Energy Islands – Floating LiDAR Measurements

Motion correction of turbulence intensity. WP1: North Sea pre-deployment verification tests

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Abbreviations

Abbreviation	Definition
CFARS	Consortium for Advancing Remote Sensing
comp.	Motion compensated
CW	Continuous wave
FLS	Floating LiDAR system
IMU	Inertial measurement unit
KPI	Key performance indicator
LEG	Lichteiland Goeree platform, Netherlands
LiDAR	Light detection and ranging
MBE	Mean bias error
MRU	Motion reference unit
MSL	Mean sea level
NaN	Not-a-number
PDV	Pre-deployment verification
RLL	Reference Land LiDAR
RMSE	Root mean square error
Roadmap	Carbon Trust Offshore Wind Accelerator Roadmap
RTO	Regression through origin, single-variant regression
SWLB	Seawatch Wind LiDAR Buoy
TI	Turbulence intensity
uncomp.	Not motion compensated (uncompensated)
UTC	Universal time coordinated
VAD	Velocity–azimuth display

Conventions

Convention	Description
Directions	Directions are given in degrees (∘) increasing clockwise from North. The direction is defined as incoming: 0∘ means wind blowing from North, 90∘ from East etc. Directions are relative to true north.
Turbulence intensity	Turbulence intensity is defined as the standard deviation of horizontal wind velocity fluctuations divided by the horizontal mean wind velocity during 10-minute long averaging intervals.
Time	All times are UTC and timestamps mean the beginning of an averaging interval.

1. Introduction

Estimates of turbulence intensity (TI) from floating LiDAR systems (FLS) are influenced by motion. Rotational and translational motion in all six degrees-of-freedom leads to an overestimation of TI measured by a FLS when compared to values acquired by a collocated fixed LiDAR system of the same type. Energinet has asked Fugro to correct the TI measurements from the SEAWATCH Wind LiDAR Buoys (SWLB) deployed in the North Sea for buoy motions. The correction of measured TI for buoy motions is split in two (2) work packages:

- WP1: Correction of TI measured during PDV (this report).
- WP2: Correction of TI measured during campaign.

This report describes two comparisons of FLS measurement data against fixed reference LiDARs.

1. SWLB data from WS170 deployed at the LEG platform against a fixed WindCube LiDAR [1]; and
2. SWLB data from WS191 deployed at Frøya against a fixed ZX 300 LiDAR [2].

SWLB WS181 has also been validated at Frøya and is used in the project. Though, the configuration of its motion sensor has been changed to sampling at 2 Hz only after the PDV. Therefore, the TI assessment in this report is limited to the PDV data from WS170 and WS191.

The ZX 300 used on the buoys and onshore at Frøya are continuous-wave velocity-azimuth-display (VAD) scanning profiling LiDARs while the WindCube used on the LEG platform is a pulsed Doppler-beam-swinging (DBS) profiling wind LiDAR. For both comparisons, three datasets are available that constitute the data basis of this report:

- Reference "land" LiDAR (RLL) data
- FLS data, uncompensated
- FLS data, motion-compensated

Table 1.1 gives information about the LiDAR units used during both pre-deployment verification (PDV) trials.

System	Location	LiDAR unit	Firmware
RLL1	LEG (fixed)	-	-
FLS1	WS170	585	v2.202

RLL2	Frøya (fixed)	627	v2.202
FLS2	WS191	862	v2.2034

Table 1.1: Details of LiDAR units

1.1 Guidelines for assessment of turbulence intensity

The Offshore Wind Accelerator Roadmap (Roadmap) [3] is a widely accepted guidance document that suggests methods and key performance indicators (KPIs) including acceptance thresholds for FLS unit verifications. Unfortunately, this accounts only for the assessment of primary wind data, i.e., 10-minute average wind speed and direction. For secondary wind data, like TI, the Roadmap does not prescribe any acceptance criteria. Instead, it only recommends measuring TI and compare it to measurements from a trusted reference source. It then details that a comparison against conventional (i.e., in-situ) anemometry is recommended. For the comparison it defines the slope of single variant regression, i.e., linear regression through the origin (RTO) as the first KPI and its correlation co-efficient as the second KPI. Due to the weaknesses of the suggested KPIs, detailed in [4], we do not use them in this report.

Instead, the CFARS Site Suitability Initiative [5] can be seen as a first guidance document for the assessment of TI estimates from FLS. It suggests using the Mean Bias Error (MBE) for each 1m/s-wide wind speed bin i

$$MBE_i = \frac{1}{N_i}\sum_{n=1}^{N_i}(TI_{comp,n,i} - TI_{ref,n,i})$$

where TI_{comp} is the comparison quantity (TI_{FLS}), TI_{ref} is the reference quantity (TI_{RLL}), N_i is the number of values in wind speed bin i, and n is the individual datapoint. In addition to the MBE as an estimator of accuracy, the Root Mean Square Error (RMSE) shall be used to measure the TI precision. It is calculated according to

$$RMSE_i = \sqrt{\frac{1}{N_i}\sum_{n=1}^{N_i}(TI_{comp,n,i} - TI_{ref,n,i})^2}$$

Furthermore, CFARS suggests using representative TI in comparisons. Representative TI is defined as the 90th percentile of a TI distribution. It is calculated from $TI_{mean,i}$, the mean of all TI values in a bin and $TI_{std,i}$, its standard deviation by

$$TI_{Rep,i} = TI_{mean,i} + 1.28TI_{std,i}$$

The representative TI error being the difference between the representative TI from FLS and RLL. In this report we will use MBE, representative TI error and RMSE as primary benchmark criteria.

Plots of the benchmark data will show which velocity bins are significant according to the following criteria:

$$n_i > \frac{N}{2n_b},$$

where $n_b$is the number of bins, N the total number of data points, and $n_i$the number of data points in bin i. And

$$\frac{\sigma(d_i)}{\sqrt{n_i}}\frac{V_{ref,i}}{100} < 0.03m/s,$$

where $d_i$is the data in bin i, $\sigma(d_i)$ the standard deviation of data in bin i, and $V_{ref,i}$ the mean value of the reference wind speed in bin i. These significance criteria are adopted from Eqs. L.2 and L.3 of IEC [8].

2. Instrumentation and measurement configuration

2.1 Summary of instrumentation and measurement scheme

Buoys WS170 and WS191 were used for the data acquisition during the pre-deployment validations reported in this document. These two SWLB buoys are not optimized for deriving motion-compensated estimates of turbulence intensity, as neither line-of-sight velocities[1] from the LiDAR are recorded, nor velocity data from surge and sway directions are available.

The measurement platform of the FLS is a SEAWATCH Wind LiDAR Buoy based on the original SEAWATCH Wavescan Buoy design. The wind LiDAR used in this project is the marinized version of the ZX 300 LiDAR type (units 585 and 862) including their Airmar 200 meteorological station positioned on the mast of the buoys.

To estimate wave statistics, the buoys are equipped with an inertial measurement unit (IMU). This IMU is part of the Wavesense wave sensor. Its software is optimized for computations in the frequency domain. It is set up to generate and store bursts of 2048 samples with 2 Hz frequency every ten minutes. These bursts of motion data are available for the four degrees of freedom pitch, roll, yaw, and heave. Surge and sway data are not available with the used configuration.

Furthermore, accurate heading data is acquired by a Septentrio DualGPS system. The GPS system outputs timestamped yaw and pitch data with a frequency of 1 Hz. It is used to assign accurate timestamps to the Wavesense motion data.

2.2 LiDAR measurement principle

The SWLB is equipped with a ZX 300M continuous-wave (CW) profiling wind LiDAR that can measure wind velocities remotely. The LiDAR continuously emits an infrared laser beam. The beam is deflected from the zenith by the half-cone opening angle (30.6°) and rotates around the zenith with a continuously changing azimuth angle. In this way, the laser beam illuminates a measurement cone during each full beam rotation.

By determining the Doppler shift of radiation that is backscattered into the direction of the laser source, the LiDAR device is able to determine the radial velocity of particles and aerosols that are moving with the speed of the wind. One full rotation along the measurement cone takes one second. All radial velocities determined during this period are then processed to reconstruct one three-dimensional wind vector.

During each of these scanning cycles, optical focusing concentrates the laser radiation onto one desired measurement elevation above the LiDAR and several elevations can be scanned consecutively after refocusing. The LiDAR on the SWLB is configured to scan a total of 11

[1] VAD scanning profiling wind lidar reconstruct three-dimensional wind vectors from at least 3 (49 in the case of the ZX 300) radial velocity samples measured along the laser beam (i.e., line-of-sight velocities). The lidars used on WS170 and WS191 measure these line-of-sight velocities as intermediate values but do not record them. This is one of the reasons that make it impossible to correct the TI estimates in the way that Fugro uses for other projects.

elevations which takes approx. 17 seconds. As a result approx. 36 samples from each measurement elevation can be taken during an averaging period of 10 minutes length.

Horizontal homogeneity of the wind field is an underlying assumption of the wind vector reconstruction process, i.e., the estimated wind vectors are only representative for the real wind conditions if the wind velocity is constant at all positions along the measurement cone. For mean wind speed and direction, it is sufficient that the wind field is homogeneous in the mean. In non-complex terrain (like offshore) this requirement is usually fulfilled.

For correct measurements of turbulence intensity (TI), the wind field above the LiDAR would need to be constant at all times. This is by definition not the case in turbulent flow. Also, the non-zero averaging length along the laser beam that increases with measurement height and the limited sampling frequency lead to systematic measurement errors and increase the uncertainty of TI measurements from profiling wind LiDAR [6].

2.3 Motion-compensation of turbulence intensity values

Measurements of turbulence intensity with a profiling CW wind LiDAR from a moving platform like the SWLB are influenced by platform motion. The influence of motion is dependent on the amplitude and frequency of the motion in all six degrees of freedom as well as the prevailing wind conditions. For being able to estimate TI with an accuracy similar to measurements from a fixed LiDAR device of the same type, motion compensation must be applied. In cooperation with the Norwegian University of Science and Technology (NTNU), Fugro developed and validated a method to measure and remove the effect of motion from the measurements [7]. This method cannot be applied for the available buoy data as the LiDAR line-of-sight velocities have not been recorded, and the timestamps of the motion data are not sufficiently accurate. Furthermore, no motion data in surge and sway degrees of freedom are available. Instead, a modified methodology for motion correction had to be developed and tested. In the following, we will describe the data processing performed on the available data from buoys WS170 and WS191:

- lidar1hz files: Unaveraged LiDAR data sampled via MODBUS
- PFF data: Wavesense motion data
- sept*__SBF_AttEuler1.txt files: Septentrio motion data

These data are not transmitted by satellite communication but are downloaded from the buoys during service visits or after recovery. The data is then post-processed to calculate motion-compensated wind data. The data processing consists of the following steps:

1. Assign accurate timestamps to Wavesense motion data by synchronization with DGPS yaw and pitch data
2. Find correct timing of first beam of each velocity-azimuth display (VAD) scan

3. Calculate 10-minute mean wind speed and direction including 180 deg ambiguity correction
4. Generate synthetic line-of-sight data from known beam geometry, timing and mean wind data, without turbulence
5. Perturbate synthetic line-of-sight data using motion data for a series of possible temporal offsets between LiDAR and motion timing
6. Reconstruct three-dimensional wind vectors from the synthetic motion-perturbed line-of-sight data
7. Subtract wind speed fluctuations of the synthetic wind vector data from the lidar1hz data and find temporal offset with the lowest resulting wind speed variance
8. Calculate the standard deviation of horizontal wind speed fluctuations by subtracting the motion-perturbed values from the measured values, assuming that they are statistically uncorrelated
9. Average TI reduction over all measurement elevations and one hour to smoothen the motion-compensated TI results

Estimates of motion-compensated turbulence intensity on a 10-minute level (i.e., TI values) are the main output of the described method. These values can be processed as if they were acquired by a fixed LiDAR unit. Still, it should be noted that the uncertainty is higher than if the values were produced with the method described in [7]. For best TI estimates, it is recommended that future measurement campaigns will be performed with new or upgraded SWLB that measure timestamped motion data in six degrees of freedom and record LiDAR line-of-sight velocities.

3. Data handling

3.1 Data file description

Files: *WS170atLEG_data.csv*

This file contains mean wind speed as measured by the reference LiDAR (U_RLL), TI data from the fixed reference LiDAR (TI_RLL), mean wind speed data as calculated by the internal data processing of the floating LiDAR (U_FLS_ZPH), TI estimates without motion compensation (TI_FLS_unc) and with motion compensation (TI_FLS_com). For each of these values one data column represents data from one measurement elevation. Seven numbered columns represent the seven comparable measurement elevations at the LEG platform, 62, 90, 115, 140, 165, 190, and 240 meters above mean sea level.

WS191atTitran_data.csv

This file contains mean wind speed as measured by the reference LiDAR (U_RLL), TI data from the fixed reference LiDAR (TI_RLL), mean wind speed data as calculated by the internal data processing of the floating LiDAR (U_FLS_ZPH), TI estimates without motion compensation (TI_FLS_unc) and with motion compensation (TI_FLS_com). For each of these values one data column represents data from one measurement elevation. Ten numbered columns represent the ten comparable measurement elevations at the Frøya test site, 40, 60, 80, 100, 120, 140, 160, 180, 200 and 250 meters above mean sea level.

3.2 Data filtering

For the data comparisons, we exclude data that is filtered by either the reference LiDAR or the FLS and remove data from intervals during which the mean wind speed measured by the reference LiDAR was lower than 2 m/s. The motivation to apply this low wind speed filter is that, first, very low wind speeds are of low importance for wind site assessment, and second, data quality is known to be low at very low wind speeds. No other filters were applied to the data presented in this report. All filtered values are marked as “NaN” in the data files.

4. Results

In the following, PDV results are presented and interpreted. Within each subsection, we first report the results of WS170 at LEG and then WS191 at Frøya. For the assessment, we use the KPIs introduced in Section 1.1.

4.1 Mean bias error

Figures 4.1 and 4.2 show the mean bias error of TI estimates from the FLS with and without motion compensation based on data from the deployment of WS170 at the LEG platform and WS191 at the Frøya test site, respectively. The MBE is binned by 1m/s wide velocity bins with significant and insignificant bins indicated by filled and unfilled markers, respectively. As significance criteria we adopted the guidance given in Eqs. L.2 and L.3 of IEC [8].

The MBE results of motion-compensated TI data from WS170 are close to zero for nearly all velocity bins and nearly all elevations. The largest deviations are observed at the highest elevation (240m) for low wind speeds (<6m/s). Here, the MBE is negative for the compensated values. This is not surprising as the uncompensated values are already close to zero. This is suspicious because uncompensated TI values from moving platforms must be larger than TI measured by a fixed LiDAR. Therefore, it has to be assumed that the deviation originates from the measurements rather than the process of motion compensation. At other measurement elevations, the MBE is slightly negative for some wind speed bins. For the interpretation it should be considered that TI measurements performed with the WindCube (RLL) are not necessarily leading to the same estimates as measurements with a ZX 300 LiDAR (FLS). Therefore, it is for example possible that the motion-compensated TI values from the ZX LiDAR are higher than the real atmospheric turbulence intensity, although they are lower than the reference values. This hypothesis cannot be tested within the limitations of these PDV trials, namely in the absence of trusted wind data from in-situ anemometry.

For data from WS191 at Frøya MBE values after motion compensation are mostly small and positive, i.e., TI values are slightly higher than values from the reference LiDAR of the same type. The largest positive deviations are found for low wind speeds and high elevations. Characteristic patterns in the compensated data are similarly found in the uncompensated data which implies that they are caused by insufficiencies in the test setup rather than problem with the applied motion compensation algorithm. An example for such an insufficiency is that under certain conditions, the cloud detection and removal algorithm of the lidar on the FLS does not work correctly and very large wind speed fluctuations are measured by the FLS, while RLL data does not suffer from the same effect. This can lead to a positive MBE for both, the uncompensated and compensated FLS data.

Overall, no linear trend of sensitivity to mean wind speed or measurement elevation is apparent from the MBE data for the motion-compensated FLS.

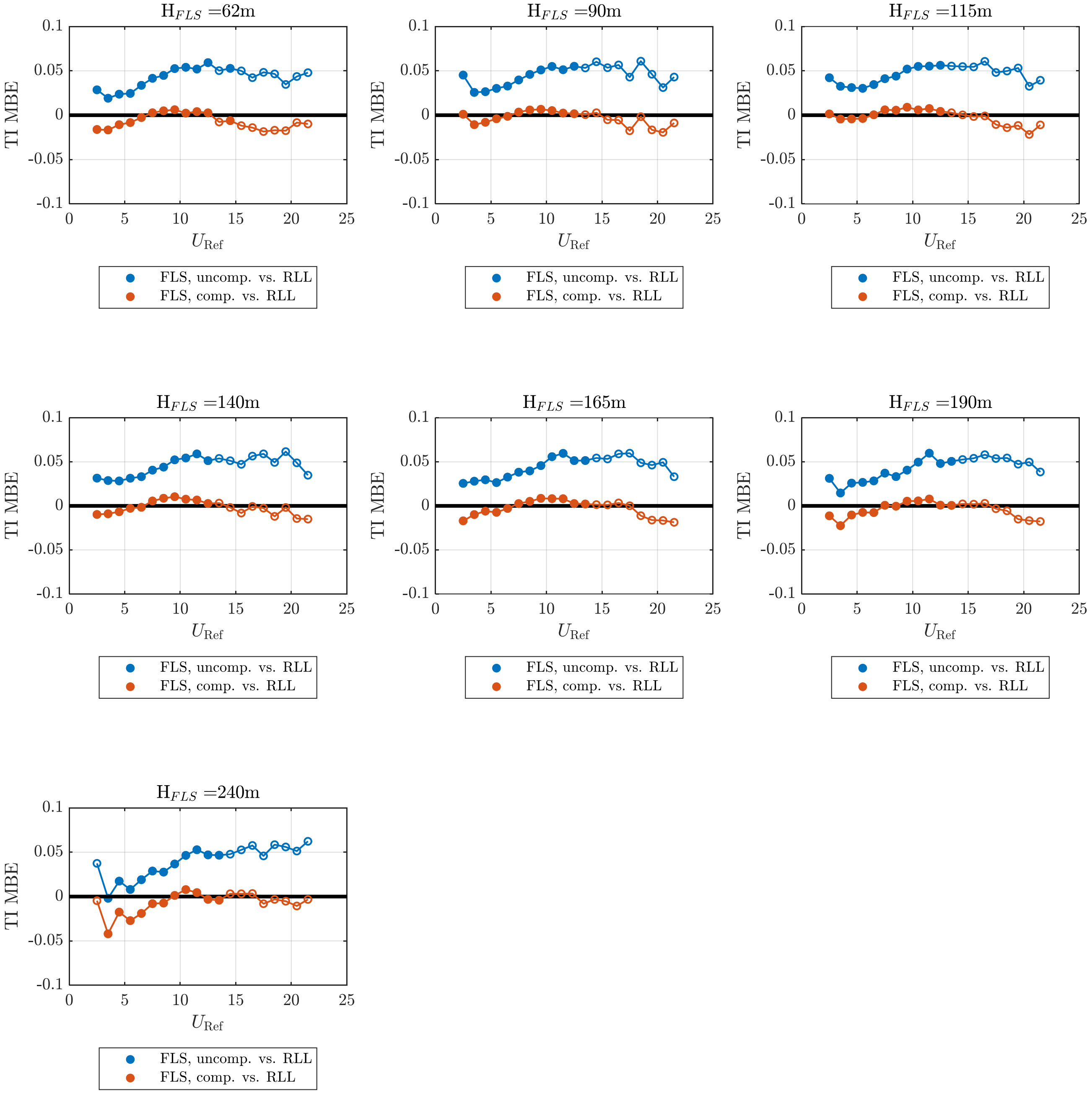

Figure 4.1: Mean bias error (MBE) of TI for data from WS170 at LEG platform with (red) and without (blue) motion compensation for all comparable measurement elevations.

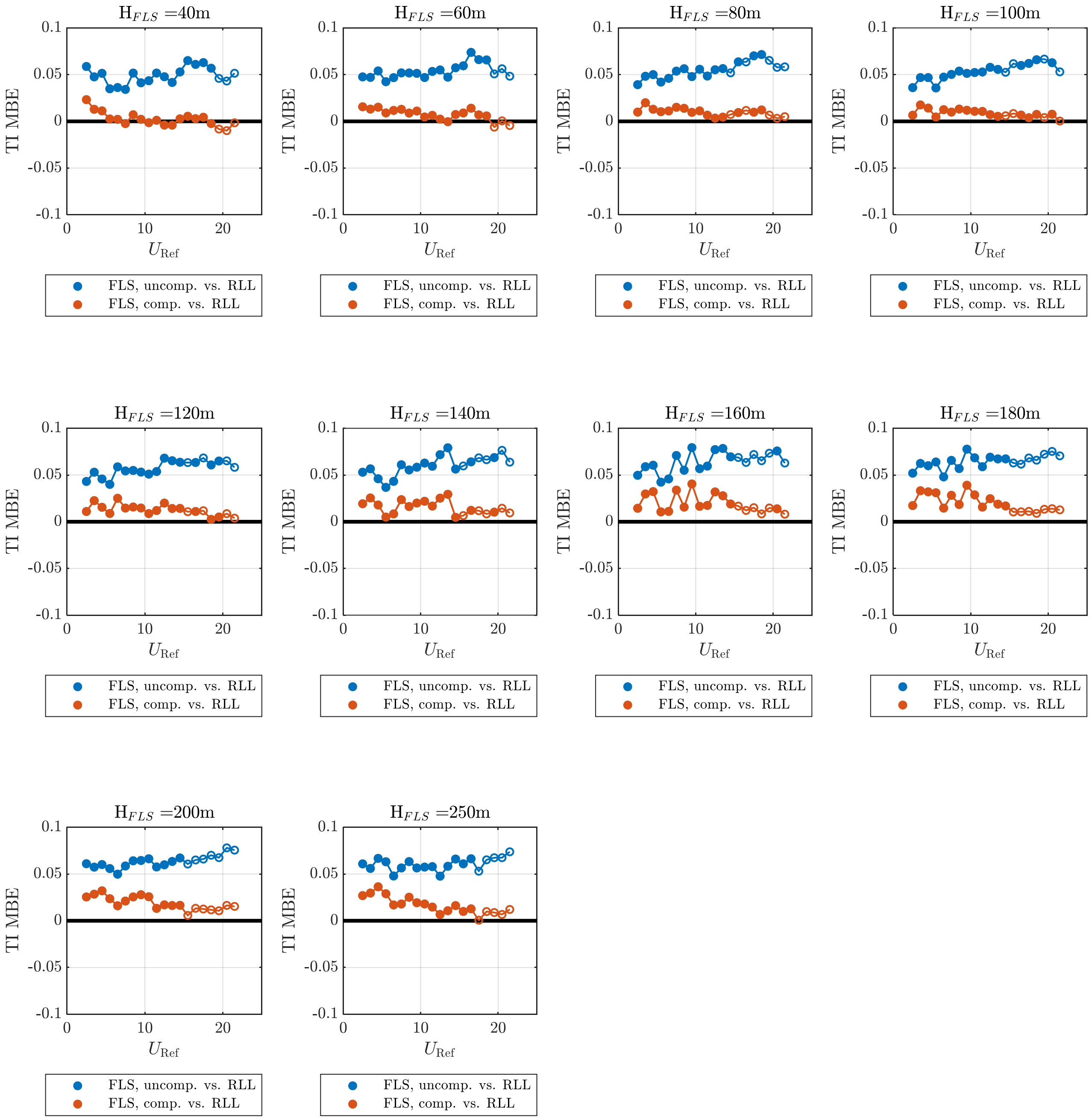

Figure 4.2: Mean bias error (MBE) of TI for data from WS191 at the Frøya test site with (red) and without (blue) motion compensation for all comparable measurement elevations.

4.2 Representative TI error

Figures 4.3 and 4.4 show the velocity-binned mean error of representative TI. For WS170, the motion-compensated values of representative TI are similar to the representative TI values measured by the RLL. Strong positive values are present for the lowest wind speed bin (3m/s) at high elevations. As for MBE, negative values are present at the highest height where even the uncompensated are already close to zero.

Motion-compensated measurements from WS191 taken at elevations up to 100m above ground show good representative TI results. For higher elevations between 120m and 180m large positive values are found for some velocity bins. Separate analysis of data within the affected velocity bins has shown that the most likely origin of these outliers is non-successful cloud detection and removal within the floating ZX 300 LiDAR. When the time series of reconstructed horizontal wind speeds shows fluctuations between measurements corresponding to the desired elevation and the higher elevation of cloud layers, very large TI measurements can be the consequence. With additional filtering, the effect can be mostly removed. No such additional filters have been applied to the data presented here.

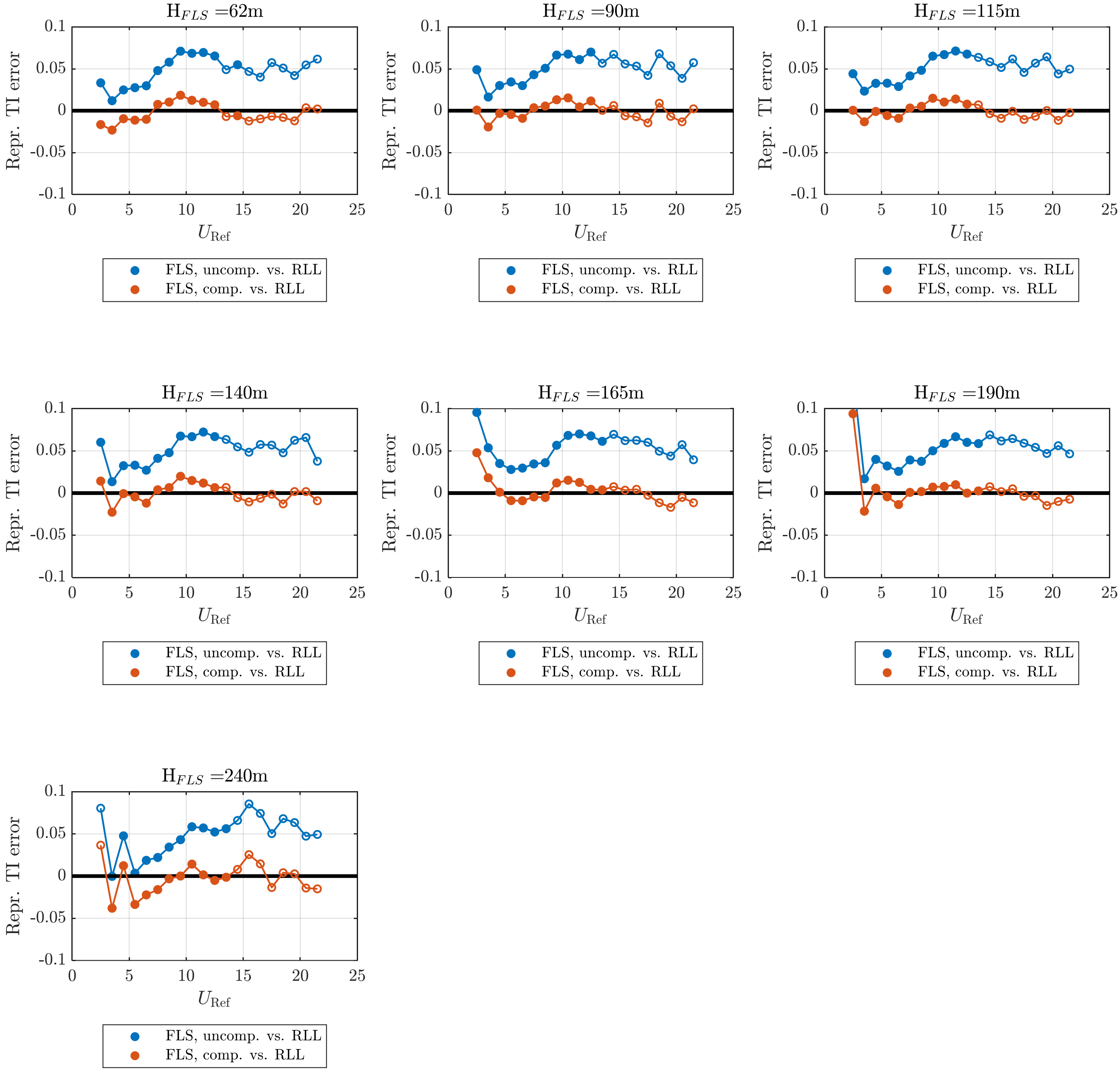

Figure 4.3: Error of representative TI for data from WS170 at LEG platform with (red) and without (blue) motion compensation for all comparable measurement elevations.

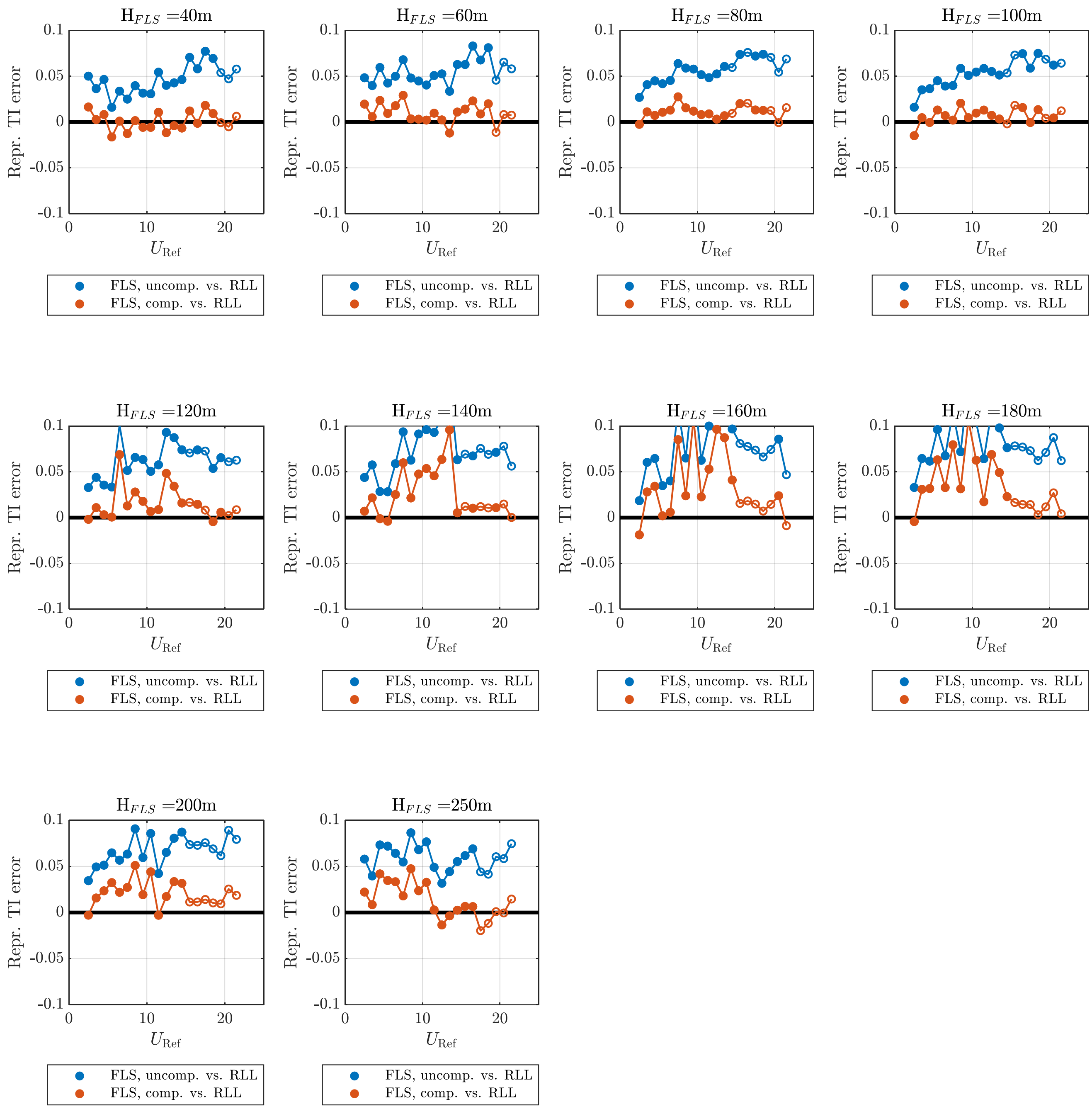

Figure 4.4: Error of representative TI for data from WS191 at Frøya with (red) and without (blue) motion compensation for all comparable measurement elevations.

4.3 Root mean square error

While the previous figures quantified the accuracy of motion-compensated FLS TI, Figures 4.5 and 4.6 present RMSE as a measure of precision. Generally speaking, the reduction depends on the velocity with stronger reduction at higher wind speeds. The RMSE values of motion-compensated TI data are the lowest at high wind velocities.

For data from WS170 every RMSE value at each elevation and each velocity bin was reduced by the motion compensation. The only exception to this statement is present at the highest elevation (240m) at very low wind speeds (<3m/s), where the RMSE values for motion-compensated TI data is slightly higher than their uncompensated counterparts.

Data from WS191 show good results for measurement elevations up to 100m. Above this value the effect of not successful cloud removal increases the RMSE values.

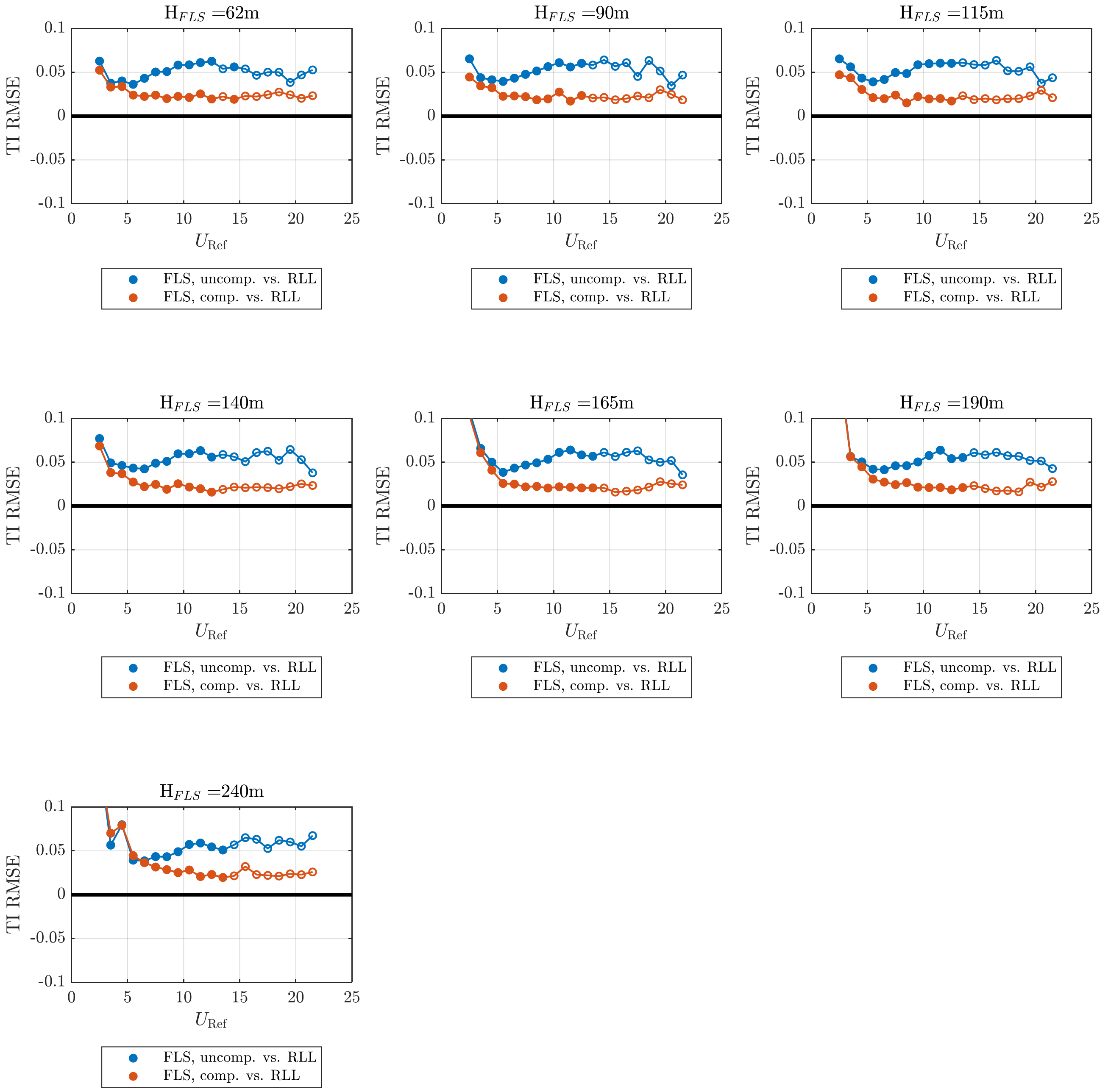

Figure 4.5: Root mean square error (RMSE) of FLS TI for data from WS170 at LEG platform with (red) and without (blue) motion compensation for all comparable measurement elevations.

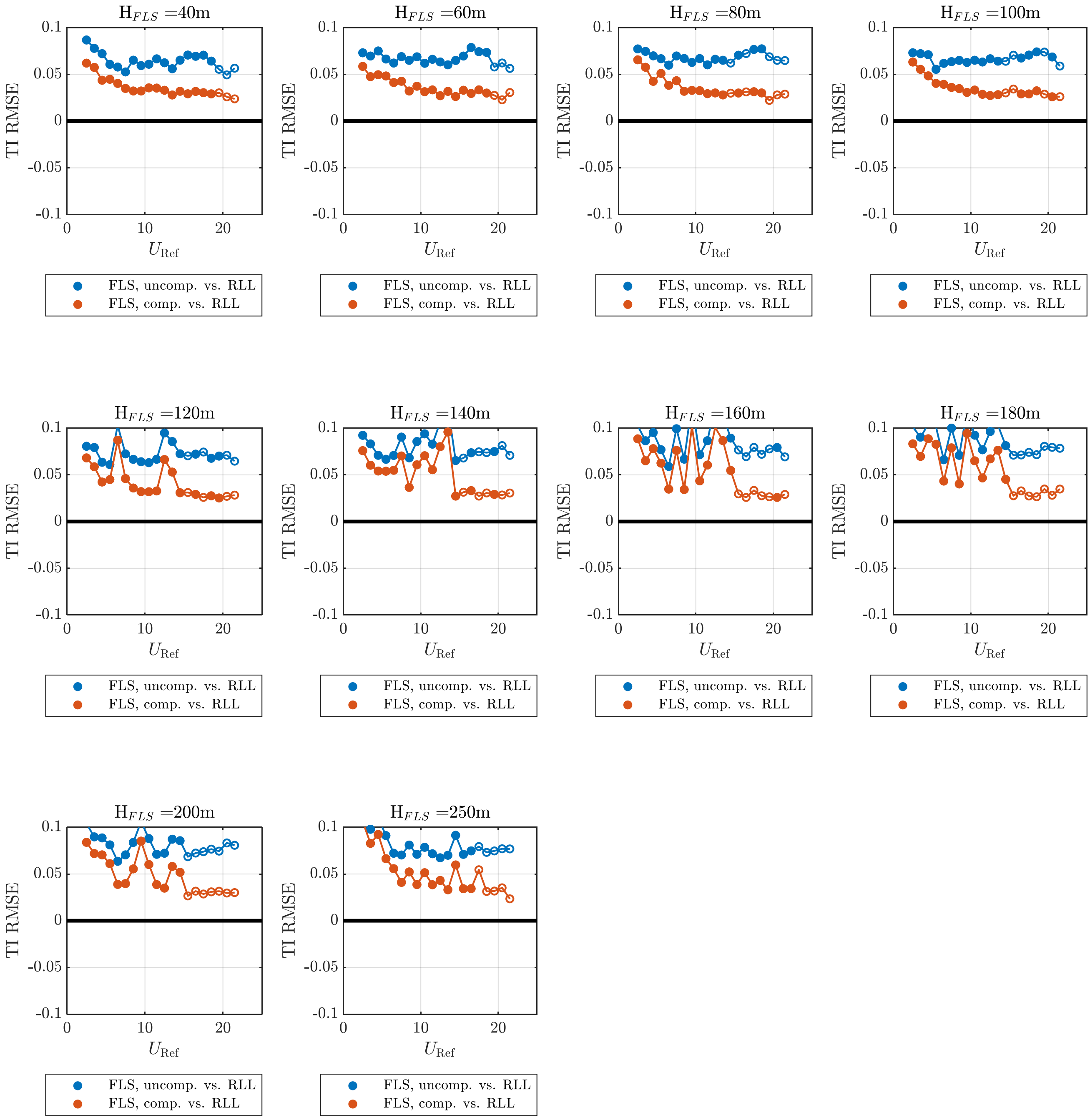

Figure 4.6: Root mean square error (RMSE) of FLS TI for data from WS191 at Frøya with (red) and without (blue) motion compensation for all comparable measurement elevations.

5. Conclusion

This report describes the application of a motion compensation algorithm on TI data from two SWLBs during PDVs. SWLB WS170 has been trialed against a fixed WindCube LiDAR on the platform at Lichteiland Goeree and WS191 has been trialed against a fixed ZX300 LiDAR at Fugro's Frøya test site. Data basis for the motion compensation process are the unaveraged reconstructed wind vectors from the floating LiDARs and motion data from the Wavesense instrument as well as the Septentrio DPGS system onboard the FLS. This method has been custom-made for this project.

On average, the mean bias of motion-compensated TI data from WS170 at LEG is zero and only at high measurement elevations and low wind speeds some higher negative values are found. There is strong indication that what appears as overcompensation at the first glance is actually an effect of comparing different measurement technologies (ZX vs. WindCube). Also, representative TI and RMSE results from WS170 at LEG are satisfactory after motion compensation.

Data interpretation of results from the WS191 trial at Frøya is more complex. Results from measurement elevations up to 100m are acceptable for all wind speed ranges. But some strong deviations are found for higher measurement elevations. These deviations can be attributed to problems with the cloud detection and removal algorithm of the floating LiDAR that, when not working correctly, can result in too high TI values. It is therefore not concerning for the assessment of the motion compensation method.

Despite the limited data basis without line-of-sight velocity measurements and incomplete motion data, the method applied for motion compensation of the measured turbulence intensity performs well. The estimated values of turbulence intensity from the SWLBs are significantly closer to values from the fixed reference LiDARs than the uncompensated original values. Therefore, using the compensation method on campaign data is expected to reduce measurement errors induced by buoy motion and provide more accurate turbulence intensity estimates.

6. References

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[3] OWA, "Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR technology. Version 2.0, October 2018," 2018.

[4] F. Kelberlau, V. Neshaug and A. Venu, "Assessment of turbulence intensity estimates from floating lidar," *J. Phys.: Conf. Ser.,* vol. 2507, no. 1, p. 012014, 2023.

[5] CFARS, "Site Suitability Initiative: An Open Source Approach to Evaluate the Performance of Remote Sensing Device (RSD) Turbulence Intensity Measurements & Accelerate Industry Adoption of RSDs for Turbine Suitability Assessment," 2021.

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[7] F. Kelberlau, V. Neshaug, L. Lønseth, T. Bracchi and J. Mann, "Taking the motion out of floating lidar: Turbulence intensity estimates with a continuous-wave wind lidar," *Remote Sensing,* vol. 12, no. 5, 2020.

[8] IEC, *61400-12-1:2017 edition 2.0 Wind energy generation systems – power performance measurements of electricity producing wind turbines,* 2017.

Appendix A

Tabulated results

A. Tabulated results

Tables 4.1 and 4.2 show the TI error results of the motion-compensated FLS. MBE values with a magnitude beyond ±1% TI are marked yellow and values above ±2% TI are marked red. For representative TI the respective thresholds are ±1.5% and ±3%. For RMSE the definition of a constant threshold does not appear useful due to the higher values at low wind speeds. The calculation of average values in the last column is based on the velocity bins from 4 m/s to 16 m/s and the average values in the last row of each error type is based on the comparable measurement heights excluding the lowest elevation.

Aggregated TI data

Mean bias error (MBE)

Height [m]	2…3	3…4	4…5	5…6	6…7	7…8	8…9	9…10	10…11	11…12	12…13	13…14	14…15	15…16	16…17	17…18	18…19	19…20	20…21	21…22	*4…16*
62	-1.6 %	-1.7 %	-1.1 %	-0.8 %	-0.3 %	0.3 %	0.5 %	0.6 %	0.2 %	0.4 %	0.3 %	-0.8 %	-0.6 %	-1.2 %	-1.4 %	-1.8 %	-1.7 %	-1.7 %	-0.8 %	-1.0 %	**-0.7 %**
90	0.1 %	-1.1 %	-0.8 %	-0.4 %	-0.1 %	0.4 %	0.6 %	0.7 %	0.5 %	0.2 %	0.2 %	0.1 %	0.3 %	-0.5 %	-0.5 %	-1.8 %	-0.2 %	-1.7 %	-1.9 %	-0.9 %	**-0.3 %**
115	0.1 %	-0.4 %	-0.4 %	-0.4 %	0.0 %	0.6 %	0.6 %	0.9 %	0.6 %	0.8 %	0.4 %	0.3 %	0.0 %	-0.1 %	-0.1 %	-1.0 %	-1.4 %	-1.2 %	-2.2 %	-1.1 %	**-0.2 %**
140	-1.0 %	-0.9 %	-0.7 %	-0.3 %	-0.2 %	0.6 %	0.9 %	1.0 %	0.8 %	0.7 %	0.3 %	0.3 %	-0.2 %	-0.8 %	-0.1 %	-0.3 %	-1.2 %	-0.2 %	-1.4 %	-1.5 %	**-0.2 %**
165	-1.7 %	-1.0 %	-0.6 %	-0.7 %	-0.3 %	0.3 %	0.5 %	0.9 %	0.8 %	0.8 %	0.3 %	0.2 %	0.1 %	0.1 %	0.3 %	0.0 %	-1.1 %	-1.6 %	-1.7 %	-1.9 %	**-0.3 %**
190	-1.1 %	-2.2 %	-1.0 %	-0.7 %	-0.8 %	0.1 %	0.0 %	0.5 %	0.6 %	0.8 %	0.1 %	0.1 %	0.2 %	0.2 %	0.3 %	-0.3 %	-0.6 %	-1.5 %	-1.7 %	-1.8 %	**-0.4 %**
240	-0.5 %	-4.2 %	-1.8 %	-2.7 %	-1.9 %	-0.8 %	-0.7 %	0.1 %	0.8 %	0.4 %	-0.3 %	-0.4 %	0.3 %	0.3 %	0.3 %	-0.8 %	-0.3 %	-0.5 %	-1.1 %	-0.3 %	**-0.7 %**
…	**-0.8 %**	**-1.6 %**	**-0.9 %**	**-0.9 %**	**-0.5 %**	**0.2 %**	**0.3 %**	**0.7 %**	**0.6 %**	**0.6 %**	**0.2 %**	**0.0 %**	**0.0 %**	**-0.3 %**	**-0.2 %**	**-0.9 %**	**-0.9 %**	**-1.2 %**	**-1.5 %**	**-1.2 %**	**0.0 %**

Representative TI error

Height [m]	2…3	3…4	4…5	5…6	6…7	7…8	8…9	9…10	10…11	11…12	12…13	13…14	14…15	15…16	16…17	17…18	18…19	19…20	20…21	21…22	*4…16*
62	-1.7 %	-2.3 %	-1.0 %	-1.1 %	-1.0 %	0.7 %	1.0 %	1.8 %	1.2 %	1.0 %	0.7 %	-0.7 %	-0.6 %	-1.2 %	-1.0 %	-0.7 %	-0.8 %	-1.2 %	0.4 %	0.2 %	**-0.3 %**
90	0.1 %	-1.9 %	-0.3 %	-0.5 %	-0.9 %	0.3 %	0.6 %	1.3 %	1.5 %	0.5 %	1.2 %	0.0 %	0.6 %	-0.6 %	-0.7 %	-1.5 %	0.9 %	-0.7 %	-1.3 %	0.2 %	**-0.1 %**
115	0.1 %	-1.3 %	-0.1 %	-0.6 %	-0.9 %	0.3 %	0.5 %	1.5 %	1.0 %	1.4 %	0.8 %	0.7 %	-0.4 %	-0.9 %	-0.1 %	-1.0 %	-0.7 %	0.0 %	-1.2 %	-0.2 %	**-0.1 %**
140	1.4 %	-2.3 %	-0.1 %	-0.4 %	-1.2 %	0.4 %	0.6 %	2.0 %	1.5 %	1.2 %	0.6 %	0.7 %	-0.6 %	-1.0 %	-0.6 %	-0.1 %	-1.3 %	0.2 %	0.2 %	-0.9 %	**0.0 %**
165	4.8 %	1.8 %	0.1 %	-0.9 %	-0.9 %	-0.5 %	-0.5 %	1.2 %	1.5 %	1.3 %	0.4 %	0.4 %	0.8 %	0.3 %	0.4 %	-0.3 %	-1.1 %	-1.7 %	-0.5 %	-1.1 %	**0.3 %**
190	9.4 %	-2.1 %	0.6 %	-0.4 %	-1.4 %	0.1 %	0.2 %	0.7 %	0.8 %	1.0 %	0.0 %	0.3 %	0.8 %	0.2 %	0.5 %	-0.4 %	-0.3 %	-1.5 %	-1.0 %	-0.7 %	**0.3 %**
240	3.7 %	-3.8 %	1.2 %	-3.4 %	-2.2 %	-1.6 %	-0.3 %	0.0 %	1.4 %	0.1 %	-0.5 %	-0.1 %	0.8 %	2.5 %	1.4 %	-1.4 %	0.4 %	0.3 %	-1.4 %	-1.5 %	**-0.2 %**
…	**2.5 %**	**-1.7 %**	**0.1 %**	**-1.0 %**	**-1.2 %**	**0.0 %**	**0.3 %**	**1.2 %**	**1.3 %**	**0.9 %**	**0.5 %**	**0.2 %**	**0.2 %**	**-0.1 %**	**0.0 %**	**-0.8 %**	**-0.4 %**	**-0.7 %**	**-0.7 %**	**-0.6 %**	**0.2 %**

Root Mean Square Error (RMSE)

Height [m]	2…3	3…4	4…5	5…6	6…7	7…8	8…9	9…10	10…11	11…12	12…13	13…14	14…15	15…16	16…17	17…18	18…19	19…20	20…21	21…22	*4…16*
62	5.2 %	3.3 %	3.4 %	2.4 %	2.3 %	2.4 %	2.0 %	2.2 %	2.1 %	2.5 %	2.0 %	2.2 %	1.9 %	2.3 %	2.2 %	2.4 %	2.7 %	2.4 %	2.0 %	2.3 %	**2.5 %**
90	4.5 %	3.5 %	3.2 %	2.3 %	2.3 %	2.2 %	1.9 %	2.0 %	2.7 %	1.7 %	2.3 %	2.1 %	2.1 %	1.9 %	2.0 %	2.3 %	2.1 %	3.0 %	2.5 %	1.9 %	**2.4 %**
115	4.7 %	4.4 %	3.0 %	2.1 %	2.0 %	2.4 %	1.5 %	2.2 %	2.0 %	2.0 %	1.7 %	2.3 %	1.9 %	2.0 %	1.9 %	2.0 %	2.0 %	2.3 %	2.9 %	2.1 %	**2.4 %**
140	6.9 %	3.8 %	3.7 %	2.7 %	2.2 %	2.5 %	1.9 %	2.5 %	2.2 %	2.0 %	1.6 %	1.9 %	2.2 %	2.1 %	2.2 %	2.1 %	2.0 %	2.2 %	2.5 %	2.3 %	**2.6 %**
165	10.3 %	6.1 %	4.1 %	2.6 %	2.5 %	2.2 %	2.2 %	2.1 %	2.2 %	2.1 %	2.1 %	2.1 %	2.1 %	1.6 %	1.7 %	1.8 %	2.2 %	2.8 %	2.5 %	2.4 %	**2.9 %**
190	15.5 %	5.6 %	4.5 %	3.1 %	2.7 %	2.4 %	2.7 %	2.2 %	2.1 %	2.1 %	1.9 %	2.1 %	2.3 %	2.0 %	1.7 %	1.8 %	1.6 %	2.7 %	2.2 %	2.8 %	**3.2 %**
240	15.1 %	7.0 %	7.9 %	4.5 %	3.7 %	3.2 %	2.9 %	2.5 %	2.8 %	2.1 %	2.3 %	2.0 %	2.2 %	3.2 %	2.3 %	2.2 %	2.1 %	2.4 %	2.3 %	2.6 %	**3.8 %**
…	**8.9 %**	**4.8 %**	**4.3 %**	**2.8 %**	**2.5 %**	**2.5 %**	**2.1 %**	**2.2 %**	**2.3 %**	**2.1 %**	**2.0 %**	**2.1 %**	**2.1 %**	**2.2 %**	**2.0 %**	**2.1 %**	**2.1 %**	**2.5 %**	**2.4 %**	**2.3 %**	**2.4 %**

Table A.1: Aggregated TI error numbers for MBE, representative TI and RMSE of compensated FLS for WS170 at LEG.

Aggregated TI data

Mean bias error (MBE)

Height [m]	2…3	3…4	4…5	5…6	6…7	7…8	8…9	9…10	10…11	11…12	12…13	13…14	14…15	15…16	16…17	17…18	18…19	19…20	20…21	21…22	*4…16*
40	2.3 %	1.3 %	1.1 %	0.3 %	0.2 %	-0.2 %	0.7 %	0.2 %	-0.1 %	0.1 %	-0.4 %	-0.4 %	0.3 %	0.5 %	0.3 %	0.4 %	-0.2 %	-0.8 %	-1.0 %	-0.2 %	**0.2 %**
60	1.6 %	1.3 %	1.5 %	0.9 %	1.2 %	1.3 %	0.9 %	1.1 %	0.5 %	0.6 %	0.2 %	0.0 %	0.7 %	0.9 %	1.4 %	0.7 %	0.6 %	-0.6 %	0.1 %	-0.5 %	**0.7 %**
80	1.0 %	2.0 %	1.3 %	1.0 %	1.1 %	1.5 %	1.4 %	1.0 %	1.1 %	0.7 %	0.3 %	0.5 %	0.7 %	0.9 %	1.2 %	1.0 %	1.2 %	0.7 %	0.3 %	0.5 %	**1.0 %**
100	0.7 %	1.8 %	1.4 %	0.5 %	1.3 %	1.0 %	1.3 %	1.2 %	1.1 %	1.1 %	0.7 %	0.5 %	0.6 %	0.8 %	0.7 %	0.4 %	0.7 %	0.4 %	0.8 %	0.0 %	**0.8 %**
120	1.1 %	2.3 %	1.5 %	0.9 %	2.5 %	1.5 %	1.6 %	1.5 %	0.9 %	1.2 %	2.0 %	1.4 %	1.4 %	1.1 %	1.1 %	1.2 %	0.3 %	0.5 %	0.9 %	0.4 %	**1.3 %**
140	1.9 %	2.5 %	1.8 %	0.5 %	0.8 %	2.4 %	1.6 %	2.0 %	2.2 %	1.7 %	2.5 %	2.9 %	0.5 %	0.7 %	1.2 %	1.2 %	0.8 %	1.0 %	1.4 %	0.9 %	**1.5 %**
160	1.4 %	3.0 %	3.2 %	1.1 %	1.1 %	3.4 %	1.6 %	4.0 %	1.7 %	1.7 %	3.2 %	2.8 %	1.9 %	1.7 %	1.2 %	1.5 %	0.8 %	1.5 %	1.4 %	0.8 %	**1.9 %**
180	1.7 %	3.3 %	3.2 %	3.1 %	1.5 %	2.8 %	1.8 %	3.9 %	2.9 %	1.6 %	2.5 %	1.9 %	1.7 %	1.0 %	1.1 %	1.1 %	0.9 %	1.3 %	1.4 %	1.3 %	**2.0 %**
200	2.6 %	2.9 %	3.2 %	2.4 %	1.6 %	2.1 %	2.6 %	2.8 %	2.6 %	1.3 %	1.7 %	1.6 %	1.7 %	0.6 %	1.3 %	1.3 %	1.2 %	1.1 %	1.6 %	1.5 %	**1.9 %**
250	2.7 %	3.0 %	3.6 %	2.9 %	1.7 %	1.8 %	2.5 %	1.9 %	1.8 %	1.5 %	0.7 %	1.1 %	1.6 %	1.0 %	1.3 %	0.1 %	1.0 %	0.9 %	0.7 %	1.2 %	**1.6 %**
…	**1.7 %**	**2.3 %**	**2.2 %**	**1.3 %**	**1.3 %**	**1.8 %**	**1.6 %**	**2.0 %**	**1.4 %**	**1.1 %**	**1.3 %**	**1.2 %**	**1.1 %**	**0.9 %**	**1.1 %**	**0.9 %**	**0.7 %**	**0.6 %**	**0.8 %**	**0.6 %**	**1.6 %**

Representative TI error

Height [m]	2…3	3…4	4…5	5…6	6…7	7…8	8…9	9…10	10…11	11…12	12…13	13…14	14…15	15…16	16…17	17…18	18…19	19…20	20…21	21…22	*4…16*
40	1.6 %	0.3 %	0.8 %	-1.6 %	0.1 %	-1.3 %	0.2 %	-0.6 %	-0.6 %	1.1 %	-1.2 %	-0.4 %	-0.7 %	1.2 %	-0.1 %	1.8 %	0.9 %	-0.1 %	-0.5 %	0.6 %	**0.1 %**
60	2.0 %	0.6 %	2.4 %	0.9 %	1.8 %	2.9 %	0.4 %	0.3 %	0.2 %	1.0 %	0.2 %	-1.2 %	1.1 %	1.4 %	2.3 %	0.9 %	2.0 %	-1.1 %	0.8 %	0.8 %	**1.0 %**
80	-0.2 %	1.1 %	0.7 %	1.1 %	1.3 %	2.8 %	1.6 %	1.2 %	0.8 %	0.9 %	0.3 %	0.7 %	1.0 %	2.0 %	2.1 %	1.3 %	1.3 %	1.3 %	-0.1 %	1.6 %	**1.1 %**
100	-1.5 %	0.5 %	0.0 %	1.3 %	0.7 %	0.2 %	2.1 %	0.5 %	1.0 %	1.3 %	0.7 %	0.3 %	-0.2 %	1.8 %	1.6 %	-0.1 %	1.4 %	0.4 %	0.5 %	1.2 %	**0.7 %**
120	-0.2 %	1.1 %	0.3 %	0.1 %	6.9 %	1.3 %	2.8 %	1.8 %	0.7 %	0.9 %	4.8 %	3.4 %	1.6 %	1.7 %	1.5 %	0.8 %	-0.4 %	0.6 %	0.2 %	0.9 %	**1.5 %**
140	0.7 %	2.2 %	-0.1 %	-0.4 %	2.5 %	6.0 %	2.1 %	4.8 %	5.4 %	4.6 %	6.4 %	9.6 %	0.5 %	1.2 %	1.0 %	1.2 %	1.1 %	1.1 %	1.5 %	0.0 %	**2.6 %**
160	-1.9 %	2.8 %	3.4 %	0.2 %	0.6 %	8.5 %	2.4 %	10.8 %	2.3 %	5.3 %	9.6 %	8.7 %	4.1 %	1.5 %	1.8 %	1.5 %	0.7 %	1.4 %	2.4 %	-0.9 %	**3.3 %**
180	-0.4 %	3.1 %	3.2 %	6.3 %	3.3 %	8.0 %	3.2 %	10.6 %	6.3 %	1.7 %	6.9 %	4.9 %	2.3 %	1.7 %	1.4 %	1.4 %	0.3 %	1.2 %	2.7 %	0.4 %	**3.4 %**
200	-0.3 %	1.6 %	2.4 %	3.2 %	2.2 %	2.7 %	5.1 %	1.9 %	4.4 %	-0.3 %	1.7 %	3.3 %	3.2 %	1.1 %	1.1 %	1.4 %	1.0 %	0.9 %	2.5 %	1.9 %	**2.1 %**
250	2.2 %	0.8 %	4.2 %	3.5 %	3.3 %	1.8 %	4.7 %	2.4 %	3.3 %	0.3 %	-1.4 %	-0.4 %	0.2 %	0.7 %	0.6 %	-2.0 %	-1.2 %	0.1 %	-0.1 %	1.5 %	**1.2 %**
…	**0.2 %**	**1.4 %**	**1.7 %**	**1.5 %**	**2.3 %**	**3.3 %**	**2.4 %**	**3.4 %**	**2.4 %**	**1.7 %**	**2.8 %**	**2.9 %**	**1.3 %**	**1.4 %**	**1.3 %**	**0.8 %**	**0.7 %**	**0.6 %**	**1.0 %**	**0.8 %**	**2.5 %**

Root Mean Square Error (RMSE)

Height [m]	2…3	3…4	4…5	5…6	6…7	7…8	8…9	9…10	10…11	11…12	12…13	13…14	14…15	15…16	16…17	17…18	18…19	19…20	20…21	21…22	*4…16*
40	6.2 %	5.7 %	4.4 %	4.5 %	4.0 %	3.5 %	3.2 %	3.2 %	3.6 %	3.5 %	3.3 %	2.8 %	3.2 %	2.9 %	3.2 %	3.0 %	2.9 %	3.0 %	2.6 %	2.4 %	**3.6 %**
60	5.9 %	4.8 %	5.0 %	4.8 %	4.1 %	4.3 %	3.2 %	3.7 %	3.1 %	3.3 %	2.7 %	3.2 %	2.6 %	3.3 %	3.0 %	3.3 %	3.0 %	2.8 %	2.3 %	3.1 %	**3.6 %**
80	6.6 %	5.8 %	4.3 %	5.1 %	3.8 %	4.3 %	3.2 %	3.3 %	3.3 %	2.9 %	3.0 %	2.8 %	3.0 %	3.0 %	3.1 %	3.1 %	3.0 %	2.2 %	2.8 %	2.9 %	**3.6 %**
100	6.3 %	5.5 %	4.8 %	4.0 %	3.9 %	3.6 %	3.5 %	3.1 %	3.3 %	2.9 %	2.7 %	2.8 %	3.0 %	3.4 %	2.9 %	2.9 %	3.2 %	2.9 %	2.6 %	2.6 %	**3.5 %**
120	6.8 %	5.9 %	4.2 %	4.5 %	8.7 %	4.6 %	3.6 %	3.2 %	3.2 %	3.3 %	6.6 %	5.3 %	3.1 %	3.1 %	2.9 %	2.6 %	2.8 %	2.5 %	2.7 %	2.8 %	**4.1 %**
140	7.6 %	6.0 %	5.4 %	5.4 %	5.5 %	7.0 %	3.7 %	6.1 %	7.0 %	5.6 %	8.0 %	9.6 %	2.7 %	3.1 %	3.3 %	2.7 %	3.1 %	2.9 %	2.8 %	3.1 %	**5.0 %**
160	8.9 %	6.5 %	7.8 %	6.3 %	3.5 %	7.6 %	3.4 %	10.2 %	4.4 %	6.1 %	10.1 %	8.7 %	5.5 %	3.0 %	2.6 %	3.3 %	2.8 %	2.7 %	2.6 %	2.9 %	**5.4 %**
180	8.3 %	7.0 %	8.9 %	8.3 %	4.3 %	7.9 %	4.0 %	9.4 %	6.5 %	4.7 %	6.7 %	7.6 %	4.5 %	2.8 %	3.3 %	2.7 %	2.7 %	3.5 %	2.8 %	3.5 %	**5.5 %**
200	8.4 %	7.2 %	7.0 %	6.1 %	3.9 %	4.0 %	5.5 %	8.5 %	6.0 %	3.9 %	3.5 %	5.8 %	5.2 %	2.7 %	3.2 %	2.9 %	3.1 %	3.2 %	3.0 %	3.0 %	**4.8 %**
250	10.6 %	8.3 %	9.2 %	6.6 %	5.6 %	4.1 %	5.2 %	3.9 %	5.1 %	3.8 %	4.3 %	3.3 %	6.0 %	3.4 %	3.4 %	5.5 %	3.1 %	3.2 %	3.5 %	2.3 %	**5.0 %**
…	**7.6 %**	**6.3 %**	**6.1 %**	**5.6 %**	**4.7 %**	**5.1 %**	**3.9 %**	**5.5 %**	**4.6 %**	**4.0 %**	**5.1 %**	**5.2 %**	**3.9 %**	**3.1 %**	**3.1 %**	**3.2 %**	**3.0 %**	**2.9 %**	**2.8 %**	**2.9 %**	**4.9 %**

Table A.2: Aggregated TI error numbers for MBE, representative TI and RMSE of compensated FLS for WS191 at Frøya.