

## Complex Terrain and Wind Lidars

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# Complex Terrain and Wind Lidars

Risø-PhD-Report

Ferhat Bingöl  
Risø-PhD-52(EN)  
August 2009

Risø DTU  
National Laboratory for Sustainable Energy

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**Title:** Complex terrain and wind lidars  
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**Abstract:**

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This thesis includes the results of a PhD study about complex terrain and wind lidars. The study mostly focuses on hilly and forested areas. Lidars have been used in combination with cups, sonics and vanes, to reach the desired vertical measurement heights. Several experiments are performed in complex terrain sites and the measurements are compared with two different flow models; a linearised flow model LINCOM and specialised forest model SCADIS.

**Contract no.:**

In respect to the lidar performance in complex terrain, the results showed that horizontal wind speed errors measured by a conically scanning lidar can be of the order of 3-4% in moderately-complex terrain and up to 10% in complex terrain. The findings were based on experiments involving collocated lidars and meteorological masts, together with flow calculations over the same terrains. The lidar performance was also simulated with the commercial software WAsP Engineering 2.0 and was well predicted except for some sectors where the terrain is particularly steep.

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Subsequently, two experiments were performed in forested areas; where the measurements are recorded at a location deep-in forest and at the forest edge. Both sites were modelled with flow models and the comparison of the measurement data with the flow model outputs showed that the mean wind speed calculated by LINCOM model was only reliable between 1 and 2 tree height ( $h$ ) above canopy. The SCADIS model reported better correlation with the measurements in forest up to  $\sim 6h$ . At the forest edge, LINCOM model was used by allocating a slope half-in half out of the forest based on the suggestions of previous studies. The optimum slope angle was reported as  $17^\circ$ . Thus, a suggestion was made to use WAsP Engineering 2.0 for forest edge modelling with known limitations and the applied method. The SCADIS model worked better than the LINCOM model at the forest edge but the model reported closer results to the measurements at upwind than the downwind and this should be noted as a limitation of the model. As the general conclusion of the study, it was stated that the lidars can be used in complex terrain with the known limitations and the support of flow models.

**Pages:60**  
**References:52**

*The thesis consists of a synopsis followed by journal articles and is submitted to the Danish Technical University in partial fulfilment of the requirements for the PhD degree.*

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To my father Faik Bingöl, the first engineer I met...

*Tanıdığım ilk mühendis, babam Faik Bingöl'e...*



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# 1 Introduction

The term “complex terrain” can be simply defined as any site where the wind is under effect of the terrain. This general definition includes landscapes with either vegetation or sudden elevation changes. In recent years, the interest of the European wind energy industry for such sites has increased. Formerly, they were considered as suboptimal for investments. This is not a coincidence and there are many reasons for such interest; most importantly the following two. Firstly, most of the suitable flat terrains have already been used. One example to this case is Northern Europe where the installed capacity is reaching its limit on flat terrain and the investors became more interested in complex sites. Secondly, the market is also growing in regions where wind resources are not fully utilized, like Mediterranean countries, where the land surface is dominated by rough terrain in the form of hills, mountains and forests. In both cases, the terrain poses a challenge for flow modelling because the assumptions of classical boundary-layer theory are violated which has a great impact on the site assessment. Therefore, current site assessment techniques are not *generally* reliable in such conditions, which may lead to reduced turbine/wind park life-time and loss of investment.

Despite the drawbacks, the statistics show that the total installed capacity in EU25 <sup>1</sup> zone grows 8000 MW/year since 2004 reaching 64000 MW in 2008 and an increasing growth rate is expected till 2030 (EWEA, 2008). Current wind production covers 4.2% of all electricity demand in EU27 <sup>2</sup> (EEA, 2009). The growth rate and the commitment of the industry show that the interest in complex terrain wind farming will increase.

According to the European Environmental Agency (EEA), 42% of the 5.4 million km<sup>2</sup> EU27 land is covered with forests (Eurostat, 2008; EEA, 2009). A spatial view of the land use in Europe and its neighbours can be seen in figure 1 (JRC, 2006). Most of the forested areas are distributed in Sweden, Spain, Finland, France, Germany and Italy, in order of biggest percentage. It is the Risø Forest Study Group’s estimation, after personal communication with major wind turbine developers, that 20 – 30% of the total European wind energy growth takes place in areas where the wind flow is affected by forests.

A terrain slope map of Europe as derived from GLOBE Digital Elevation Maps (Hastings et al., 1999) shows that the largest percentage of the current installed capacity is in Northern Europe where the largest portion of the available flat homogeneous terrain is located (figure 2). Furthermore, the figure also shows that the new wind parks with higher capacity are chosen to be located away from the steeper areas. Areas where forest and high terrain slopes coincide have been even more clearly avoided by the developers (figure 3).

Based on this spatial information, one can assume that the complex sites will be one of the major challenges that the wind industry will face in order to reach the goals mentioned in the second paragraph.

In addition to land cover and elevation complexity challenges in the terrain, the wind industry faces another equally important challenge related to the size of the wind turbines. In the last decade, the turbine hub heights have doubled, reaching a minimum of 100 m with 100 m of rotor diameter. The top and bottom edges of the blade of such turbines are typically at 150 and 50 m above ground level (a.g.l.), respectively. If one has to identify the wind conditions at these heights, knowledge beyond the classical site assessment methods would be needed (Peña,

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<sup>1</sup>European Union : Austria, Belgium , Cyprus, Czech Republic, Denmark, Estonia , Finland , France , Germany, Greece, Hungary, Ireland, Italy , Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom.

<sup>2</sup>EU27 was formed in 2007 with addition of Bulgaria and Romania to the EU25



2009). Procedures are needed for the verification of the power curve for wind turbines erected in complex terrain because the power curve variation is 6 – 8%, higher compared to that measured over flat terrain (Pedersen et al., 2002).

This multitude of factors has created the need for a new generation of measurement devices with certain capabilities. The instruments should be able to measure up to 200 m to cover the whole rotor swept area. They must be able to perform in profile measurement standards (e.g. IEC (2005)) and be easy to install/operate in complex terrains.

The above requirements cannot easily be fulfilled with conventional meteorological masts. For example, the installation of a meteorological mast at a forest site and its maintenance, is a big logistical problem. Furthermore minor adjustments on the position of the meteorological mast entails almost the same amount of work as installing it.

A category of instruments which can meet these goals is the wind energy Light Detection and Ranging (lidar) instruments. Traditional lidars are well-known but they are too expensive to use, have a short life span and are difficult to operate both physically and computationally. In recent years, the British company QinetiQ implemented previous lidar knowledge into a wind energy lidar concept and produced a relatively small, cheap and easy to handle, vertical wind profile measurement system; ZephIR<sup>3</sup>. ZephIR can be set up in approximately 1 hour in full operation mode and can be mobilized with a minor effort. The instrument can measure between 10 and 180 m. The first prototype was bought by Risø in 2004 and was tested over flat terrain. Preliminary tests provided the knowledge of the technical limitations of the instrument and the possible improvements (Jørgensen et al., 2004; Antoniou et al., 2004; Bingöl, 2005). In 2005, the commercial model of the instrument came into the market and since then both versions have been widely used at Risø (Smith et al., 2006; Antoniou et al., 2006; Peña et al., 2007; Mikkelsen et al., 2008; Courtney et al., 2008; Peña et al., 2009b). Nowadays, there are similar instruments produced by other companies, like the Leopshere’s Wind-Cube or the Sgurr Energy’s Galion.

The main drawback of the wind lidars is that the horizontal wind measured from the instruments are based on the assumption that the data are collected on flat homogeneous terrain. Hence an adaptation to complex terrain is needed. Lidars have been previously adapted to various needs and used out of their designed envelope (Bingöl, 2005; Mikkelsen et al., 2008; Bingöl et al., 2009c; Trujillo et al., 2009). Such adaptations are of interest to wind turbine producers, wind park developers and the boundary layer meteorology community, as well as the lidar producers.

The lidars are also becoming a part of international standards. The International Electrotechnical Commission (IEC) is revising the current “Power Performance Measurement Techniques” standard (IEC 61400-12-1) for including the use of lidars for vertical wind speed profile measurements. When this thesis was being written the revision of the standard was in progress.

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<sup>3</sup>ZephIR wind energy lidar is owned by Natural Power Ltd. since 2006.

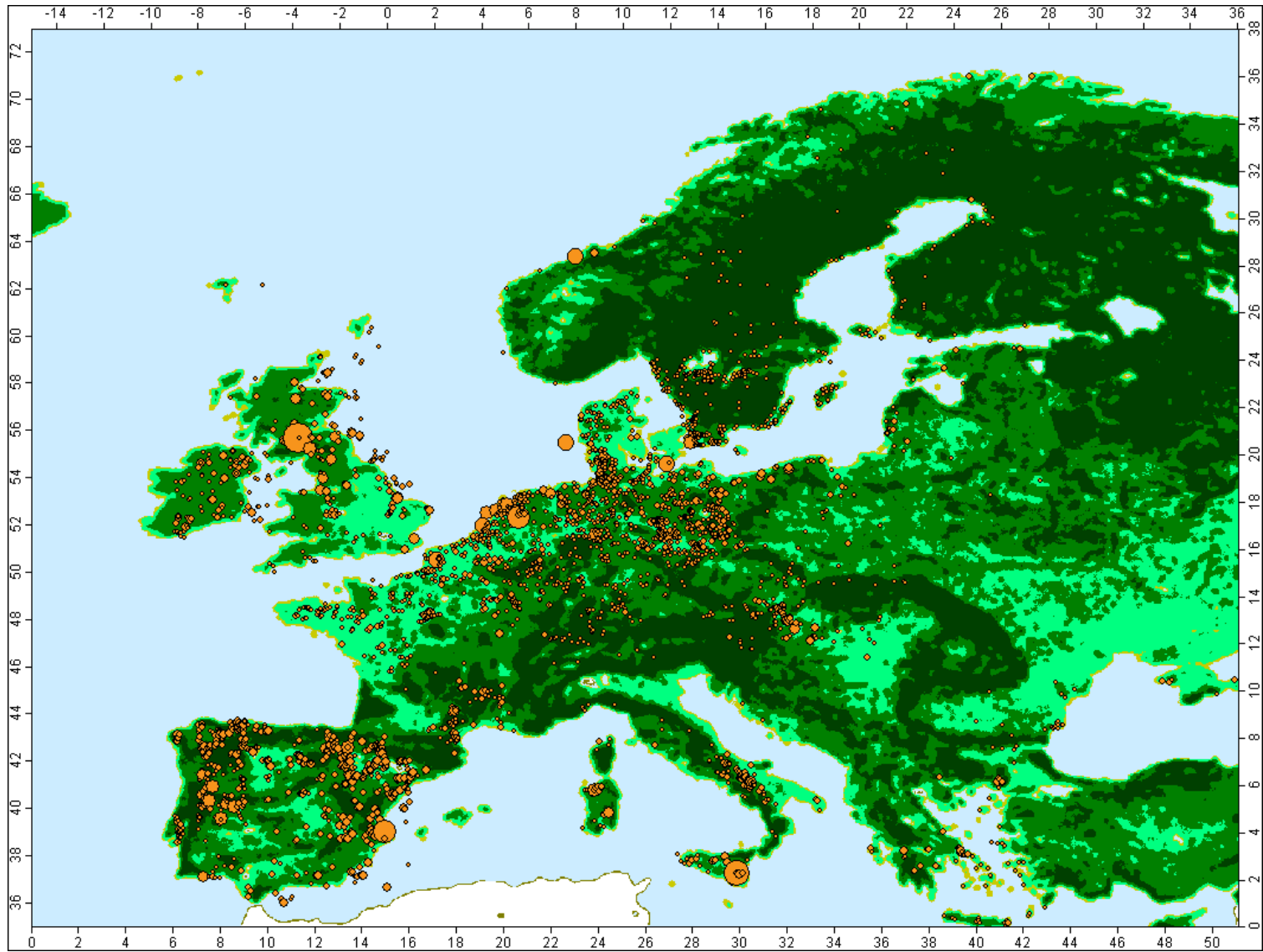


Figure 1. Spatial distribution of land use in Europe derived from an EEA study ([JRC, 2006](#)). Dark green areas are forest; green areas are sparse forest or shrub/herbaceous cover. Light green areas are crop land. Wind park locations with capacity between 3 and 322 MW are denoted by orange disks. The diameter of the disk is proportional to the installed capacity ([TheWindPower.net, 2009](#)).

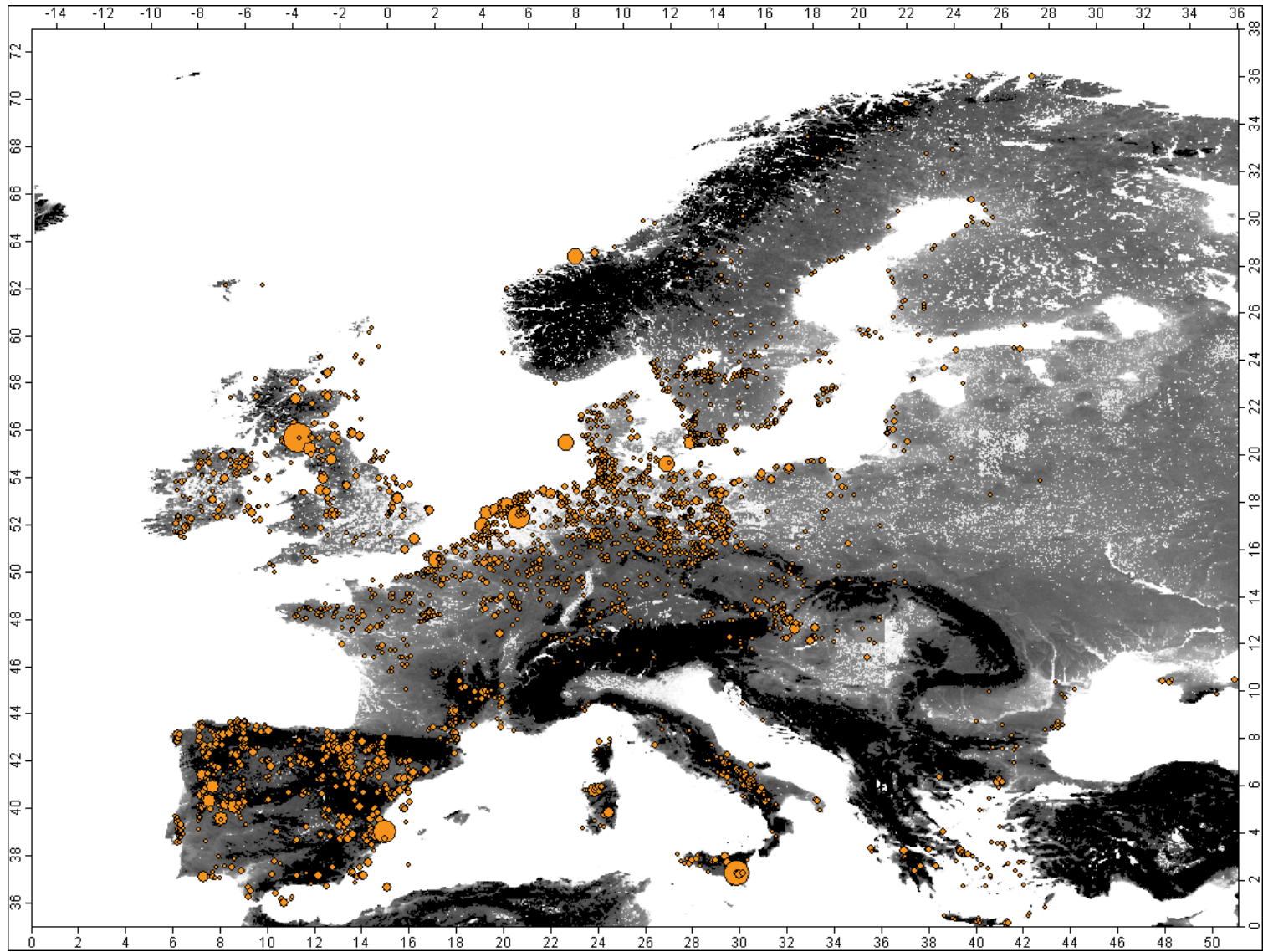


Figure 2. Terrain slope map of Europe and its neighbours derived from 1 km grid size map of [Hastings et al. \(1999\)](#). The black areas are the regions where the slope is higher than  $20^\circ$ . Wind park locations with capacity between 3 and 322 MW are denoted by orange disks. The diameter of the disk is proportional to the installed capacity.

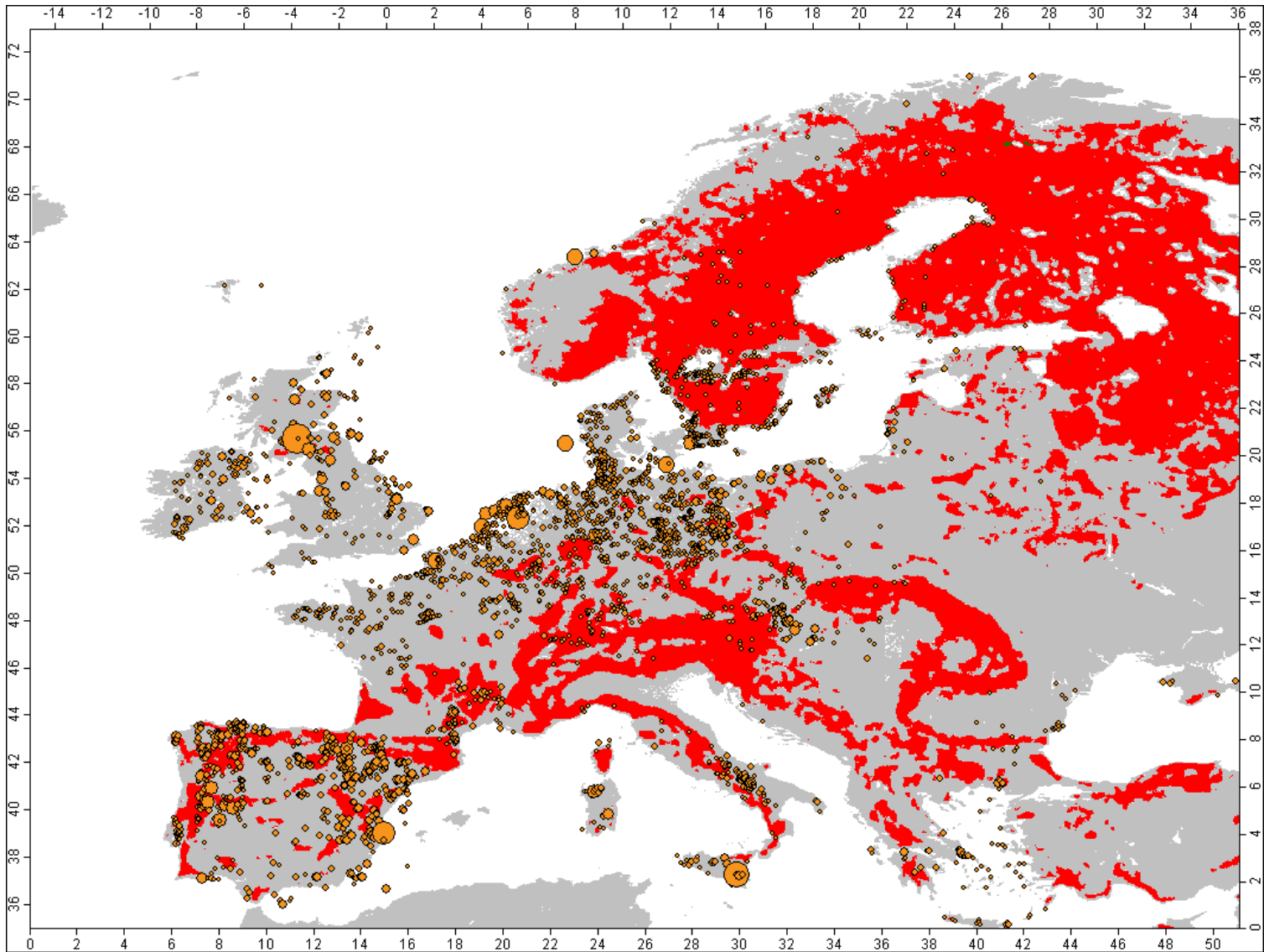


Figure 3. Areas where forest and high terrain slopes coincide, denoted by red colour. The grey areas are the rest of the terrain. Wind park locations with capacity between 3 and 322 MW are denoted by orange disks. The diameter of the disk is proportional to the installed capacity.

## 2 Structure of the thesis

The main focal points of the present thesis - lidar instruments and wind flow over complex terrain, primarily forests - are both relatively new areas of research and very much “work in progress”. Studying the way they interact requires a step-by-step approach in order to understand key aspects of each one.

Having acknowledged more research and installation of turbines go side-by-side over “complex terrain”, it is worthwhile to define the term in more detail. The author’s definition of complex terrain is given in the next section. Subsequently, background information is given on the instruments and their modes of operation, followed by brief descriptions of the experiments and results. The order in which the experiments were conducted and the results are presented follows a logical progression as knowledge gained in each experiment was instrumental in designing and analysing the following ones.

Any published/submitted section of the study is referred to the related articles after a brief introduction explaining its input to the thesis because the author prefers to include only the knowledge that is not already presented in the journal publications. In addition to the journal papers, a number of conference papers and two technical reports were published during the study period:

### Reports

- Dynamic wake meandering modelling  
Larsen, G. C.; Madsen, H. A.; **Bingöl, F.**; Mann, J.; Ott, S.; Sørensen, J. N.; Okulov, V.; Troldborg, N.; Nielsen, M.; Thomsen, K.; Larsen, T. & Mikkelsen, R.; Risø Report [Risø-R-1607\(EN\)](#) 2007
- Modelling conically scanning lidar error in complex terrain with WAsP Engineering  
**Bingöl, F.**; Mann, J. & Foussekis, D.; Risø Report [Risø-R-1664\(EN\)](#) 2008

### Conference Proceedings

- European Wind Energy Conference 2009, France  
Lidar performance in complex terrain modelled by WAsP engineering  
**Bingöl, F.**; Mann, J. & Foussekis, D.; Conference paper and presentation
- European Wind Energy Conference 2009, France  
Wind and turbulence at a forest edge  
Dellwik, E. ; **Bingöl, F.** ; Mann, J. & Sogachev, A.; Presentation
- ISARS 2008, Denmark  
Fast wake measurements with LiDAR at Risø test field  
**Bingöl, F.** ; Trujillo, J.J. ; Mann, J. & Larsen, G.C.; Conference paper and presentation DOI: [10.1088/1755-1315/1/1/012022](#)
- ISARS 2008, Denmark  
LiDAR error estimation with WAsP engineering  
**Bingöl, F.** ; Mann, J. & Foussekis, D. ; Conference paper and poster DOI: [10.1088/1755-1315/1/1/012058](#)
- ISARS 2008, Denmark  
Laser measurements of flow over a forest  
Mann, J. ; Dellwik, E. ; **Bingöl, F.** & Rathmann, O.; Conference paper and poster DOI: [10.1088/1755-1315/1/1/012050](#)



- European Wind Energy Conference 2008, Belgium  
Wind profile measurements over a forest with lidar  
Rathmann, O. ; Mann, J. ; Dellwik, E. & **Bingöl, F.**; Presentation
- Advances in Turbulence 9 2007, Portugal  
Laser based measurements of profiles of wind and momentum flux over a canopy  
Mann, J. ; **Bingöl, F.** ; Dellwik, E. & Rathmann, O.; Conference paper DOI: [10.1007/978-3-540-72604-3\\_218](https://doi.org/10.1007/978-3-540-72604-3_218)
- 3rd PhD Seminar 2007, Pamplona  
Wind Profiles and Forest  
**Bingöl, F.**; Mann, J. ; Dellwik, E. & Rathmann O.; Presentation
- European Wind Energy Conference 2007, Milan  
Laser measurements of wake dynamics  
**Bingöl, F.** ; Mann, J. & Larsen, G. C.; Conference paper and presentation
- The Science of Making Torque from Wind 2007, Denmark  
Wake meandering - an analysis of instantaneous 2D laser measurements  
**Bingöl, F.** ; Larsen, G.C. & Mann, J.; Conference paper and presentation  
DOI: [10.1088/1742-6596/75/1/012059](https://doi.org/10.1088/1742-6596/75/1/012059)
- Nordic wind power conference 2007, Denmark  
Lidars in wind energy  
Mann, J. ; **Bingöl, F.** ; Mikkelsen, T. ; Antoniou, I. ; Courtney, M.S. ; Larsen, G.C. ; Dellwik, E. ; Trujillo, J.J. & Jørgensen, H.E.; Presentation



# 3 What is complex terrain?

As it is stated in the introduction, the IEC 61400-12 standard defines complex terrain as “*the terrain surrounding the test site that features significant variations in topography and terrain obstacles that may cause flow distortion*” (IEC, 2005). The mentioned *distortion* occurs due to three major effects in the standard:

- average flow inclination angles as high as  $\pm 15^\circ$
- substantially higher (e.g. double) turbulence intensity than that over a flat terrain
- isotropic turbulence

The standard also states that the classification of the complex terrain is “work in progress” for next editions. When this thesis was written, the standard was under revision. For now, the listed parameters picture the flow in complex terrain but this is not a strict classification. Therefore, the author thinks that his understanding of the term should be explained. However, parametrizing complex terrain is beyond the scope of this thesis and a mild classification is introduced *only* to describe the level of the complexity of the terrain, which is used in the rest of the thesis. The aim is to make it easier for the reader to identify the referred terrain conditions in the text.

The term complex terrain is divided into the moderately-complex, complex and highly-complex sub-categories. The complexity classes are determined based on the current general knowledge and understanding of the “European Wind Atlas” (EWA) (Troen and Petersen, 1989), but re-arranged and extended using the combinations of roughness classes and landscape types. In EWA the terrain is classified based on roughness length,  $z_o$  (Classes), and landscape types (Types). The roughness length changes between 0 and 0.4 m and there are 5 different types of landscapes. The sketches of the related terrain types are illustrated in figure 4.

## 3.1 Flat terrain

A terrain is defined as flat when the flow above can be assumed to be horizontally homogeneous. In the EWA classification, Class 0, 1 and 2 are flat terrains. Class 0 is the class for the water areas ( $z_o = 0.0002$  m). Class 1 is the terrestrial areas with few wind breakers. Bushes or farms are also included in Class 1 ( $z_o = 0.03$  m). If the number of wind breakers is higher but the distance between farms or similar structures is more than 1000 m, the terrain is classified as Class 2, which has the highest roughness length for flat terrain ( $z_o = 0.10$  m). If the landscape includes plain areas, water bodies and is located far from mountains, it also defined as landscape Type 1.

In this thesis, any combination of Type 1 landscape with the above mentioned roughness classes is called flat terrain. Flat terrains in Europe are denoted by light green and light grey colours in figure 1 and 2, respectively.

## 3.2 Moderately-complex terrain

Beyond flat terrain, the understanding of the author about the roughness length and landscape type differs from the suggestions of EWA where all urban and forest areas are put into one single class; Class 3 with  $z_o = 0.40$  m.

When it comes to any type of terrain with high roughness, a single class would not be adequate to identify the effect of the terrain characteristics on wind flow. Hence, it is deemed necessary to divide it into several classes.



In this thesis, the first subclass is called moderately-complex terrain and occurs in different landscape types and vegetations. These different terrains are assigned the same complexity level, because their effects are similar for wind turbines and thus for wind energy.

### Hilly sites

The first example to the moderately-complex terrain is the non-forested hilly sites with a maximum  $z_o$  of 0.10 m. In such sites the dominant effect on the wind is not due to the roughness, but the landscape type. EWA assigns this landscape to Type 1 or 2 where the horizontal dimensions of the hills are less than a few kilometres and the terrain does not include any high vegetation. Sites with maximum elevation differences up to 100 m and slopes between  $5^\circ$  and  $10^\circ$  are called moderately-complex terrain in this study. Such sites in Europe are denoted by dark grey colours in figure 2.

### Vegetated sites

The author also classifies the “flat terrain with low-level sparse vegetation” where canopy height is between 5 to 10 m as the moderately-complex terrain. The effect of the vegetation does not dominate but it is still apparent on the wind flow. The terrain has a roughness length equal to or higher than 0.4 m and the landscape type is categorised as Type 2 or 3 in EWA.

This type of terrain is also named as moderately-complex in the thesis because the effects of the vegetation are similar to those of small hills causing similar flow inclinations and are not as pronounced as those caused by denser vegetation (e.g. forests). Furthermore in such terrains the heights of interest for wind energy are not under the effect of the vegetation significantly. Such sites in Europe are shown in green colours in figure 1.

## 3.3 Complex terrain

When the elevation differences are higher (e.g. mountains) or the vegetation becomes more dense and taller (e.g. forests), the effect on the flow is more pronounced. The following terrain types are assigned to the same complexity level, termed complex terrain.

### Mountains

When the slope is bigger than  $\approx 10^\circ$  the terrain has much more dramatic effects on the wind flow. The wind separates from the terrain to a larger extent and creates higher turbulence and negative wind gradients. In such sites the horizontal dimensions of the mountains are of several kilometres.

The roughness length does not differ from the moderately-complex sites if there is no high vegetation, but the landscape type is equivalent to EWA Type 4 or 5. In this study, such sites are named as complex terrain and are denoted by black colour in figure 2.

### Forests

The effect of the vegetation is dominant on the wind flow around it if the canopy height is higher than  $\approx 10$  m. If the location of interest is under the effect of sudden changes of roughness length or canopy height, the site will show complex terrain flow characteristics, even if the surrounding terrain is flat. Unless the chosen

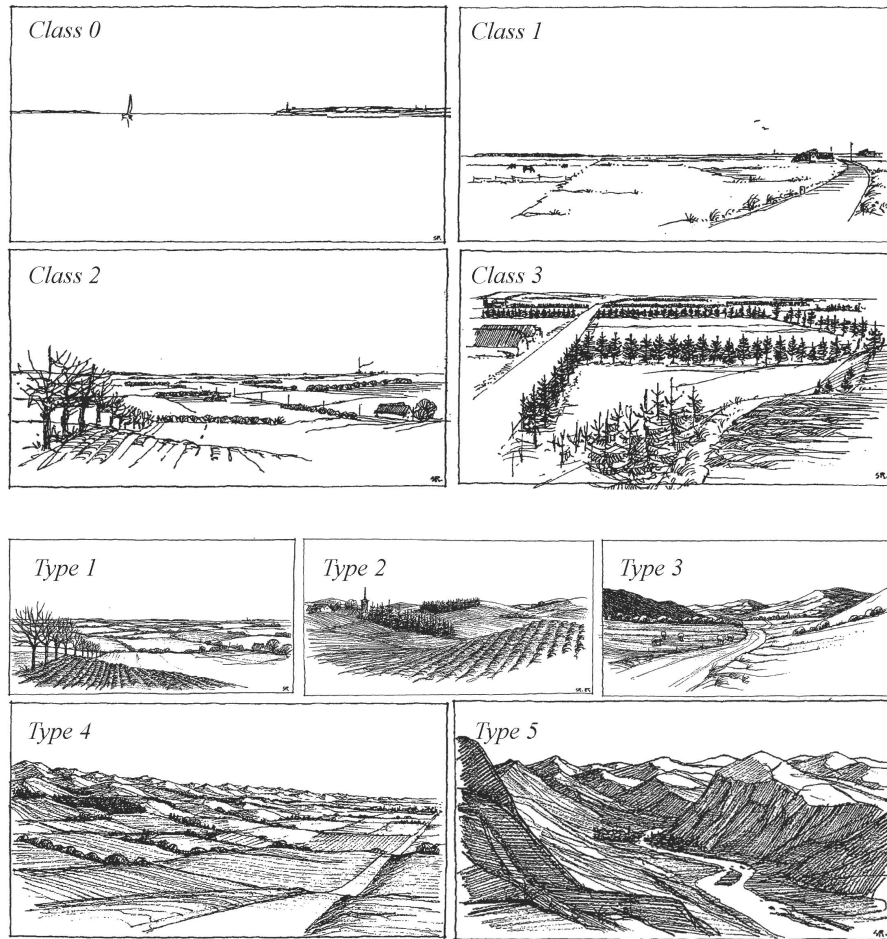


Figure 4. Examples of terrains corresponding to the EWA roughness classes (top four) and landscape types (bottom five). In this study Classes 0,1 and 2 in combination with landscape Type 1 are defined as flat terrain. Sites with either vegetated areas or hills as in landscape Types 1 and 2 are defined as semi-complex terrain. Sites with high terrain slopes or vegetation over 10 m as in landscape types 3, 4 and 5 are defined as complex terrain. Any site including vegetation and high slopes at the same time is defined as highly complex terrain. (Sketches are used with permission and are taken from European Wind Atlas, [Troen and Petersen \(1989\)](#))

location for a turbine is deep enough in the forest where the wind flow is in equilibrium or far away from the forest where the effect of is minimal, the wind conditions are totally different than those over the surrounding flat terrain.

The roughness length of the forest is much more difficult to determine and differs based on the vegetation type and to a lesser degree on wind speed. Such sites have not been classified in EWA and are denoted by dark green colour in figure 1.

### 3.4 Highly-complex terrain

The term is used by the author to describe sites including any combination of semi-complex or complex site characteristics (e.g. forested hill/mountain). Such sites in Europe are denoted by red colour in figure 3. No further classification is made after this level.



## 4 Lidar theory & methods

The lidars have become a part of wind energy meteorology after 1997 (Mayor et al., 1997). The capabilities of the instrument were well-known but the necessary investment was too high for many applications and the operating heights were not relevant to wind energy related studies. Therefore, the usage of lidars is recent and it started after the “wind energy lidars” are developed (Jørgensen et al., 2004).

Each article submitted with this thesis includes a section describing the use of each lidar limited to the purposes which it was used for. The author also gives a combined knowledge on lidar theory and methodology as presented below.

### 4.1 ZephIR

The British company QinetiQ designed a cost effective lidar model, ZephIR, in 2002. Risø DTU bought the first *prototype* (figure 5-right) in 2004 and the *commercial* version (figure 5-left) in 2005.

The prototype and the commercial models differ from each other mainly in physical appearance and in minor signal processing capabilities. The prototype is a combination of two parts; an optical head and the laser source/sensor. The parts are separated by means of an optical cable, while in the commercial model the two part have to be assembled directly together with a third containing a battery. For both versions, comparisons with several tall, meteorological masts have already proven the instrument to be accurate over flat homogeneous terrain (Antoniu et al., 2004; Smith et al., 2006) and offshore (Peña et al., 2009b). In complex terrain, the interpretation of the lidar data is still under development and Bingöl et al. (2009b) addresses this issue.

The instrument is a scanning tool that focuses the laser beam at different heights between 10 and 180 m and essentially assesses the radial velocity along the beam direction at the point of focus. The laser beam is deflected an angle  $\phi \approx 30^\circ$  from the vertical by making use of a prism, which rotates one full revolution every second. The along beam or radial velocity component of the wind is thus measured on a circle as indicated in figure 6-(left). The ZephIR is a continuous wave lidar, therefore it can only measure at the focus height. For each focus height, the prism rotates three times before the instrument changes focus to the next height. At each full revolution, 49 radial velocities are recorded and a total of 147 measurements in three seconds are used to derive the wind speed. It is possible to change the focus distance in 1 second. The number of prism rotations, the signal processing speed and the recursive focus height change can be adjusted freely for the prototype model (Bingöl, 2005; Bingöl et al., 2009c).

In conical scanning mode, the measured radial wind speed,  $v_r$ , combined with the scan azimuth angles,  $\theta$ , are fitted to the function (Harris et al., 2006, 2007):

$$v_r(\theta) = |A \cos(\Theta - \theta) + B| \quad (1)$$

where

$$U = \frac{A}{\sin \phi} \quad w = \frac{B}{\cos \phi} \quad . \quad (2)$$

The instrument can only measure the absolute value of the velocity. Therefore, the wind direction,  $\Theta$ , is directly taken from the fit with a ambiguity of  $180^\circ$  which can be identified with the wind direction readings from the instrument’s built-in mast. If the built-in vane is not present, as in prototype, a wind direction measurement is needed. The instrument records the 3 second statistics as well as the 10 minutes averages and one can use the raw data, which can be also

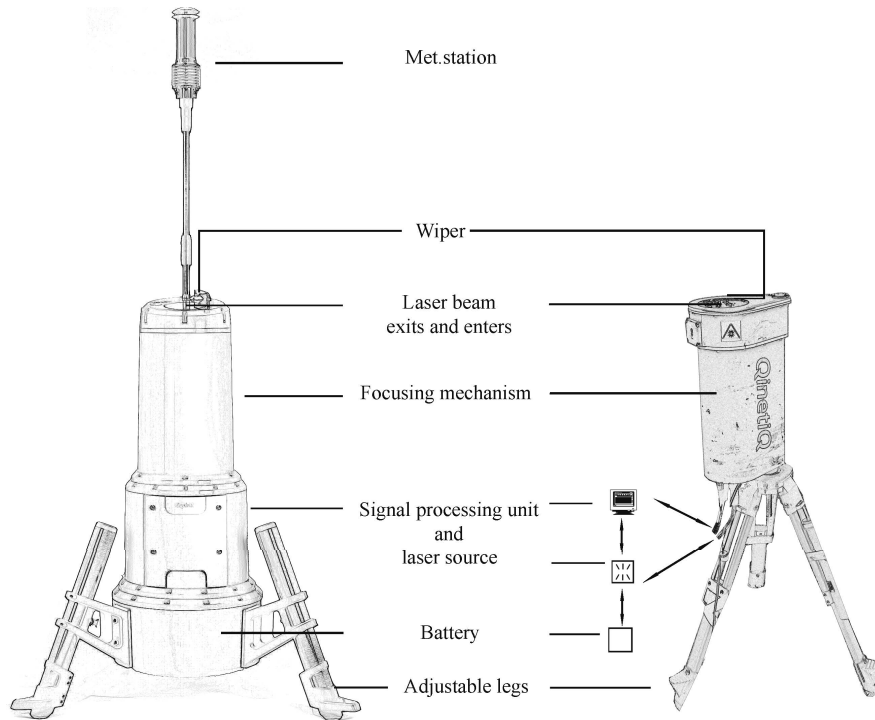


Figure 5. The ZephIR models which are used in the study. **Left:** The commercial model which is 1.7 m tall and 0.5 m width. The instrument weights 100 kg. **Right:** The prototype which is 1.5 m tall with adjustable legs. Including the signal processing unit, laser source/sensor and battery which are separated from the head by means of an optical cable, it weights 120 kg.

recorded on demand, to calculate longer period averages or turbulence parameters. In this study, 30 minutes radial wind speeds are used, if the raw data are present, otherwise 10 minutes averages are preferred.

It is possible to remove the prism from a lidar and turn it into a “straight shooter” scanner where it measures the wind speed in the direction it is pointed. This working mode is referred as *staring mode* in this study. In staring mode, the beam direction is fixed and the instrument focuses at different distances and measures the component of the wind vector (figure 6-right). The wind direction cannot be measured. Therefore, the beam direction must be known and the measured data must be used combined with a wind direction measurement instrument.

The staring mode approach was applied for the first time by [Harris et al. \(2006\)](#) with the aim of investigating possibilities for controlling the wind turbine based on upstream wind measurements with the prototype model of the ZephIR lidar. Subsequently, the prototype is used in other experiments in this context, like by mounting on a wind turbine to measure the wake behind ([Bingöl et al., 2009c](#); [Trujillo et al., 2009](#)), for synchronized multi-lidar field measurements ([Mikkelsen et al., 2008](#)) and horizontal wind profile measurements ([Bingöl et al., 2009a](#)).

## Thesis References

PAPER I : [Bingöl, Mann, and Larsen \(2009c\)](#) on p.47

PAPER II : [Trujillo, Bingöl, Larsen, Mann, and Kühn \(2009\)](#) on p.49

PAPER V : [Bingöl, Mann, Dellwik, Sogachev, and Rathmann \(2009a\)](#) on p.55

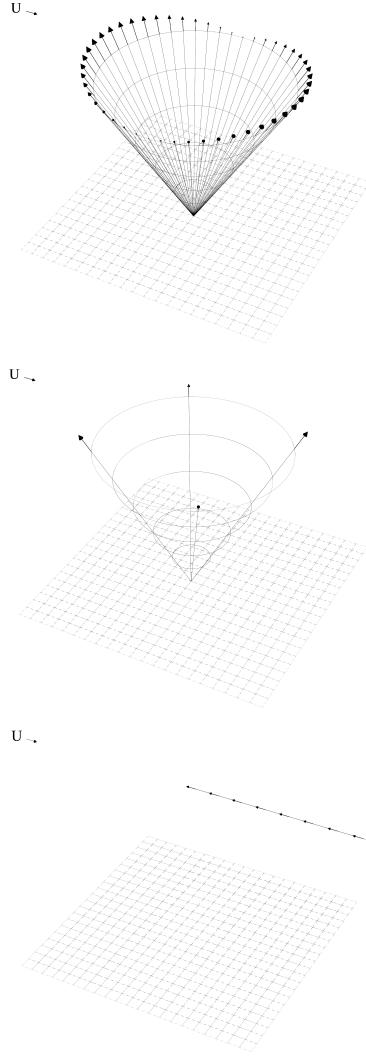


Figure 6. Lidar working modes. The arrows denote the laser beam direction and the measured wind components. **Top:** The original conical scanning mode of ZephIR. At upwind and downwind directions the absolute value of the along beam velocity component has the maximum value. When the wind is perpendicular to the beam direction the wind component on the radial vector has a minimum value. **Middle:** Conical Scanning Mode of the Windcube lidar. The data is recorded only in four equally separated sectors on the conical circle. **Bottom:** Illustration of the Staring Mode. The beam direction is fixed and the instrument focuses at different distances and measures the component of the wind vector indicated by the arrows. In this mode, the lidar data is used combined with separate wind direction measurements.

## 4.2 Windcube

The second wind energy lidar that came into the market is the Windcube, developed by the French company LeoSphere. The Windcube lidar is also a vertical profile measurement device and used in more recent studies (e.g. Peña et al. (2009a)). Evaluation reports, mostly for the measurements over flat terrain, are also available recently (Albers and Janssen, 2008).

Contrary to the ZephIR, Windcube is a pulse lidar, which measures the wind speed and direction at measurement points  $90^\circ$  apart from each other on the conical scan circle for all chosen heights simultaneously. Each sector is scanned

for 1 second and every 6 seconds (2 extra seconds are used to move the wedge), the values are used to derive wind speed and direction profiles; calculated via (Lindelöw, 2007);

$$u = \sqrt{u_1^2 + u_2^2} \quad (3)$$

where  $u_1$  and  $u_2$  are the horizontal plane wind speed components, derived as

$$u_1 = v_r(0) - v_r(\pi), \quad u_2 = v_r(\frac{\pi}{2}) - v_r(\frac{3\pi}{2}) \quad (4)$$

and

$$w = \frac{v_r(0) + v_r(\pi)}{2 \cos \phi} = \frac{v_r(\frac{\pi}{2}) + v_r(\frac{3\pi}{2})}{2 \cos \phi}, \quad \Theta = \arctan(u_1, u_2) \quad (5)$$

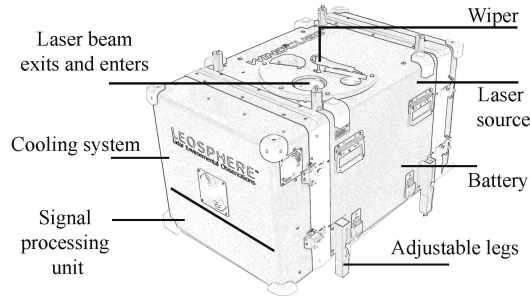


Figure 7. Leosphere Windcube; the laser source is located right on top of the unit and generates the beam in the direction to the the prism located under the beam exit lense where it is tilted to upwards. The dimensions are  $0.7m \times 0.4m \times 0.4m$  and the instrument weights  $\approx 55$  kg.

The Windcube is equally mobile to ZephIR with the added advantage that the wedge opening angle,  $\phi$ , can be adjusted between  $15^\circ$  and  $30^\circ$ . This option is introduced as a “bypass” for complex terrain problems such as inhomogeneous flow. This hypothesis is discussed in the section 4.3. Windcube is also being used in staring mode in recent studies (e.g. Mikkelsen et al. (2008)) but there is no published journal article available on the topic that the author is aware of.

## Thesis Reference

PAPER IV : Mann, Peña, Bingöl, Wagner, and Courtney (2009) on p.53

## 4.3 The conical scanning error in complex terrain

The success of the lidar conical scan operation is limited to flat terrain. In complex terrain, the flow is no longer homogeneous and that can give a large bias on the horizontal wind speed estimated from the lidar up to 10% in horizontal wind speed measurements (Bingöl et al., 2008a). The basic problem also applies to any other conically scanning lidar and sodars as well (Bradley, 2008). Some of the lidar producers present the smaller half opening angle (Leosphere, 2009) or custom scan regimes (SgurrEnergy, 2009) as one of the possible solutions to overcome the problem caused by the inhomogeneous flow.

The error can be illustrated as in figure 8 where the horizontal wind speed  $U$  is taken constant, but the vertical wind speed  $w$  is assumed to change linearly with the downwind position; parametrised with a factor of  $\alpha$ . This is similar to the case over a hill. The upstream has positive and the downstream has negative

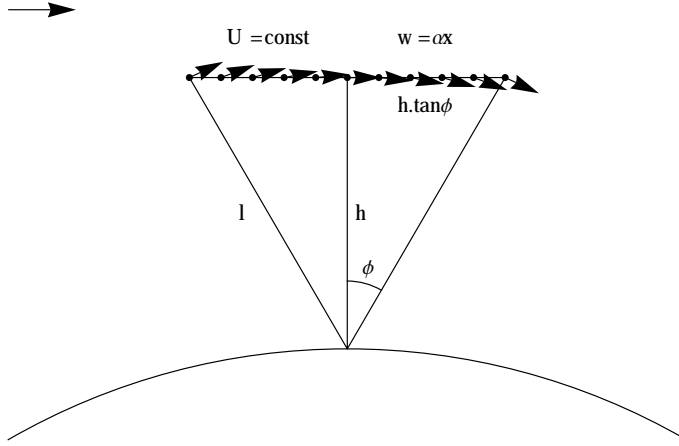


Figure 8. Simplified lidar scanning geometry in a linearly changing mean flow. The lidar is shooting upstream and downstream with a half opening angle  $\phi$ .

tilt relative to the top of the hill. The projected wind speed on the upwind and downwind beams are

$$v_{up} = -(U + h\alpha) \sin \phi \quad v_{down} = (U + h\alpha) \sin \phi \quad . \quad (6)$$

Assuming horizontal inhomogeneity, the horizontal velocity can be calculated as

$$U_{lidar} = \frac{v_{down} - v_{up}}{2 \sin \phi} = U + h\alpha, \quad (7)$$

which shows, in the case of a negative  $\alpha$  that the horizontal wind is *underestimated* (Bingöl et al., 2008a). A simplified three dimensional analysis of the error is derived by Bingöl et al. (2008b) (chapter 2) where the the mean wind field  $\mathbf{U} = (u, v, w)$  is assumed to vary linearly. In such case, the wind vector estimations become:

$$u_{lidar} = u + h \frac{\partial w}{\partial x} \quad (8)$$

$$v_{lidar} = v + h \frac{\partial w}{\partial y} \quad (9)$$

$$w_{lidar} = w - \frac{l}{2} \tan^2 \phi \frac{\partial w}{\partial z} \quad (10)$$

where  $l$  is the focus distance  $h/\cos \phi$ . Equation 10 shows that the error due to inhomogeneity of the mean flow vanishes for the vertical component as the half opening angle  $\phi$  goes to zero. The errors on the horizontal components are independent of  $\phi$ .

## Thesis Reference

PAPER III : Bingöl, Mann, and Foussekis (2009b) on p.51

## 4.4 Simulation of lidar

Conical scanning mode of the lidar can be simulated in flow models. An automated script for commercial software WAsP Engineering has been written by the author for the ZephIR and Windcube lidars and has been published in the period of the study (Bingöl and Mann, 2009). The method can be simplified as below and can be adapted to different scanning regimes such as different  $\phi$ .



A unit vector in the direction of the laser beam can be written as,

$$\mathbf{n} = (\cos \theta \sin \phi, \sin \theta \sin \phi, \cos \phi) \quad (11)$$

where  $\phi$  is half opening angle and  $\theta$  is the geographical angle in which the beam is pointing. As it is previously stated, assuming the flow field to be roughly homogeneous over the averaging circle with a mean  $U = (u, v, w)$ . The radial velocity in the direction of the laser beam, the radial wind speed  $v_r$ , calculated at  $\theta$  azimuth of the prism is the projection of  $\mathbf{U}$  onto  $\mathbf{n}$ :

$$v_r(\theta) = \mathbf{n}(\theta) \cdot \mathbf{U}(\mathbf{n}(\theta)l - (0, 0, z')), \quad (12)$$

where  $z'$  is absolute position of the instrument a.g.l. if it is placed on an artificial elevation (e.g. tower).

For ZephIR lidar, after calculating 60 points on the conical circle, all three velocity components can be obtained through a linear fit to trigonometric series

$$a + b \cos \theta + c \sin \theta, \quad (13)$$

as;

$$u = \frac{b}{\sin \phi} \quad v = \frac{c}{\sin \phi} \quad w = \frac{a}{\cos \phi} \quad \Theta = \arctan \frac{v}{u} . \quad (14)$$

For Windcube, radial wind speed  $v_r$  from calculated at four measurement points are used in eq.3 - 5 directly to derive wind speed components and direction.

## Thesis Reference

PAPER III : [Bingöl, Mann, and Foussekis \(2009b\)](#) on p.51

## 4.5 Extracting momentum flux from the lidar

Momentum flux measurements are important in order to understand the atmospheric flow over the terrain. It is possible to extract the momentum flux from lidars in conical scanning mode. In the present study momentum fluxes are estimated from the ZephIR lidar using the method outlined below ([Mann et al., 2009](#)).

The variance of the radial velocity can be calculated as ([Eberhard et al., 1989](#)):

$$\begin{aligned} \sigma^2(v_r(\theta)) &= \left\langle [\mathbf{n}(\theta) \cdot \mathbf{u}'(\mathbf{n}(\theta)l)]^2 \right\rangle \\ &= \sigma_u^2 \sin^2 \phi \cos^2 \theta + \sigma_v^2 \sin^2 \phi \sin^2 \theta + \sigma_w^2 \cos^2 \phi + \\ &\quad 2 \langle u'v' \rangle \sin^2 \phi \cos \theta \sin \theta + \\ &\quad 2 \langle u'w' \rangle \cos \phi \sin \phi \cos \theta + \\ &\quad 2 \langle v'w' \rangle \cos \phi \sin \phi \sin \theta \end{aligned} \quad (15)$$

For the upwind ( $\theta = 180^\circ$ ), and the downwind ( $\theta = 0^\circ$ ) the variances can be extracted as,

$$\begin{aligned} \sigma_{\text{up}}^2 \equiv \sigma^2(v_{\text{up}}) &= \sigma_u^2 \sin^2 \phi + \sigma_w^2 \cos^2 \phi \\ &\quad - 2 \langle u'w' \rangle \sin \phi \cos \phi \end{aligned} \quad (16)$$

$$\begin{aligned} \sigma_{\text{down}}^2 \equiv \sigma^2(v_{\text{down}}) &= \sigma_u^2 \sin^2 \phi + \sigma_w^2 \cos^2 \phi \\ &\quad + 2 \langle u'w' \rangle \sin \phi \cos \phi . \end{aligned} \quad (17)$$

The momentum flux is the difference between eq.16 and 17:

$$\langle u'w' \rangle = \frac{\sigma_{\text{down}}^2 - \sigma_{\text{up}}^2}{4 \sin \phi \cos \phi} . \quad (18)$$

Momentum fluxes can also be extracted from Windcube measurements but it is not used by the author in his study therefore it is not presented in the thesis. However it can be found in the thesis references ([Mann et al. \(2009\)](#) section 2 - page 4).

## Thesis References

PAPER IV : [Mann, Peña, Bingöl, Wagner, and Courtney \(2009\)](#) on p.53



# 5 Modelling

Wind energy flow models are mainly used to identify the possible mechanical loading effect of the flow on the wind turbines or to estimate the wind energy potential of a site. In this respect, there are many studies on how to model a moderately complex or a complex terrain. Mostly, advanced CFD models are used to predict the flow over hills (Bechmann et al., 2007b,a) or for site assessment (Palma et al., 2008). Linear flow models are also widely used (Reutter et al., 2005; Hui and Crockford, 2007) but most of them do not include flow separation therefore the wind speed is misrepresented in complex terrain. Corrections or limitations based on relatively new parameters like ruggedness index (RIX) have been suggested and compared with measurements to identify any improvement (Bowen and Mortensen, 2004; Mortensen et al., 2006). Nevertheless, improving linear flow models for complex terrain is still “work in progress” (Corbett, 2007; Berg and Ott, 2009). A brief description of such models in wind energy can be found in Palma et al. (2008).

Two types of models are used in the current study:

## 5.1 LINCOM

LINCOM is a fast linearised and spectral wind flow model for use over flat and hilly terrain Astrup et al. (1997). The model is implemented in the commercial software WAsP Engineering 2.0 and includes additionally turbulence models which are designed also for moderately complex terrain but in highly-complex terrain it is known to be unreliable (Mann et al., 2002). WAsP Engineering uses elevation and roughness contour maps with geostrophic or measured wind as inputs. In this thesis the LINCOM flow model is used with two objectives;

1. within its working envelope for flow calculations or modelling lidars in moderately complex terrain (Bingöl et al., 2009b),
2. outside of its working envelope, compared with another model to identify its limitations in complex terrain such as forest. Some recommendations have been made by WAsP Engineering developers in 2006 about how to implement a forest (Dellwik et al., 2006). One of these recommendations was to increase the elevation of the forest area by the measured displacement height,  $d$ . Another idea was to allocate a terrain slope in front of the forest for forest edge calculations. Both suggestions are examined in this study Bingöl et al. (2009a).

### Thesis Reference

PAPER III : Bingöl, Mann, and Foussekis (2009b) on p.51

PAPER V : Bingöl, Mann, Dellwik, Sogachev, and Rathmann (2009a) on p.55

## 5.2 SCADIS

The SCADIS model is specifically developed for forest sites and based on  $\kappa - \omega$  closure scheme ( $\kappa$  is the turbulent kinetic energy and  $\omega = \varepsilon/\kappa$  is the specific dissipation, where  $\varepsilon$  is the dissipation rate of  $\kappa$ ). The model includes the Reynolds averaged Navier-Stokes equations, the continuity equation, equation for moisture and heat transport. Time marching methods to solve the set of non-linear equations with proper boundary conditions are used (Sogachev et al., 2002; Sogachev, 2009).

The forest is parametrized with the ground roughness,  $z_g$ , and the drag forces of the trees according to the tree type and height,  $h$ . The drag forces are spatially distributed and defined by Leaf Area Density (LAD) and the wind speed profile inside the canopy ([Raupach and Shaw, 1982](#)).

#### **Thesis Reference**

PAPER V : [Bingöl, Mann, Dellwik, Sogachev, and Rathmann \(2009a\)](#) on p.55

# 6 Experiments & results

## 6.1 Wake experiment

The vast majority of wind turbines are today erected in wind farms. As a consequence, wake generated loads are becoming more and more important. A new experimental technique had been developed previously (Bingöl, 2005) to measure the instantaneous wake deficit directly. The experimental studies were repeated with improved methods of data collection and analysis in early 2006, before the PhD studies started, and completed in the first year of the study. The results are subject to two papers which are written by two different main authors. The input of the experiment to the thesis is the improved knowledge of lidar signal processing and data analysis which are crucial for the following experiments.

In the first part of the experiment which was also the topic of the first paper, the instrument was used in staring mode, mounted behind a wind turbine. The lidar was making a pan movement between  $\pm 30^\circ$  generating an arc scan behind the wind turbine where the focus distance was kept constant (figure 9). The results were used as a preliminary verification of a wake meandering model that essentially considers the wake as a passive tracer (Bingöl et al., 2008a).

In the second part of the study lidar was used with the wedge to scan an area behind the turbine. Additional to the previous mode the instrument was updated with a specially designed mechanism that enables the wedge to move only in a range of  $38^\circ$  in total, moving back and forth instead of making full rotations. The wedge oscillation generates a vertical movement of the beam, and together with the mechanically generated horizontal panning movement, 2-D scanning pattern was obtained (Bingöl et al., 2008a; Trujillo et al., 2009).

In general, the predicted wake movements showed a convincing agreement with the measured wake movements, thus supporting the basic wake meandering hypothesis stated in the paper.



Figure 9. The wake measurement experimental set-up at Risø Test Center at Roskilde Denmark. **Left:** The prototype lidar mounted at the back of the Tellus turbine. **Right:** The field view. The 30 m tall meteorological mast is located in the dominant wind direction 37 m away from the turbine.

### Thesis References

PAPER I : Bingöl, Mann, and Larsen (2009c) on p.47

PAPER II : Trujillo, Bingöl, Larsen, Mann, and Kühn (2009) on p.49

## 6.2 Hills and mountains

Conically scanning lidars assume the flow to be homogeneous in order to deduce the horizontal wind speed as it has been described in section 4.3. However, in moderately complex or complex terrain this assumption is not valid implying a risk that the lidar will derive an erroneous wind speed. The magnitude of this error was measured by collocating a meteorological mast and a lidar at two Greek sites, one hilly and one mountainous. In order to predict the error for various wind directions the flows at both sites were simulated with the linearised flow model LINCOM as described in section 4.4. The measurement data were compared with the model predictions with good results for the hilly site, but with less success at the mountainous site (Bingöl et al., 2009b). The maximum error for the sites investigated was of the order of 10%.

### Thesis Reference

PAPER III : Bingöl, Mann, and Foussekis (2009b) on p.51

## 6.3 Momentum fluxes

Momentum flux measurements are important for testing models of the atmospheric flow over terrain. The author has taken part in a common article of the Risø Remote Sensing Group. The study differs from previous studies by focusing on the lower 200 m of the atmosphere, using both ZephIR and WindCube lidars. The results were compared with sonic measurements of the momentum flux up to 160 m above the terrain surface. In addition a novel method to estimate the momentum flux was tested, which does not use the individual radial wind speeds as it is described in section 4.5, but rather the entire Doppler spectrum. The author has taken part in the analysis of the turbulence parameters derived from the ZephIR lidar and implementation of the new method.

### Thesis Reference

PAPER 4 : Mann, Peña, Bingöl, Wagner, and Courtney (2009) on p.??

## 6.4 Forest profiles

Two experiments were made to investigate the mean wind profile and turbulence statistics above dense beech forests by use of a laser Doppler anemometer additional to conventional cups and sonics; both forest edge and deeper into the forest were examined. The experiments were performed at two different forest sites in Denmark, Sorø and Falster, in 2006-2007 and in 2008, respectively.

One of the experiments focused on the wind profiles far away from the forest edge ( $> 18$  tree height; h) up to 180 m a.g.l. ( $\approx 6.7h$ ); all above the canopy. The other was focused on the flow at the edge of the forest measured with two meteorological masts, inside and outside of the forest, and a vertical lidar outside the forest up to 100 m a.g.l. ( $\approx 4.3h$ ) (figure 10). The measured profiles were compared with the LINCOM and the SCADIS model outputs.

Results showed that the mean wind speed calculated by LINCOM flow model was only reliable between 1h and 2h above canopy. The SCADIS model reported better correlation with the measurements up to 160 m which is more useful for wind energy applications. At the forest edge LINCOM model was used by allocating a  $17^\circ$  slope half-in half-out of the forest, which was the optimum slope and allocation method observed (Bingöl et al., 2009b). The SCADIS model calculations were in better correlation with the measurements than the LINCOM

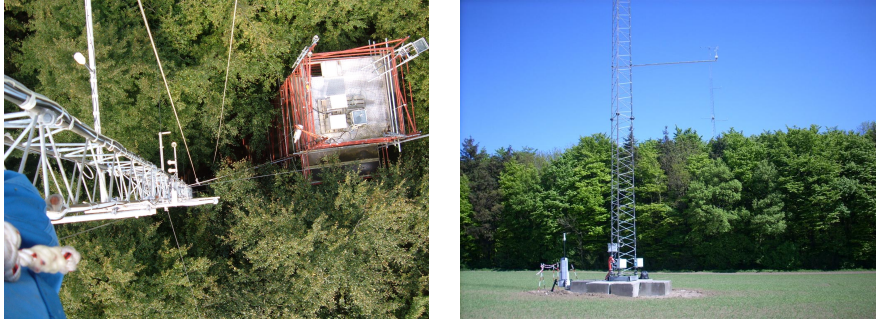


Figure 10. The experimental set-ups at forest sites. **Left:** The measurement location at the Sorø site taken from the meteorological mast. The tower can be seen on top right where the lidar was located in winter period. **Right:** The Falster site; all instruments are in operation.

model at the forest edge but the model reported better results at upwind than the downwind and this should be noted as a limitation of the model.

### Thesis Reference

PAPER V : [Bingöl, Mann, Dellwik, Sogachev, and Rathmann \(2009a\)](#) on p.55

## 6.5 Validation of cone angle hypothesis

The hypothesis that reducing the cone angle will not change the systematic error on the horizontal wind measured by the lidar (section 4.3) was tested with measurements on a non-forested hilly site in Greece. The experiment was made by CRES and statistical data were shared with the author <sup>4</sup>. The study is not published and data analysis is only presented in this section of the thesis.

One ZephIR and two Windcube lidar units were located next to a tall meteorological mast at Greece Renewable Energy Laboratories test site at Lavrio (figure 11). The site, which is a moderately complex terrain, is located 38 km SE of the center of Athens close to the coast of the Aegean Sea [Bingöl et al. \(2008a\)](#). At Lavrio, the highest point is 200 m a.s.l. and main wind direction is 0° North.

The experiment took place between 2008-Sep-17 and 2009-Jan-17. The measurement location was on a hill with a gentle slope of approximately 10° in the main wind direction sector to both sites. Further away the northerly sector is a flat terrain, southerly sector includes more hill after approximately 150 m (figure 12).

The 100 m triangular lattice reference meteorological mast was equipped with cup anemometers and vanes at three heights (54, 76 and 100 m). Cups are to the east and vanes are to the west. The lidars were located between 12 and 20 m north of the mast. One of the Windcube units and the ZephIR lidar were in operation with a  $\phi = 30^\circ$  prism while the other Windcube operated with  $\phi = 15^\circ$ . The ZephIR unit measured at 54, 78, 100 and 120 m. Both Windcube units measured at 40, 54, 78, 100, 120, 140 and 160 m.

The data from northerly sector,  $0 \pm 15^\circ$  were selected for comparison. All available data, 1163 of 10 minutes runs, were used. Initially, the horizontal wind speed, wind direction and standard deviation of the horizontal wind speed were compared with the sonic anemometers at same heights; 54, 78 and 100 m (figure 13,14 and 15). The results agreed with a previous experiment at the same site for the same

<sup>4</sup>Courtesy from Dimitri Foussekis, The Centre for Renewable Energy Sources (CRES) GREECE





Figure 11. The experimental set-up at Lavrio, Greece for the comparison of the lidars in different working modes.

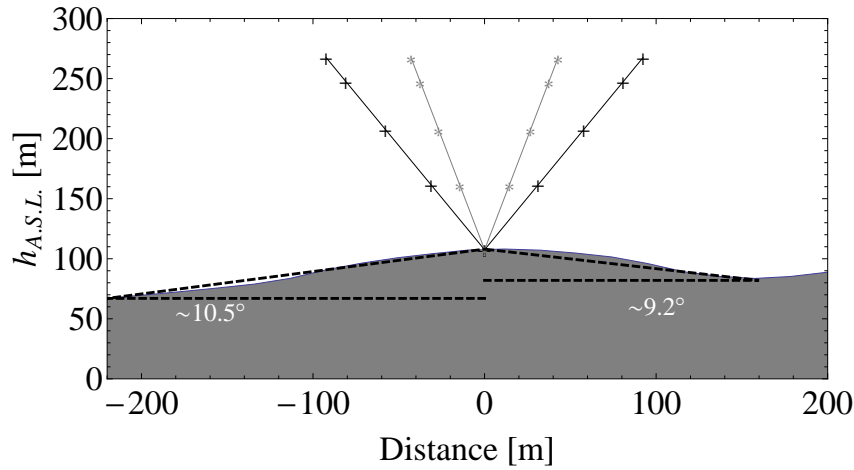


Figure 12. The hill transect at Lavrio. Left is northerly direction which is the dominant wind direction.

wind sector [Bingöl et al. \(2008a\)](#). The horizontal wind speed measurements from the lidars were in good correlation but wind direction and the standard deviation of the horizontal wind speed deteriorate for the 15° Windcube.

Subsequently, horizontal wind speed and flow inclination angles were compared between the 30° prism instruments and the 15° Windcube for available common heights (figure 16 and 17). The results showed that the horizontal wind speed measurements were not effected by the cone angle. However, the flow inclination angles showed less scatter with the lower cone angle as it was expected.

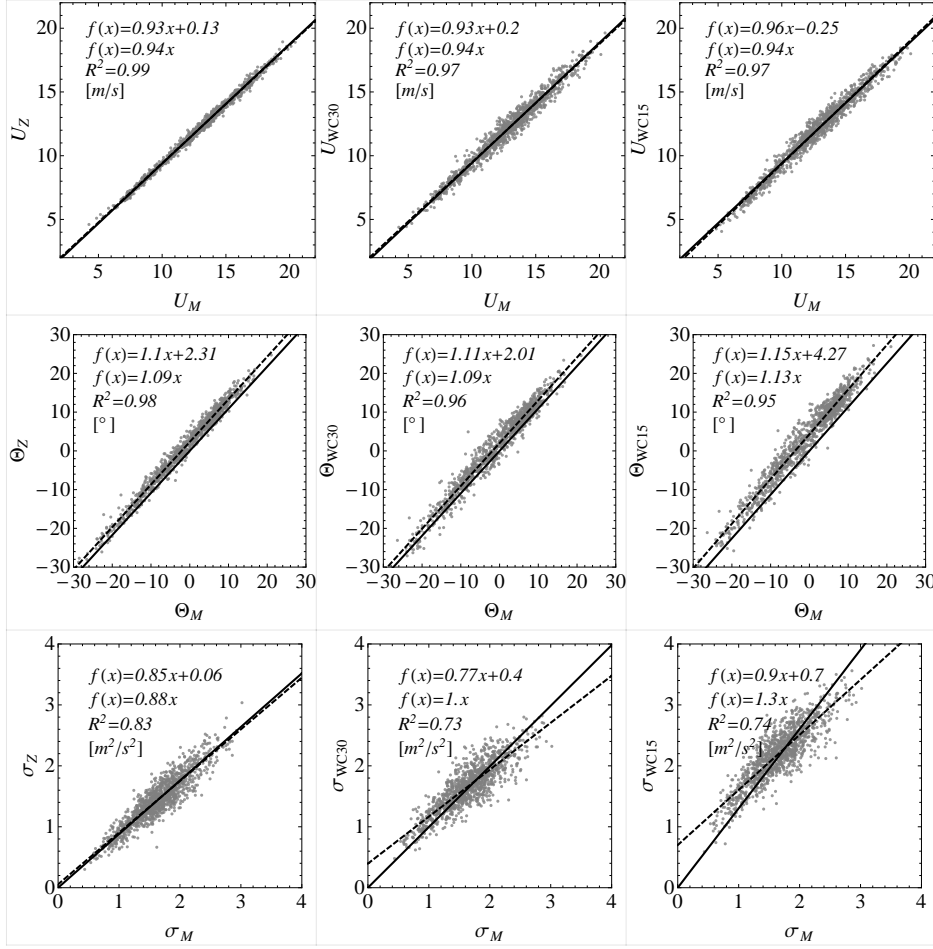


Figure 13. Lidars vs. Sonics at 54 m. Top row is the horizontal wind speed, middle row is the wind direction and bottom row is the standard deviation of the horizontal wind speed.

As a conclusion, it can be stated that the lower half opening angle,  $\phi = 15^\circ$  do not help in complex terrain on improving the horizontal wind speed measurements. For any other statistical term the  $\phi = 15^\circ$  has an even higher bias in measurements. Therefore, the hypothesis described at the beginning of this section agrees with the measurements and the  $30^\circ$  prism is advised by the author instead of  $15^\circ$  prism at such sites.

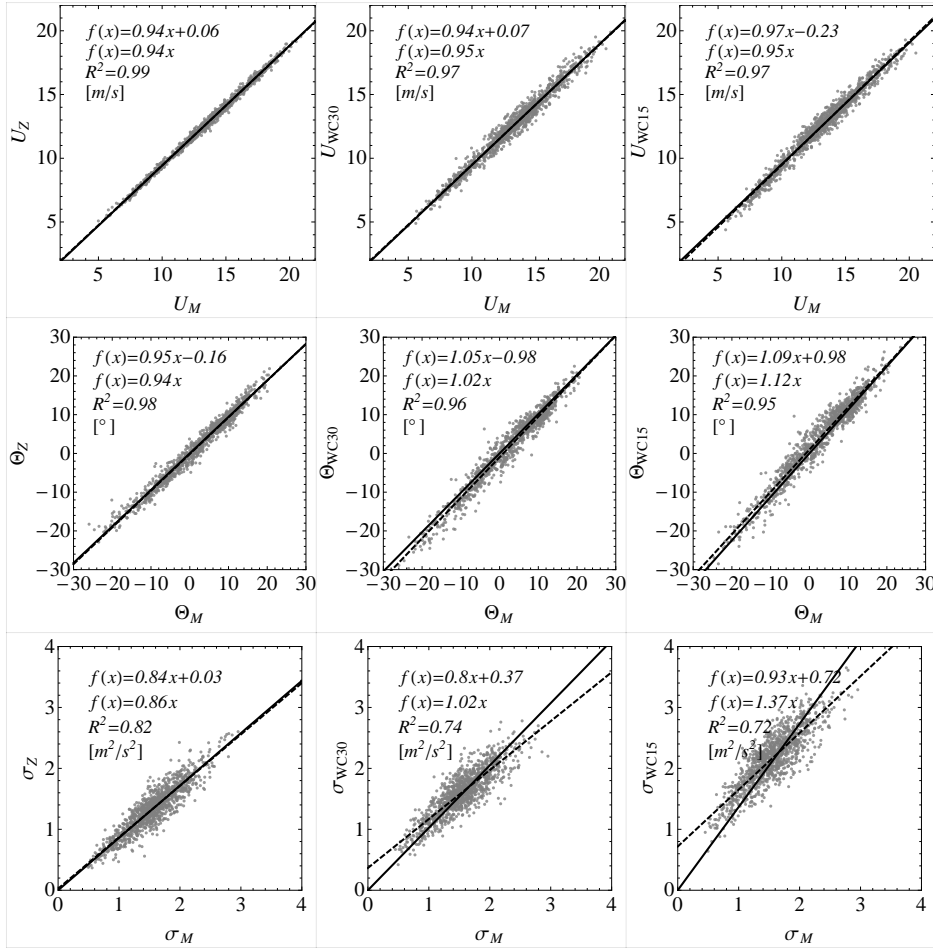


Figure 14. Lidars vs. Sonics at 78 m. Top row is the horizontal wind speed, middle row is the wind direction and bottom row is the standard deviation of the horizontal wind speed.

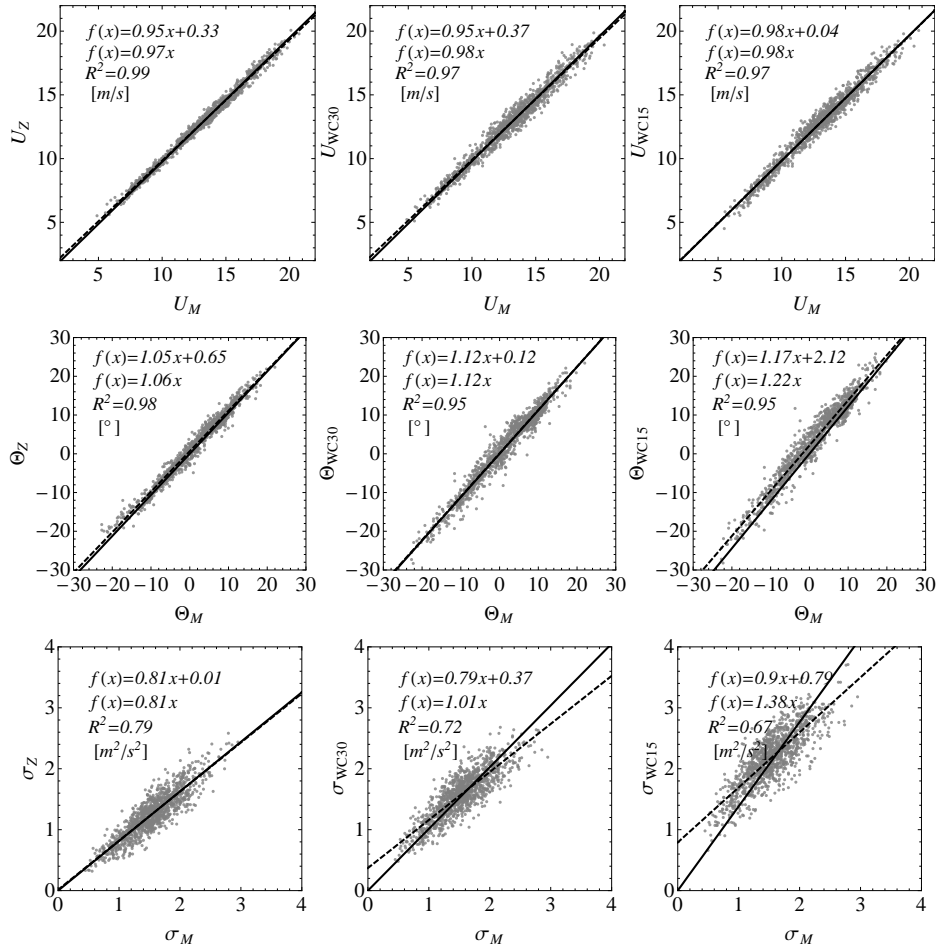


Figure 15. Lidars vs. Sonics at 100 m. Top row is the horizontal wind speed, middle row is the wind direction and bottom row is the standard deviation of the horizontal wind speed.

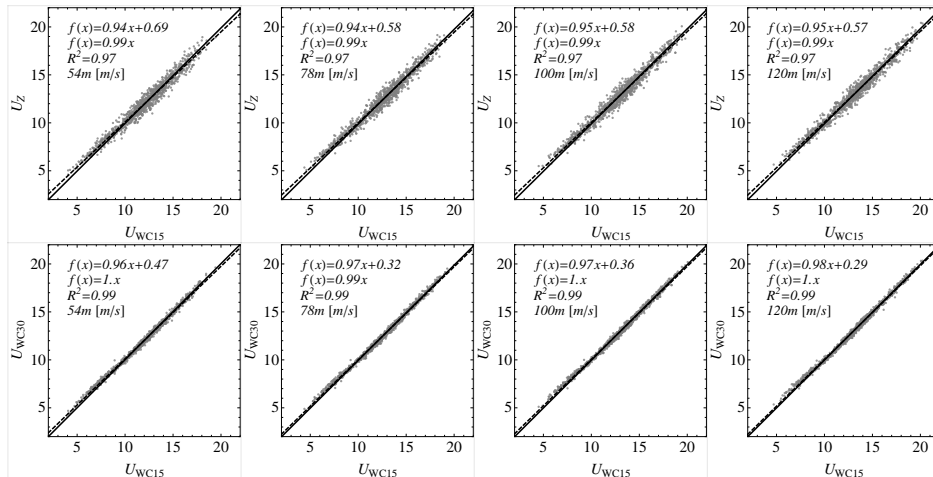


Figure 16. Horizontal wind speed correlation between the 30° prism instruments vs. 15° Windcube for available heights; 54,78,100 and 120 m. The ZephIR is at the top.

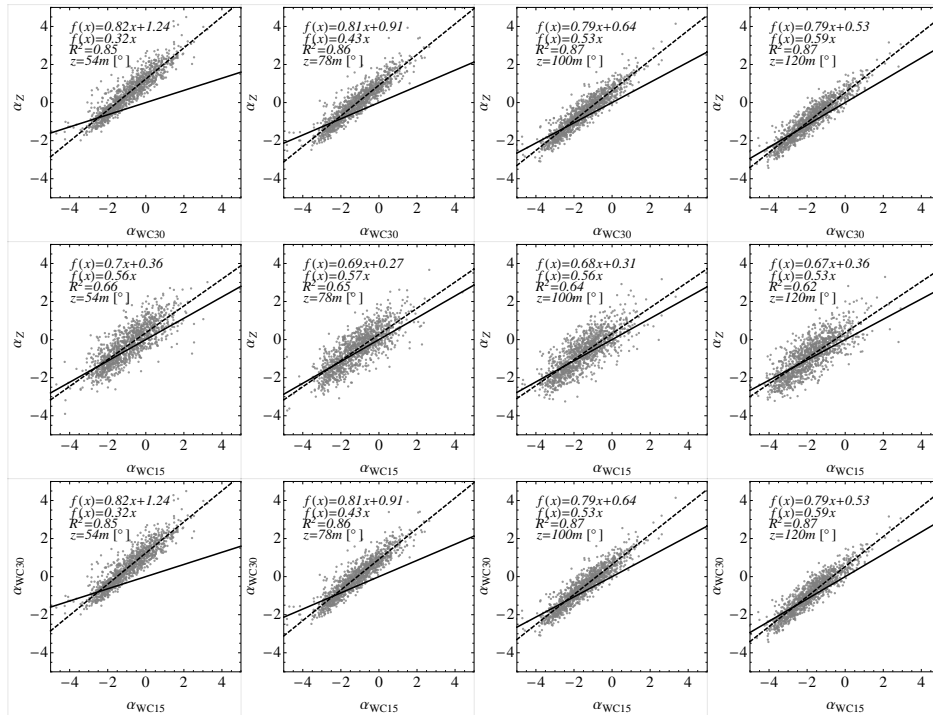


Figure 17. Flow inclination angles correlation between the 30° prism instruments vs. 15° Windcube for available heights.

## 7 Conclusion

In this study, several experiments in moderately-complex and complex terrains were performed in order to understand the flow behaviour and the possibilities of using flow models in this study. The experiments were conducted using wind energy lidars in combination with conventional measurement instruments like cups, vanes and sonics. The lidar measurement quality and the possible signal processing improvements were investigated prior to the complex terrain experiments and the resulting knowledge was used in suitable adaptations for complex terrain site measurements.

The lidars were used in two different working modes; conical and staring scanning modes. The results showed that horizontal wind speed errors measured by a conically scanning lidar can be of the order of 3-4% in moderately-complex terrain and up to 10% in complex terrain. This is due to the lack of horizontal homogeneity of the flow, which is assumed in the interpretation of the lidar data. The findings were based on experiments involving collocated lidars and meteorological masts, together with flow calculations over the same terrains. For that calculation, the commercial software WAsP Engineering 2.0, which includes the LINCOM flow model, was used to simulate the error which was well predicted except for some sectors where the terrain was particularly steep. This is not surprising, since LINCOM is built on a linearised 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.

The hypothesis that the lidar conical scan error due to inhomogeneity of the mean flow is independent of the half opening angle  $\phi$  on the horizontal components has been supported with experimental results from moderately-complex terrain site measurements. The synchronized measurements from the lidars with different half opening angles and meteorological mast instruments reported no positive effect of smaller half opening angle in horizontal wind speed measurements, contrary to what was being suggested by some of the producers and academics. The measurements agreed with the described hypothesis and it can be concluded that smaller half opening angles can only be helpful in sites with the presence of dense canopy or obstacles, in order to measure the desired height easily.

In two forested sites, mean wind profiles and turbulence statistics above dense beech forests were measured with meteorological masts and lidars and the results were compared not only with the LINCOM flow model but also with a specialised forest  $\kappa - \omega$  flow model; SCADIS. In both experiments, a simple method was used to derive turbulence parameters from lidars in order to compare them with the models. The measurements from deep in-forest locations (18 tree height; h) showed high turbulence level close to the canopy top and were highly dependent on distance to the forest edge. Subsequently, an experiment at the edge of another beech forest was performed and the effects of the edge on the flow was measured with two meteorological masts inside and outside of the forest, equipped with sonic anemometers below and above the canopy, in combination with a conically scanning lidar at the field mast location measuring up to  $\approx 4.3h$  and a staring mode lidar measuring the horizontal wind profile at  $\approx 1.3h$ . The comparison of the measurement data with the flow model outputs showed that the mean wind speed calculated by the LINCOM model was only reliable between  $1h$  and  $2h$  above the canopy and that the rest of the parameters, like wind direction, vertical wind speed and turbulence parameters were unreliable. This limitation at a forest site is not acceptable for wind energy site assessments, because the typical hub heights for present day wind turbines are above 90 m ( $\approx 4h$  in the experiment site), but it should be noted that certain developments in the linearised flow models

portend a near future update and correction to the problem (Berg and Ott, 2009). The SCADIS model reported better correlation with the measurements within the forest up to  $6.4h$ , which is more useful for wind energy applications.

The lidar conical scan errors in the forest edge experiment were in the order of  $\approx 3\%$  in lower heights ( $< 1.5h$ ) where the flow inclination was maximum. It can be concluded that the effects of the forest edge on lidar measurements at lower heights are similar to those of hills and are less affected at heights above. At the forest edge the LINCOM model was adapted by allocating a slope at the forest edge. An optimum slope angle of  $17^\circ$  was observed based on the comparison of different slope allocation methods and values. Therefore, it is suggested that WAsP Engineering 2.0 be used for forest edge modelling with awareness of its limitations and the specified adaptations. The SCADIS model worked better than the LINCOM model at the forest edge, but the model reported better results when the wind is entering the forest rather than exiting and this should be noted as a limitation of the model.

As a general conclusion of this study, lidars can be used in complex terrain with support of flow models which should include well defined flow separation predictions. It is important to note that modelling must be accompanied by flow analysis before and after the measurements. Prior to the measurements, models should be used to detect possible suitable locations for lidar placement. This can be done with linearised or advanced CFD models because any of these can perform a simple assessment based on rough calculations of error values. Thus, the majority of sub-optimal locations can be eliminated. Subsequently, any attempt to correct the lidar data must be performed with an advanced flow model, preferably a CFD model that has already been tested in complex terrain with measurements. It is advised that the described modelling steps for lidar data correction should be included in wind turbine and site assessment and implemented in well established international standards (e.g. IEC 61400 series) after further studies.

As a final comment, the author would like to bring to attention certain shortcomings of the current commercial versions of the lidar instruments. Some of the experiments, which are conducted in this study or cited in the manuscript, would not have been possible without full software and hardware access to the instruments. The re-formulation of signal processing methods and the physical manipulation of instrument parts were essential to achieve the necessary scanning speed and to create custom scan regimes. This underlines the importance of instrument flexibility for a wide range of uses (e.g. in complex terrain). Unfortunately, most of the producers of currently available commercial models are gradually stepping back from such an approach in an effort to create stable, robust instruments. In order to achieve faster development in lidar technology in complex terrain, the author believes that these instruments must be accessible in a software as well as a hardware level, and suggests a more detailed documented developer interface mode.

Concluding, current standards of the instruments are adequate to perform wind measurements over most of the terrain types and it is believed that it is possible for lidars to replace conventional meteorological mast in the future if the data interpretation is improved, particularly.

# References

- A. Albers and A. Janssen. Windcube evaluation report. Technical report, Deutsche WindGuard Consulting GmbH, Mar 2008. URL [http://www.leosphere.com/file/deutsche\\_windguard\\_report\\_windcube\\_evaluation.pdf](http://www.leosphere.com/file/deutsche_windguard_report_windcube_evaluation.pdf). PP08007 (Accessed 31 July 2009).
- I. Antoniou, H. E. Jørgensen, T. Mikkelsen, T. F. Petersen, G. Warmbier, and D. Smith. Comparison of wind speed and power curve measurements using a cup anemometer, a lidar and a sodar. In *European Wind Energy Conference and Exhibition / UK*, page 47–51. EWEC, November 2004. URL [http://www.2004ewec.info/files/EWEC\\_SC\\_BOOK\\_LOW.pdf](http://www.2004ewec.info/files/EWEC_SC_BOOK_LOW.pdf). (Accessed 20 August 2009).
- I. Antoniou, H. E. Jørgensen, T. Mikkelsen, S. T. Frandsen, R. J. Barthelmie, C. Perstrup, and M. Hurtig. Offshore wind profile measurements from remote sensing instruments. In *European Wind Energy Conference and Exhibition, Athens - Greece*, 2006.
- P. Astrup, T. Mikkelsen, and N. Jensen. A fast model for mean and turbulent wind characteristics over terrain with mixed surface roughness. *Radiat Prot Dosimetry*, 73(1-4):257–260, 1997.
- A. Bechmann, J. Johansen, and N. N. Soerensen. The Bolund experiment - Design of measurement campaign using CFD; Wind conditions in complex terrain. Report RISO-R-1623(EN), Risoe National Lab., DTU, Wind Energy Dept., Roskilde Denmark, Dec 2007a. URL <http://www.risoe.dtu.dk/rispubl/reports/ris-r-1623.pdf>. (Accessed 20 August 2009).
- A. Bechmann, N. N. Sørensen, J. Johansen, S. Vinther, B. S. Nielsen, and P. Botha. Hybrid RANS/LES Method for High Reynolds Numbers, Applied to Atmospheric Flow over Complex Terrain. *Journal of Physics: Conference Series*, 75(1):012054, 2007b. doi: 10.1088/1742-6596/75/1/012054.
- J. Berg and S. Ott. A new linearized flow model for complex terrain. In *EWEC 2009 Proceedings*, page 7, 2009. URL <http://www.ewec2009proceedings.info/proceedings/statscounter.php?id=5&IDABSTRACT=236>.
- F. Bingöl. Adapting Laser Doppler Anemometer into Wind Energy. Master’s thesis, Technical University of Denmark, 2005. MEK-FM-EP 2005-02.
- F. Bingöl and J. Mann. Lidar performance estimation script for WAsP Engineering. Technical report, Risø DTU, Apr 2009. URL <http://www.wasp.dk/Download/WENGscripts.htm>. (Accessed 20 August 2009).
- F. Bingöl, J. Mann, and D. Foussekis. Lidar error estimation with wasp engineering. *IOP Conference Series: Earth and Environmental Science*, 1:012058 (9pp), 2008a. doi: 10.1088/1755-1315/1/1/012058. URL <http://www.iop.org/EJ/abstract/1755-1315/1/1/012058/>.
- F. Bingöl, J. Mann, and D. Foussekis. Modeling conically scanning lidar error in complex terrain with WAsP Engineering. Report Risø-R-1664(EN), Risø National Laboratory for Sustainable Energy - DTU, Roskilde Denmark, November 2008b. URL <http://www.risoe.dtu.dk/rispubl/reports/ris-r-1664.pdf>. ISBN 978-87-550-3712-0 (Accessed 20 August 2009).
- F. Bingöl, J. Mann, E. Dellwik, A. Sogachev, and O. Rathmann. Flow over limited size forest; measurements and modelling. *Wind Energy*, 2009a. Submitted for publication.



- F. Bingöl, J. Mann, and D. Foussekis. Conically scanning lidar error in complex terrain. *Meteorologische Zeitschrift*, 18(2, Sp. Iss. SI):189–195, 2009b. ISSN 0941-2948. doi: 10.1127/0941-2948/2009/0368. (Open Access).
- F. Bingöl, J. Mann, and G. C. Larsen. Lidar measurements of wake dynamics Part I: One Dimensional Scanning. *Wind Energy*, 2009c. doi: 10.1002/we.352. Published online.
- A. Bowen and N. Mortensen. WASP prediction errors due to site orography. Technical Report Risø-R-995(EN), Risø National Laboratory, 2004. URL [www.risoe.dtu.dk/rispubl/VEA/veapdf/ris-r-995.pdf](http://www.risoe.dtu.dk/rispubl/VEA/veapdf/ris-r-995.pdf).
- S. Bradley. Wind speed errors for lidars and sodars in complex terrain. In *IOP Conference Series: Earth and Environmental Science*, volume 1 of *IOP Conference Series*, page 012061 (7pp), 2008. doi: 10.1088/1755-1315/1/1/012061.
- J.-F. Corbett. *RAMSIM: A fast computer model for mean wind flow over hills*. PhD thesis, Risø National Laboratory DTU, Jun 2007. URL <http://www.risoe.dtu.dk/rispubl/reports/ris-phd-17.pdf>. Risø-PhD-17(EN) (Accessed 20 August 2009).
- M. Courtney, R. Wagner, and P. Lindelöw. Testing and comparison of lidars for profile and turbulence measurements in wind energy. In *IOP Conference Series: Earth and Environmental Science*, volume 1, page 012021 (14pp), 2008. doi: 10.1088/1755-1315/1/1/012021.
- E. Dellwik, L. Landberg, and N. O. Jensen. WASP in the forest. *Wind Energy*, 9(3):211–218, 2006. doi: 10.1002/we.155.
- W. L. Eberhard, R. E. Cupp, and K. R. Healy. Doppler lidar measurement of profiles of turbulence and momentum flux. *Journal of Atmospheric and Oceanic Technology*, 6(5):809–819, Oct 1989. doi: 10.1175/1520-0426(1989)006<0809:DLMOP>2.0.CO;2.
- E. E. A. EEA. Europe’s onshore and offshore wind energy potential. EEA Technical report 6/2009, European Environmental Agency, Kongens Nytorv 6, DK - 1050 Copenhagen K, Denmark, 06 2009. URL <http://www.eea.europa.eu/publications/europes-onshore-and-offshore-wind-energy-potential>. ISSN 1725-2237 (Accessed 20 August 2009).
- Eurostat. European forest week. Press Release, Oct 2008. URL <http://europa.eu/rapid/pressReleasesAction.do?reference=STAT/08/146&format=PDF&aged=0&language=EN&guiLanguage=en>. (Accessed 31 July 2009).
- EWEA. Pure Power - Wind Energy Scenarios up to 2030. Technical report, EWEA, Mar 2008. URL [http://www.ewec2008.info/fileadmin/ewea\\_documents/documents/publications/reports/purepower.pdf](http://www.ewec2008.info/fileadmin/ewea_documents/documents/publications/reports/purepower.pdf). (Accessed 20 August 2009).
- M. Harris, M. Hand, and A. Wright. Lidar for turbine control. Technical Report NREL/TP-500-39154, NREL, January 2006. URL <http://www.nrel.gov/wind/pdfs/39154.pdf>.
- M. Harris, D. J. Bryce, A. S. Coffey, D. A. Smith, J. Birkemeyer, and U. Knopf. Advance measurement of gusts by laser anemometry. *J. Wind Eng. Ind. Aerodyn.*, 95:1637–1647, 2007.

- D. A. Hastings, P. K. Dunbar, G. M. Elphinstone, M. Bootz, H. Murakami, H. Maruyama, H. Masaharu, P. Holland, J. Payne, N. A. Bryant, T. L. Logan, J.-P. Muller, G. Schreier, and J. S. MacDonald. The global land one-kilometer base elevation (globe) digital elevation model, version 1.0. Digital data base on the www and cd-roms, National Oceanic and Atmospheric Administration, National Geophysical Data Center, 325 Broadway, Boulder, Colorado 80305-3328, U.S.A., 1999. URL <http://www.ngdc.noaa.gov/mgg/topo/globe.html>. (Accessed 20 August 2009).
- S. Hui and A. Crockford. Wind profiles and forests : Validation of wind resource assessment methodologies including the effects of forests. Master's thesis, Technical Univ. of Denmark, Lyngby Denmark, Aug 2007. URL <http://www.fm.mek.dtu.dk/upload/institutter/mek/fm/eksamensprojekter/crockford&hui2007.pdf>. (Accessed 20 August 2009).
- IEC. 61400-12-1: Power performance measurements of electricity producing wind turbines. Technical report, International Electrotechnical Commission, 2005. Ed.2.
- T. J. R. C. JRC. Global land cover 2000 - Europe. Technical report, European Environmental Agency, Nov 2006. URL <http://dataservice.eea.europa.eu/dataservice/metadetails.asp?id=955>.
- H. Jørgensen, T. Mikkelsen, J. Mann, D. Bryce, A. S. Coffey, M. Harris, and D. A. Smith. Site wind field determination using a CW Doppler lidar - comparison with cup anemometers at Risø. In *Proc. EWEA Special Topic Conference: The Science of Making Torque from Wind / The Netherlands*, pages 261–266. Delft University, April 19-21 2004.
- Leosphere. Windcube information booklet, 2009. URL <http://www.leosphere.com/pdf/Leosphere-Windcube.pdf>. (Accessed 20 August 2009).
- P. Lindelöw. Uncertainties in wind assessment with lidar. Risø Report Risø-I-1234(EN), Risø DTU, Jan 2007.
- J. Mann, S. Ott, B. H. Jørgensen, and H. P. Frank. WAsP Engineering 2000. Technical Report Risø-R-1356(EN), Risø National Laboratory DTU, Roskilde, Denmark, Aug 2002. URL <http://www.risoe.dtu.dk/rispubl/VEA/veapdf/ris-r-1356.pdf>. ISBN 87-550-3095-5 (Accessed 20 August 2009).
- J. Mann, A. Peña, F. Bingöl, R. Wagner, and M. S. Courtney. Lidar scanning of momentum flux in and above the surface layer. *Journal of Atmospheric and Oceanic Technology*, 2009. Submitted.
- S. D. Mayor, D. H. Lenschow, R. L. Schwiesow, J. Mann, C. L. Frush, and M. K. Simon. Validation of NCAR 10.6- $\mu$ m  $\text{CO}_2$  Doppler lidar radial velocity measurements and comparison with a 915-MHz profiler. *Journal of Atmospheric and Oceanic Technology*, 14:1110–1126, 1997. doi: 10.1175/1520-0426(1997)014<1110:VONMCD>2.0.CO;2.
- T. Mikkelsen, J. Mann, M. Courtney, and M. Sjöholm. Windscanner: 3-D wind and turbulence measurements from three steerable doppler lidars. *IOP Conference Series: Earth and Environmental Science*, 1:012018 (9pp), 2008. doi: 10.1088/1755-1315/1/1/012018.
- N. G. Mortensen, A. J. Bowen, and I. Antoniou. Improving WAsP predictions in (too) complex terrain. In *EWEA 2006*, number 2006 in Proceedings of the 2006 European Wind Energy Conference and Exhibition. EWEA, EWEA, Feb 2006. URL [http://www.ewec2006proceedings.info/allfiles2/116\\_Ewec2006fullpaper.pdf](http://www.ewec2006proceedings.info/allfiles2/116_Ewec2006fullpaper.pdf).

- J. Palma, F. Castro, L. Ribeiro, A. Rodrigues, and A. Pinto. Linear and nonlinear models in wind resource assessment and wind turbine micro-siting in complex terrain. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(12):2308 – 2326, 2008. ISSN 0167-6105. doi: 10.1016/j.jweia.2008.03.012.
- A. Peña. *Sensing the wind profile*. PhD thesis, Copenhagen University / Risø DTU, Mar 2009. URL <http://www.risoe.dtu.dk/rispubl/reports/ris-phd-45.pdf>. (Accessed 20 August 2009).
- A. Peña, C. B. Hasager, S.-E. Gryning, M. Courtney, I. Antoniou, T. Mikkelsen, and P. Sorensen. Offshore winds using remote sensing techniques. *Journal of Physics: Conference Series*, 75:012038 (11pp), 2007. doi: 10.1088/1742-6596/75/1/012038.
- A. Peña, S.-E. Gryning, and C. B. Hasager. Comparing mixing-length models of the diabatic wind profile over homogeneous terrain. *Theoretical and Applied Climatology*, 999:999, 2009a. doi: 10.1007/s00704-009-0196-8.
- A. Peña, C. B. Hasager, S.-E. Gryning, M. Courtney, I. Antoniou, and T. Mikkelsen. Offshore wind profiling using light detection and ranging measurements. *Wind Energy*, 12(2):105–124, Mar 2009b. ISSN 1095-4244. doi: 10.1002/we.283.
- T. F. Pedersen, S. Gjerding, P. Ingham, P. Enevoldsen, J. K. Hansen, and H. K. Jørgensen. Wind turbine power performance verification in complex terrain and wind farms. Technical report, Risø National Laboratory, Apr 2002. URL <http://www.risoe.dtu.dk/rispubl/VEA/veapdf/ris-r-1330.pdf>. Risø-R-1330(EN) (Accessed 20 August 2009).
- M. R. Raupach and R. H. Shaw. Averaging procedures for flow within vegetation canopies. *Boundary-Layer Meteorology*, 22(1):79–90, Nov 1982. doi: 10.1007/BF00128057.
- K. Reutter, R. G. Flay, and E. M. McIntosh. An application of the wasp program in complex, forested terrain as part of a wind farm feasibility study. *Wind Engineering*, 29:491–502(12), Dec 2005. doi: 10.1260/030952405776234562.
- SgurrEnergy. Galion, 2009. URL [http://www.sgurrenergy.com/Products/Galion\\_brochure\\_B1.pdf](http://www.sgurrenergy.com/Products/Galion_brochure_B1.pdf). (Accessed 20 August 2009).
- D. A. Smith, M. Harris, A. S. Coffey, T. Mikkelsen, H. E. Jørgensen, J. Mann, and R. Danielian. Wind lidar evaluation at the Danish wind test site in Høvsøre. *Wind Energy*, 9(1-2):87–93, Jan-Apr 2006. doi: 10.1002/we.193.
- A. Sogachev. A note on two-equation closure modelling of canopy flow. *Boundary-Layer Meteorology*, 130(3):423–435, Mar 2009. ISSN 0006-8314. doi: 10.1007/s10546-008-9346-2.
- A. Sogachev, G. V. Menzhulin, M. Heimann, and J. Lloyd. A simple three-dimensional canopy – planetary boundary layer simulation model for scalar concentrations and fluxes. *Tellus*, 54(5):784–819, 2002. doi: 10.1034/j.1600-0889.2002.201353.x.
- TheWindPower.net. Windparks in Europe. Database, TheWindPower, 2009. URL <http://www.TheWindPower.net>. (Accessed 31 July 2009).
- I. Troen and E. Petersen. *European Wind Atlas*. Risø National Laboratory, 1989. ISBN 87-550-1482-8.
- J. J. Trujillo, F. Bingöl, G. C. Larsen, J. Mann, and M. Kühn. Lidar measurements of wake dynamics, Part II : Two dimensional scanning. *Wind Energy*, 2009. Manuscript under review.

# Paper I: Light detection and ranging measurements of wake dynamics, Part I: One-dimensional scanning

**Authors:** Ferhat Bingöl, Jakob Mann and Gunner C. Larsen  
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# Paper II: Light detection and ranging measurements of wake dynamics, Part II: Two-dimensional scanning

**Authors:** Juan José Trujillo, **Ferhat Bingöl**, Jakob Mann and Gunner C. Larsen  
**Journal:** Wind Energy  
**Status:** Manuscript under revision



# Paper III: Conically scanning lidar error in complex terrain

**Authors:** Ferhat Bingöl, Jakob Mann and Dimitri Foussekis  
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# Paper IV: Lidar scanning of momentum flux in and above the surface layer

**Authors:** Jakob Mann, Alfredo Peña, **Ferhat Bingöl**, Rozenn Wagner and Michael S. Courtney  
**Journal:** Journal of Atmospheric and Oceanic Technology  
**Status:** Manuscript under revision



# Paper V: Flow over limited size forest; measurements and modelling

**Authors:** Ferhat Bingöl, Jakob Mann, Ebba Dellwik, Andrey Sogachev and Ole Rathmann

**Journal:** Wind Energy

**Status:** Manuscript under revision

# Resume

*Denne PhD afhandling fremviser resultater fra et studie af vindmåling omkring og over komplekst terræn. Atmosfærisk strømning og turbulens er målt fra jorden med vind lidar (fjern måling).*

Studiet har fokuset på vindens strømning over bakker og skovområder. Vind lidars er blevet anvendt i kombination med meteorologimaster monteret med in-situ instrumentation i form af cup anemometre, sonics, og vind vanes.

Flere eksperimenter og forsøg er udført ved forskellige forsøgspladser i komplekst terræn, og målingerne herfra er blevet sammenlignet med to forskellige strømningssmodeller: En lineariseret strømningssmodel, LINCOM, samt en speciel vind model for strømning i og over skov, SCADIS.

Ved anvendelse af vind lidar som vind profiler, det vil sige de scanner vinden konisk over komplekst terræn, viser studiet, at de målte horisontale vindhastigheder kan være behæftet med fejl af størrelsesordenen 3-4 % over bakket terræn, og med helt op til 10 % over stejlt terræn.

Disse resultater stammer fra studier, hvor vind lidars og meteorologiske master har været opstillede side om side, og hvor også vind strømningen over terrænet samtidig blev modelleret.

Vind lidarens målinger kunne også simuleres vha. en kommerciel vind model (WAsP Engineering 2.0) endog med tilfredsstillende resultater, undtagen for sektorer hvor terrænet var meget stejlt.

Der blev yderligere gennemført to eksperimenter med vind lidaren: Ét hvor horisontale vindprofil målinger blev foretaget fra en lysning inde i en skov, og et ved selve skovkanten.

Begge disse eksperimenter blev modelleret, og målingerne viste, at vindhastigheder beregnet med LINCOM (WAsP) modellen kun var troværdige i et begrænset område mellem 1 til 2 trækrone-højder over skoven.

Derimod viste SCADIS modellen bedre korrelation med målingerne i højder op til 6 gange trækrone toppen.

Ved skovkant forsøget blev LINCOM modellen benyttet i forbindelse med at skovkanten i modellen blev udglattet som en rampefunktion. Den optimale rampehældning blev fundet til 17 grader. På dette grundlag er det blevet foreslået at benytte WAsP Engineering 2.0 til skovkant modellering i kombination med den foreslåede metode.

Ved modellering af inflow-strømningen til skovkanten viste SCADIS modellen at have fortrin over LINCOM modellen, selv om også denne viste begrænsninger, som dog var mindst opstrøms for skovkanten.

Den generelle konklusion, som kan uddrages fra PhD studiet, er, at laser-baserede vind profiler (vind lidars) nu også kan finde anvendelse til måling af vindhastighedsprofiler over komplekst terræn, forudsat at man kender til vind lidarenes principielle begrænsninger, og samtidig med, at man benytter sig af støtte til fortolkning af måleresultaterne fra vindmodeller.

## Özet

*Bu çalışma kompleks araziler ve lidarlar üzerine yapılmış bir doktora çalışmasıdır. Ünvanın onayı için Danimarka Teknik Üniversitesi Makine Mühendisliği Fakültesi Rüzgar Enerjileri bölümüne yazarın ilgili yayınlarıyla birlikte teslim edilmiştir.*

Şu günlerde Avrupa rüzgar enerjisi sektörünün kompleks arazilere ilgisi artmaktadır. Daha önceleri, bu tür araziler yatırım için uygun olmayan araziler olarak tanımlanırdı. İlginin bu günlerde artmasının birden fazla sebebi bulunuyor ve şu ikisi en büyük etkenler olarak tanımlanabilir. İlk olarak, rüzgar yatırımı yapılacak düz araziler neredeyse tümüyle kullanılmış durumdadır. Kuzey Avrupa buna örnek verilebilir. İkinci olarak ise pazar, rüzgar konusunda kapasitesinin tümünü kullanmayan ülkelere doğru genişlemektedir. Buna örnek olarak Akdeniz ülkeleri verilebilir ki bu ülkelerde araziler ya irili ufaklı tepelerle ya da ormanlık arazilerle sıkça kaplıdır. Her iki durumda da bu tür araziler günümüzde kullanılan rüzgar kapasitesi ölçüm teknikleri için gerekli olan modelleme yazılımları için bir sorun oluşturmaktadır. Temel sebep, halihazırda kullanılan Sınır Tabaka Meteoroloji (Boundary Layer Meteorology) bilgisinin bu tür arazilerde yetersiz kalmasıdır. Bu sebeple yatırım amaçlı ön analiz çalışmalarında kullanılan teknikler genel anlamda her arazi için yeterli olmamaktadır ve sonuç olarak yanlış kapasite hesaplamalarına ve yatırım kaybına neden olmaktadır.

Kompleks arazilerin tüm bu olumsuz yönlerine karşın, AB ülkeleri arasında rüzgar enerjileri 2004 yılından beri her sene 8000 MW'lık bir artma ile büyüyerek 2008 yılında 64000 MW'a ulaşmıştır ve bu büyüme oranının 2030 yılına kadar devam edeceği tahmin edilmektedir. Şu andaki rüzgar enerjisi üretimi Avrupa'nın toplam yüzde 4.2'lik talebini karşılamaktadır. Bu büyüme hızına ve talebin artış trendine bakarak ilk paragrafta anlatılan sebepleri de hesaba katarak yatırımcıların kompleks arazilere talebinin artarak devam edeceğini öngörmek yanlış olmaz.

Avrupa Çevre İşleri İdaresinin (European Environmental Agency - EEA) verilerine göre 5.4 milyon karelik Avrupa toprağının yüzde 42'si ormanlık veya yüksek bitkilerle kaplıdır. Risø Bilim Merkezinde, Rüzgar Enerjileri biriminde bulunan Ormanlar Çalışma Grubunun türbin üreticileri ile birebir görüşmelerle edindiği izlenim, Avrupa'daki yeni rüzgar parklarının yüzde 20 ila 30'unun ormanlık arazilere yakın ya da ormanlık arazilerde kurulduğudur. Buna ek olarak, veriler yeni ve büyük rüzgar parklarının özellikle dik arazilerden uzağa kurulmaya çalışıldığını da göstermektedir. Bu iki istatistik verinin bileştirilmesiyle görülmektedir ki, iki farklı problemin aynı anda vuku bulduğu arazilerin yatırımcılar tarafından neredeyse tümüyle göz ardı edilmektedir. Bu verilerin ışığında kompleks arazilerin ilk paragrafta belirtilen hedeflere ulaşma da önemli bir engel oluşturacağı söylenebilir.

Tüm bunlara ek olarak, rüzgar enerjileri sektörü başka bir problem daha yüzyüzedir. Geçtiğimiz on yıl içinde rüzgar türbinlerinin yüksekliği ikiye katlanmış ve 100 m civarına gelmiştir. Bu tip bir türbinin alt ve üst kanat ucu noktaları 50 ila 150 metre arasındadır. Eğer bir yatırımcı ya da geliştirici bu tür bir türbin için arazi kapasite ölçümü yapmaya kalkarsa aynı tip türbinler için düz arazilerde yapılan ölçümlerle karşılaştırıldığında yüzde 6 ila 8 arası hatalı hesaplamalar yapabilir.

Tüm bu negative etkenlerin ve pazarın büyüme hızındaki beklentilerin sonucu olarak sektör yeni ölçüm cihazlarına ihtiyaç duymaktadır. Bu tür arazilerde ölçüm yapılabilmesi için yeni nesil bir ölçüm cihazının tüm kanat alanını içine alarak 40 ila 200 metre yükseklikte rüzgar ölçümleri yapabilmesi, ve belirli standard ile kullanılabilmesi gerekmektedir (örn. IEC:61400-12). Ayrıca bu tür arazilerde kolayca kurulabilmeli ve kullanılabilmelidir. Bu özelliklere sahip bir ölçüm mevcut

meteorolojik ölçüm direkleriyle hayli zordur. Örneğin, bir ölçüm direğini bir ormanlık arazide kullanmak tam bir lojistik problemdir ve dahası direk konumunda yapılacak en ufak bir değişiklik direği tümüyle yeniden inşa etmekle aynı zahmettedir. Bu ölçüm kriterlerine sahip yeni bir cihaz, lidar (Light Detection and Ranging) yakın bir geçmişte pazara girmiştir. İngiliz araştırma merkezi QinetiQ 2004 senesinde rüzgar enerji ölçümlerine uyumlu bir lidar cihazını tasarlamıştır. Ürünün marka adı ZephIR'dır. Cihazın üretim ve satış hakları 2006 senesinden itibaren, yine İngiliz, Natural Power Ltd. şirketi tarafından satın alınmıştır. ZephIR yaklaşık 1 saat gibi kısa bir sürede tümüyle çalışır şekilde kurulabilir ve kurulum yeri çok az bir külfetle çok kolayca değiştirilebilir. Cihaz 40 ila 180 metre yükseklikteki rüzgar akımını başarıyla ölçebilmektedir. Günümüzde, başka firmalar da yeni lidar cihazları üretmektedir. Örneğin Fransız şirket Leoshere Windcube adlı ve İskoç şirket Scurr Enerji Galion adlı iki modeli kullanıma sunmuştur. Bu tez çalışmasında ZephIR ve Windcube lidarlarla birlikte kullanılmıştır.

Lidar cihazlarının negatif yönü rüzgar akımının homojen olarak arazi üzerinde dağıldığını farz etmesidir ve bu sebeple kompleks arazilerde kullanımı için bir adaptasyon süreci gerekmektedir. Lidarlar daha önce bir çok farklı ölçüm şekillerine göre başarıyla adapte edildiklerinden dolayı bu konudaki yetenekleri daha önceden kanıtlanmıştır. Ayrıca lidarlar bir standardizasyona oturtulma süreci içindedir. Uluslararası Elektroteknik Komisyonu (International Electrotechnical Commission -IEC) Güç Performansı Ölçüm Teknikleri standardını (Power Performance Measurement Techniques- IEC 61400-12-1) şu an için lidarları da kapsayacak şekilde güncellemektedir. Bu tez yazıldığı sırada belirtilen çalışma halen devam etmekteydi ve tez sonuçlarının standartın güncellenmesinde kullanılması düşünülmektedir.

Bu doktora çalışması kapsamında kompleks araziler üzerinde rüzgarın davranış şekillerini araştırmak üzere bir çok deney yapıldı. Öncelikle, ölçüm kalitesi ve geliştirilebilecek sinyal analiz teknikleri kompleks arazi deneylerinden önce belirlendi ve yenilendi. Deney sonuçlarına göre cihazların farklı kompleks arazilerde yüzde 3 ila 10 arası hata yaptığı gözlemlendi. Bu hataya temel sebep yukarıda da bahsedildiği gibi lidarların arazi üzerindeki rüzgarları homojen olarak kabul etmesinden kaynaklanmaktadır. Kompleks arazilerde bu yaklaşım kullanılmamalı ve yeni analiz teknikleri uygulanmalıdır. Zira, hata cihazın kendisinden değil verinin analiz edilme şeklinden gelmektedir. Tezin geri kalan bölümünde ormanlık arazilerde lidarlar da kullanılarak ölçümler yapılmış ve bu araziler iki farklı akışkan modeli ile modellenmiştir. Toplanan deneysel sonuçlar ve modelleme verileri LINCOM akışkanlar modelinin limitler dahilinde ormanlık arazilerde kullanılabileceğini ancak diğer test edilen model, SCADIS akışkanlar modelinin daha başarılı olduğunu göstermiştir. Yazar, bu tez çalışmasını tamamladığında LINCOM akışkan modeli bir yenilenme devresi içindeydi.

Genel olarak söylenebilir ki, lidarlar kompleks arazilerde akışkan modelleri yardımıyla başarıyla kullanılabilir. Özellikle, Türkiye gibi kompleks arazilerin ağırlıkta olduğu ülkelerde, veri analizlerinin cihazların standart yazılımından yaratılan sonuçlarla değil tez içinde vurgulanan özel analiz yöntemleriyle toplanması tavsiye edilir. Diğer gözardı edilmemesi gereken noktalar şunlar olabilir. Tasvir edilen modelleme tekniği ölçüm yapılmadan önce cihazın nereye konacağını belirlemek için kullanılmalıdır. Bu tür bir gereksinim için bir çok akışkan modeli bir arazi de hangi noktanın bir diğerinden daha elverişli olduğunu kolaylıkla söyleyebilir. Ölçüm yapıldıktan sonra eğer veriler bir düzeltme evresinden geçirilecekse, yazara göre, tercih edilecek akışkan modeli daha önce kompleks arazilerde ölçümlerle denenmiş bir yazılım olmalıdır.





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