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MASC – a small Remotely Piloted Aircraft (RPA) for wind energy research

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Abstract. Originally designed for atmospheric boundary layer research, the MASC (Multipurpose Airborne Sensor Carrier) RPA (Remotely Piloted Aircraft, also known as Unmanned Aerial Vehicle, UAV) is capable of making in-situ measurements of temperature, humidity and wind in high resolution and precision. The autopilot system ROCS (Research Onboard Computer System) enables the aircraft to fly pre-defined routes between way-points at constant altitude and airspeed. The system manages to operate in wind speeds up to 15 m s^{-1} safely. It is shown that a MASC can fly as close as one rotor diameter upstream and downstream of running wind turbines at these wind speeds and take valuable data of incoming flow and wake. The flexible operation of an RPA at the size of a MASC can be a major advantage of the system compared to tower measurements and remote sensing in wind energy research. In the project "Lidar Complex" comparisons of RPA measurements with lidar systems and tower measurements are carried out at two different test sites. First results, including turbulence and wake measurements, from a campaign in autumn 2013 are presented.

1 Introduction

Small Remotely Piloted Aircraft (RPA, also known as Unmanned Aerial Vehicle, UAV) have been increasingly used in atmospheric sciences throughout the last decade. In atmospheric boundary layer (ABL) research, systems like SUMO (Reuder et al., 2009) for vertical sounding of the atmosphere, or the M^{2}AV (Spieß et al., 2007; Martin et al., 2011), which is additionally capable of measuring turbulent fluxes of sensible heat (Martin and Bange, 2014) and individual turbulent outbursts like entrainment (Martin et al., 2014), have become valuable instruments for data collection. Also outside Europe similar systems are operated, as presented in Thomas et al. (2012) and Bonin et al. (2013). Boundary-layer research has become increasingly interesting for the wind-energy community, since efficiency of wind turbines is directly related to the effects in the boundary layer. Therefore the same (Reuder and Jonassen, 2012) or similar (Subramanian et al., 2012) RPA that have been used for fundamental boundary-layer research have recently been applied in wind-energy research. The thermal stratification of the atmosphere, which can be investigated with vertical profiles collected by RPA, has effects on wind shear and turbulence. Both of these effects have large impact on the efficiency and fatigue of wind turbines. Simple analysis of wind sites assuming the wind profiles of thermally neutral stratification neglect these effects and can lead to a wrong estimation of the risks associated with the deployment of a wind energy converter (WEC). While large-eddy-simulation (LES) is used to study the effects of turbulence in detail (e.g. Zhou and Chow, 2012; Wu and Porté-Agel, 2012, 2011), measurements are necessary to validate and initialize these studies. Small RPA as a flexible and cost-effective tool can serve this purpose. It is shown in this paper how the small RPA MASC (Multi-purpose Airborne Sensor Carrier), which was developed at the University of Tübingen, based on the experiences with the M^{2}AV, is now used in the project "Lidar Complex" for wind energy research (see Fig. 1).

Figure 1. Research RPA MASC in front of a Kenersys K110 WEC (picture taken by Joe Smith, University of Tübingen).

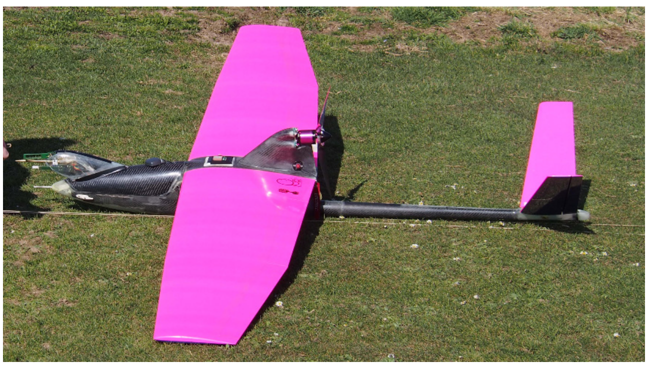

Figure 2. Research RPA MASC.

2 System description

MASC is a small fixed wing RPA with one electrical pusher engine (see Fig. 2). Three different wing sizes exist for the aircraft ranging from 2.60 to 3.40 m. With minimum battery and payload the total weight of the MASC is less than 5 kg. Flight time in this configuration is limited to approximately 15 min. The endurance can be increased up to one hour by adding more batteries. The total weight of the system will than exceed 7.5 kg. For take-off, a bungee launch procedure is performed at the University of Tübingen. The alternative of a landing gear limits take-off and landing spots to flat runways and would also increase total weight of the aircraft. For slow and safe landings the MASC is equipped with flaps to decelerate before touch down. Table 1 summarizes the characteristics of the MASC aircraft.

Table 1. Characteristics of the MASC RPA.

wing span	2.60 m, 3.00 m or 3.40 m
rudder configuration	ailerons, flaps, v-tail
weight	5–7.5 kg, depending on battery load
payload	max. 1.5 kg
endurance	15–60 min, depending on battery load
cruising speed	24 m s^{-1}
propulsion	electrical pusher motor
take-off	bungee launch

2.1 Autopilot

The ROCS (Research Onboard Computer System), developed at the Institute of Flight Mechanics and Control (iFR) at the University of Stuttgart, is a autopilot system with waypoint navigation capabilities. Its embedded linux system, enhanced with an FPGA (Field Programmable Gate Array) chip, provides computing power for complex navigation tasks. In the field of meteorological measurements, only a fraction of the possibilities are used so far.

The basic sensor suite of the ROCS autopilot consists of a single-channel GPS receiver, a micro-electro-mechanical-system (MEMS) inertial measurement unit (IMU) as well as barometric and differential MEMS pressure transducers. From this, position, velocity, and attitude of the UAV are estimated using a extended Kalman Filter (EKF). The estimates are then used in the guidance process to keep the UAV on the desired flight track. An overview of performance characteristics is given in Table 2.

Table 2. Typical ROCS autopilot performance.

tracking accuracy	±5 m
altitude precision	±2 m
airspeed precision	±1 m s^{-1}

2.2 Meteorological measurement system

The meteorological measurement system consists of sensors for all thermodynamic scalars. It is designed to be able to measure turbulent fluxes and structures, providing good measurements up to a cut-off frequency of 10–20 Hz for wind and temperature measurements and 1 Hz for humidity. A central data logging unit called AMOC (Airborne Meteorological Onboard Computer) stores raw sensor data at a sampling rate of 100 Hz onto a SD-card. A 1 Hz telemetry downlink

Table 3. MASC measurement equipment characteristics.

variable	sensor type	accuracy
temperature	PT100 and thermocouple	±0.5 K
humidity	capacitive sensor P14-Rapid	±3 % RH
pressure	barometer HCA-BARO	±0.5 hPa
wind	five hole probe, plus GPS/INS	±0.5 m s^{-1}

for live observation on a groundstation laptop is provided by the system.

There are two temperature sensors installed in parallel – a thermocouple and a resistance thermometer - both in a fine wire design. A detailed description of these sensors can be found in Wildmann et al. (2013). Detailed information on the flow probe setup is presented in Wildmann et al. (2014). In both papers the data logger AMOC is also described in more detail. The complementary measurement of ground speed and orientation of the aircraft with the commercial Inertial Navigation System (INS) IG-500N by SBG systems enables in-situ wind measurement. The commercial capacitive humidity sensor P14 Rapid by Innovative Sensor Technology (IST) with custom electronics and a MEMS barometer (HCA-BARO by Sensortechnics) complete the thermodynamic measurement.

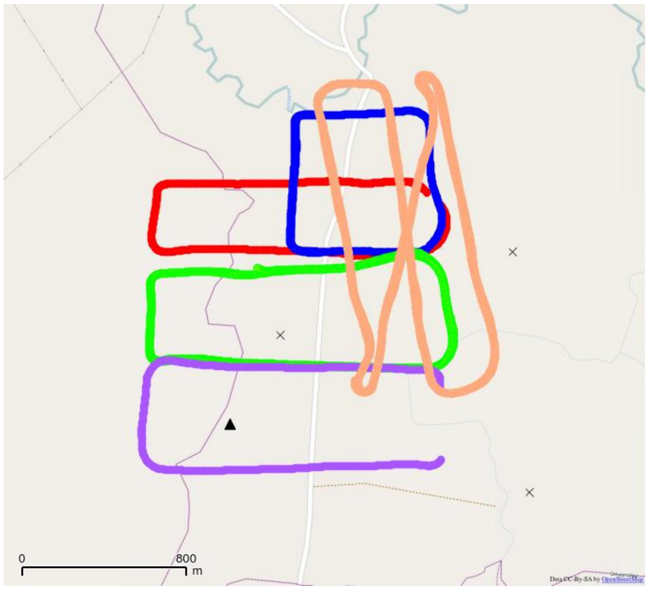

Figure 3. Extracts of recorded flight tracks at test site Grevesmuehlen. Vertical profiles up to 500 m are measured with a square pattern (blue). Rectangular "racetrack" patterns at constant altitude serve to measure turbulence parameters upstream (purple), downstream (red) and between the wind turbines (green, orange). The position of the WECs is depicted as crosses in the map, the measurement tower as a black triangle.

3 Project "Lidar Complex"

The project "Lidar Complex" was initiated by the research network "WindForS" (www.windfors.de), based in Southern Germany. The goal of the project is to establish lidar technology for wind energy plant site evaluation in complex terrain. Additional goals are the comparison of different measurement techniques and the validation of wind field models in terrain that does not conform to IEC61400. It is planned to design a turbulent wind field generator, fed by real measurement data, which can be used to analyse WEC behaviour. An experiment was carried out in October 2013 in flat terrain in Northern Germany to establish a baseline for the comparison of all instruments. In spring 2014, experiments at the test site in complex terrain in the Swabian Alb will be extended.

3.1 Test site Grevesmühlen/Baltic Sea

The test site in Grevesmühlen, located approximately 15 km upcountry of the coast of the Baltic Sea in Germany, was included in the project "Lidar Complex" as a reference site for measurements in a terrain with a low complexity level. Although there are several small areas of sparse woods and different crop types, the orography is flat and the terrain conforms with IEC standards. The site has three WECs (Kenersys K110 2.4 MW, K100 2.5 MW and K82 2.0 MW) placed in a triangle with 1.2–1.5 km distance to each other. In main wind direction, which is from the south-west, a measurement tower is placed in front of one of the WECs. The tower is equipped with a sonic anemometer at hub height, three cup anemometers, three wind vanes, a rain sensor, a temperature sensor at hub height, a barometric pressure sensor and a humidity sensor. Besides a measurement tower there are also two lidar systems installed in the vicinity of this particular WEC. One of them, a Leosphere "Windcube v2" pulsed lidar, is situated close to the measurement tower, looking upwards and the other one is a forward looking, nacelle-based lidar that was provided by SWE (Rettenmeier et al., 2010; Peña et al., 2013). Figure 3 shows several different flight paths that were performed at this site in a four day campaign from 21 to 24 October 2013.

3.2 Test site Schnittlingen/Swabian Alb

One of the biggest accumulations of WECs in the state of Baden-Württemberg, Germany, can be found on a plateau in the Swabian Alb, close to the town Schnittlingen. It consists of nine converters in total, seven of them in a one kilometer square that was chosen as the core site for first flight tests with MASC in May 2013. These seven converters have hub heights between 70 and 105 m and nominal power of 850 kW to 2.7 MW. A 100 m meteorological meaurement tower is installed on site and will be re-equipped with meteorological instruments in 2014. The terrain at this test site has a much higher complexity level compared to Grevesmühlen.

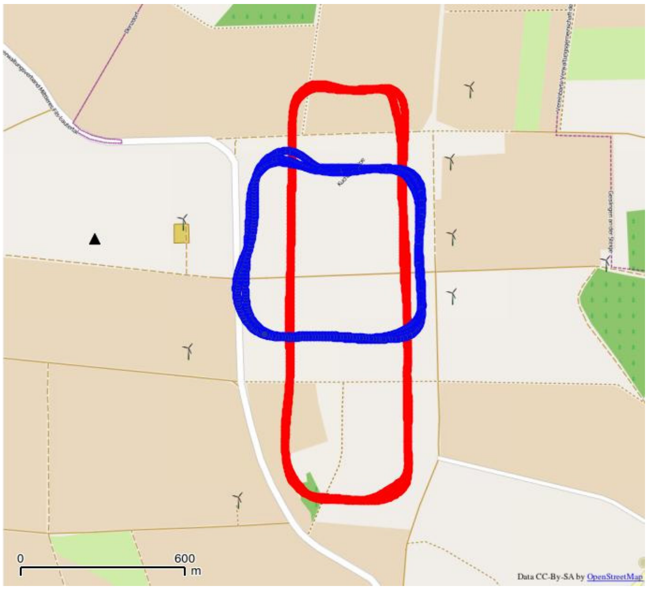

Figure 4. Extracts of recorded flight tracks at test site Schnittlingen. Vertical profiles up to 500 m were measured with a square pattern (blue). Rectangular "racetrack" patterns at constant altitude serve to measure turbulence parameters (red). The position of the WECs can be seen from the OpenStreetMap layer, the measurement tower is depicted as a black triangle.

The wind field is highly influenced by the so-called "Albtrauf", which is an approximately 100 m steep escarpment about 2 km upstream in the main wind direction of the test site. One research goal of the project is to investigate the impact of the escarpment on the wind field.

4 Results

4.1 Flight performance in high wind speeds and in the wake of wind turbines

A short test experiment in late spring 2013 at the test site in the Swabian Alb was used as a proof of concept. Experience was gained about optimal flight strategies and quality of sensor data in the immediate vicinity of WECs.

MASC showed good performance throughout the experiment. The maximum wind speeds that were found during these days were 12 m s^{-1}. More flights were conducted in October 2013 at the site in Grevesmühlen. Again, MASC was able to take data up- and downstream of a wind turbine in wind speeds up to 15 m s^{-1}. Figure 5 shows the precision of the autopilot controlled flight in the wake of a WEC in comparison to flight legs in the undisturbed boundary layer. While in all three depicted variables (course, altitude and airspeed) the presence of the wake can be observed at around 300 m flight leg distance, the aircraft never entered a critical state. The largest deviations from the demand values can be found in the course with up to 10 m deflection. This behaviour is intended, since course deviations are least critical for meteorological measurements and the autopilot controller was tuned accordingly.

4.2 Comparative measurements upstream

In the experiment in Grevesmühlen, a wide variety of measurement equipment was present as described in Sect. 3. A first analysis of the data was carried out to show if systematic errors between the different sensors could be obseserved. The best agreement of all measurements can be found between ground-based lidar and tower-based sonic anemometer measurements. The reason is, that these measurements have the least spatial offset and thus measure the same air mass at the same time. The time series of sonic measurements in the observed period has a standard deviation of approx. 1 m s^{-1}. Deviations among the measurement systems are within this range, so that a good agreement can be assumed. Figure 6 shows data from sonic anemometer measurements on the tower, data from the nacelle-based lidar, the ground-based lidar and RPA measurements. Since RPA measurements are not point measurements, the sections of straight and level flight (legs) that were approximately 800 m long were extracted and averaged for the comparison. The error bars show the standard deviation of the measurements within these legs. It is evident that a perfect agreement between the sensors is not possible, because spatial and temporal biases can have large effects on the instantaneous wind measurement in the turbulent boundary layer. Given these conditions, the agreement is a good basis for further investigations on the wind field at the site in Grevesmühlen and for the next experiments in complex terrain. The good accuracy of wind-vector measurements from RPA has also been shown in other studies (Martin et al., 2011; van den Kroonenberg et al., 2008).

4.3 Measurements in the wake of a wind turbine

As shown in Fig. 5, MASC is able to fly safely in the wake of a 2.4 MW WEC. At the test site in Grevesmühlen, measurement flights were performed in the wake with flight legs in six distinct heights from just below the hub of the turbine at 75 m, up to 225 m. The flight legs are oriented perpendicular to the main wind direction. The resulting wind measurements presented in Fig. 7 show a picture of the shape and intensity of the wake in a distance of four rotor diameters behind the WEC. For better visualization, the linear interpolation technique after Akima (1978) was applied between the measurements of the single flight legs at different altitudes, while the original flight leg paths are still depicted with black lines. Since the flight legs are not performed in parallel at the same time, the shape of the wake is somewhat distorted. Two flight legs at each altitude are used to average the results. The wind speed drops from about 12 m s^{-1} in the free stream to about 5–6 m s^{-1} in the wake of the turbine. This is a wind speed deficit of about 50–60 % in a four rotor diameter distance to

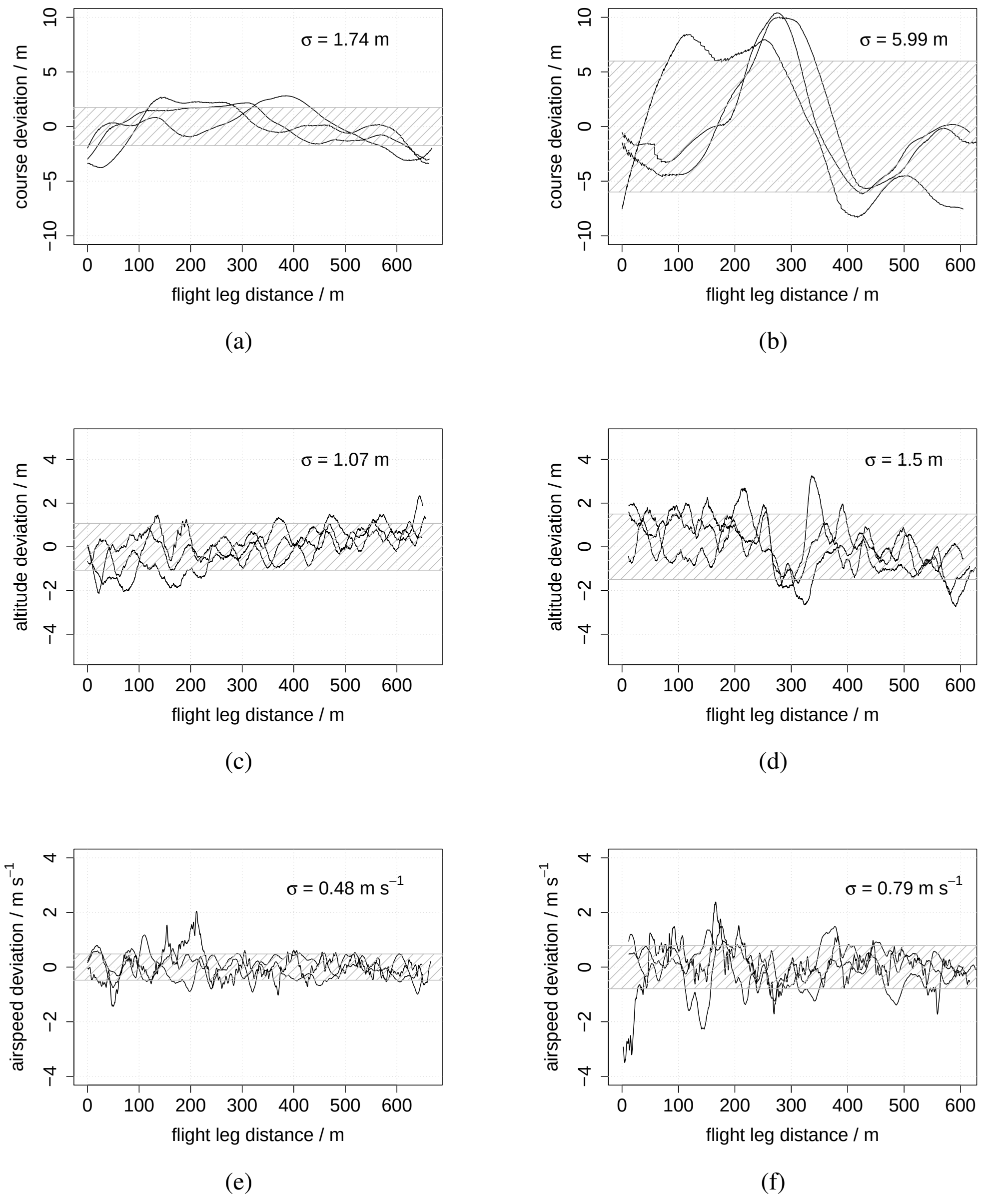

Figure 5. Performance of MASC with ROCS autopilot in undisturbed atmosphere **(a)**, **(c)**, **(e)** and behind a wind turbine **(b)**, **(d)**, **(f)**. All data were measured during the same flight (see green track in Fig. 3). The figures show three successive, individual flight legs at 100 m altitude (= hub height). Offsets between demanded values for course, altitude and airspeed were subtracted and can be higher than the standard deviations σ. An average wind speed of 7 m s^{-1} perpendicular to the flight path was present throughout the flight.

the turbine. These values are in agreement with lidar measurements performed by Iungo et al. (2013) or Käsler et al. (2009) for similar sized turbines and wind speeds.

4.4 Turbulence characteristics in a wind park

Turbulence has a high impact on efficiency of a wind turbine and also on the fatigue of rotors. However, a quantitative description of the effects of turbulence is difficult and not yet available. MASC with its instrumentation for small scale turbulence measurement can deliver valuable data for studies towards a deeper insight into the effects of turbulence on the turbines. Figure 8 shows measurements of turbulent kinetic energy (TKE) upstream and downstream a wind turbine calculated from wind measurements of MASC according to:

$$\mathrm{TKE} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right) \tag{1}$$

with standard deviations σ of the wind-vector components u, v and w for 700 m long flight legs. As expected, an increased level of turbulence is found in the wake of the turbine, which slowly starts to decay in a distance between 400 and 600 m.

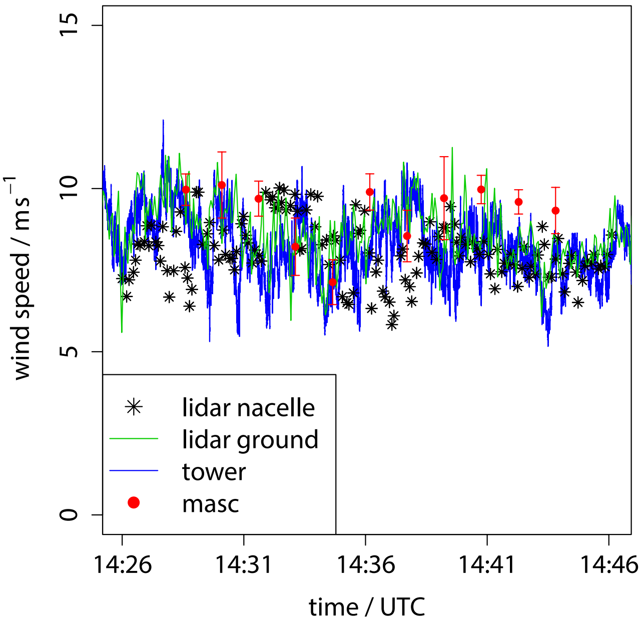

Figure 6. Comparison of horizontal wind speed in the main wind direction measured by tower wind sonic, nacelle-based lidar, ground-based lidar and MASC on 22 October 2013. For the nacelle based lidar, a measuring point 80 m in front of the nacelle was chosen, for the ground based lidar a measurement point at hub height close to the tower was selected.

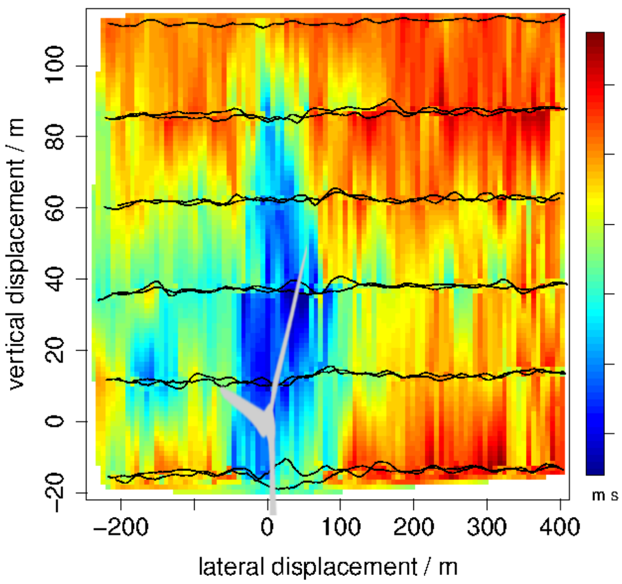

Figure 7. Wind speed measurement from RPA MASC in the wake of a K110 WEC. Flight legs (black lines) are performed perpendicular to the main wind direction, four rotor diameters downstream of the WEC, in six distinct altitudes. Linear interpolation was applied between the wind speed measurement of the single legs and visualized with a colour scale. The position of the WEC is illustrated by the gray shade.

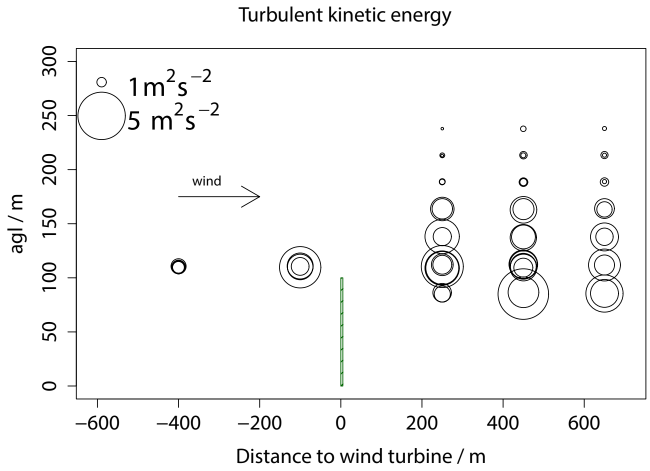

Figure 8. Turbulent kinetic energy measured in flight legs behind a WEC (green line) in different distances and in comparison to upstream turbulence. Each circle represents one single flight leg.

In this case it also appears that a higher degree of turbulence is present upstream, very close to the wind turbine.

5 Conclusions

Remotely Piloted Aircraft of type MASC with an instrumentation that allows vertical soundings of the atmosphere as well as in-situ turbulence measurement are not only a valuable tool for fundamental boundary layer research, but can be directly applied for wind energy research. Even in high wind speeds, the RPA MASC is able to operate safely, also in the wake of large WEC. Its flexible operation in almost any location and low operating cost makes it superior to stationary measurement equipment like towers and lidars for short, focussed experiments. It is shown how the data collected by MASC can provide information about inflow conditions, the wake structure of a WEC and the turbulence of the inflow and wake of the turbine. In the project “Lidar Complex”, MASC is first used extensively in wind energy research.

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