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Wind inflow modeling for Airborne Wind Energy Systems

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1 Introduction

Wind is a highly variable source of renewable energy. This variability needs to be understood and handled in order to reduce cost, maximize power production and improve electrical grid feed-in quality. Each location has its own wind characteristics affected by longitude and latitude, terrain complexity, proximity to the ocean and so on. Wind speed fluctuates across a wide frequency spectrum, from long-term climate changes, annual, lunar and diurnal cycles to high-frequency turbulence. Conventional wind turbines, which operate within the lower parts of the atmosphere, use meteorological masts or Light Detection And Ranging (LiDAR) for resource assessment and established wind and turbulence models to estimate annual energy yield and mechanical loads. High altitude wind energy devices such as Airborne Wind Energy Systems (AWESs) and tall wind turbines beyond 10 MW will operate within vastly different wind conditions and can not rely on the validity of these models. Simplified model assumptions are insufficient to represent these conditions. While long-term average wind speeds are generally stronger at higher altitudes, short-term winds vary significantly with atmospheric stability. These different stratification conditions significantly affects wind conditions, especially at higher altitudes and can result in a multimodal probability distribution which can not be adequately represent by a single Weibull distribution fit. We therefore aim to derive a general engineering wind inflow model based on measurements, mesoscalic weather simulation and Large Eddy Simulation (LES) that provides developers and researchers with more realistic wind conditions aloft beyond 300 m. Practical and economic considerations for AWES mean we focus on resource assessment at *mid-altitudes* up to 1200 m, an altitude range spanned by the highly-variable boundary layer.

The common way to gather wind and weather data at these altitudes are sparsely deployed weather balloons (radiosondes), which measure data while quickly ascending through the Atmospheric Boundary Layer (ABL) [1]. This measurement technique however, does not offer continuous data acquisition and has an inherently low temporal and vertical resolution which is not sufficient for assessing the potential of mid-altitude winds. The low temporal resolution of radiosondes leads to considerable undersampling and a loss of higher frequency information. Recent developments in wind LiDAR technology enable high temporal and vertical resolution measurements in higher altitudes. These devices measure the spectral shift between the emitted light pulse and returning scattered light of aerosols transported with the wind [2]. Therefore, aerosol load limits this measurement technique. The primary aerosol source is the Earth's surface. Particles depend on vertical mixing to be transported aloft. As a result, aerosol load decreases with altitude and drops to levels too low for LiDAR devices to reliably measure the wind speeds[3]. This vertical mixing within the ABL is dictated by the vertical surface heat flux (SHF) which varies with the diurnal cycle, season and weather. This leads to an inherent bias of LiDAR measurements towards higher wind speed and times of increased vertical mixing. Extensive cloud coverage or fog increases the availability close to the LiDAR due to the high amount of backscattering particles or water droplets.

However, this also reduces the distance which laser beams penetrate into the cloud or fog, often leading to data loss further aloft. Other issues of LiDAR measurement campaigns are that they are expensive and time consuming. Due to inherent temporal and spatial averaging LiDAR measurements can only give a rough estimate of turbulence intensity. As of now, no high altitude measurement device can reliably gather high frequency data for an extended time period.

Therefore, solely relying on measurements is not feasible. In our research we combine results from measurements, long-term meoscale numerical weather prediction models, namely the Weather Research and Forecasting (WRF) model, with turbulent fluctuation calculated by the Parallelized Large-eddy Simulation Model (PALM). We investigate the wind resource up to 1200 m over generally flat terrain at Pritzwalk in northern Germany. The measurement campaign which was part of the *OnKites II* project at the Fraunhofer Institute for Wind Energy Systems (IWES) lasted six months between September 2015 and February 2016. To increase precision of the WRF simulation, we enhance boundary and initial conditions by implementing LiDAR wind speed measurements as partial forcing terms at multiple altitudes using observation nudging (OBS nudging). A measurable improvement in horizontal wind speed and direction precision, in comparison to reference simulation without OBS nudging, can be observed as surface influence weakens. The results of the WRF model are then used to drive PALM which generates a short-term data set at 1 Hz resolution suitable for characterizing turbulence. By combining these data sets, we aim to derive an engineering inflow model that can be used to optimize the flight path, power production, structural design and size the aircraft, tether and ground stations of AWESs.

A preliminary investigation of the upper limit on traction power and optimal operating altitude, based on LiDAR measurements, shows that optimal altitude varies significantly with stratification conditions and does not always align with the altitude of highest wind speed. The idealized, quasi steady-state traction power model by Schmehl et al. [4] includes losses caused by misalignment of wind direction and AWES position, but neglects gravity, tether drag and detailed flight maneuvering. The bottom sub-figure in figure 1 shows the hourly wind speed profiles, altitude of highest wind speed (X) and estimated optimal operating altitude (◯). The profiles are colored according to wind direction. The top sub-figure shows measured 10 minute mean wind speed. The wind speed trend follows a more typical diurnal cycle of with the development of a low level jet during the night. Optimizing the trajectory and altitude for various sizes of AWES using a more detailed aerodynamic model as well as the derived wind inflow model will yield a more realistic estimate of AWES potential.

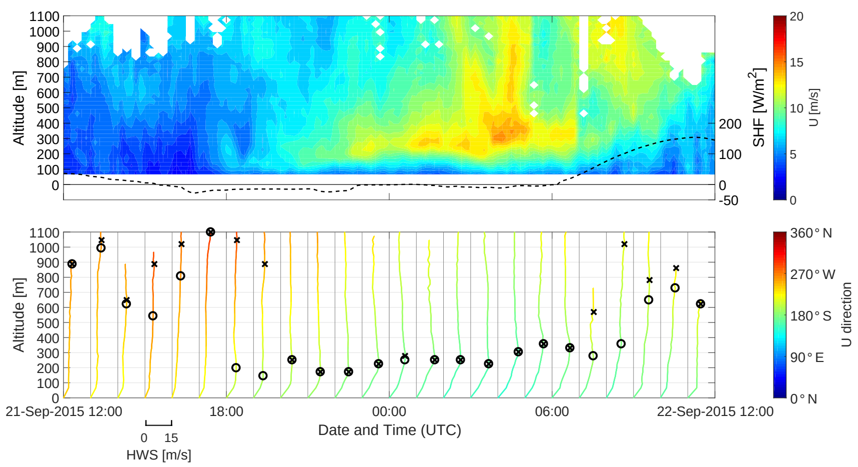

Figure 1: Visualization of measured 10-minute mean wind speed and wind direction of a 24 hour period between September 11-12th 2015. The top sub-figure shows the LiDAR-measured wind speed and WRF calculated SHF(dashed line). The bottom figure shows each hours wind speed profile colored according to wind direction. X marks the altitude of highest wind speed and ◯ denotes optimal operating altitude according to the idealized traction power approximation.

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