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# Lidar performance in complex terrain modelled by WAsP Engineering

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## Abstract

A conically scanning lidar measures the vertical wind profiles in any height between 10 to 150m under the assumption of a homogenous wind field. In reality, especially over complex terrain, the flow is far from homogeneous. In this presentation we investigate the consequences of this on the precision of the wind measurements. We do that in two ways. Firstly, we compare collocated mast and lidar measurements from two experiments in complex terrain in Greece. Secondly, we simulate the flow over those terrains with Risø DTU software, WAsP Engineering 2.0, in order to predict the lidar performance. The measurement data are compared with the model predictions with good results for the hilly site, but with less success at the mountainous site. This is a deficiency of the flow model, but the methods presented in this paper can be used with any flow model.

## 1 Introduction

Lidars (**l**ight **d**etection **a**nd **r**anging) are becoming an alternative to meteorological masts for vertical profile measurements for the assessment of wind energy potential. They have several advantages over traditional anemometry such as ease of deployment and that large heights can be reached without excessive costs [1]. They have shown encouraging results reproducing cup anemometer wind speeds within a few percents both on- and off-shore, and several different types of lidars have been investigated thoroughly [2, 3].

This success has been limited to flat terrain and it is the purpose of this paper to investigate the performance in mountainous terrain, occasionally called *complex terrain*. Here the flow is no longer homogenous and that can give a large bias on the horizontal wind speed estimated from the lidar.

We studied the bias caused by inhomogeneous flow, both by comparing collocated mast and lidar measurements in complex terrain, and by predicting the bias by help of a simple flow model. We focus on the continuous wave (cw) lidar ZephIR developed by QinetiQ [4], but the basic problem also applies to any other lidar and sodars as well [5].

The ZephIR is used to measure a vertical wind profile with the height ranging from 10 to 150 m. At each altitude it measures the radial velocity in a circular pattern with a cone angle of 30.4° from which the horizontal wind speed can be derived. The crucial assumption in the process of calculating the horizontal wind from the radial measurements is that the flow is homogeneous within the scanned area. Any lack of homogeneity will introduce an error. To model lidar measurements and predict the error for different wind directions for a particular terrain we have analyzed two experimental data sets from two Greek sites: Lavrio and Panachaiko. At Lavrio, Centre for Renewable Energy Sources (CRES) [6] has a test facility and at Panachaiko a wind park. In both

sites the lidar is far from any wind turbine and very close to the meteorological reference mast. While the first site is situated in a gently sloping terrain the second site has a very complex structure and flow conditions. At both sites the lidar and meteorological mast data have been collected and flows for the same conditions are simulated with the WASP Engineering flow software developed by Risø [7]. Finally, real data are compared with the model results. WASP Engineering model is a linear flow model where the flow is modeled for neutral conditions. Additional tools for turbulent flow are not used in the data analysis.

## 2 Simplified analysis

We now derive where the mean wind field can vary linearly in any way and where the wind speed is determined from the lidar by fitting a trigonometric function to the radial velocities [8]. Without loss of validity the analysis is ignoring the fact that the QinetiQ lidar only measures the magnitude of the radial wind speed, not the sign.

Assume the mean wind field  $\mathbf{U} = (U, V, W)$  to vary linearly

$$U_i(\mathbf{x}) = U_i(\mathbf{0}) + x_j \frac{\partial U_i}{\partial x_j} \quad (1)$$

over a volume enclosing the lidar scanning circle. The origo of the coordinate system  $\mathbf{x} = \mathbf{0}$  is the center of the scanning circle elevated by  $h$  over the instrument. Let

$$\mathbf{n} = (\cos \theta \sin \varphi, \sin \theta \sin \varphi, \cos \varphi) \quad (2)$$

denote a unit vector in the direction of the laser beam, where  $\varphi$  is the half opening angle of the cone and  $\theta$  the azimuthal angle. The radial wind speed  $v_r$  measured at an azimuthal angle  $\theta$  is the projection of  $\mathbf{U}$  onto  $\mathbf{n}$ :

$$v_r(\theta) = \mathbf{n}(\theta) \cdot \mathbf{U}(\mathbf{n}(\theta)l - (0, 0, h)), \quad (3)$$

where the velocity field is evaluated in the position of the focus of the laser beam. Here  $l = h/\cos \varphi$  is the focus distance. The additional variations of the radial velocity due to lack of homogeneity may be expressed as  $v_r'(\theta) = v_r(\theta) - \mathbf{n}(\theta) \cdot \mathbf{U}(\mathbf{0})$ , and it can be written in terms of the velocity gradient:

$$v_r'(\theta) = n_i(\theta) (n_j(\theta)l - \delta_{j3}h) \frac{\partial U_i}{\partial x_j}. \quad (4)$$

Substituting (2) into this equation and ordering the terms as a Fourier series in  $\theta$  we finally get

$$\begin{aligned} v_r(\theta) &= W \cos \varphi + \frac{l}{2} \sin^2 \varphi \overbrace{\left( \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \right)}{= -\partial W / \partial z} \\ &+ \left( U \sin \varphi + l \sin \varphi \cos \varphi \frac{\partial W}{\partial x} \right) \cos \theta \\ &+ \left( V \sin \varphi + l \sin \varphi \cos \varphi \frac{\partial W}{\partial y} \right) \sin \theta \\ &+ \frac{l}{2} \sin^2 \varphi \left( \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} \right) \cos 2\theta \\ &+ \frac{l}{2} \sin^2 \varphi \left( \frac{\partial U}{\partial y} - \frac{\partial V}{\partial x} \right) \sin 2\theta. \end{aligned} \quad (5)$$

The horizontal and vertical wind speeds are derived from the lidar measurements by fitting a trigonometric series  $a + b \cos \theta + c \sin \theta$  to the data. The vertical wind speed is then  $a/\cos \varphi$  while the horizontal components are  $b/\sin \varphi$  and  $c/\sin \varphi$ , respectively. In the presence of a linear

deviation from homogeneity we thus get for the wind vector estimated from the lidar:

$$U_{\text{lidar}} = U + h \frac{\partial W}{\partial x} \quad (6)$$

$$V_{\text{lidar}} = V + h \frac{\partial W}{\partial y} \quad (7)$$

$$W_{\text{lidar}} = W - \frac{l}{2} \tan^2 \varphi \frac{\partial W}{\partial z} . \quad (8)$$

The important lesson to learn from these equations is that the error due to inhomogeneity of the mean flow will vanish for the vertical component as the half opening angle  $\varphi$  goes to zero, but the errors on the horizontal components are independent of  $\varphi$  [9].

### 3 The Experiments

The Lavrio site is located 38 km SE of the center of Athens close to the coast of the Aegean Sea. The experiment took place between 2008-Dec-01 and 2008-Jan-15. The highest point is 200 m ASL and main wind direction is  $0^\circ$ . The 100 m triangular lattice reference meteorological mast is equipped with cup anemometers and vanes at five heights (10 m, 32 m, 54 m, 76 m, 100 m). Cups are to the east and vanes are to the west. There are also ultrasonic 3D Gill anemometers at three heights (34 m, 78 m, 98 m) which are not used in this study due to problems with icing but this does not influence the used cup anemometers and vanes. Additionally, the temperature profile is measured using differential thermometers, as well as, the atmospheric pressure and the solar radiation. Dedicated instrumentation is used for signal protection, filtering and conditioning. The sensors are supported on the mast by the aid of telescopic booms of rectangular cross-section, made of high strength aluminum alloy. The boom cross-section is 50 mm×50 mm at base and 30 mm×30 mm at the end where the sensors are supported. All wind sensors (even the top ones) are mounted at a height of 45 cm above the boom and at a distance of 310 cm from the outer mast leg. The lidar is located nearly 12 m north of the mast. The measurement heights are 32 m and 78 m.

The Panahaiko site is located 165 km northwest of Athens, at Vounogiorgis mountain south east of the village Sella, 14 km south of the Patras Sea. The experiment ran from 2007-Sep-19 to 2007-Oct-11. The terrain in the vicinity of the site is very complex. Highest point is 2000 m in the region where the experiment surrounding is between 1700 and 1750 m ASL. The prevailing wind directions are ENE and SW. The triangular lattice reference meteorological mast has six cup anemometers (10 m, 20 m, 30 m, 40 m, 54 m) and two vanes (40 m, 54 m). Additionally, there are also air temperature and relative humidity measurements at 54 m. The boom cross-section is 40 mm×40 mm. All wind sensors are mounted at a height of 75 cm above the boom and at a distance of 225 cm from the outer mast leg. The lidar is located nearly 20 m WSW of the mast. The lidar measurement heights are 30 m and 55 m.

In both experiments lidar data are collected by the standard QinetiQ software and synchronized with mast data by the CRES WindRose software. Instruments are calibrated according to the requirements of IEC61400-12-1:2005/Annex F and MEASNET guidelines at CRES Laboratory for Wind Turbine Testing.

## 4 Theory and Method

### 4.1 WAsP Engineering

WAsP Engineering is a linearized flow model developed at Risø DTU. We have tested the model with different resolutions and map sizes and have chosen a small enough resolution that the results did not change significantly. The resolution should be so fine that the lidar's scanning circle is well resolved. For those reasons we choose for the Lavrio site a 4 m resolution with a 2.5 km map size and for the Panahaiko site a 10 m with a 5 km map size.

## 4.2 Modeling the lidar error

We want to calculate the radial velocity in the direction of the laser beam  $v_r$  in the points forming a circle, where the lidar is measuring. Then we use these values to derive horizontal wind speed in the same way as it is done in the QinetiQ ZephIR. We also calculate the horizontal wind speed at the mast position at the relevant heights.

The QinetiQ ZephIR makes scans in different heights with 50 data points on each circle. These data are fitted to a rectified trigonometric function to give the horizontal wind speed, the vertical wind speed and the wind direction. The instrument has a sign ambiguity on the wind vector, but that is resolved by crudely measuring the wind direction at the instrument.

To simulate the flow in the surroundings of the lidar and the meteorological mast we have constructed a piece of software in C# that calls the WASP Engineering flow calculation libraries. The following step are done:

- The measurement coordinates and measurements heights are set for the mast and the lidar.
- The unit vectors  $\mathbf{n}$  in a right handed coordinate system with the first axis is pointing towards east, the second axis towards north and the third upwards are calculated for each beam direction on the scanning circle

$$\mathbf{n}(\theta) = \{\sin \theta \sin \varphi, \cos \theta \sin \varphi, \cos \varphi\} \quad (9)$$

where  $\varphi$  is the half opening angle of the cone, approximately  $30.4^\circ$  for the ZephIR, and  $\theta$  is the geographical angle in which the beam is pointing.

- The position of the  $i$ th measurement point with a geographical angle  $\theta_i$  on the circle is given by

$$\mathbf{p}_i = h / \cos \varphi \mathbf{n}(\theta_i) + \mathbf{p}_{lidar} \quad (10)$$

where  $h$  is the measurement height, and  $\mathbf{p}_{lidar}$  is the position of the lidar. WASP Engineering uses the AGL (Above Ground Level) values as heights. So, the height for each point put in must be updated according to the difference between the lidar and point position elevations in order to find the height which is at the conical scan level. After that the horizontal wind speed  $U_h$ , the wind direction  $\theta_w$  and the tilt angle  $\phi_w$  can be calculated with WASP Engineering at these points.

- The wind vectors are projected on to laser beam direction by

$$v_r(\theta) = U_h \mathbf{n}(\theta) \cdot \{-\sin \theta_w, -\cos \theta_w, \tan \phi_w\} \quad (11)$$

- In a homogeneous flow  $v_r$  versus  $\theta$  would take the form of a simple trigonometric function. In complex terrain it may be quite different, but it is still fitted to

$$v_r = U_h \sin \varphi \cos(\theta - \theta_w) + w \cos \varphi \quad (12)$$

giving estimates of  $U_h$ ,  $\theta_w$  and the vertical wind speed  $w$ . We ignore the absolute value because the sign of the wind vector is known from the model.

- For the mast simulation, horizontal wind speed, wind direction and tilt values are computed for each cup and vane height.
- The final outcome is the ratio between  $U_h$  derived from the lidar circle and the horizontal wind speed at the cup position. A value of one would have been obtained over flat, homogeneous terrain.

## 5 Results

At Lavrio, most of the winds are northerly which means it is blowing from lidar to the mast. The scatter plots (Figure 1-top) show generally 5% to 7% errors in wind speed measurements. For the

WAsP Engineering model we have used 3 km to 3 km map with 4 m resolution simulating the wind direction from  $0^\circ$  to  $360^\circ$  with  $2^\circ$  bins. We have used all the data from the mast at each height and averaged them according to the wind direction in  $10^\circ$  bins.

The comparison between the model and the measurements is shown in Figure 1 (lower two plots) and shows good correlation in some sectors. The mast is voluminous, thus the selected data must be far from boom direction which is  $113^\circ$ . These sectors are marked with light grey areas in the plots for  $\pm 30^\circ$ . The ideal ratio line of one is also shown and it represents the cases where there is no difference between the lidar and the mast measurements. The black line is the model and the points are the measurement results.

Especially for northerly directions the model predicts the lidar error well for both heights, while for the southerly directions the prediction is not so good. We believe this can be a result of the limitation of WAsP Engineering. In southerly directions very close to the site there are steep slopes. In this sector and height, the flow model has difficulties predicting the tilt angles as compared to sonic measurements for periods with no icing problems.

The second site, Panahaiko, is much more complex than Lavrio, so there are many sectors which could be problematic for WAsP Engineering to model. The scatter plots in Figure 2 (top) show data for all directions. The mast at Panahaiko is smaller than at Lavrio so the sector with flow distortion is smaller ( $\pm 25^\circ$ ) shown in grey in the figure. The boom direction is  $210^\circ$ .

The comparison between the modeled error and the measurements as a function of direction is shown in Figure 2 (lower two plots). It is not a perfect prediction, but the model gives the right order of magnitude for this complex site.

The outliers mainly seen for the larger heights in figure 1 and 2 are probably due to cloud return as discussed in [10].

## 5.1 Ruggedness index (RIX)

The ruggedness index (RIX) of a given site is defined as the fractional extent of the surrounding terrain which is steeper than a certain critical slope [11, 12]. The index was proposed as a coarse measure of the extent of flow separation and, thereby, the applicability of WAsP, since it assumes that the surrounding terrain is sufficiently smooth to ensure mostly attached flows. The operational envelope of WAsP is, strictly speaking, a RIX value of  $\sim 0\%$ . This requirement also applies for WAsP Engineering since it is the same type of linearised flow model. The RIX concept has been used extensively over the last 10 years in wind resource assessment and siting studies in complex terrain.

The RIX value for one site is calculated for a number of radii originating at the site, by dividing each line into segments defined by the crossing of the line with the height contours. The sum of the line segments representing slopes greater than a critical slope (0.3 for our study as it is used in WAsP) divided by the total sum of the segments is then the RIX value of the radius in question [11]. The overall RIX value for the site, the site ruggedness index, is then simply the mean of the sector-wise RIX values.

Figure 3 shows a graphical representation of the ruggedness index for the two experimental sites. The center points are the lidar positions. Site ruggedness index for Lavrio and Panahaiko are 10% and 30% respectively. At both sites high RIX values seem to be correlated with the sectors where the model has problems predicting the error.

## 6 Conclusion

Lidars, used over flat homogeneous terrain, show errors in the mean wind speed of only a few percent. We have shown that in complex terrain of the type commonly used for wind turbine parks, errors in the horizontal wind speed as measured by a conically scanning lidar can be of the order of 10%. This is due to the lack of horizontal homogeneity of the flow, which is assumed in the interpretation of the lidar data. The findings are based on two experiments involving collocated lidars and meteorological masts in complex terrain, together with flow calculations over the same terrains. For that calculation we use WAsP Engineering, and we find that the calculations match the experiment except for some sectors where the terrain is particularly steep. This is not

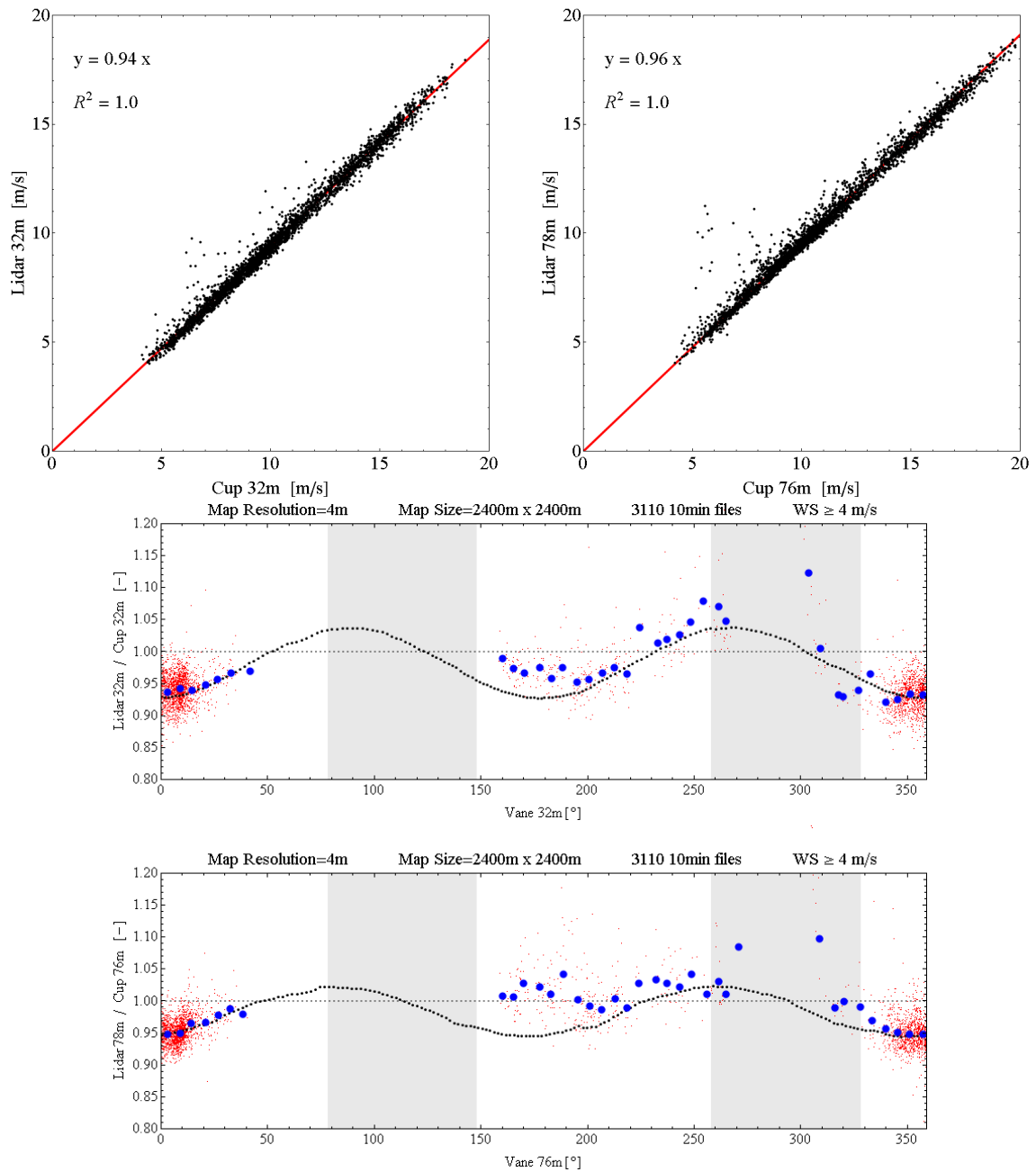


Figure 1: Lavrio: The scatter plots show generally 4% to 6% errors in wind speed measurements (top). Lower two plots are the comparison between the model and the measurement data for two different heights. Small red dots are the error ratio for each 10 minutes measurement, big red dots are the averaged  $6^\circ$  bins according to the wind direction and medium black dots are the model results. The mast shadow is marked with grey rectangles. The ideal ratio line of one, dashed blue, is also shown and it represents the cases where there is no difference between the lidar and the mast measurements. Especially for northerly directions the model predicts the lidar error well for both heights, while for the southerly directions the prediction is not so good.

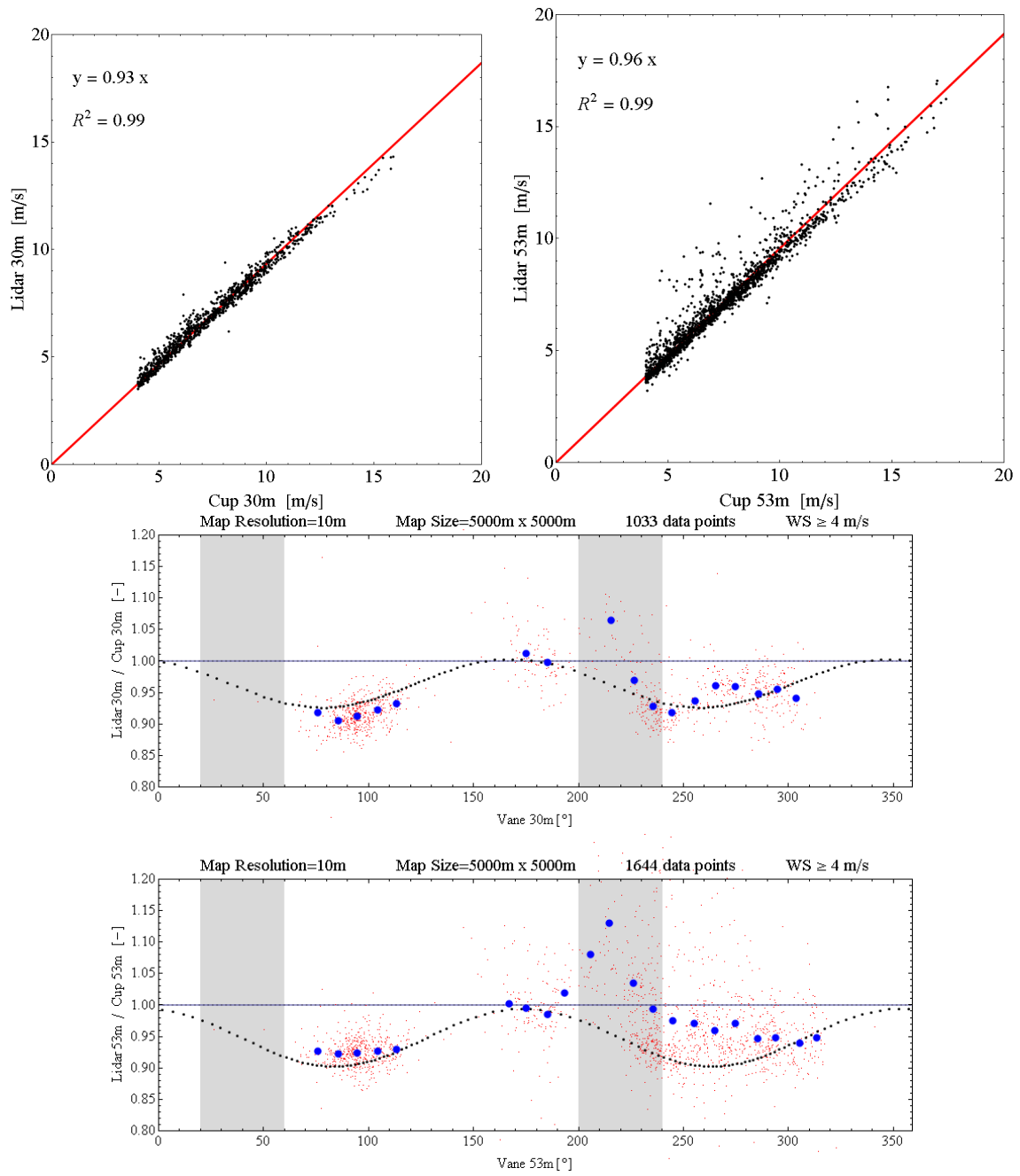


Figure 2: Panahaiko: The scatter plots show generally 4% to 7% errors in wind speed measurements (top). Lower two plots are the comparison between the model and the measurement data for two different heights. Small red dots are the error ratio for each 10 minutes measurement, big red dots are the averaged  $10^\circ$  bins according to the wind direction and medium black dots are the model results. The mast shadow is marked with grey rectangles. The ideal ratio line of one, dashed blue, is also shown and it represents the cases where there is no difference between the lidar and the mast measurements. It is not a perfect prediction, but the model gives the right order of magnitude for this complex site.



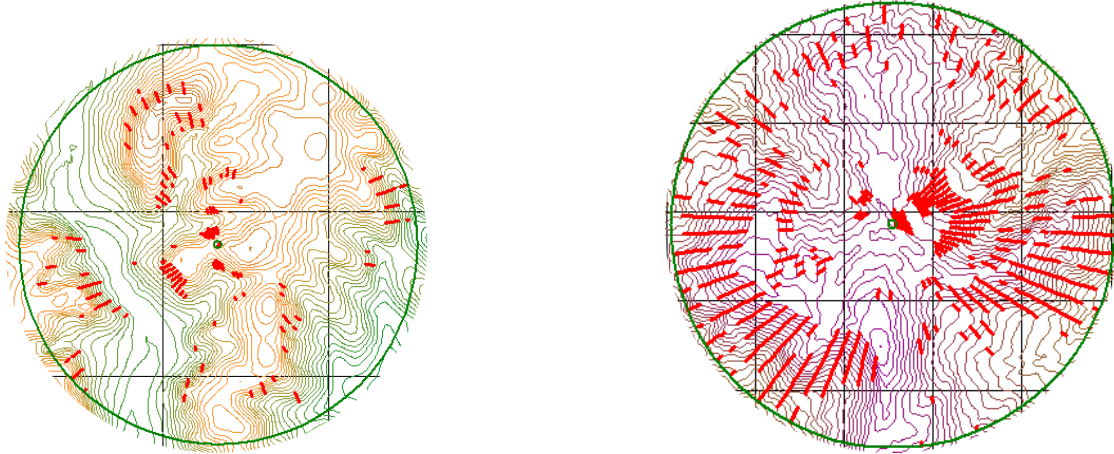


Figure 3: RIX plots for both sites; Lavrio (left), Panahaiko (right). Middle point is where the lidar is. RIX values (red) are calculated for the map size (each square is 1x1 km) and 0.3 RIX threshold with WAsP Tools. The sector where the model has problem have high RIX values. The site RIX value for Lavrio and Panahaiko are 10% and 30% respectively which is outside the operation envelope of WAsP Engineering.

surprising, since the WAsP Engineering is built on a linearized flow model, which is only valid for limited terrain slopes. To make more reliable predictions of the error in very steep terrain, other more advanced flow models must be used. We investigate the resolution needed for the WAsP Engineering calculations.

We envisage two solutions on how lidars can be used to estimate wind resources in complex terrain. The first is to use a conically scanning lidar, but instead of using the horizontal winds prone to errors, one could use the radial speeds directly to assimilate into a flow model. The second is to use several lidars focused roughly at the same point, so the assumption of homogeneity of the flow is superfluous. This last concept is suggested by [13].

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