

RC1: '[Comment on wes-2026-94](#)', Anonymous Referee #1, 09 Jul 2026 [reply](#)

Understanding the accuracy of scanning LiDAR pointing is very important for a range of applications. The present paper by M. Young and colleagues addresses this in a highly technical, well structured and extensive report. As a LiDAR user, I was happy to see several personal concerns addressed. Relying on 'common' approaches such as static hard-targeting and sea surface leveling, or more recent approaches such as dynamic hard-targeting, the authors estimate absolute azimuthal accuracies by computing azimuthal offsets and error. These angular uncertainties can be translated into vertical (height) uncertainties for a given sample range. This work can help future users to better anticipate risks, and adapt their experimental configurations as a function of their needs.

Whilst recommending this study for publication, I invite the authors to consider my comments and questions, which I hope will help clarify the scope and content of the study.

[Reply:](#) We would like to thank the referee for providing constructive feedback which have helped us improve the quality of the manuscript.

Key comments :

My main concern is the definition of what accuracy is, and perhaps my comments will encourage you to better define it:

[Reply:](#) Thank you for bringing up the definition of accuracy - while it is referred to in the title we did not explicitly define the meaning in the manuscript. By accuracy we mean how close the elevation angle of the lidar is to truth. We have added clarification of this to Section 2.1:

By definition, θ_e and Φ_e measure the accuracy (i.e. closeness to truth) of θ_{lidar} and Φ_{lidar} with the uncertainty of these quantities dependent on the specific calibration methodology implemented to estimate them.

- Whilst you produce absolute uncertainties, its relative importance will depend on the local vertical gradient in horizontal wind speed (dependent at leading order on both the height above the surface, and the wind speed and associated wind shear), and whether a user wishes to be focusing on specific structures (wind turbine wakes) and length scales (e.g. turbulent intensity).

[Reply:](#) Thank you for highlighting this important point. We agree that this is important and is why we added a discussion of the impact of the different elevation error results found among the methods on the wind speed variation at 100m across a range of vertical wind shear conditions (cf Figure 15, now Figure 14). Due to the significant vertical variations in mean wind and turbulence conditions within the lower atmospheric boundary layer (i.e. 0-400m), it is of our opinion that it is desirable to minimise uncertainty in the elevation error as much as possible for any scanning lidar measurements at low elevation angles ($<5^\circ$). However, as shown in Figure 14, it is possible for the error tolerance to be larger (up to 0.2°) for measurement ranges within 1.5-2 km of the unit which is encouraging for studies utilising lidars at near range.

- An important but briefly mentioned result is that for 'temporally consecutive scans of the same static hard target, Φ_{lidar} is constant' (L322). Are these scans of the same type as those presented in Figure 4 and 5, and if so, please refer to these figures here. If possible, I believe these results (showing that Φ_{lidar} is constant) should be shown, at least in the appendix, to convince the reader that there is no error here other than the pixel picking confidence level (cf. Table 5). Furthermore, I invite you to detail the duration of which each scan is performed. Indeed, the hard target gives you an average target position over the duration of the scan, which helps ensure that Φ_{lidar} is constant by smoothing possible higher-frequency fluctuations. What is your take on the possible higher-frequency modulations that cannot be captured here? Could elevation angle accuracy be sensitive to gusts, turbulence, that could modulate the LiDAR attitude through pressure fluctuations and possible vibrations and resonance? I have a personal interest in your take on

beam pointing accuracy at high-frequencies, and believe this should be discussed/presented as a limitation (up to a certain extent) of your accuracy estimates.

Reply: Thank you for raising this point. The temporally consecutive hard target scans used to determine constant ϕ_{lidar} for the static hard target method were also multi-elevation angle PPI scans (i.e. the same as those used in Figures 4 and 5 (now Fig. 4 and Fig. A1). To show evidence of this assumption we have added an example to Figure A2 in Appendix A1. The study by Vasiljević et al., (2016) found a similar result for the long-range WindScanner, which we also now refer to. The duration of each scan shown in Figure A2 is approximately 4.5 minutes, with a full duration of approximately 18 minutes between the start of the first scan to the end of the last scan. The devices were installed and tethered to very stable surfaces (roof tops) so minimal movements were expected during the test. Unfortunately testing the sensitivity of the elevation errors due to high frequency vibrations and other possible sources was not possible with the experiment setup.

The sentence (originally Line 322) has been modified to:

We found that for temporally consecutive multi-elevation PPI scans of the same static hard target, ϕ_{lidar} was constant (see Figure A2, Appendix A1). This repeatability within the scan resolution of 0.01° has also been noted for the long-range WindScanner system (Vasiljević et al., 2016).

We have added the following sentence to the discussion section

Testing the sensitivity of the elevation errors specifically due to high frequency vibrations and resonance experienced by the devices was not possible with the experiment setup.

Vasiljević, N., Lea, G., Courtney, M., Cariou, J. P., Mann, J., & Mikkelsen, T. (2016). Long-range WindScanner system. *Remote Sensing*, 8(11), 896.

Minor comments (line by line) :

- L38 : You highlight the importance of accurately knowing lidar positioning errors here. Saying this here may lead readers to think that this only applies to LiDAR coastal deployments on land. It may be worth reformulating. You could introduce coastal deployments in the previous paragraph, and focus this one on the general need to accurately know lidar positioning errors.

Reply: Thank you for pointing this out. We have removed reference to onshore deployments on the coast here to more generalise the sentence. The sentence now reads:

Measurement campaigns using one or more scanning lidar devices provide a cost-effective way of obtaining high-quality wind resource measurements at distances of 3-10 km (e.g. Shimada et al., 2025).

- L47 : I find that the $\Delta\phi$ annotation is ambiguous here, and it may be clearer to directly refer to psi offsets or error. Talking about the variations of $\Delta\phi$ is ambiguous as I do not know at this point if you are talking about an offset, an error, or fluctuations around and offset to which you would need to attach information about the frequency of these variations, which you do not thoroughly detail this further in the manuscript.

Reply: Thank you for raising this issue. We agree that the terminology used was unclear and instead of using $\Delta\phi$ ambiguously we now clearly define the elevation angle error as $\Phi_e (= \Phi_{\text{lidar}} - \Phi_{\text{ref}})$ and this terminology is used throughout the manuscript.

- L97 : You write ‘additional uncertainties’, but they are not additional or new. They are always there. I would suggest presenting the paragraph by first presenting all identified sources of error (or making a reference to your Table 5). You can then say that offshore motion adds further complexity. Furthermore, your mention of the ‘weight of the lidar head’ gives the impression that this is the only source of SLiDAR error.

Reply: Thank you for pointing this out. We have removed the sentence to avoid causing confusion and instead now state the following.

Despite this, coastal deployments experience much smaller variations in device tilt compared to offshore devices installed on a moving transition piece. Therefore the absence of significant device tilt variations are expected to partially reduce the uncertainties of both SS and other beam calibration methods.

- L133 : I would complete this sentence by writing that vertical variations are expected to be larger in the lower part of the boundary layer, or in and around turbine wakes.

Reply: Thank you for this suggestion. We have updated the sentence as follows:

In this study we focus on quantifying Φ_e as opposed to θ_e since horizontal wind speed variations are expected to be smaller than vertical variations in the lower atmospheric boundary layer, including in and around turbine wakes, and thus the beam horizontal position has a smaller impact on the measurement uncertainty (e.g. Rouholahnejad et al., 2026).

- L164 : It may be useful to already mention here that the possible tidal phase lag in your study area due to the distance of the tidal gauge is accounted for in the error estimates, and make a reference to the information you present in Table 5.

Reply: Thank you for this suggestion. We have added the following sentence

Note that the distance of the tidal gauge from the experiment location may introduce additional uncertainties (e.g. phase lag) which are taken into account in Section 2.4 (Table 4).

- Figure 3: This figure needs a spatial scale, and a marker for the tidal gauge, or at least an arrow pointing in the direction of where the tidal gauge is.

Reply: Thank you for pointing this out. The figure has been updated to include spatial scales and an inset map showing the location of the tidal gauge w.r.t the site.

- L237 : From what database, with what frequency and over what duration, was your reference mean sea level computed ? There is a possible ambiguity here between the hydrographic/historic water level reference, and the tidal gauge reference ?

Reply: The lidar mean sea level heights are derived from the total station system's GNSS ellipsoidal height, converted to orthometric height using the local geoid model where a reference mean sea level surface is defined. The mean sea level heights are therefore independent of the tidal signal. The tidal gauge provides the sea level height in meters above or below mean sea level. Since it is a relative quantity, it is not expected to introduce ambiguity.

- L290 : Whilst I am aware of the literature on the topic of backlash, I recommend that you define the term here.

Reply: Thank you for this suggestion. The reference to backlash has been moved to new section 2.3.4 Scan Setup and the term is now defined as follows:

In scanning lidar systems, mechanical backlash, defined as the effect of motion lost as the scan head mechanism reverses direction, can introduce small positioning errors (e.g. $\pm 0.025^\circ$; Vasiljević et al., 2016).

- L452 : I note the conservative nature of your filtering here. Considering this, could you clarify here why you have surface detections beyond 0° in elevation in your figure 10i ? Do you expect a bias on your results due to the fact that you are eliminating so much data, and therefore the effective area over which you keep the intercepts with the data ?

Reply: This is a good point. Surface detection above 0° lidar elevation is possible because of the positive elevation errors of the devices (i.e. the lidar elevation is always higher than the true

elevation). However at near-horizontal angles these detections become more uncertain and are associated with higher errors in determining the inflection point (as shown by σ_{ss}). We suspect that some of the results originally shown were being biased by the filtering. Based on a comment raised by Reviewer 2, we re-calculated the R^2 of the sigmoid fits up to a distance of 100m past the inflection point instead of across the entire range, as the reviewer rightly pointed out that this was dominated by variance associated with the long-tail of the sigmoid. After updating this, much more data (generally ~75%) are left after applying the filters and some of the biasing in ϕ_e has been removed (particularly that originally present in ϕ_e between -2° and -1.5° for SL South).

We have added the following text to clarify why surface detections at $\phi_{lidar} > 0^\circ$ are possible

Note that sea surface detections at $\phi_{lidar} > 0^\circ$ are possible because of the positive ϕ_e of the devices in the direction of NOAH (Fig. 8).

- L453 : I understand here that you are left with 30-50 % and 50-90 % of data to work with after filtering. Is this correct ? I believe this sentence is worth clarifying to remove any ambiguity.

Reply: Thank you for noticing this. This interpretation is correct and the sentence has now been updated to the following for clarity, with some modifications based on the revisions made to the filtering, based on comments raised by reviewer 2:

Based on these results, relatively conservative goodness-of-fit thresholds of $R^2 > 0.8$ and $\sigma_{ss} < 20$ m are applied to remove bad data associated with near-horizontal elevation angles, resulting in approximately 75 % of valid scan data over the elevation angle range of $-1.5^\circ \leq \phi \leq -0.5^\circ$ after filtering.

- L466 : Belt or gear systems seems to have a lot of importance on the errors you quantify for either RHI or PPI scans, and I am happy to see that this is being addressed in your work. Would it not be more convenient to evaluate PPI and RHI accuracy as a function of the system version using a hard target solution instead ? Has this been done elsewhere ? Have you tried hard-targetting a drone by alternating between RHIs and PPIs ? Whilst I agree that the SSL technique is straightforward to test this, the high uncertainties associated with the SSL technique may mean that it is not be the best candidate for this comparison.

Reply: This is a very good point. The marked difference between the elevation errors determined from sea surface RHI versus PPI scans for SL South was unexpected. The actual cause is unknown and the attribution to scan head design/firmware made originally on Line 466 was rather speculative. We have therefore moved the discussion on this point to the discussion section instead. Unfortunately, we were not able to specifically test consecutive RHI versus PPI scans on the SHT/DHT methods which may have helped provide an answer. For the static hard target and drone methods, multiple PPI scans at different elevation angles were used. These scans therefore effectively use the same scan strategy as the PPI SS scans (but scan through more elevation angles), but the resulting elevation error still falls in between the sea surface RHI and PPI scans and is not the same as the sea surface PPI scans, which would be more expected. For all PPI scans used for static hard targets, drone method, and sea surface method, the same redundant fixed scan was used to account for backlash.

We have elaborated on this in the Discussion section:

As shown in the results presented here, the SS method exhibited differences between the two different lidars tested, with SL South exhibiting a pronounced difference between the elevation error estimates obtained from RHI and PPI scans. Since the methodology and scan scenario applied to both devices was the same, one possible cause is that an additional scan head control error in SL South was introduced during the sea surface scan sequence that was not accounted for by the recommended backlash settings implemented. This may stem from the different type of scan head mechanism (e.g. belt driven for SL South versus gear driven for SL North), and firmware/software versions depicting scanner head control (Table 1). However, a control error was not observed while performing the multi-elevation PPI

scans for both the hard target and drone methods. Since it was not possible to verify this further, the cause is unknown. Such factors should be investigated in future work.

We have also modified the attribution in the Conclusions to:

The source of this difference is unknown, although one possibility is that an additional control error was introduced during the sea surface scan sequence, stemming from the different scan head design and software/firmware of the system.

Typos :

- L4 : Consider adding a comma after '3-10 km' for the clarity of the sentence, and also consider also providing vertical scales relevant to wind turbines.

[Reply](#): Corrected, and added heights 50-300 m.

- L70 : I suggest deleting half to sentence to have it begin at 'Its variability'

[Reply](#): Corrected

- L227 : space missing in 'levelingmethodologies'

[Reply](#): Corrected