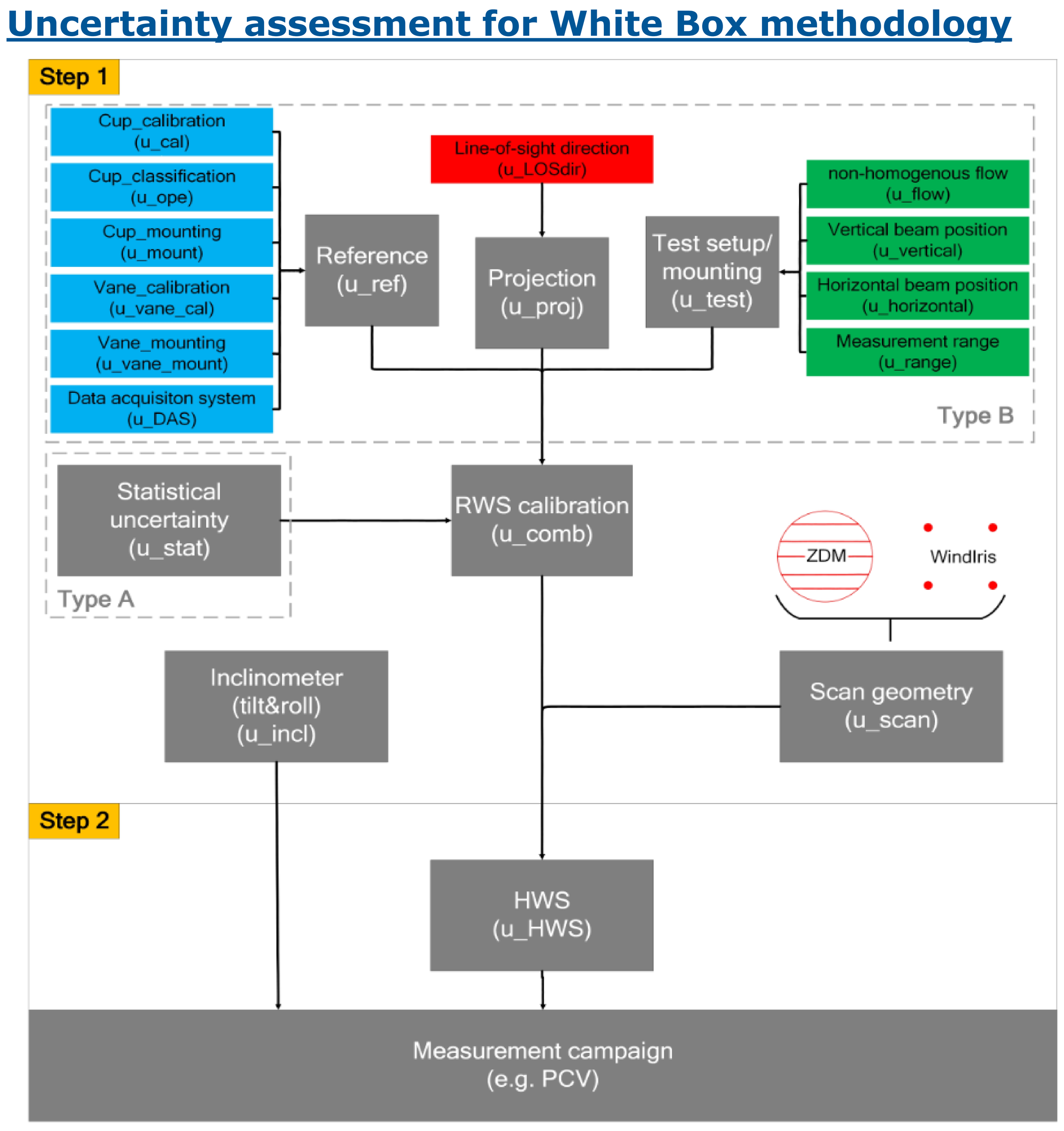


White Box (left) and Black Box (right) results (Unit 1)

- Comparable results for both test sites and both LiDAR types.
- Slopes close to unity for both WB and BB.
- Squared correlation coefficient:
  - WB: 0.991 – 0.997
  - BB: 0.980 – 0.989
- For most analysis rel. mean WS difference below 1%.

Assessment of LiDAR performance

Uncertainty assessment for White Box methodology



Uncertainty schema for White Box methodology [1] [2] [3].

Differences in uncertainty assessment

- Less complex for BB methodology.
- Different uncertainty components, depending on the test site and test setup.
- Slightly higher statistical uncertainty for BB methodology, but not that much higher

DNV GL internal KPIs and ACs for accuracy assessments

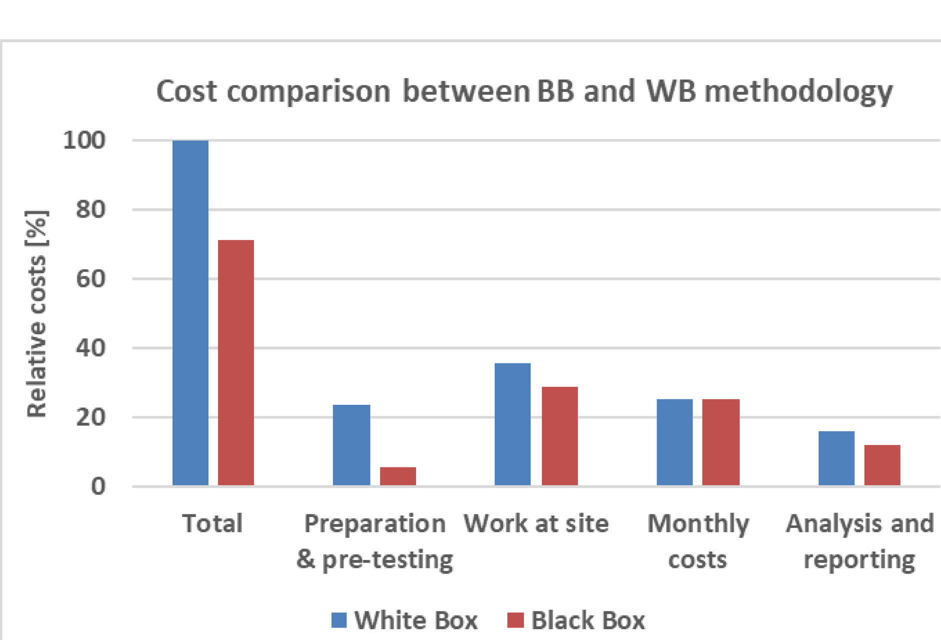
KPI	Definition / Rationale	Black box AC's		White box AC's	
		Best Practice	Minimum	Best Practice	Minimum
C_{mwsd}	**Mean Wind Speed -Difference** Absolute difference of mean wind speeds between LiDAR and reference as measured over the whole verification campaign duration, expressed as percentage relative to the Campaign Mean Wind.	< 1 %	1 – 1.5 %	<1%	1 – 1.5 %
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin.	0.98 – 1.02	0.97 – 1.03	0.99-1.01	0.98-1.02
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Correlation Coefficient returned from single variant regression.	>0.98	>0.97	>0.99	>0.98

In practice, further KPIs and ACs, e.g. for data coverage, system and data availabilty should be considered for both methodologies. Additionally, KPIs and ACs for other verification parameters of the white box methodology (e.g. Scan gemometry) should be defined.

Conclusions

	White Box	Black Box
Pros	• Most proven method for verification of nacelle LiDARs • Generic method for verification of Line-of-sight velocity	• Shorter campaign duration (about 4-6 weeks) • Less costly (about 70 % of WB) • Less complex → Less experience needed
Cons	• Longer campaign duration (about 6-12 weeks) • More costly (see bar chart below) • More complex → More experience needed	• Higher statistical uncertainty, due to higher scatter • Specific for each type of device/Reliability on manufacturer algorithm

- Both methodologies are applicable for the verification of nacelle-mounted LiDAR systems
- Comparable results for different test sites, site specifics and LiDAR types.
  → BB and WB are applicable at different sites and for different LiDAR types
- Slightly better regression coefficients (slope, R², mean dev.) for WB
  → Different KPIs and ACs for assessment of LiDAR performance needed
- WB methodology is more complex than BB methodology:
  → Longer campaign duration
  → Higher costs (see bar chart beside)
  → More complex uncertainty assessment



Different methodologies for different applications?

White Box		Black Box	
Applications where a "calibration" of the LiDAR is needed	Power Curve Verification according to coming IEC Standard	Lidar Assisted Control (LAC)	Other applications

References

1. Generic methodology for calibration profiling nacelle lidars, DTU Wind Energy E-0086, A. Borraccino et al., July 2015
2. Calibrating Nacelle lidars, DTU, Michael Courtney, DTU Wind Energy E-0020, January 2013
3. IEC 61400-12-1: Power performance measurements of electricity producing wind turbines. Ed. 2., Apr. 2017