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Sensitivity of space and time on scanning LiDAR data correlation and the implications on synchronisation of bi-static systems

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SUMMARY

When possible, running a cross comparison between two or more instruments that are out on the field is an important check for accuracy, consistency and reliability of the instruments in question. As part of the Carbon Trust OWA Offshore wakes campaign, two scanning LiDAR systems were deployed to give near full coverage of the host offshore wind farm.

As part of the programme, periodic checks were performed to give confidence on how each system was performing, and to confirm that system output remained consistent. The LiDARs were several kilometres apart and the scan patterns were not synchronised temporally or spatially. It was, however, possible to pick out data points from the two LiDAR datasets that could be used for such a cross comparison based on their spatial and temporal separation. The line of sight velocities were compared for certain beam angle scenarios.

A cross comparison of radial wind speeds from the two LiDARs is carried out as a base case. The effect of time offsets and azimuth angle offsets between the LiDARs on the relationships between radial wind speed values in the base case is explored. Results showed that unintended or unknown temporal or spatial offsets lead to uncertainty in measurements from a bi-static system. The synchronisation of the LiDARs in both the time and space domains seems essential to help reduce measurement uncertainty when engaging a bi-static system.

INTRODUCTION

The use of remote sensing techniques relying on the detection of backscattered light waves, such as ground-based LiDAR (Light Detection And Ranging), for wind energy applications has become more and more common over the past years. A LiDAR is a device that measures wind speeds by emitting a laser beam into the atmosphere and calculating the Doppler shift in backscatter from the laser when it interacts with particles that are entrained in the air. The wind speed measured is only the component of the wind velocity vector that lies along the beam, which is called the radial velocity or the line of sight (LOS) velocity, v_{LOS} .

There are several types and designs of LiDAR devices that have different applications. They are most commonly used as wind profilers for wind resource assessment and power performance testing, often alongside met masts, supplementing one another [1]. The attraction of LiDAR profilers comes from their capability of measuring wind at various heights throughout the entire rotor diameter of wind turbines (up to and beyond the maximum rotor tip height) and also from

their lower costs when compared with high met masts, especially offshore and on complex terrain [2].

Other LiDAR systems that have been developed for wind measuring purposes for wind energy applications include nacelle based LiDARs, which are used, for instance, for wind turbine power curve measurements [3] and power performance assessments [4], and scanning LiDARs, for example, for wind turbine wake measurements [5].

The laser beam from a LiDAR is only capable of sensing radial wind speeds. By orientating the beam from one device in different directions a horizontal wind vector can be calculated using the radial wind speed values measured at the different beam headings. LiDAR profilers and nacelle based LiDARs are both capable of determining a wind speed vector (be it a 3-D or a 2-D vector) over a short time period, however a scanning LiDAR does not do this. A scanning device has its beam constantly pointing in one direction out of its scan head. The scan head rotates to perform 2-D scans by varying either its azimuth angle or its elevation angle to perform PPI (plan position indicator) or RHI (range height indicator) scans respectively, or the beam can be made to stare in one direction (LOS mode) while collecting data, in each case recording radial wind speed values.

It is possible to combine beams from several scanning LiDARs so that they sample the same volume of air. In doing so, a 3-D wind vector for that packet of air can be reconstructed from the radial wind speed values and the beam geometries. This can be done using a bi-static scanning LiDAR system, under the assumption that the wind has no vertical component, by having the beams scan the same volume of air simultaneously. However, a question can be raised as to how certain one can be that the beams point in exactly the right direction at an exact time.

There is always some uncertainty to any measurement that is made. The subject of data measurement and collection always goes hand in hand with the matter of uncertainty budgets or calculations that such tasks bring along. Scanning LiDARs are relatively novel devices in the wind energy sector, and certain aspects of uncertainties brought about by their measurements are still being studied. The uncertainty chain linking all the processes and parameters involved in sampling data is extensive (system uncertainty, coordinate transformation uncertainty, in-situ uncertainty, etc.). The objective of this exercise was to look at data from a bi-static LiDAR system out on site and identify some uncertainties linked to the space and time in which the LiDARs measured in relation to each other.

The effect of inaccuracies in azimuth angle and timestamp readings on v_{LOS} measurements from two LiDARs that are sampling the same space and time were looked into by producing a series of correlations for the v_{LOS} values from the systems based on certain criteria and on the base case of the LiDARs pointing their beams at each other.

SETUP

As part of the Carbon Trust OWA Offshore wakes campaign two LiDARs, Windcube 200S units from Leosphere, were deployed on a wind farm site with about 6.2km between them horizontally and only a 16m height difference and they were each set to measure up to a distance of 6km. One unit was located on a met mast platform and the other on a transformer substation platform. They will be referred to as the met mast LiDAR and transformer LiDAR respectively. More information on the location, setup and installation of the LiDARs can be found in [6].

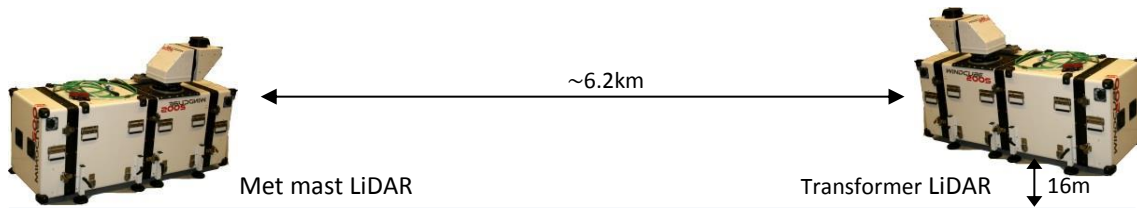


Figure 1 - Horizontal and vertical distance between the LiDAR units

The scanning LiDARs ran pre-defined sets of scan patterns passing through several cross sections of the wind farm as well as parts of the free stream sectors through a combination of PPI, RHI and LOS scans. In PPI mode the LiDAR scans a range of azimuth angles while keeping a constant elevation angle and in RHI mode the LiDAR beam's azimuth angle is fixed while its elevation angle changes. The LOS mode is a staring mode during which the beam points in a fixed direction.

COMPARISON OF RADIAL WIND SPEEDS

A comparison of v_{LOS} values from two (or more) LiDARs measured very near each other in space and time from a volume of air within reach of the systems cannot be done unless the wind direction at the measurement locations is known. The tests conducted in this case were based solely on data from the two systems in situ (azimuth & elevation angles, range, v_{LOS} , timestamp and CNR (carrier to noise ratio) values) – no external data were used. Therefore, only measurement points for when the two W200S units had their beams pointing roughly in the direction of the other system at approximately the same time could be compared against each other because the radial component of the wind on both beams was expected to be almost equal (and opposite) in magnitude, since, in theory, we would expect a correlation coefficient of -1 when comparing radial wind speeds from the two scanning units if these were measuring the exact same volume of air at precisely the same time while their beams pointed at each other. We'll refer to the azimuth angles for the met mast and transformer LiDARs when their beams were directed at each other as θ_{M0} and θ_{T0} respectively ($\theta_{T0} = \theta_{M0} + 180^\circ$).

The way to go about comparing data points was to look for data from the LiDARs that met such spatial and temporal criteria. Other constraints such as a maximum horizontal and vertical separation between pairs of data points, as well as qualitative criteria such as CNR levels, were applied.

The first test carried out was to compare v_{LOS} values from the LiDARs when their azimuth angles (θ_M and θ_T) were equal to θ_{M0} and θ_{T0} ($\pm 2^\circ$) and were sampling nearly the same volume of air along range gate/s almost simultaneously, i.e. $\theta_M \geq \theta_{M0} - 2^\circ$ and $\theta_M \leq \theta_{M0} + 2^\circ$; $\theta_T \geq \theta_{T0} - 2^\circ$ and $\theta_T \leq \theta_{T0} + 2^\circ$. Instances when the elevation angle for both systems was between 0° and 5° were picked.

The reason for using a range of values within 4° for the angles was that for an extremely narrow range the resulting dataset would be empty or have very few data points. Using a small range was necessary to have a reasonable number of data points to work with.

Maximum horizontal separation	50 metres
Maximum vertical separation	30 metres
Maximum time separation	0.5 seconds

Table 1 – Spatial and temporal criteria for base case comparison

For this base case the dataset that was compared contained pairs of radial wind speed values (corresponding to readings from the two LiDARs) such that the elements of each pair satisfied the criteria in Table 1 with respect to one another (in addition to the angle conditions).

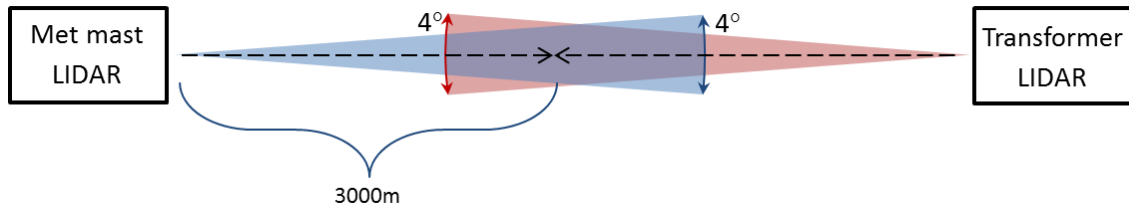


Figure 2 – Range of azimuth angles (along xy-plane) and range gate from met mast LiDAR used for cross comparison test

TIMESTAMP OFFSET

Scanning LiDARs in a bi-static configuration that are synchronised will read the same time and will both record timestamps relative to the same time reference. The second test was to look at what effect an offset between the measurement times of the met mast and transformer LiDARs might have on the v_{LOS} comparison, i.e., when the LiDARs sample volumes of air that are in close proximity to each other at slightly different times.

The same spatial criteria as in the base case were used in this test. The temporal criteria changed – the maximum time separation was set to 60 seconds. Comparisons were made for different time offsets at 1 second intervals with a tolerance of $\pm 0.5s$. So, for example, for a 10 second offset the difference between met mast LiDAR timestamp and transformer LiDAR timestamp must be between 9.5 and 10.49 seconds.

AZIMUTH ANGLE OFFSET

This case tries to reflect the hypothetical situation when two systems take a measurement at approximately the same time and supposedly at the same location but in actuality one LiDAR records the wrong azimuth angle (LiDAR reads θ_{M0} or θ_{T0} when the scan head bearing is off by a number of degrees). The same criteria as the base case are used except for the azimuth angle range of the transformer LiDAR. In this case the range for azimuth angle θ_T is $\theta_{T0} - 60^\circ$ to $\theta_{T0} + 60^\circ$. Comparisons for different angle offsets ($\Delta\theta_T$) were made.

The results shown are for data measured at 3000m from the met mast LiDAR (Figure 2). The corresponding range gate for the transformer LiDAR would depend on the horizontal distance between the systems' measurement locations.

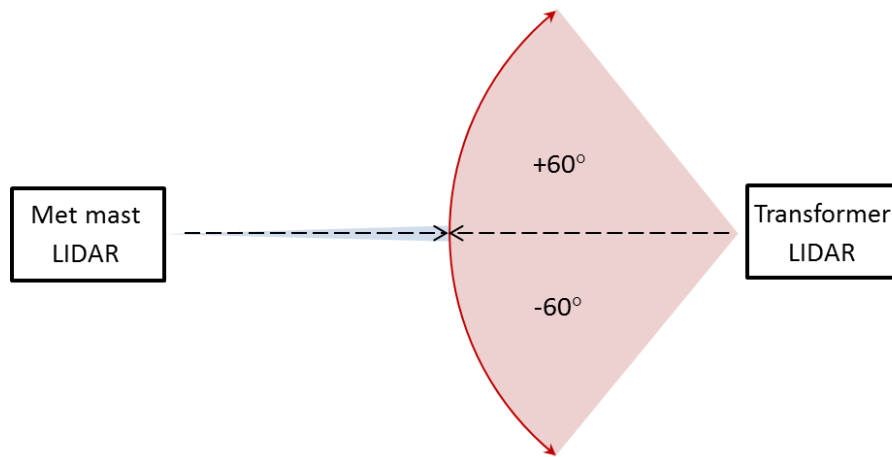


Figure 3 – For the azimuth angle offset case the transformer LiDAR had an azimuth angle between $\theta_{T0} - 60^\circ$ and $\theta_{T0} + 60^\circ$

RESULTS

Comparisons for the base case test show that there is a good relationship between v_{LOS} values from the two LiDARs. As expected the correlation coefficient is close to -1.

Several CNR thresholds were applied to determine whether the relationship varies in any way but also to see how the population of the dataset decreases. The correlation coefficients did not change much and neither did the R^2 value except for the threshold of -21dB. The R^2 improved but the data set population suffered greatly (Figure 4).

CNR values are a good metric for data quality however if this is the quality measure used then one needs to find a compromise between quality and a reasonable size dataset to work with.

When a greater time difference than 0.5 seconds between data points from each LiDAR was allowed, different correlation behaviours were noted for different time offsets. Using a CNR threshold of -27dB, there was no great change in the correlations for time offsets of less than 20 seconds. The correlation coefficients and R^2 values at 10, 15 and 20 second offsets were, respectively, -0.9962 and 0.7996, -0.9477 and 0.9329, and -0.8363 and 0.8253. A couple of outliers in the 10 seconds offset comparison reduced the R^2 value even though the correlation level was good. The lowest correlation value at this CNR level (within a range of offsets of up to 60 seconds) was for an 8 seconds offset with a coefficient of -0.7617 and R^2 of 0.6774. The correlation for a 60 seconds difference was better than that for the 8 seconds offset (correlation values shown in Figure 5).

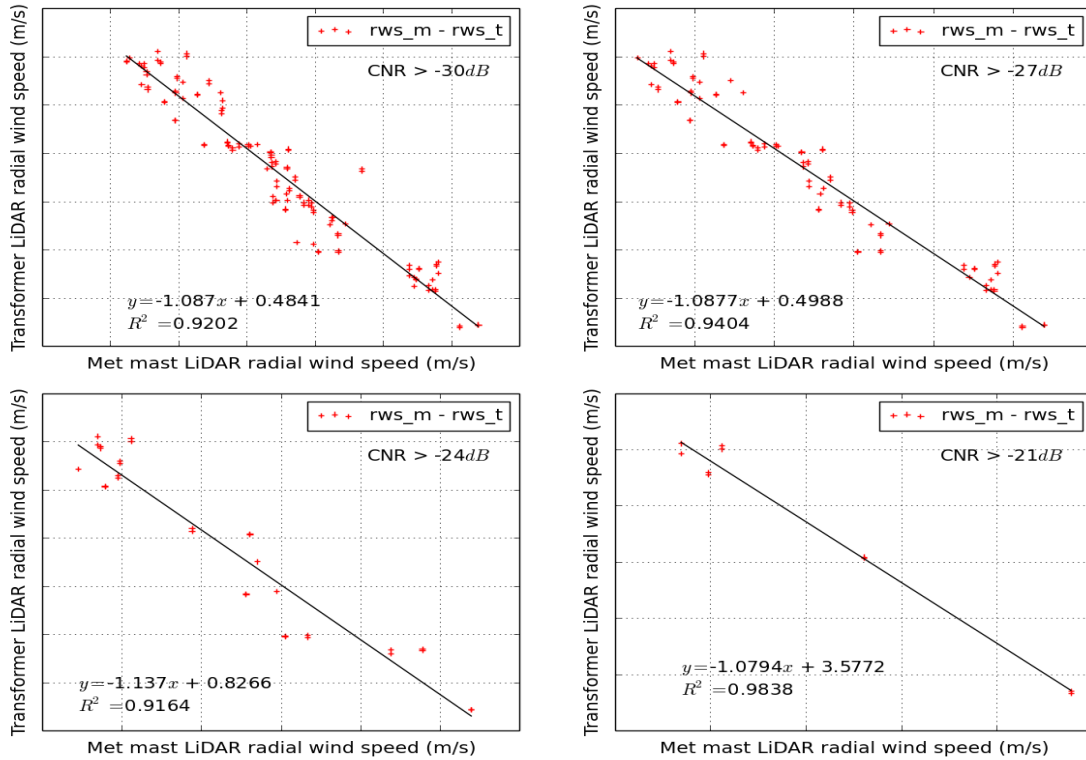


Figure 4 – Correlations of v_{LOS} from the two LiDARs (3000m from met mast LiDAR) at various CNR thresholds

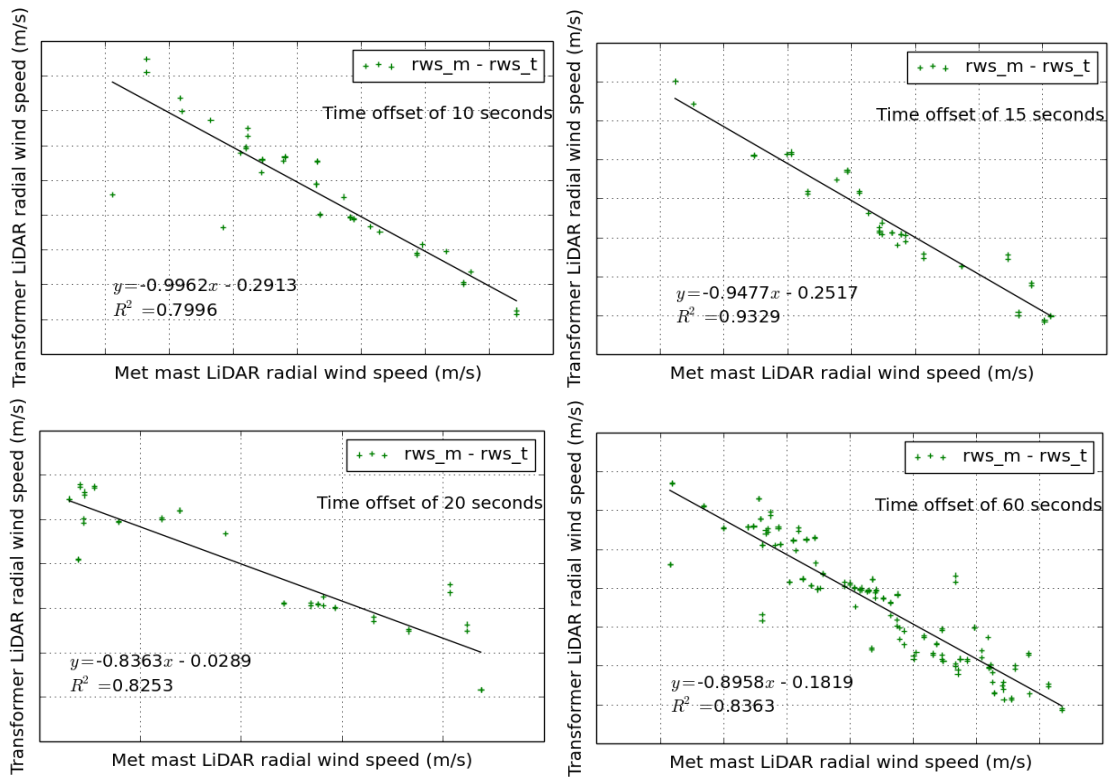


Figure 5 – v_{LOS} comparison of data points from the transformer LiDAR offset by 10, 15, 20 and 60 seconds from the met mast LiDAR (3000m from met mast LiDAR and CNR threshold of -27dB)

For the case of an azimuth angle offset (and with a time difference of no more than 1 second between elements of data point pairs from the LiDARs) the correlations veered away from the results for the base test as the hypothetical difference in azimuth angle ($\Delta\theta_T$) between the actual scanning head angle and that recorded by the system grew.

Correlations were very similar to the base case for $\Delta\theta_T$ up to 20° . At $\Delta\theta_T > 20^\circ$ the relationship between v_{LOS} values started to deviate from the base test results, though even at some greater $\Delta\theta_T$ values the relationship was still good (example at $\Delta\theta_T \approx 30^\circ$). With $\Delta\theta_T > 30^\circ$ the correlations values deviated even more as shown for $\Delta\theta_T \approx 45^\circ$ and $\Delta\theta_T \approx 60^\circ$ in Figure 6.

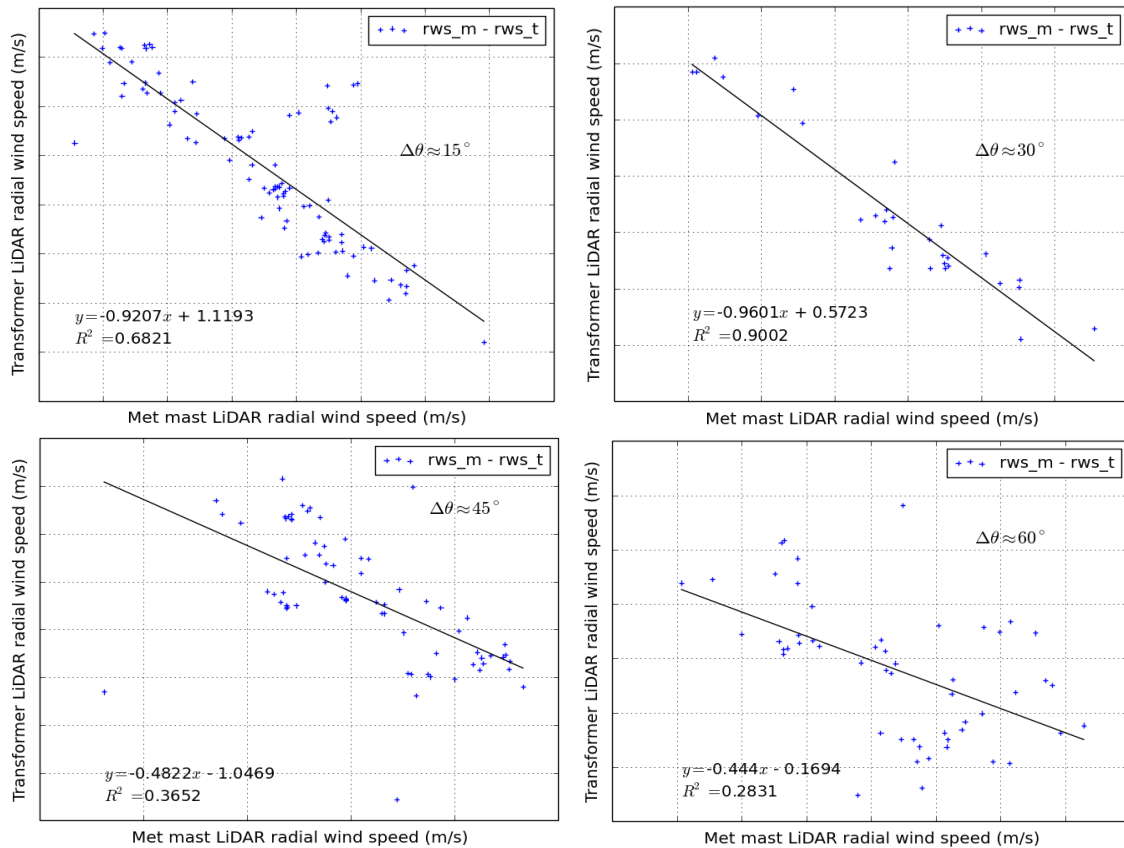


Figure 6 – v_{LOS} comparisons at various azimuth angle offsets (3000m from met mast LiDAR and CNR threshold of -27dB)

DISCUSSION

The results for the base test comparison of v_{LOS} values are close to what was expected giving correlation coefficients close to -1. Selecting data points from two LiDARs for when they point their beams at each other gives a way of comparing radial wind speed values output by the scanning units in an absolute manner. The wind direction need not be known in such case because almost the same wind velocity component is projected onto each of the beams.

As the beams begin to veer away from θ_{M0} and θ_{T0} the measurement locations along one beam move further away from those along the other thus increasing the spatial separation between them, except for instances where the beams almost intersect. In such case the spatial separation between beams where these nearly intersect might not be much, however the beams are no longer parallel and will sense different wind components that cannot be compared unless the wind direction is known.

For some given azimuth angles θ_M and θ_T for when the beams intersect the relationship between v_{LOS} values, at close proximity to the intersection, from the LiDARs will vary as wind direction changes because of the cosine relationship between the wind velocity vector and LiDAR beam orientation.

If a cross comparison exercise is intended to be carried out between two or more scanning LiDARs using only the data from these instruments, then a well-planned dedicated set of scan patterns should be written to program the LiDARs accordingly where the beams point at the other system/s. Otherwise, if other scan patterns for other analysis purposes are used, as done in this exercise, it might be possible to look for points within the data when the beams almost point at each other. Of course, the scan patterns for each system must include the appropriate azimuth and elevation angles for this to be possible.

In the case that LiDARs in a bi-static system are meant to sample some volume simultaneously but one of the LiDARs has a time offset with respect to the other system, then, if a wind vector were to be reconstructed using the two v_{LOS} values and beam geometries, the resulting vector might not be necessarily correct. The results showed that a 60 seconds offset between two LiDARs sampling volumes that were close did change the relationship between v_{LOS} values. This implies that if the LiDARs are not in synch then this will add further uncertainty to any calculations or processes which will make use of the v_{LOS} values from the bi-static system.

In a similar way, further uncertainties come into play when measurements from a bi-static system, in which one (or both) LiDAR gives inexact or incorrect beam angle readings, are used for calculations or analysis work. As the results show, an azimuth angle offset for the transformer LiDAR from what, hypothetically, the angle reading was meant to be gives incorrect radial wind speed measurements for the intended measurement location.

The ideal situation when using a bi-static LiDAR system would be to make sure that the systems are synchronised in time and to have a precise way of reading the scanning head bearing at all times. This would help reduce the uncertainties relating to time and space when making bi-static measurements of an air packet. It also would be beneficial to be able to know exactly where the LiDARs are meant to point at any given time when planning the scanning movements of the beams. This points towards the need for synchronisation of the scanning LiDARs in a bi-static configuration in both the time and space domains. Time synchronisation is easily achievable, however matching measurement locations at all times might not be attainable due the movement of the beams though some method of optimising spatial uncertainty may be possible through further work.

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