2nd generation Lidar techniques in complex forested terrain

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The advent of remote sensing has enabled the acquisition of rich, detailed and precise datasets for wind studies. However, the adoption of 1st generation remote sensing in complex forested terrain has not been without issue. 1st generation remote sensing techniques entail the acquisition of measurements over a volume in space and the heterogeneity of wind flow across this volume arising in complex forested terrain can introduce ambiguity into remote sensing measurements if not performed expertly. Nevertheless remote sensing promises the direct measurement of many key phenomena occurring in complex forested terrain which have hitherto been subject to approximations and estimations, such as flow separation and recirculation, and the recovery of flow downwind of a forest edge. 2nd generation Lidar techniques are presented and illustrated with case studies which both overcome the limitations of 1st generation techniques in complex forested terrain and enable detailed and precise measurements of these key phenomena over wide areas.

Figure 1: RHI (Range Height Indicator) scan geometry

Forest edges
Forest edges can be investigated in detail using RHI scans in which the azimuth of the beam is held constant while the elevation angle is varied to survey a vertical surface transecting the interface under investigation. This is shown above in Figure 1. Three examples of RHI scans acquired over a period of 3 minutes are shown below in Figure 2.

In Figure 2 the wind traverses a forest edge and a velocity deficit is observed to extend beyond 20 times the tree height downwind in contrast to the common heuristic or rule of thumb that indicates flow recovery by 20H downwind.
Partial recovery is witnessed. This is investigated further by comparison with CFD models presented below in Figure 3. These show disagreement with the Lidar measurements at the regions where partial recovery is observed. It was concluded that the complexity of the roughness downwind of the forest edge in a heavily rutted and recently felled area was not adequately represented in the model.

**Figure 2:** influence of a forest edge
Flow separation

A forest edge on a slope was surveyed using a Galion Lidar implementing a variety of relevant scan geometries as shown below in Figure 4. The slope was not sufficiently steep to cause flow separation and recirculation. The flow was initially surveyed using a VAD scan which indicated a veer through 180 degrees close to hub height. The VAD scan results are shown in Figure 5. This was suggestive of flow recirculation. However, the mechanism for this was unclear given the failure of models and conventional heuristics to predict flow recirculation.

An RHI scan was performed to survey the flow across the forest edge and flow recirculation was unambiguously detected. This is shown in Figure 6. Red in the colour scale indicates flow towards the device across the top of the forestry, whereas blue indicates motion away from the device associated with recirculation. Despite the shallowness of the slope, the presence of the forest edge is sufficient to modify the behaviour of the flow in a manner not captured by simple models.
The threshold, in terms of gradient, above which flow separation and recirculation can be expected, is modified by the presence of the forest edge. This has significant consequences in terms of micro-siting, wind farm layout, site assessment, and provision made for this in terms of pro-active approaches to O&M strategies, infrastructure, and the disposition of personnel and spares. In this instance a wind turbine site has been identified as not feasible due entirely to a 2nd generation wind Lidar survey which has detected flow conditions which would have proved seriously deleterious to any turbine installed immediately downwind of this forest edge.

Figure 4: RHI survey of a forest edge on a slope
Figure 5: initial VAD scan results, showing a shear profile (black) and a veer profile (red)

Figure 6: RHI results indicating flow separation and recirculation
Crossed Range Height Indicator scans (XRHI)

Convergent scan geometries such as Crossed RHIs (XRHI) illustrated below in Figure 7 can allow the acquisition of wind shear profiles at any location. Below in Figure 8 an XRHI profile acquired using Galion Lidars is compared to the profile acquired by a nearby mast instrumented with calibrated cup anemometry. Excellent agreement is observed, in some instances better than two cups anemometers installed at the same height.

Figure 7: XRHI scan geometry

Low elevation angle applications

Pulsed Lidars offer many advantages, but it is claimed that they have a minimum measurement height, typically around 40m, due to the need for the laser pulse to fully exit the device before measurements can commence. The single degree of freedom of a 1st generation device means that this standoff along the line of sight beyond which backscatter is detected corresponds to a height. This can easily be mitigated by using 2nd generation techniques which allow the elevation of the beam to be varied, such that this standoff does not determine measurement height: the elevation angle of the beam can be lowered to acquire measurements at any height regardless. A low elevation angle scan geometry is illustrated in Figure 9. The time series presented in Figure 10 shows Lidar measurements at 10m acquired using a Galion Lidar, compared to measurements acquired using a co-located 10m mast instrumented with calibrated cup anemometry, over a period of 6 weeks. The benefits of pulsed Lidar techniques can be retained when acquiring measurements at any height by using 2nd generation techniques.
Figure 8: XRHI measurements compared with a reference mast

Figure 9: low elevation angle scan geometry gives access to measurement heights below 40m while retaining the benefits of a pulsed system
Figure 10: low elevation angle scan measuring at 10m compared to a 10m mast
Conclusions

2nd generation Lidar techniques implemented here using a Galion Lidar allow the value of Lidar to be unlocked. Techniques such as XRHI scans mitigate the limitations of 1st generation devices in complex and forested terrain. Low elevation angles allow access to the measurement of key flow features such as the influence of forest edges.