

Lidar and computational fluid dynamics for resource assessment in complex terrain

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Mark Pitter^{1*} (submitting/presenting author), Claude Abiven², Klaus Vogstad³, Michael Harris¹, Will Barker¹ and Oisin Brady²

¹ Natural Power, The Old Barns, Fairoaks Farm, Hollybush, Near Ledbury, HR8 1EU, U.K.

² Natural Power, 1, rue Goethe, 67000, Strasbourg, FRANCE

³ Agder Energi, Kjøita 18, 4630, Kristiansand, NORWAY

* markp@naturalpower.com, tel: +44(0)1531 650757, fax: +44(0)1644 430009

Summary

All forms of remote wind sensing sample wind speeds from a volume of atmosphere and can therefore be subject to bias in complex terrain when compared to point measurements acquired by a cup. This paper contains a description of a complex flow conversion technique that converts raw lidar line-of-sight velocity data into precise, unbiased measurements of horizontal wind speed on hilly and mountainous sites.

The technique described here performs a volume-to-point conversion of the raw lidar measurements by using VENTOS computational fluid dynamics (CFD) calculations to model the airflow at each measurement site and a software tool called “dynamics” to calculate a set of height and direction dependent lidar conversion factors from the results of the VENTOS calculations. These conversion factors are then simply applied to produce accurate lidar wind speed measurements. Because the CFD modeling undertaken here is very specific and limited in spatial extent to the scan cone of the lidar, the VENTOS computations are fully automated and parameterized and only need to be carried out once for each repositioning of the lidar.

Results from eight wind measurement campaigns in complex terrain are reported. Bias in the unconverted lidar data varied from 1% to 11%, however in each case, the use of VENTOS CFD and dynamics reduced measurement bias versus a mast-mounted, calibrated cup anemometer to less than 2%, as measured by the best-fit linear gradient.

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Abstract

This paper reports on several campaigns where continuous wave lidar measurements were combined with VENTOS computational fluid dynamics and “dynamics” flow conversion software to provide accurate wind resource assessment in hilly and mountainous regions. The studies were validated against calibrated cup anemometers mounted on traditional meteorological masts. In each case, the use of VENTOS and dynamics reduced the lidar measurement bias for 10-minute averaged wind speed to less than $\pm 2\%$, when compared to the mast. This is comparable to cup calibration precision and is of an accuracy required for the data to be considered suitable for predicting potential wind farm output by advisory bodies and lenders.

Introduction

When used in flat regions, lidars have repeatedly been demonstrated to provide an accurate and cost effective alternative to traditional meteorological masts for wind energy resource assessment. In contrast to masts, lidars are portable, do not require planning permission and can measure wind speed and direction up to turbine hub height and beyond without excessive cost. The accuracy of lidars has been thoroughly investigated by comparing them to calibrated meteorological masts, and numerous detailed studies have reported wind speed measurements to within one or two percent [1, 2].

In hilly and mountainous areas, often referred to as complex terrain, air flow is distorted by the local topography and this can lead to bias in unadjusted lidar wind speed measurements. This issue has been successfully addressed by using VENTOS computational fluid dynamics (CFD) [3, 4], a sophisticated non-linear flow model, to convert lidar output to provide wind measurement data equivalent to that measured by a mast positioned at the scan centre. VENTOS is a well-validated CFD code that uses Reynolds averaged Navier-Stokes (RaNS) equations and the $k-\epsilon$ turbulence model [4].

The topography and roughness of the terrain around the resource assessment site is input into CFD models (offline) and used to predict the effect of the local terrain on the airflow. This calculation is then processed to generate conversion factors that can be applied to lidar measurements to remove any bias. Earlier published work investigated the potential of this approach [5-7], and this paper contains several recent case studies which further validate the methodology. In each of these cases, the ZephIR lidar was positioned in close proximity to a high quality meteorological mast.

As an alternative to flow modelling, it is also possible to use multiple lidar beams to interrogate the flow, and hence resolve the full flow vector within a small spatial volume. For example, the 3D vector can be measured by the provision of three or more lidar units positioned on the ground at an appropriate separation distance, comparable to the measurement height for best accuracy. An example is the Windscanner system under development by Risø DTU [8], which offers the potential for rapid interrogation of varying flow fields. However, as shown in this paper, excellent ten-minute averaged results can be obtained far more conveniently from a single lidar and CFD based flow correction methodology.

Analysis method

Doppler wind lidars measure wind speed by scanning a volume of atmosphere, unlike a conventional cup anemometer which can be considered a point measurement. Lidars generally make an assumption of homogenous air flow throughout the measurement volume when calculating wind speed, and in conditions of simple flow as found on flat, open sites, this assumption is valid and lidar measurements have been frequently shown to be comparable with mast mounted cups. However, this supposition is often violated in complex terrain. For example, as wind traverses a hill or a ridge the wind inflow angle varies from positive on the upslope to zero at the crest and then negative on the downslope (Fig. 1). This means that the line-of-sight

velocity measured by the lidar is reduced in both the upslope and downslope direction and this can lead to a horizontal wind speed under-read of up to 10% in extreme cases. Errors of this magnitude are clearly not suitable for predicting the energy yield of prospective wind farms to sufficient accuracy.

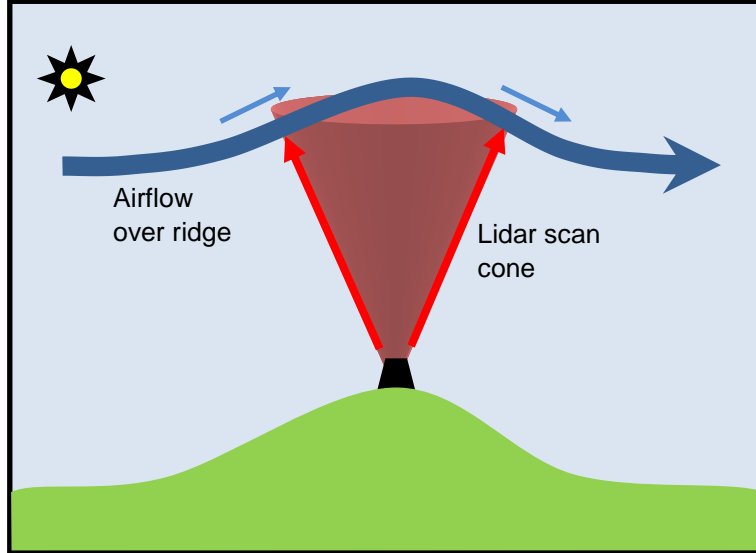


Figure 1: Complex airflow over a hill or a ridge. Radial velocity, relative to the lidar beam direction, is reduced in both the upwind and the downwind directions.

To overcome this, VENTOS CFD modelling of the airflow over the terrain around the measurement site has been combined with raw lidar measurements using a recently developed software tool called “dynamics” to produce height and direction dependent lidar conversion factors. These conversion factors are applied to ZephIR data to produce unbiased measurements of comparable accuracy to those obtained in homogenous terrain. CFD is increasingly used for flow modelling on potential wind farm sites, often to aid in vertical and horizontal extrapolations from wind speed measurement points to other regions of the site. However, the complex flow conversion method described here uses CFD to model the flow in the relatively small volume containing the lidar’s scan cone, so the process can be automated (parameterised in terms of mesh size, number of cells etc.). This is in contrast to using CFD for long range extrapolation and is only possible because the complex flow conversion problem is very specific and limited in spatial extent.

ZephIR is a conically scanning continuous wave (CW) lidar that exploits the high sensitivity of CW techniques to acquire 50 independent measurements each second as the beam is scanned through 360°. The first step in the approach taken here is to calculate the line-of-sight, or radial velocity, V_{r_i} , at each of the 50 points scanned by the ZephIR using the wind velocity characteristics generated by VENTOS.

The equation used is:

$$V_{r_i} = V_{h_i} [\sin \theta_i \sin \phi \sin \varphi_i - \cos \theta_i \sin \phi \cos \varphi_i + \tan \alpha_i \cos \phi] \quad (1)$$

where V_{h_i} is the horizontal wind speed calculated by VENTOS at each ZephIR measurement point, θ_i is the wind direction at each measurement point, measured clockwise from North, ϕ is the ZephIR conical scan angle, equal to 30.4° from vertical, φ_i is the angle of the point scanned by the ZephIR, again measured from North, and α_i is the inflow angle, that is, the angle between the flow direction and a horizontal plane.

Once the radial velocity has been derived from the VENTOS computation for each of the 50 scanned points at a particular measurement height, standard ZephIR signal processing is applied to calculate the horizontal wind speed that would be measured in this complex flow. The results from the VENTOS computations are also used to compute the horizontal wind speed at the cup height and location, nominally directly above the lidar, although a horizontal offset to the mast can be accommodated. The appropriate conversion factors for each measurement height are the ratios of the horizontal wind speeds from the CFD simulations of ZephIR and mast for each wind direction sector. VENTOS and dynamics only need to be executed once for each lidar placement and the computation takes place offline, usually before the measurement campaign begins, but conversion is possible at any stage of the campaign as the conversion factors can be applied retrospectively. In the field, the conversion factors are simply applied to the averaged ten minute data after acquisition by ZephIR. Figure 2 below summarises the complex flow conversion process used in this paper.

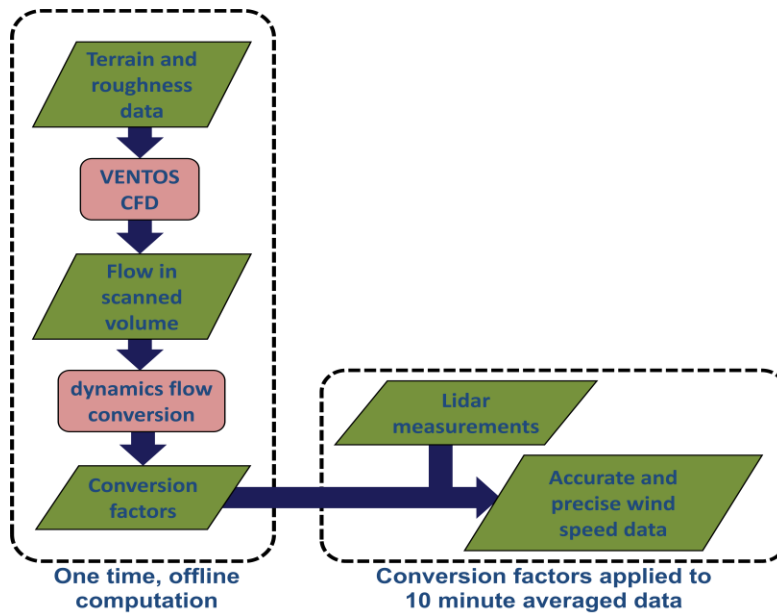


Figure 2: Summary of the VENTOS/dynamics complex flow conversion process

Case studies and results

The first case study presented here was carried out in Southern UK. The site was equipped with a meteorological mast equipped with two sets of cup anemometers at heights of 43 m and 60 m above ground level. The cups were fully calibrated and the mounting was IEC compliant [9]. Comparison within each pair of cups showed agreement to better than 1% away from mast shadowed sectors.

The ruggedness index (RIX) for the site was computed using the well known WAsP software package (see Table 1). RIX is a simple measure of terrain complexity and is defined as the fractional extent of surrounding terrain which is steeper than a certain critical slope. The RIX factors in Table 1 were calculated for the terrain within a range of 3,500 m around the mast and for a critical slope of 30%.

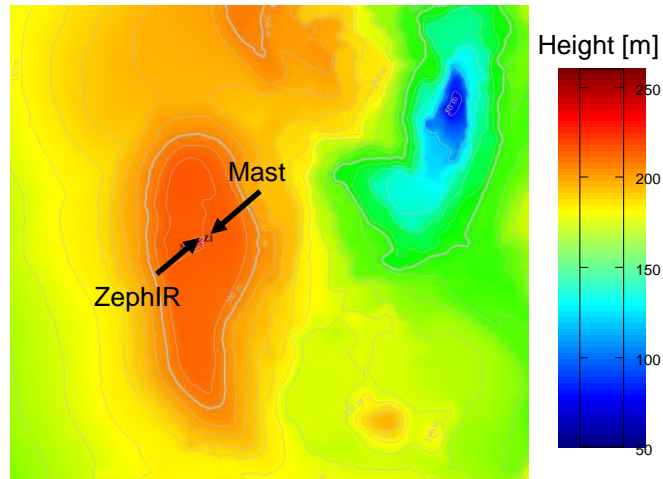


Figure 3: Contour plot of 1 km x 1 km around the test site in Southern UK.

Both WAsP and VENTOS were used to calculate flow conversion factors for the ZephIR lidar at this site. Figure 4 shows a comparison of predicted to actual measurements using the two models. As might be expected from the large RIX values in Table 1, the linear WAsP model fared less well than the non-linear VENTOS CFD code. Figure 5 shows plots of ZephIR and mast correlation for a measurement period of three months. The gradient of the ZephIR measurements changed from 0.97, a 3% under read, to 0.998 when the VENTOS/dynamics conversion factors were applied.

Sector centre [degrees]	RIX [%]
0	0.6
30	4
60	8.5
90	5.8
120	8.6
150	8.4
180	4.3
210	0.7
240	3.9
270	2.7
300	1.4
330	0.3
Average	4.1

Table 1: WAsP assessment of RIX for the test site. The western and eastern sectors exhibit the highest level of ruggedness.

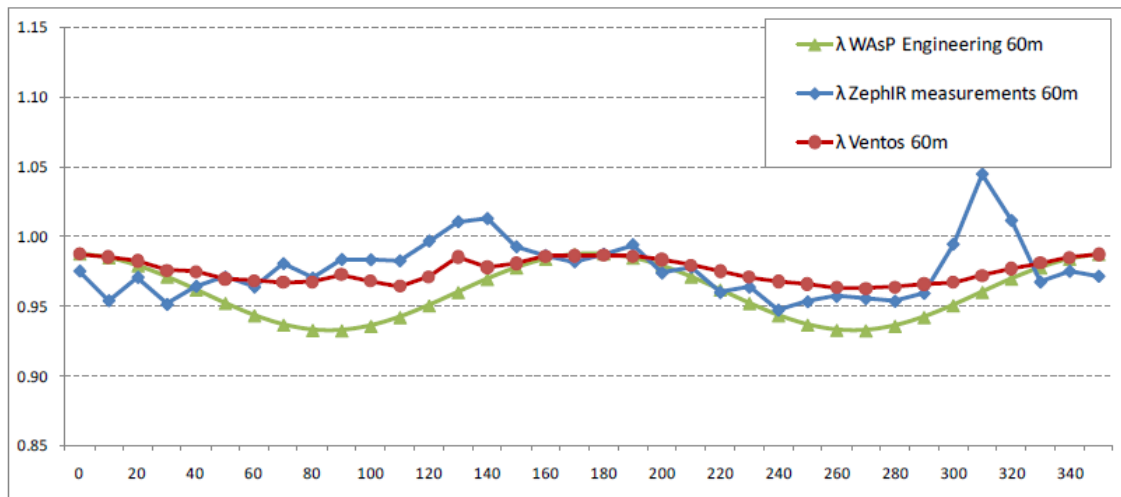


Figure 4: Sector by sector comparison of measured and predicted differences between mast and ZephIR wind speed measurements. The vertical axis is λ , the ratio of ZephIR to mast wind speed at 60 m above ground level. The blue curve plots the measured data (note the excursion around 310° is due to mast shadowing of the cup); red is the predicted results using VENTOS CFD; green is the predicted results using WASP Engineering.

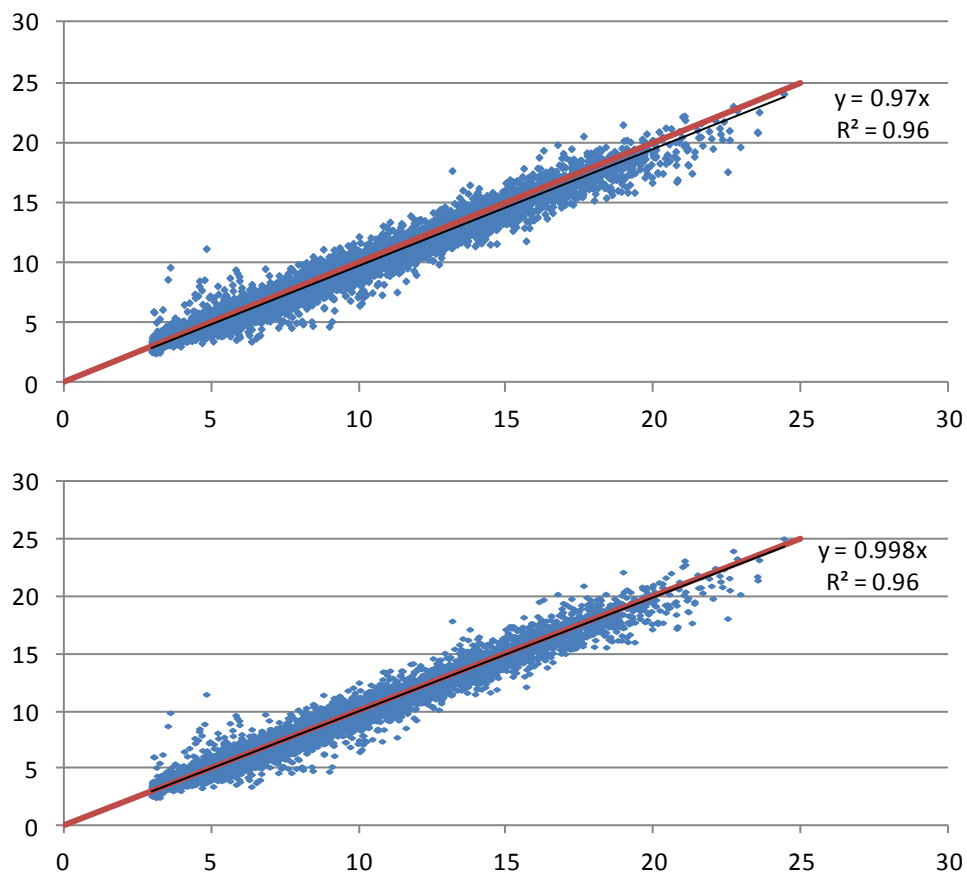


Figure 5: The upper plot shows unconverted, ten-minute averaged, ZephIR measurements (vertical axis [m/s]) versus mast measurement (horizontal axis [m/s]) at a height of 60 m. The lower plot shows the data after sector-wise conversion using VENTOS/dynamics.

The second case study was undertaken in collaboration with Agder Energi, Norway during winter 2010 at a site located in the South West of the country (Figs. 6 and 9). The site was equipped with a 80 m meteorological mast with calibrated Thies First Class cup anemometers mounted at 20, 60 and 80 m above ground level. The ZephIR was positioned within a few metres of the mast.



Figure 6: Trial site and meteorological mast in SW Norway illustrating the complexity of the terrain.

Figure 7 is a plot of the height and direction dependent conversion factors calculated before the measurement campaign by VENTOS/dynamics. At low heights, the conversion factor is very close to unity, whereas it has risen to over 4% at some directions for a height of 200 m. Typically, conversion factors decrease with increasing height as the effect of terrain reduces and geostrophic effect begin to dominate. However, the mast at this site was positioned on a relatively level ridge with steeper down slopes some way from the mast. Hence the flow at low heights was predicted to be quite homogeneous, whereas the effects of terrain speed up were expected to be observed only at higher heights.

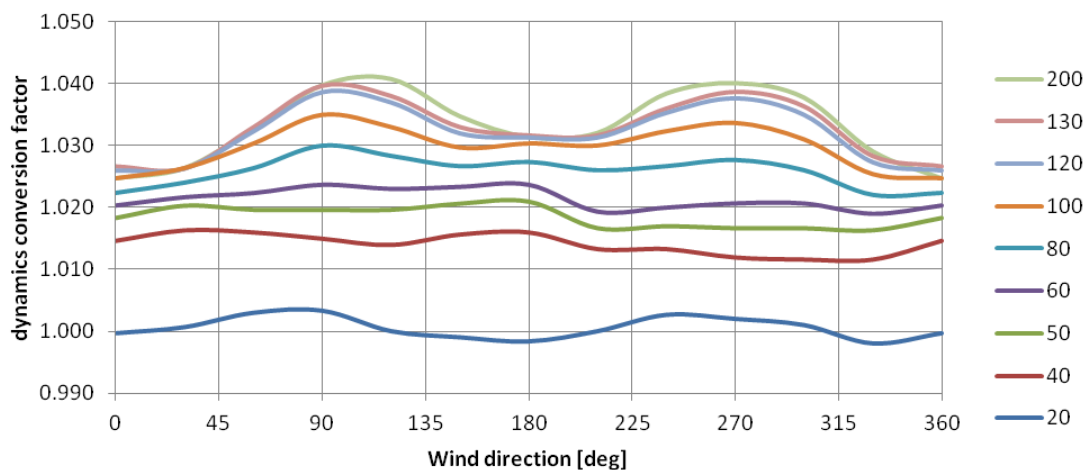


Figure 7: Height and direction dependent conversion factors calculated by VENTOS/dynamics for Norwegian trial site. The legend indicates measurement height in metres.

Figure 8 below shows converted and unconverted correlation plots of ZephIR versus cup at heights of 60 and 80 m. It can be seen that the bias of a few percent observed in the unconverted plots is eliminated after conversion and that R^2 , the coefficient of determination, is very close to unity. For the 20 m cup, gradients were 0.9995 before conversion and 0.9996 after.

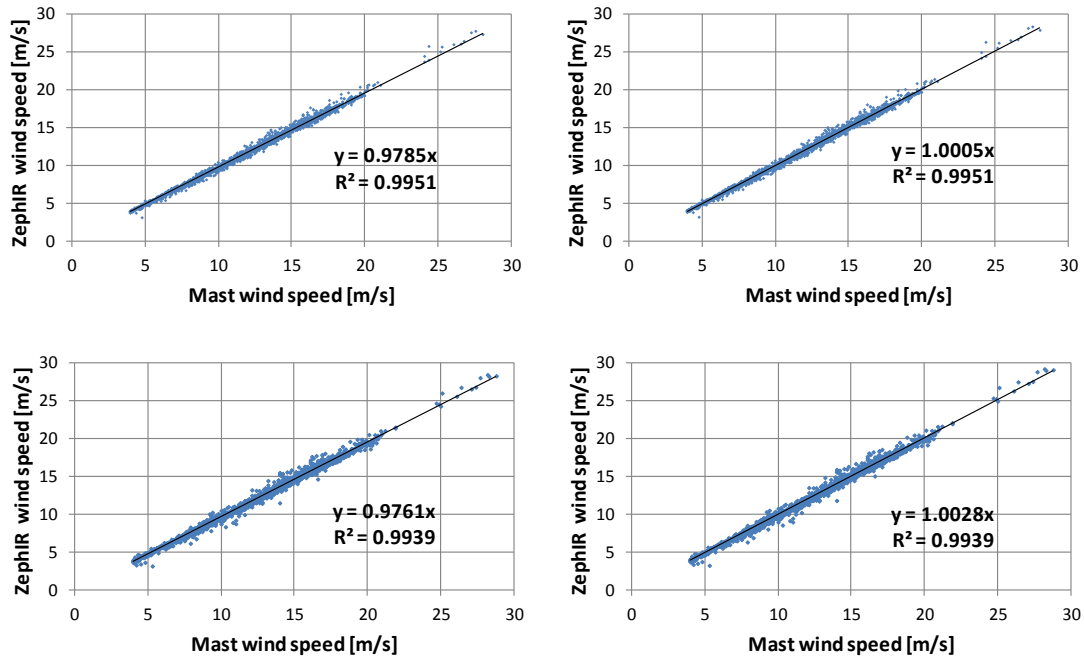


Figure 8: Correlation plots for ZephIR against the mast both before (left) and after conversion (right). Cup heights were 60 m (top row) and 80 m (bottom row).

To conclude this section on case studies, the results from blind trials on several sites in Southern Europe are summarised in Table 2. (Further details of these and other trials will be published shortly, subject to permission from partners). It can be seen that on modestly to highly complex sites across a range of measurement heights, the blind application of complex flow conversion using VENTOS/dynamics produces results that consistently lie within 2% of a co-located, mast mounted cup anemometer. In one case, the conversion factors were around 10% and the converted values within 1% of the calibrated cup.

Location	Height [m]	Forestry?	Blind test?	Unconverted regression gradient	Converted regression gradient
Greece	40	No	Yes	0.94	0.98
Greece	30	No	Yes	0.89	0.99
Greece	20	No	Yes	0.97	1.02
Spain	118	Yes	Yes	0.98	1.00
Spain	102	Yes	Yes	0.98	1.00
Spain	78	Yes	Yes	0.99	1.01

Table 2: Summary of results from a number of resource assessment campaigns in complex terrain around Southern Europe.

In addition to the studies in Table 2, a number of other campaigns have been carried out in terrain that is considered complex, based on the IEC definition. These cases have not been reported in detail here since the conversion factors were very small ($<2\%$) and the unadjusted lidar data already lay within an acceptable range of the mast measurements. The very small conversion factors required in these cases for seemingly complex terrain are likely to be a consequence of ZephIR's interrogation of 50 points around the scan disk.

Conclusions

This paper reports on several campaigns around the world using ZephIR lidars and VENTOS CFD analysis; in each case the terrain is classified as “complex” according to the IEC guidelines, and the lidar has been placed adjacent to a high standard mast to permit direct comparison of 10-minute wind parameters. A tool has been developed called “dynamics” which uses VENTOS to convert ZephIR measurements into mast-equivalent wind speeds. The terrain on which the measurements were carried out varied from moderately hilly to very mountainous and the bias introduced to uncompensated lidar measurements varied from just 1 or 2% up to a maximum of 11%. In all cases, the application of VENTOS CFD reduced the error in the lidar speed measurements compared to the masts to less than 2%, comparable to the error of a typical cup anemometer.

ZephIRs have been deployed in a wide range of hilly and mountainous terrain types, varying from modestly to highly complex. In many cases, only small conversion factors were required (less than 2%), indicating that the CW lidar measurement technique is quite robust in modestly complex flows. The conversion factors are typically (but not always) positive, reflecting hill-top and ridge-top locations, and they usually (again, not always) reduce with height as the effect on the terrain on airflow reduces. Because the ZephIR acquires 50 measurements of radial velocity during each one second scan, conversion factors are very robust to small misalignments in the direction of the ZephIR.

The results provide convincing evidence of the suitability of Doppler lidar for resource assessment in complex terrain, and of the ability of the technique for provision of bankable data of equal precision to a conventional meteorological mast. The methodology described here is fully automated and parameterised and hence quick and inexpensive to carry out.



Figure 9: ZephIR 300 lidar sited next to meteorological mast in complex terrain in Norway

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