



Floating Lidar Turbulence Intensity: Methods, Standards and Application to Offshore Wind Resource Assessment

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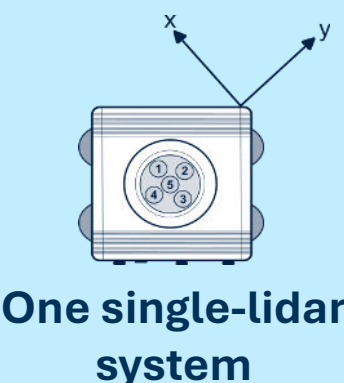
Traditional method used in the industry

Employed the instantaneous reconstructed velocities :

$$u_x, u_y, u_z$$

3 sources of error in turbulence measurement that “compensate” each other:

- Inter-beam effect : $TI \downarrow$ or $TI \uparrow$
- Intra-beam effect : $TI \downarrow$
- Instrumental noise : $TI \uparrow$



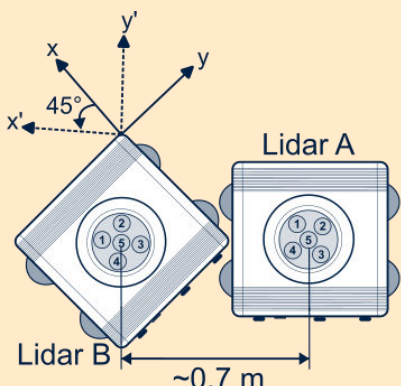
One single-lidar system

Variance method - TwinDAR©

Employed ONLY the LOS velocities

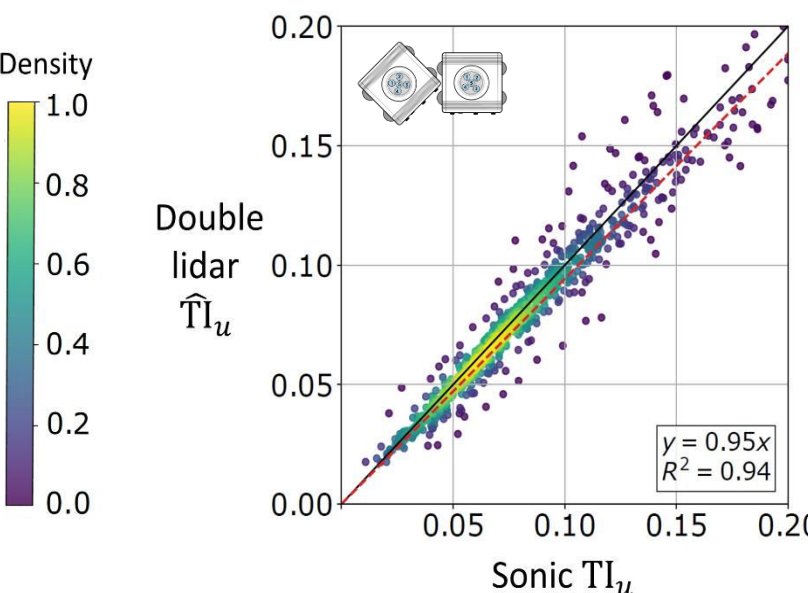
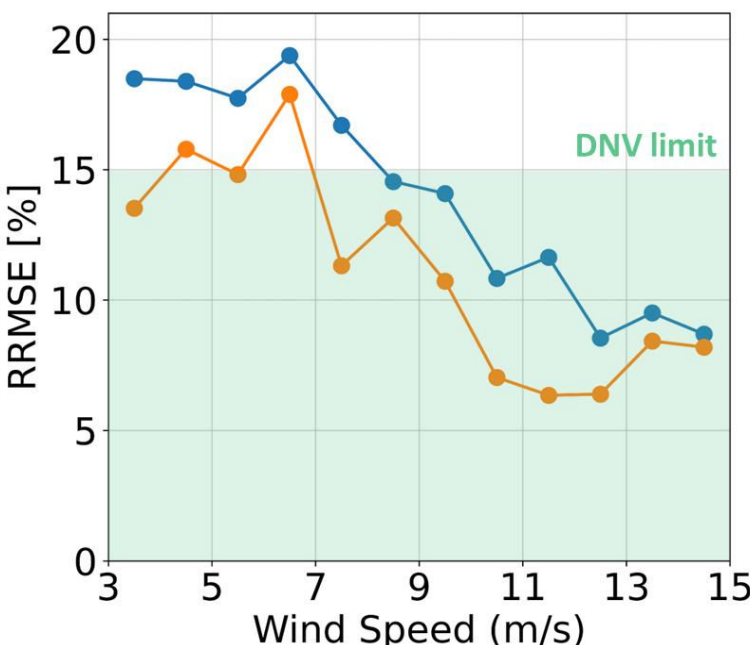
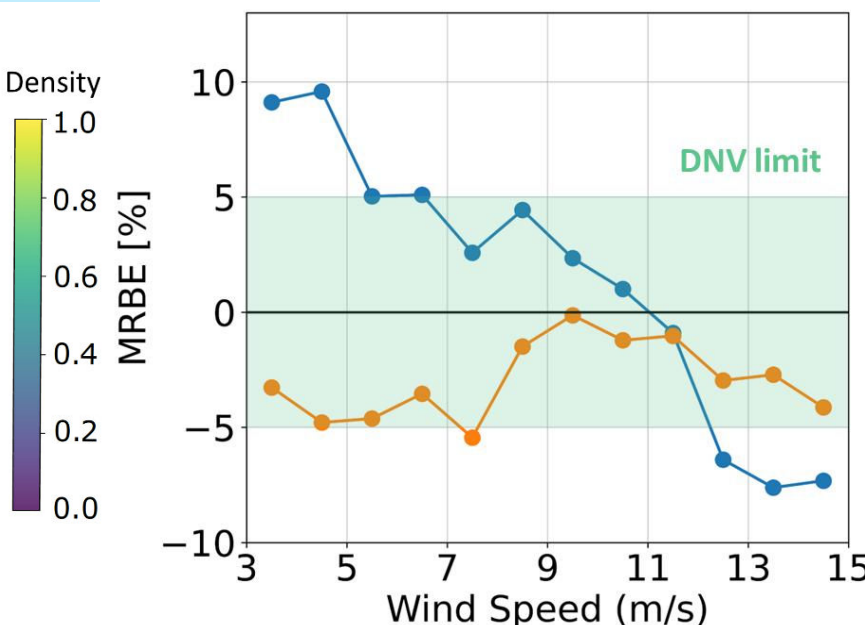
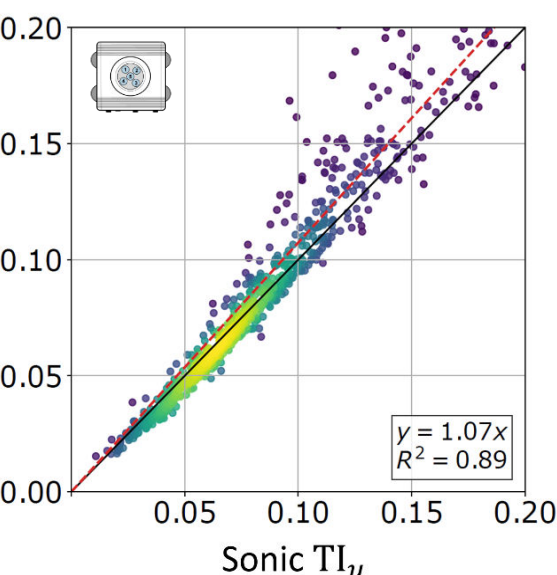
1 source of error :

- Inter-beam effect
- Intra-beam effect : $TI \downarrow$
- Instrumental noise



Dual-lidar system

Error in TI reconstruction



The variance method enables :

- Higher correlation:** improved slope and higher R^2 coefficient;
- Lower errors:** error statistics in accordance with DNV recommendations;
- Reduced site dependence:** errors less sensitive to site-specific characteristics, improving the robustness and general applicability of the method.

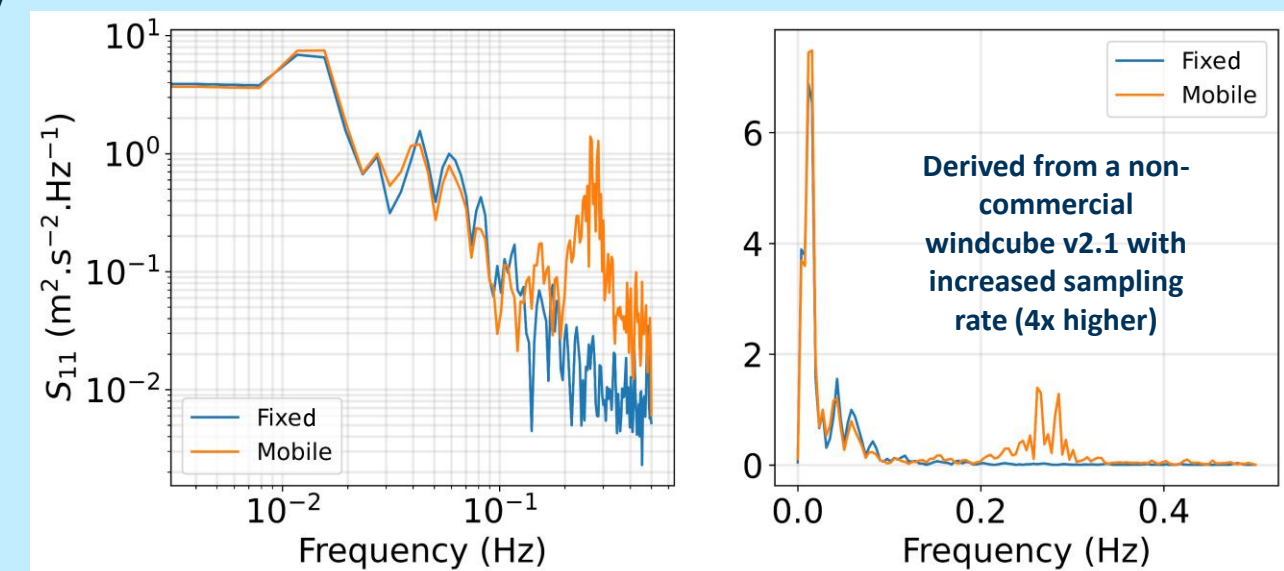
Ground-based lidar vs. Mobile lidar

Dataset

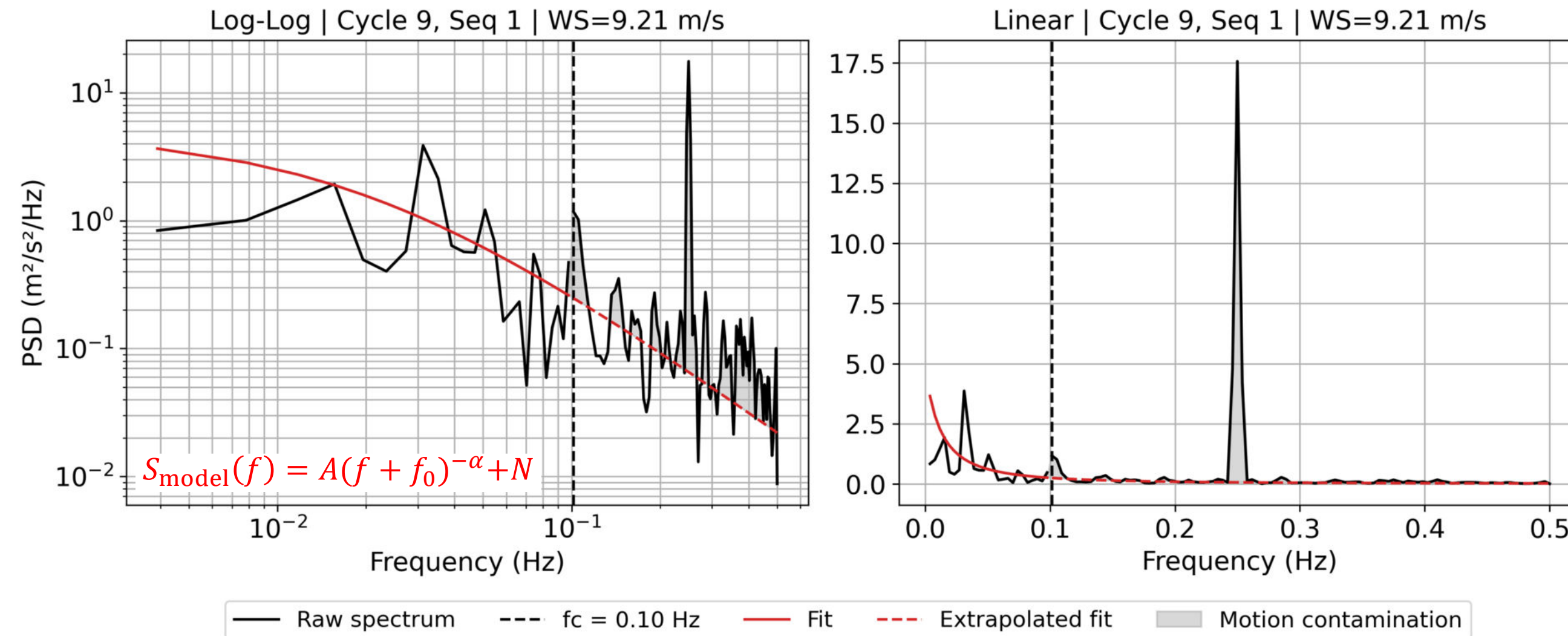
- 15 cycles of 3-hour long (45-hour long dataset);
- 1 cycle is composed of 12 sequences (regular and irregular motions);
- Motions with one or multiple degrees of freedom;
- Motion periods of 4, 6, and 8 s;
- Motion amplitudes of 5° and 15°.



Impact of motion on the raw data



- The motion generates an **energy hump** in the LOS velocities spectra;
- The motion-compensation algorithm is based on quantifying this energy hump using a **spectral approach**.



- $\sigma_{i,\text{raw}}^2 = \int_{f_c}^{f_N} S_i(f) df$

- $\sigma_{i,\text{model}}^2 = \int_{f_c}^{f_N} S_{\text{model}}(f) df$

The motion-induced variance is defined as the excess spectral energy from f_c to f_N :

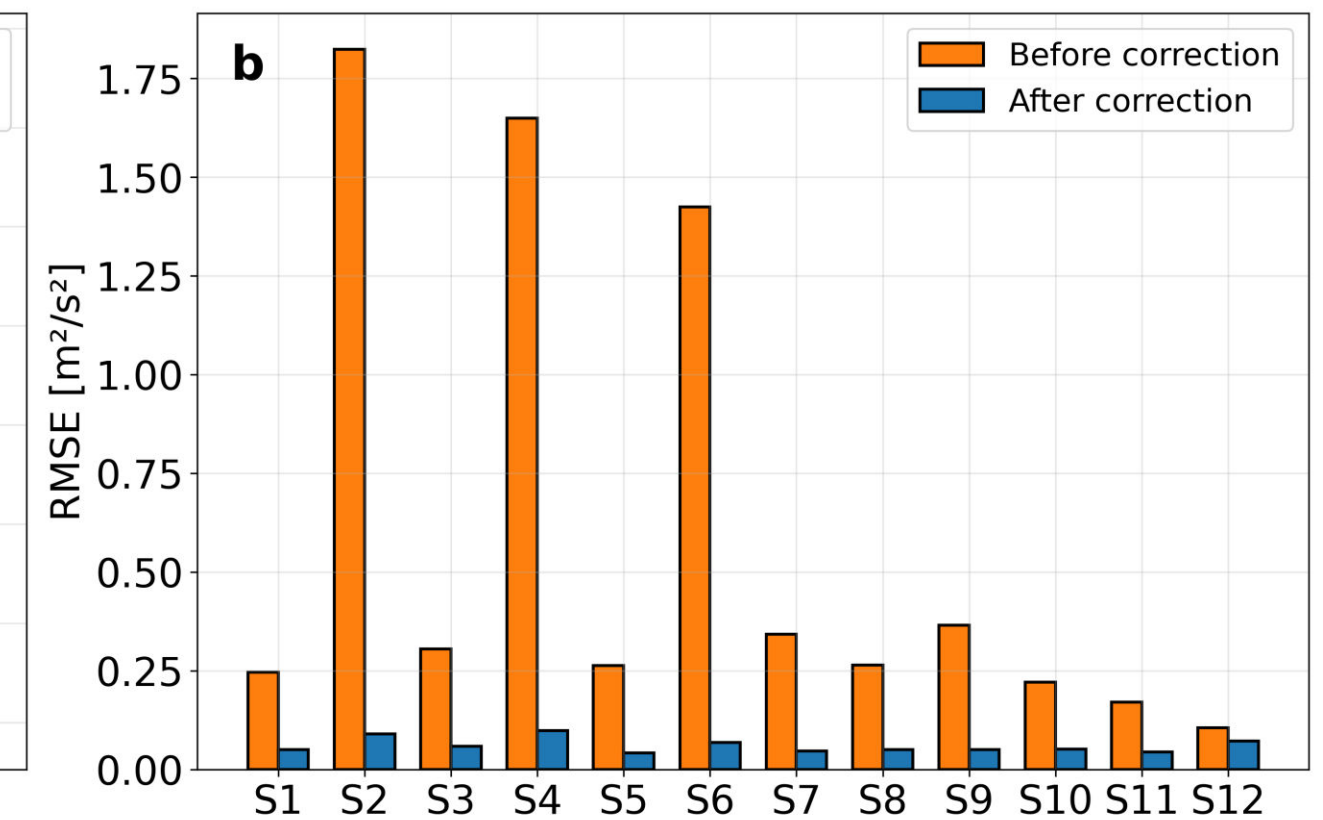
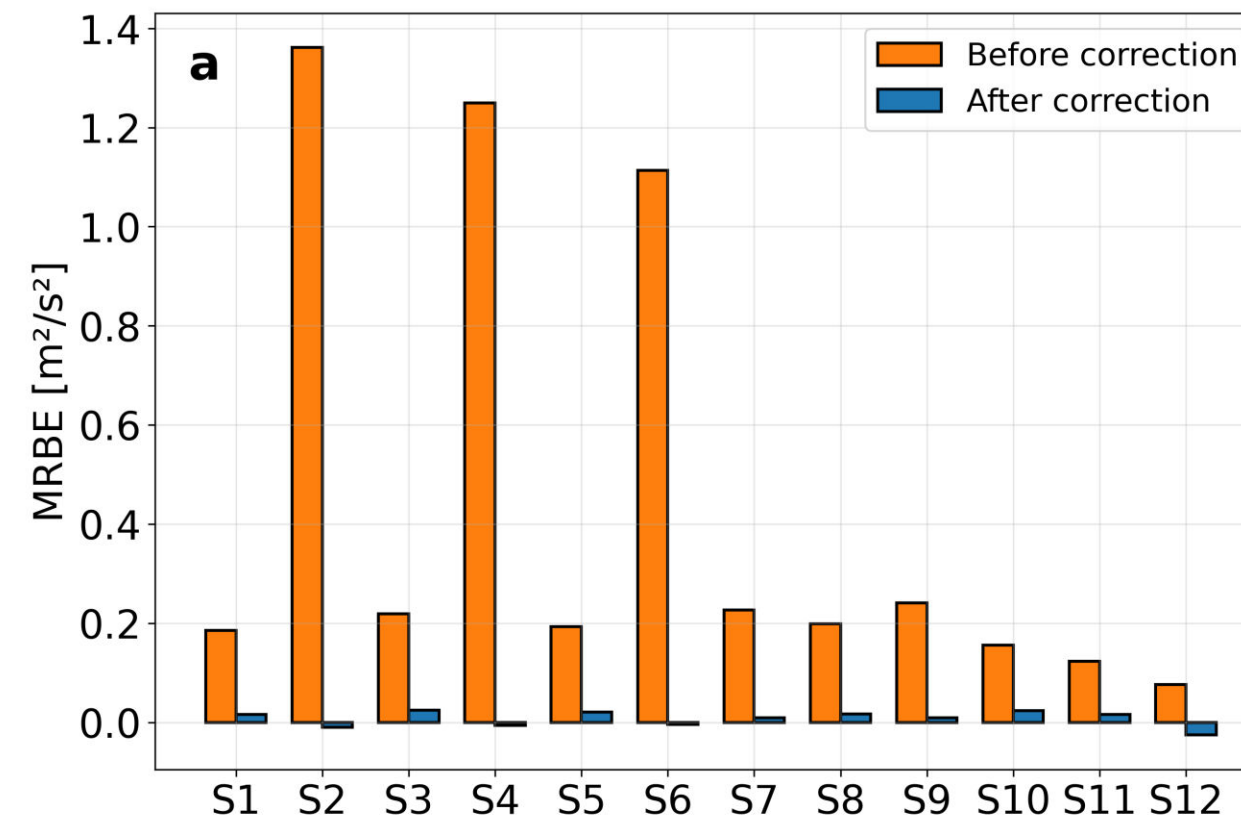
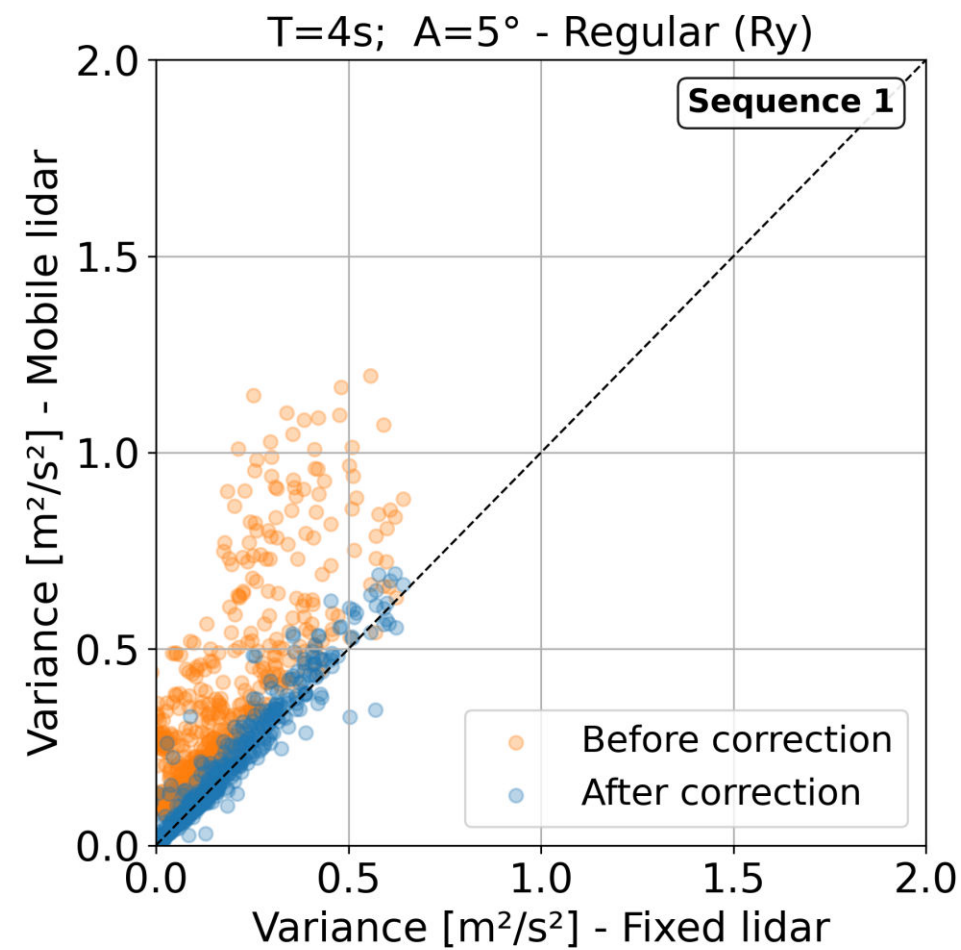
$$\sigma_{i,\text{motion}}^2 = \sigma_{i,\text{raw}}^2 - \sigma_{i,\text{model}}^2$$

The corrected variance is obtained by subtracting the estimated motion-induced component:

$$\sigma_{i,\text{corrected}}^2 = \sigma_{i,\text{time}}^2 - \sigma_{i,\text{motion}}^2$$

The total variance for each beam b_i is computed directly from the time series:

$$\sigma_{i,\text{time}}^2 = \text{VAR}(b_i(t))$$



The spectral method enables:

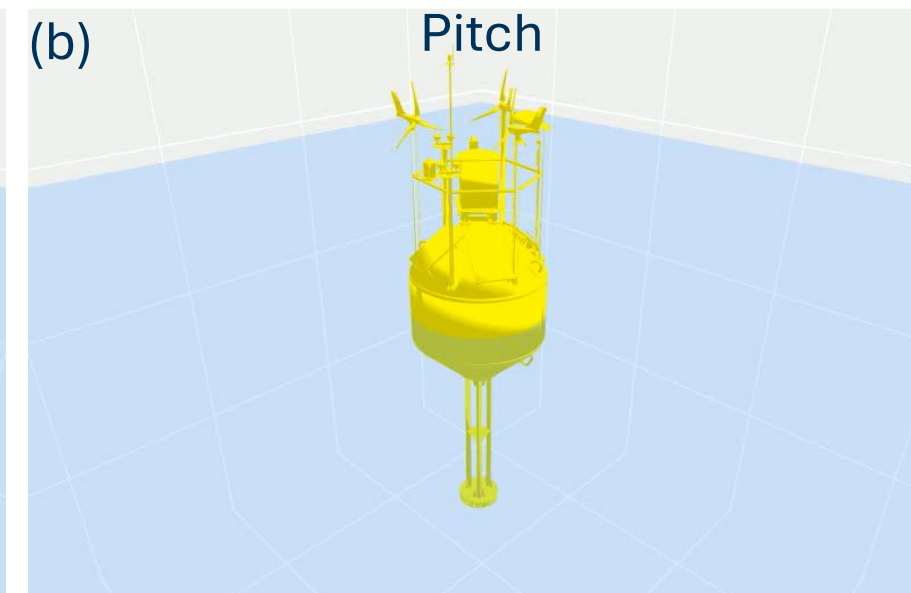
- A drastic reduction in the impact of motion on radial velocity variance measurements;
- An improvement of more than 35% in the coefficient of determination (R^2), from approximately 0.7 before correction to approximately 0.95 after correction.

Changed orientation /geometry

- Tilt: roll & pitch
- Rotation: yaw/heading
- Vertical displacement: heave

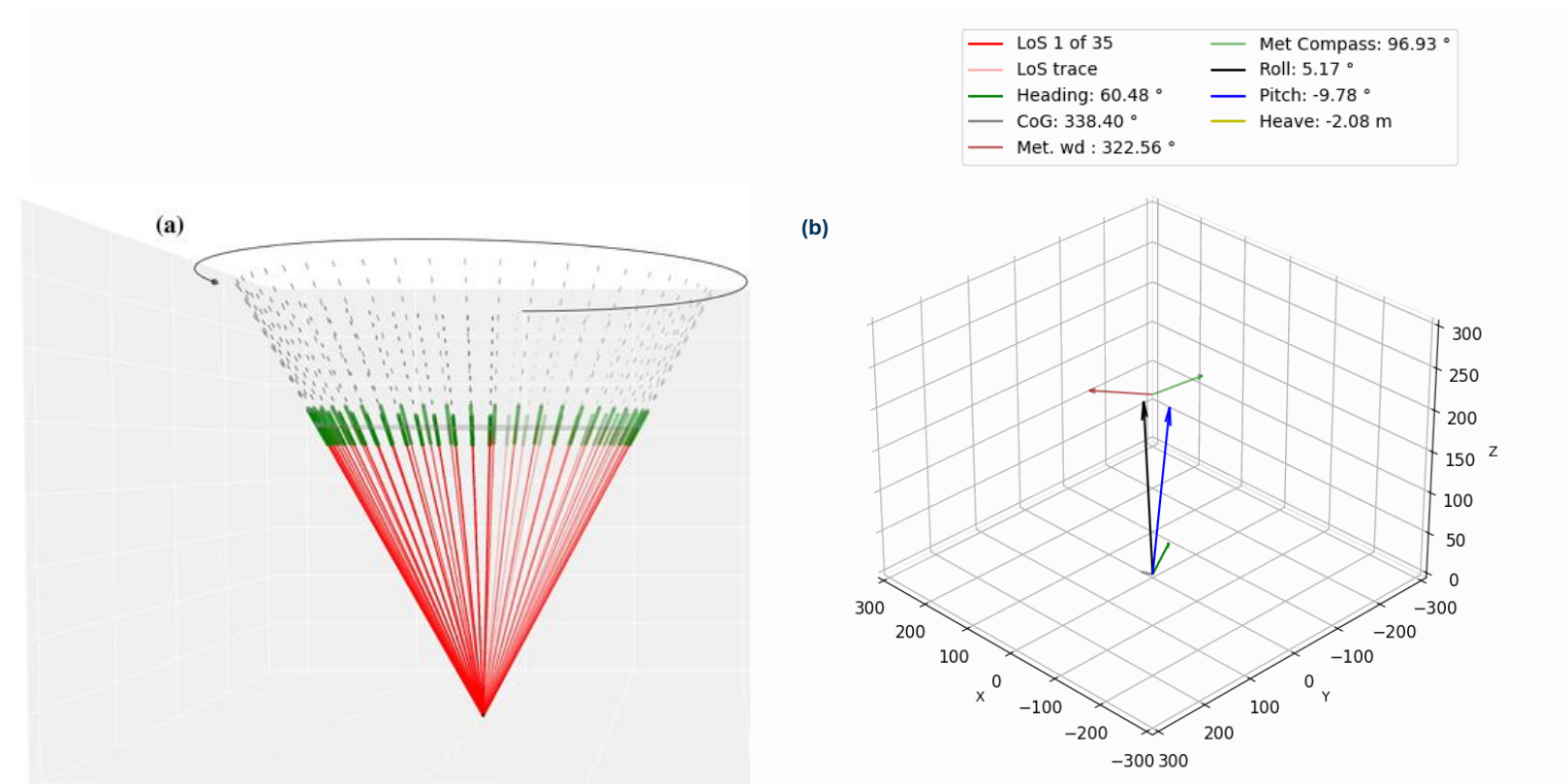
Altered velocities

- Vertical translation: heave
- Horizontal translation: surge & sway
- Tilt velocities
- Yaw velocities

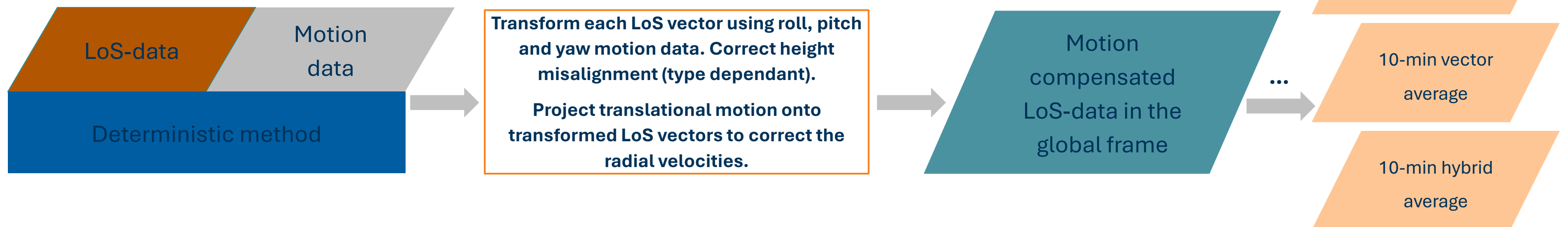


Animation showing a schematic representation of the six-degrees of freedom. Panel (a) roll, (b) pitch, (c) yaw, (d) heave, (e) surge, (f) sway.

- Line-of-Sight lidar data
- High-quality motion data
- Time synchronisation
- Knowledge about sensor position



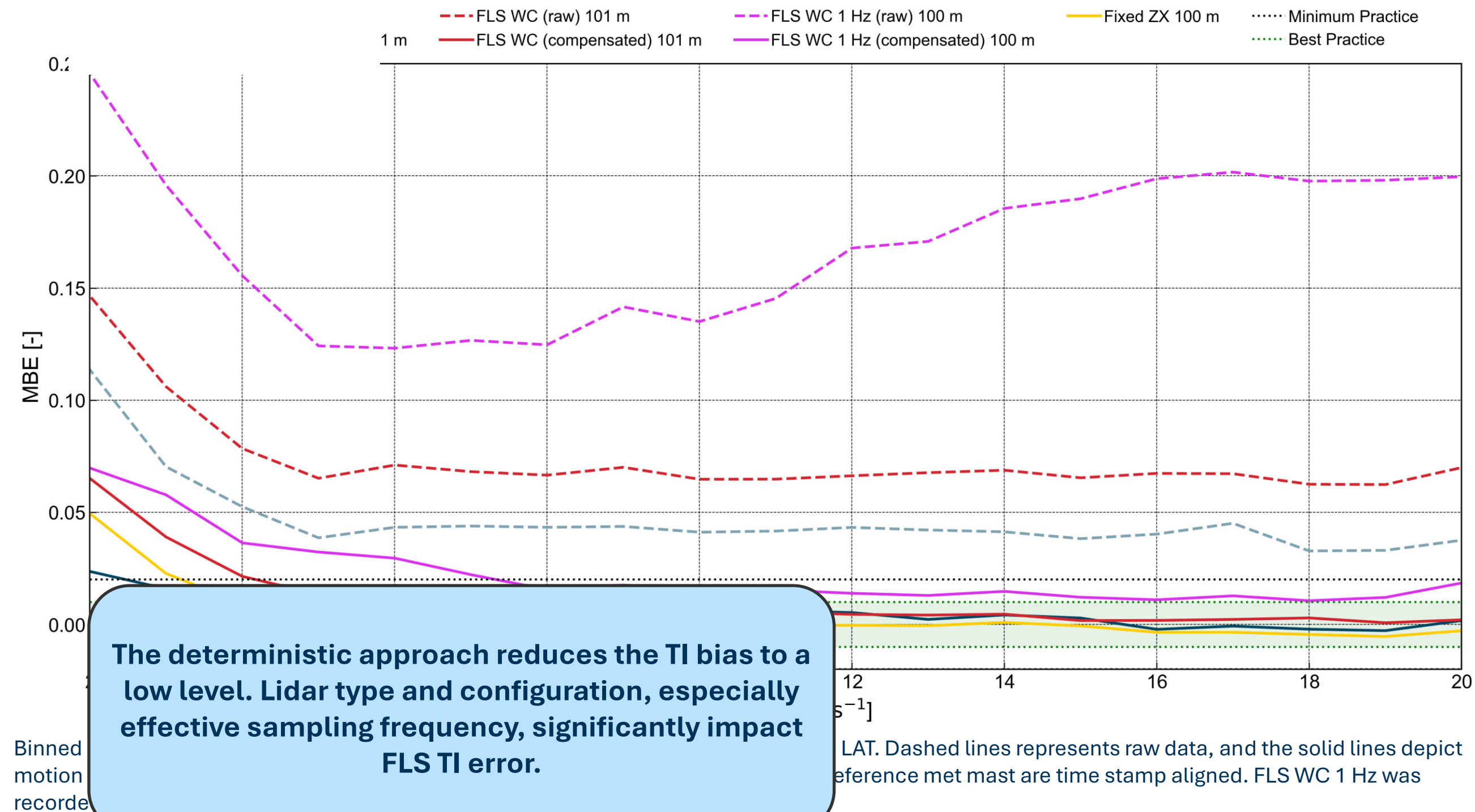
Simulation of the scanning geometry of a floating cw vertical profiling wind lidar. (a) static; (b) moving.



Motion Impact on TI Varies between Lidar Types – MBE

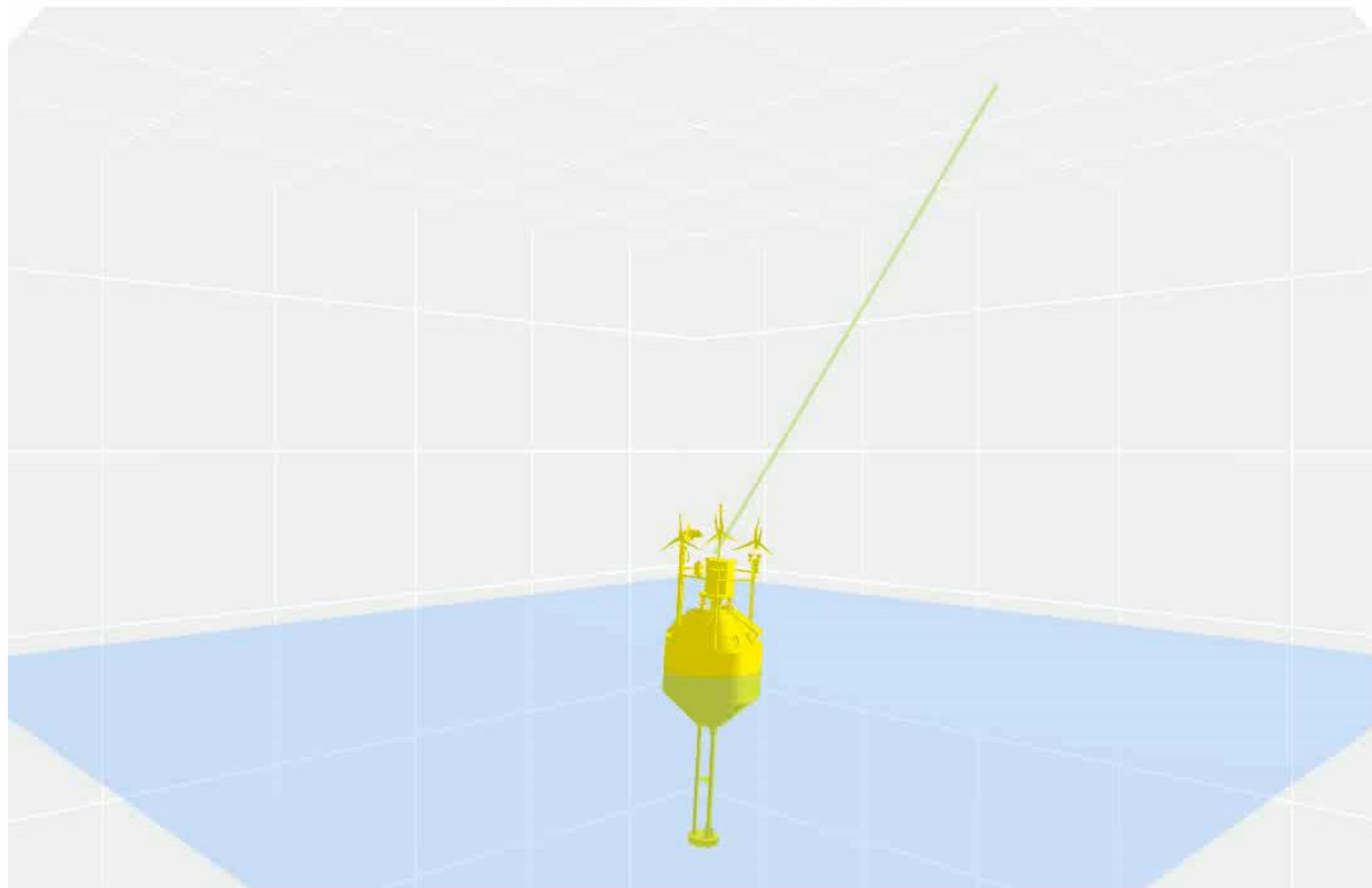
- 1 FLS ZX 50 Hz
- 2 FLS WC 5 Hz
- 3 FLS WC 1 Hz
- 4 Fixed ZX 50 Hz

Watson, W., Wolken-Möhlmann, G., and Gottschall, J.: **Evaluating the impact of motion compensation on turbulence intensity measurements from continuous-wave and pulsed floating lidars**, Wind Energ. Sci., 10, 2791–2820, <https://doi.org/10.5194/wes-10-2791-2025>, 2025.



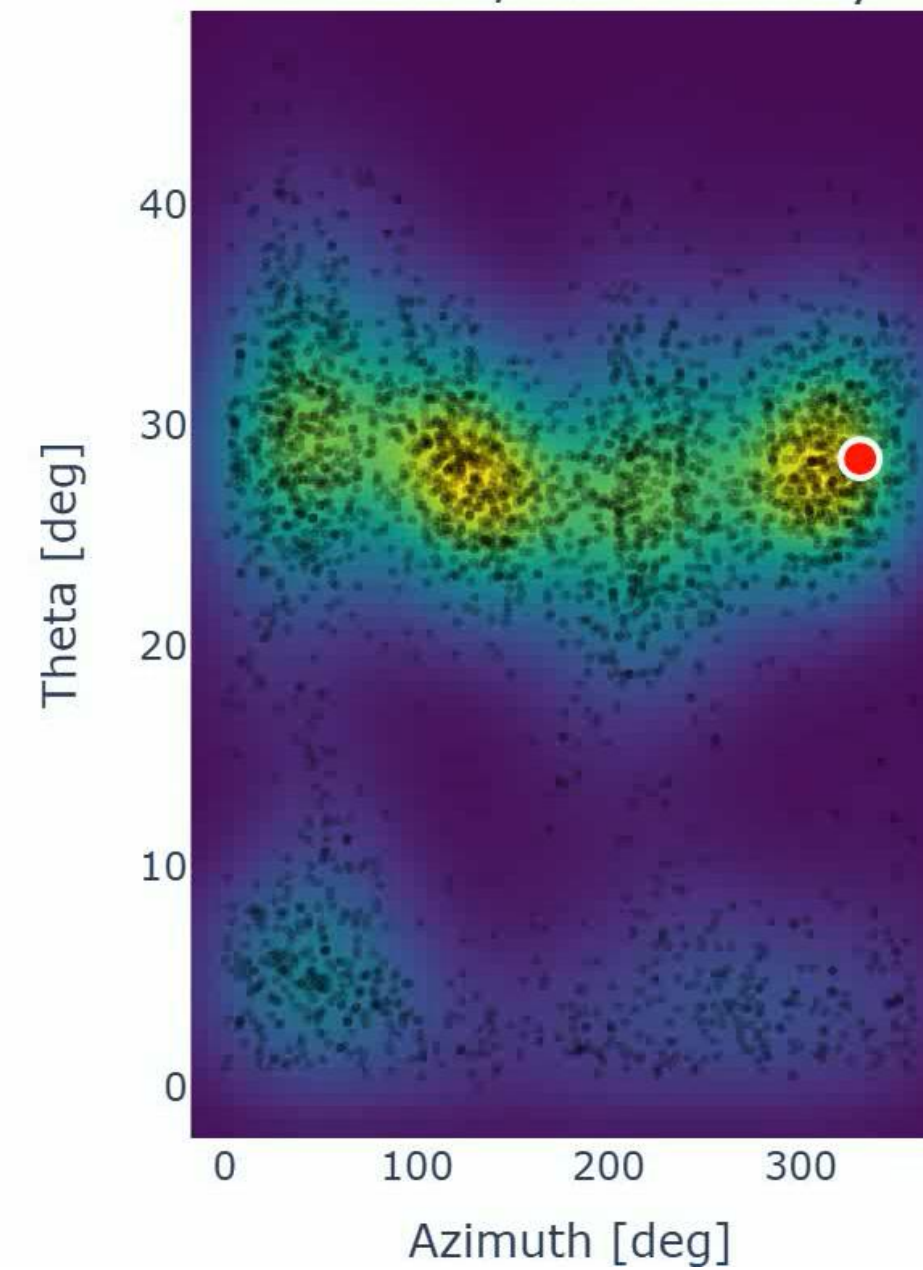
Real-time

FLS and LoS beams



Animation of a floating vertical profiling pulsed lidar. (a) shows the platform response and cumulative lidar beams; (b) depicts a density plot of azimuth and elevation; (c) the current motion.

Azimuth / theta density



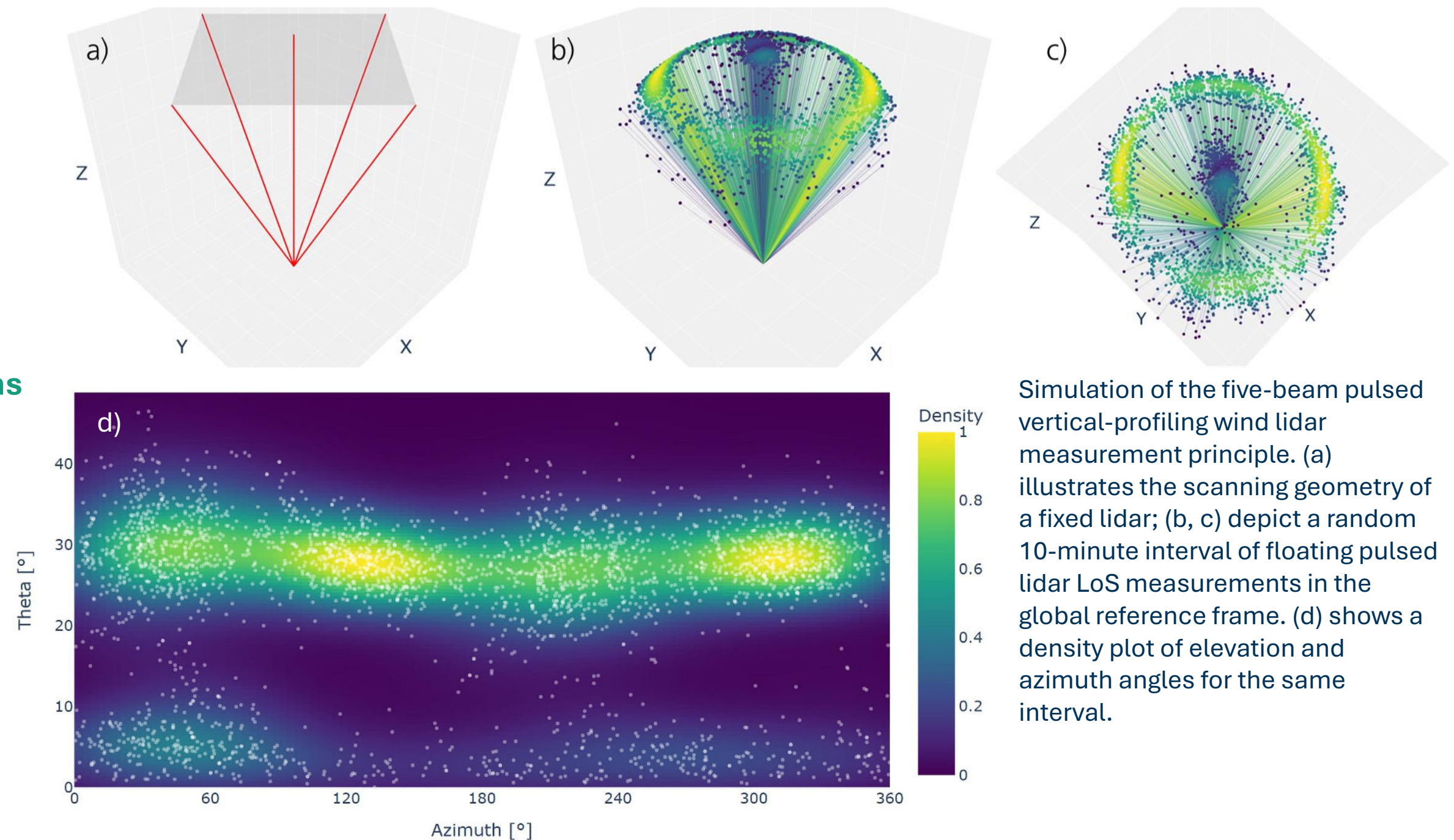
Motion



- Each beam orientation is unique, depending on the sea-state
- Number of unique beams (N) further depends on ensemble window size and effective lidar scanning frequency

$$R = \begin{bmatrix} \langle u'^2 \rangle & \langle u'v' \rangle & \langle u'w' \rangle \\ \langle v'u' \rangle & \langle v'^2 \rangle & \langle v'w' \rangle \\ \langle w'u' \rangle & \langle w'v' \rangle & \langle w'^2 \rangle \end{bmatrix} \rightarrow \text{Six unknowns}$$

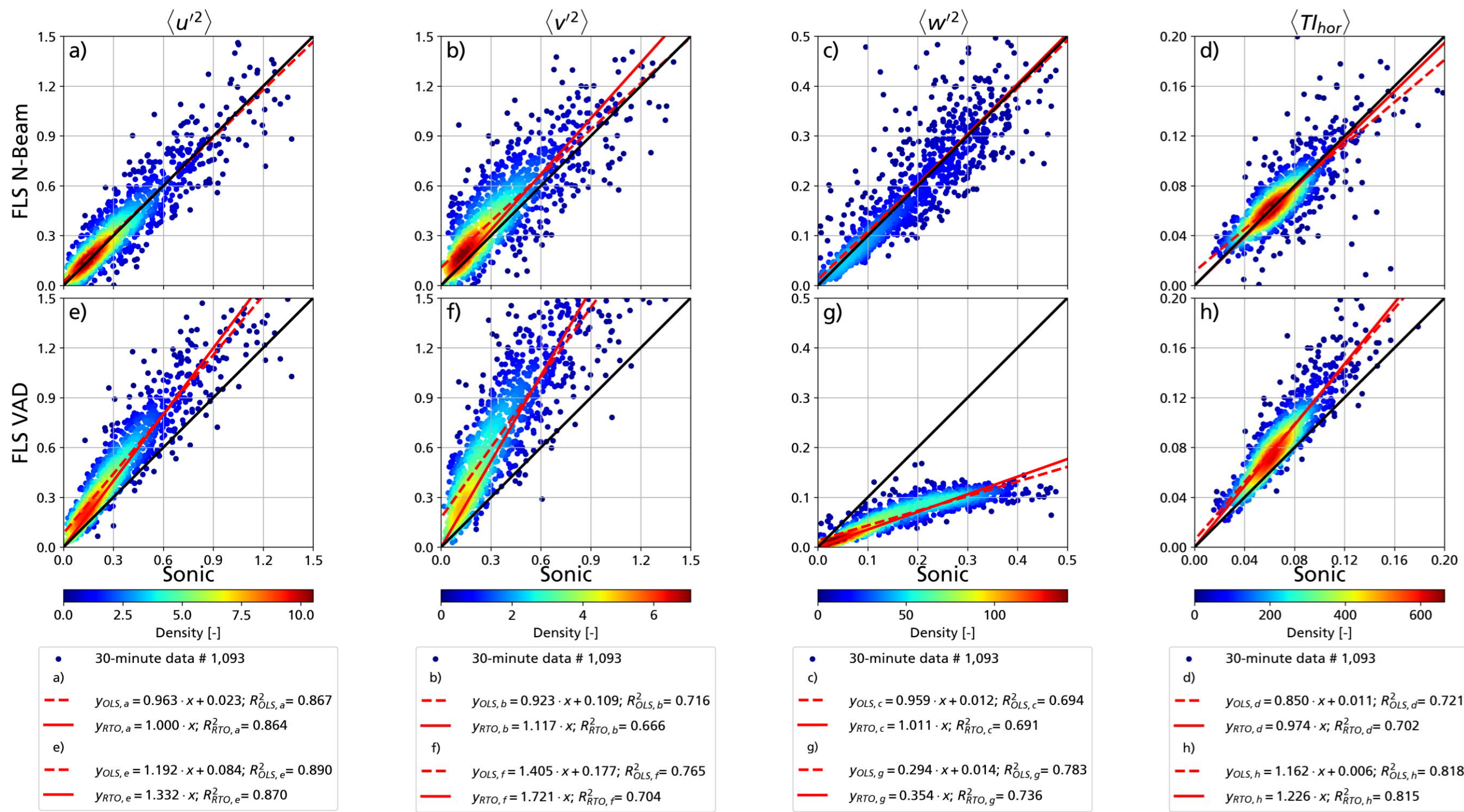
We can use the N-beams to solve the Reynolds stress tensor, avoiding the inter-beam effect.



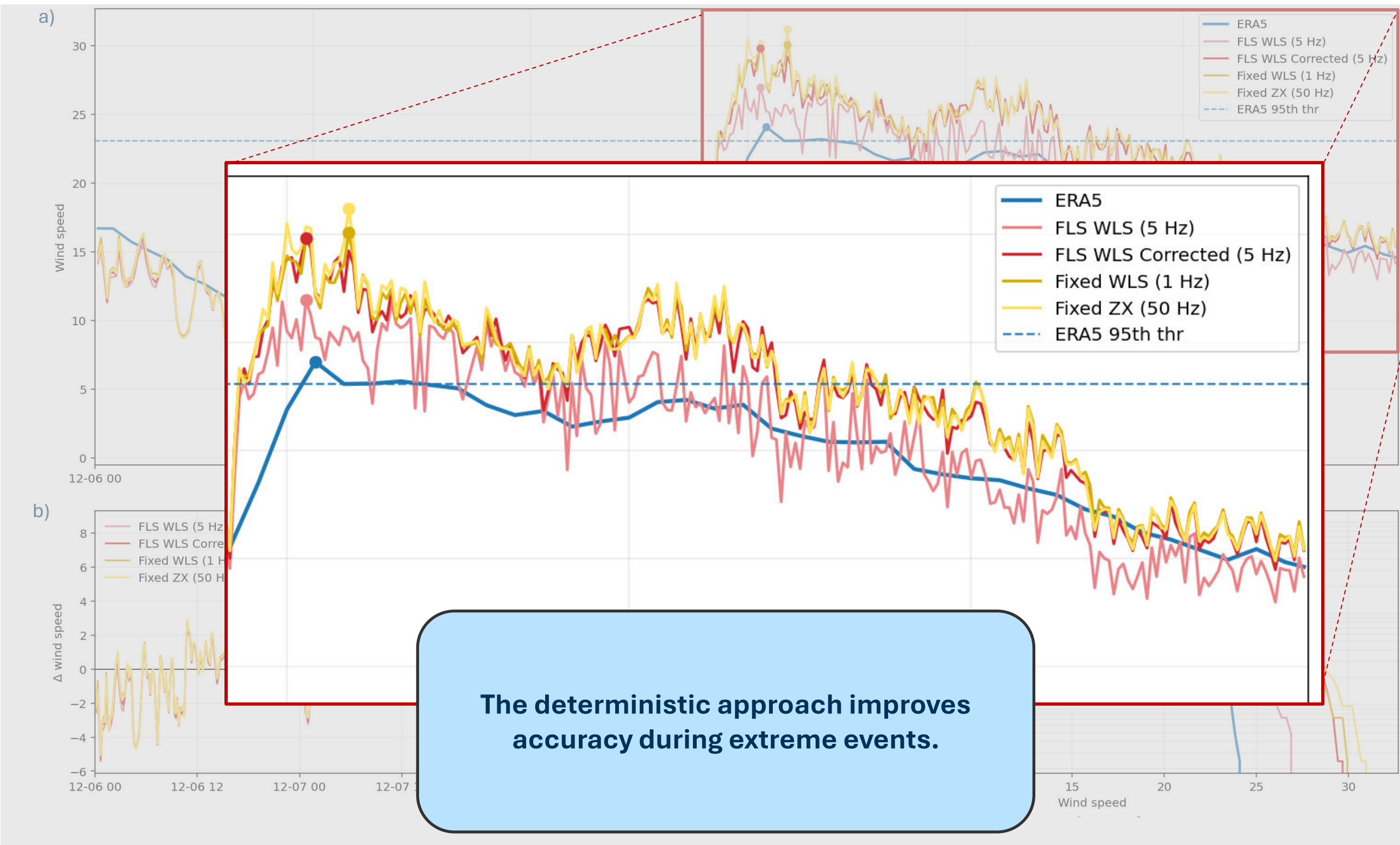
Simulation of the five-beam pulsed vertical-profiling wind lidar measurement principle. (a) illustrates the scanning geometry of a fixed lidar; (b, c) depict a random 10-minute interval of floating pulsed lidar LoS measurements in the global reference frame. (d) shows a density plot of elevation and azimuth angles for the same interval.

Comparison of N-Beam and VAD against sonic reference

Warren Watson
and Julia
Gottschall 2026
J. Phys.: Conf.
Ser. 3224 022002
“Full Reynolds
Stress Tensor
Recovery from a
Floating Five-
Beam Pulsed
Lidar”



Focus should not be limited to TI



Random extreme wind speed event.

(a) Timeseries, (b) deviation to ERA5,
(c) exceedance curve.

Turbulence measurement : What the distinct approaches reveals — what remains to be solved

Two different measurement philosophies, with well-identified technology-dependent uncertainties.

FEM — Dual-lidar / variance method

Limitations

- **Probe-time volume / intra-beam** averaging remains a systematic limitation;

Ongoing work

- Addressing the **intra-beam effect** using **LiDAR-dependent weighting function**;
- Combining the **spectral approach** and the **variance method**, corrected from the intra-beam effect (the last source of error), to provide **cup-equivalent TI**.

Fraunhofer IWES — Floating-lidar correction

Limitations

- Motion compensation reduces the bias but does not eliminate all scatter -> **Residual motion effects**;

Ongoing work

- **Validate** the **N-Beam method** against a fixed six-beam lidar to **isolate residual motion effects**;
- Investigate **custom virtual beam geometries** to resolve lidar sensitivities;

Take-away messages

- **Prefer physics-based geometric reconstruction algorithms** for turbulence measurements;
- **Perform motion compensation at the LOS level**;
- **Increase LOS acquisition frequency** (at least 1 Hz for the LOS vel.), particularly for both Fixed AND floating lidar measurements.



Thank you for your attention !