Floating DBS LIDAR: Error quantification and correction of wave induced turbulence intensity bias

T. Désert, S. Aubrun, G. Knapp, S. Kraiem, M. Bellorge, B. Clauzet, R. Barbot, L. Mourre - MATILDA

WESC : Mini-Symposium: Lidars and Floating Wind Energy
LEOSPHERE WindCube v2

Wind measurements

Five beam positions (scan ~1s) combined to compute at several altitudes:

- \( U(h) \) : from beams N-S
- \( V(h) \) : from beams E-W
- \( W(h) \) : from vertical beam

Induced errors:
Contamination by cross-correlations between the components of the wind vector and the assumption of homogeneity in the volume.

LEOSPHERE WindCube v2

Wind measurements

Five beam positions (scan ~1s) combined to compute at several altitudes:
- $U(h)$: from beams N-S
- $V(h)$: from beams E-W
- $W(h)$: from vertical beam

Induced errors:
Contamination by cross-correlations between the components of the wind vector and the assumption of homogeneity in the volume.

Turbulence Intensity (TI)

Statistical study of the acquired wind speeds:

$$V_{\text{hor}} = \sqrt{U(h)^2 + V(h)^2}$$

$$TI = \frac{\sigma_{V_{\text{hor}}}}{V_{\text{hor}}}$$

Induced errors:
Turbulence statistics filtered by the measurement volume and the "low" acquisition frequency of the lidar.

Wave induced motions (FLS)

**Rotational motions**

- \( \theta \)
- \( \varphi \)
- \( \text{pitch} \)
- \( \text{yaw} \)
- \( \text{roll} \)

**Translational motions**

- \( \text{Surge} \)
- \( \text{Sway} \)
- \( \text{Heave} \)

**Impacting**

The geometry of the measurement cone: \( \varphi \) and \( \theta \) for each beam.

The relative velocity of the lidar to the particle that backscatters the laser.
Model estimating wave induced TI
Model estimating wave induced TI

Hypothesis

Atmospheric turbulence and motion induced turbulence are independent variables

We have:
Turbulence measured by the floating lidar

We look for:
Atmospheric Turbulence

\[ \text{Var}(V_{\text{mes}}) = \text{Var}(V_{\text{atm}}) + \text{Var}(V_{\text{motion}}) \]

We estimate:
Wave induced turbulence in a turbulence free atmosphere
Model estimating wave induced TI

How the model works

*It simulates the behavior of the WindCube v2 in a turbulence free atmosphere*

**Inputs**
- 10min Mean Wind Vector (from floating lidar): **Constant**
- IMU measurements within the 10min:
  - Rotational
  - Translational

**Outputs**

\[
\begin{align*}
\mathbf{u}(t, h) &= \begin{pmatrix} u_{10\text{min}}(h) \\ v_{10\text{min}}(h) \\ w_{10\text{min}}(h) \end{pmatrix}^T \frac{\mathbf{U}^{\text{mat}}(t)}{2\sin\phi} - \frac{\mathbf{V}^{\text{trans}}(t)}{2\sin\phi} \\
\mathbf{v}(t, h) &= \begin{pmatrix} u_{10\text{min}}(h) \\ v_{10\text{min}}(h) \\ w_{10\text{min}}(h) \end{pmatrix}^T \frac{\mathbf{V}^{\text{mat}}(t)}{2\sin\phi} - \frac{\mathbf{V}^{\text{trans}}(t)}{2\sin\phi} \\
\mathbf{w}(t, h) &= \begin{pmatrix} u_{10\text{min}}(h) \\ v_{10\text{min}}(h) \\ w_{10\text{min}}(h) \end{pmatrix}^T \mathbf{W}^{\text{mat}}(t) - \mathbf{V}^{\text{trans}}(t)
\end{align*}
\]
Model estimating wave induced TI

10min estimate of the wave induced variance in horizontal speed measurement

\[
V'_{\text{hor}}(h)^2 = \frac{1}{(2\sin \phi)^2} \left( \begin{array}{c}
u_{10\text{min}}(h) \\
v_{10\text{min}}(h) \\
w_{10\text{min}}(h)
\end{array} \right)^T \begin{pmatrix}
U_{\text{mat}}^2 + V_{\text{mat}}^2 \\
+ 2 u_{10\text{min}}(h) v_{10\text{min}}(h) U_{1\text{mat}} V_{2\text{mat}} + V_{1\text{mat}} V_{2\text{mat}} \\
+ 2 v_{10\text{min}}(h) w_{10\text{min}}(h) U_{2\text{mat}} V_{3\text{mat}} + V_{1\text{mat}} V_{3\text{mat}} \\
- 2 u_{10\text{min}}(h) U_{1\text{mat}} V_{\text{trans}}^u + V_{1\text{mat}} V_{\text{trans}}^v \\
- 2 v_{10\text{min}}(h) U_{2\text{mat}} V_{\text{trans}}^u + V_{2\text{mat}} V_{\text{trans}}^v \\
- 2 w_{10\text{min}}(h) U_{3\text{mat}} V_{\text{trans}}^u + V_{3\text{mat}} V_{\text{trans}}^v \\
+ V_{\text{trans}}^u 2 + V_{\text{trans}}^v 2 \end{pmatrix} - V_{\text{hor}}(h)^2
\]

Independants

10 min Floating Lidar data
10min IMU data + model

Needs real time communication between model and FLS (or estimate)

Horizontal velocity measured by the lidar in the model definition and boundary conditions
Advantages and disadvantages of the model

**Advantages**

- Rotational and translational effects are represented by 10min mean matrices:
  - averages the effect of minor instrumental errors
  - reduces the importance of time synchronization
- Very fast computation compared to a beam by beam correction [2]

**Disadvantages**

- Does not take into account atmospheric boundary layer shear
- Filters out the 10mins that do not fit the model assumptions or do not show consistency between IMU and FLS measurements

Experimental campaign
Campaign presentation

Six months of measurements

13 weeks selected by a clustering method to best represent the overall atmospheric and sea conditions

Data filters

- 10min availability: >90%
- $2 \text{m/s} < V_{\text{hor}} < 20 \text{m/s}$
- $0 < TI < 0.4$
Experimental facilities

**Meteo Mast Fécamp (EDF Renouvelables)**
- Wire mesh Mast
- Cup anemometers (alt: 33.8 & 54.8m)
- Ground pulsed lidar Windcube v2

**Buoy WINDSEA_02 (AKROCEAN)**
- Pulsed lidar Windcube v2
- Inertial Measurement Unit
- Passive mechanical stabilisation
- Wave buoy
Wave induced TI measurement error

**Floating lidar TI bias : 54.8m**

- **Overall overestimation (~0.03)**
- **Motion induced bias ≫ lidar technological bias**

---

![Graphs showing correlation between ground lidar and anemometer, and floating lidar and anemometer with linear regression lines and R² values.](image)

- (a) Ground lidar and Anemometer: $y = 1.004x + 0.002$, $R^2 = 0.869$
- (b) Floating lidar and Anemometer: $y = 1.083x + 0.029$, $R^2 = 0.523$
Wave induced TI measurement error

*Floating lidar TI bias: 54.8m*

- **TI measurement error depends on meteoceanic conditions**
- **Best indicator: wave height which is highly correlated with wind speed**
- **No conditions = zero error from FLS**

\[ V_{\text{hor}} < 2\,\text{m/s} \]
Main Sources of TI bias

Wind rose
- in the lidar referential
- normalized wind speed

Main sources of TI error
Rotational motions
Roll modifying tilt angle of east and west beams
Translational motions
Heave has the most impact on horizontal WS
Corrected atmospheric TI estimate
Corrected atmospheric TI estimate

For all 10min measurements: 94.4m & 134.4m

(a) 94.4m: Uncorrected floating lidar

(b) 94.4m: Corrected floating lidar

(c) 134.4m: Uncorrected floating lidar

(d) 134.4m: Corrected floating lidar
Corrected atmospheric TI estimate

**Most troubled week evaluated : 94.4m**

(a) 94.4m : Uncorrected floating lidar TI measurements

(b) 94.4m : Corrected floating lidar TI measurements

Removable by spike filtering methods [3]

Conclusion
Conclusion

- The mean overestimation of the Floating WindCube v2 Turbulence Intensity measurements: 
  \(\sim 0.03\) (at Fécamp, buoy WINDSEA_02)
Conclusion

• The mean overestimation of the Floating WindCube v2 Turbulence Intensity measurements:
  ~0.03 (at Fécamp, buoy WINDSEA_02)

• No meteoceanic conditions can ensure a proper TI measurement from the FLS: need for a correction of the motion induced TI
Conclusion

• The mean overestimation of the Floating WindCube v2 Turbulence Intensity measurements:
  \[ \sim 0.03 \] (at Fécamp, buoy WINDSEA_02)

• No meteoceanic conditions can ensure a proper TI measurement from the FLS: need for a correction of the motion induced TI

• We have created a model that quickly evaluates the 10min TI error induced by the motion of the buoy:
  inputs: the six degrees of freedom of a IMU and the 10min mean wind speed data from the floating lidar
Conclusion

• The mean overestimation of the Floating WindCube v2 Turbulence Intensity measurements:
  ~0.03 (at Fécamp, buoy WINDSEA_02)

• No meteoceanic conditions can ensure a proper TI measurement from the FLS: need for a correction of the motion induced TI

• We have created a model that quickly evaluates the 10min TI error induced by the motion of the buoy:
  inputs: the six degrees of freedom of a IMU and the 10min mean wind speed data from the floating lidar

• Using the model drastically reduces the TI measurement error of the floating WindCube v2:
  It increases the coefficient of determination and reduces the mean error to ~0.005 compared to the ground lidar (could be improved with clever spike removing methods)
THANK YOU FOR YOUR ATTENTION