Evaluation of ZephIR

Internal Project

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Version 4

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Contents

1 Introduction

ZephIR is a new laser based device for wind measurements in the lower atmosphere. The device has been developed by the British company QinetiQ with special intension to the wind energy industry [1]. Deutsche WindGuard is collaborating with QinetiQ in evaluating this new technology. In this frame the ZephIR system is tested by Deutsche WindGuard against conventional wind measurements with mast mounted cup anemometers. This report briefly summarises results of the comparison of ZephIR against measurements with a 65 m high mast and a 124 m high mast as well as Deutsche WindGuards' first practical experience with the system.

2 Measurement Sites and Met Masts

2.1 Site Westdorf, 65 m Mast

The first measurements have been performed near the town Westdorf about 3 km away from the German North Sea coast. At the measurement site a 65 m high met mast serves for the measurement of the power curve of a wind turbine of type Enercon E-70 E4. The measurement site is characterised by flat farmland with open appearance. Photos of the met mast and the measurement site as well as a map of the measurement site are shown in Figure 1 to Figure 4.

The met mast is positioned 205 m, i.e. 2.5 rotor diameters, west of the wind turbine of type Enercon E-70 E4. The ZephIR has been positioned 64 m west of the mast. A second turbine of type Enercon E-66/18.70-3 is located about 464 m southeast of the mast. Both turbines strongly influence the airflow at the mast and the ZephIR when the wind is coming from East to Southeast. A third wind turbine of type Enercon E-40, located about 1 km west of the mast, does not influence the airflow at the mast and the ZephIR significantly (influence on wind speed below 1 percent). A small forest, which is located a few hundred meters south of the met mast, is expected to have a small influence on the wind measurements at winds from South. The measurement site follows the requirements of the standard IEC 61400-121 [2] for wind turbine power curve testing.

At top of the met mast two cup anemometers of type Thies First Class and Vector A100X are mounted at 65 m height above ground on a U-shaped boom. A third anemometer of type Vector A100X is mounted on a side boom at a height of 31 m, pointing to west. All cup anemometers have been calibrated in a wind tunnel according to DKD and MEASNET. The validity of the calibrations has been checked by means of in-situ tests. The wind measurements with the mast follow the requirements of IEC 61400-121 [2].

Within the wind direction sector 235°-325° the two cup anemometers on the mast top, the ZephIR, as well as the wind turbine Enercon E-70 E4 are exposed to nearly the same wind conditions. This sector is applied for the comparison of cup anemometer measurements and the wind measurements with the ZephIR as well as for the evaluation of the wind turbine power curve.

Figure 1: Photo of the 65 m high met mast and wind turbine of type Enercon E-70 E4 in Westdorf. The photo has been taken near to the position of the ZephIR.

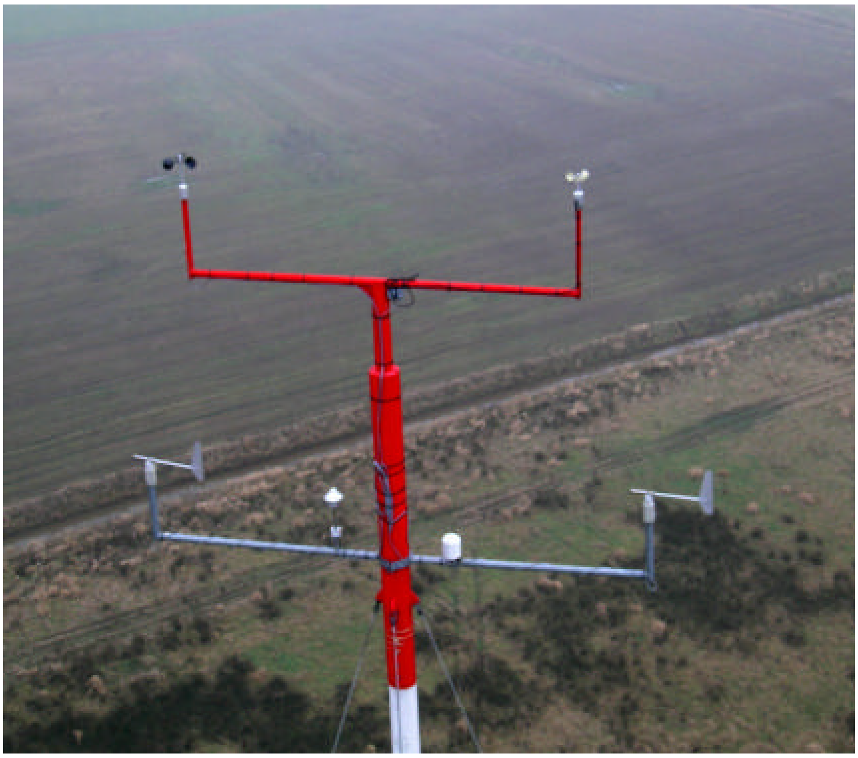

Figure 2: Photo of the mast top in Westdorf.

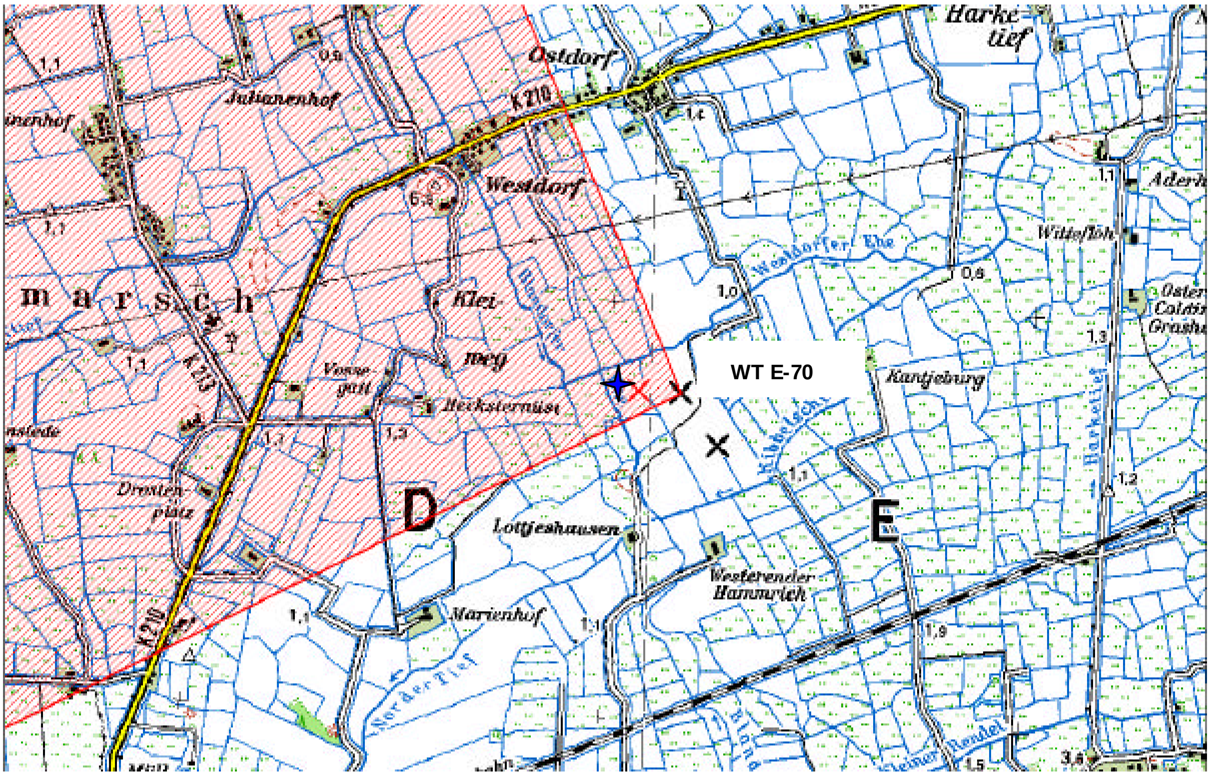

Figure 3: Map of the measurement site Westdorf. The measurement sector of 235°-325° is indicated by red shading. The black crosses mark the position of wind turbines. The red cross marks the position of the met mast. The blue cross marks the position of the ZephIR.

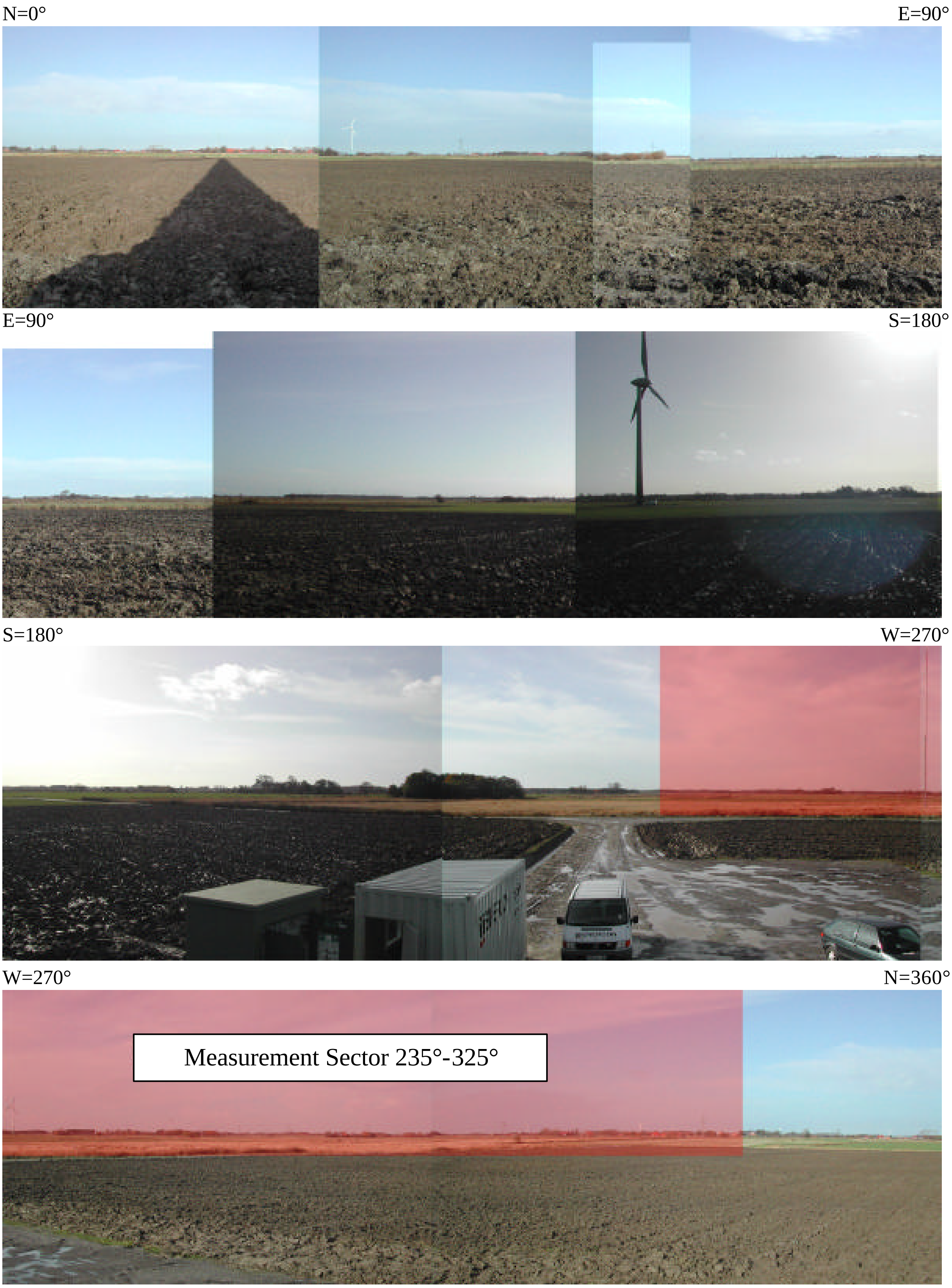

Figure 4: Photos of the measurement site Westdorf as taken from the wind turbine E-70 E4. The measurement sector is marked by red shading.

2.2 Site Emden, 124 m Mast

At the measurement site Emden a 124 m high met mast serves for the measurement of the power curve of a wind turbine of type Enercon E-112. The measurement site is located directly at the North Sea coast at the bay Dollart, west of the city Emden. The measurement site is characterised by flat farmland with open appearance between western and northern direction of the met mast. In northern to eastern direction the wind is coming over a car manufacturing plant /Volkswagen and over the city of Emden. The southern direction is characterised by sea (bay Dollart) up to distances between 4 km and 10 km and open farmland in larger distances (Netherlands). Photos of the met mast and the measurement site as well as a map of the measurement site are shown in Figure 5 to Figure 8.

The met mast is positioned 228 m, i.e. 2.0 rotor diameters, west of the wind turbine of type Enercon E-112. The ZephIR has been positioned 83 m west of the mast. There are several wind turbines located in the direct vicinity of the met mast and the ZephIR. Due to this only in the wind direction sector 136°-226° the met mast and the wind turbine E-112 are exposed to the same wind conditions. In addition, the ZephIR measurements might interfere with the wake of the next neighbouring turbine of type Enercon E-66/15.66 (67 m hub height) in the wind direction sector 199°-226°. Thus, the wind direction sector for the evaluation of the ZephIR had finally to be reduced to the sector 136°-199°. The measurement site follows the requirements of the standard IEC 61400-121 [2] for wind turbine power curve testing.

At top of the met mast two cup anemometers of type Thies First Class and two cup anemometers of type Vector A100X are mounted at 124 m height above ground side by side on a rig. The rig is aligned such that in the measurement sector 136°-226° no mutual influence of the anemometers is given. All cup anemometers have been calibrated in a wind tunnel according to DKD and MEASNET. The validity of the calibrations has been checked by means of in-situ tests. The wind measurements with the mast follow the requirements of IEC 61400-121 [2].

Figure 5: Photo of the 124 m high met mast and wind turbine of type Enercon E-112 in Emden. The ZephIR is marked by a blue cross.

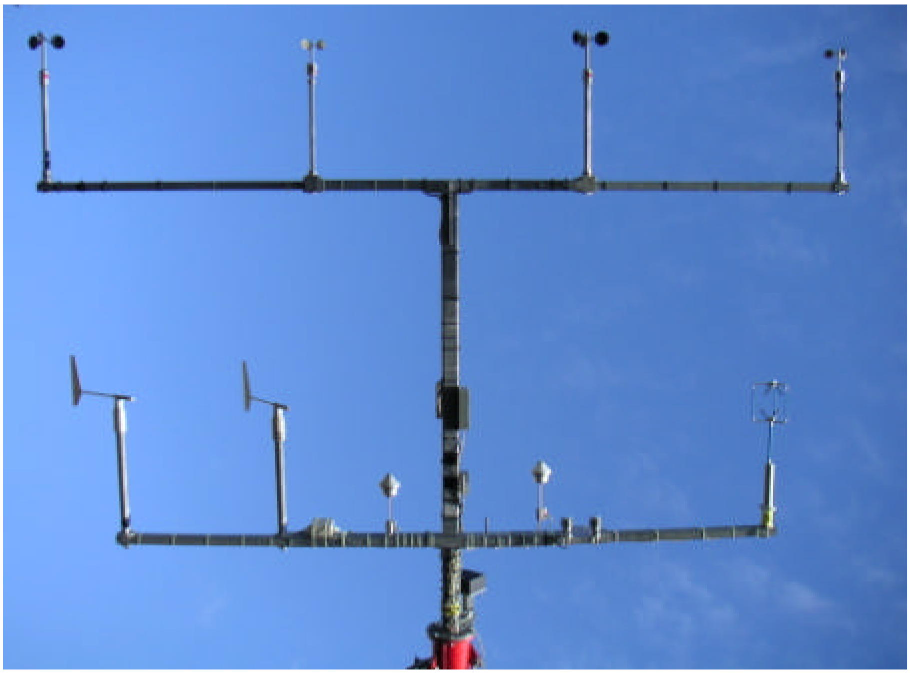

Figure 6: Photo of the mast top in Emden.

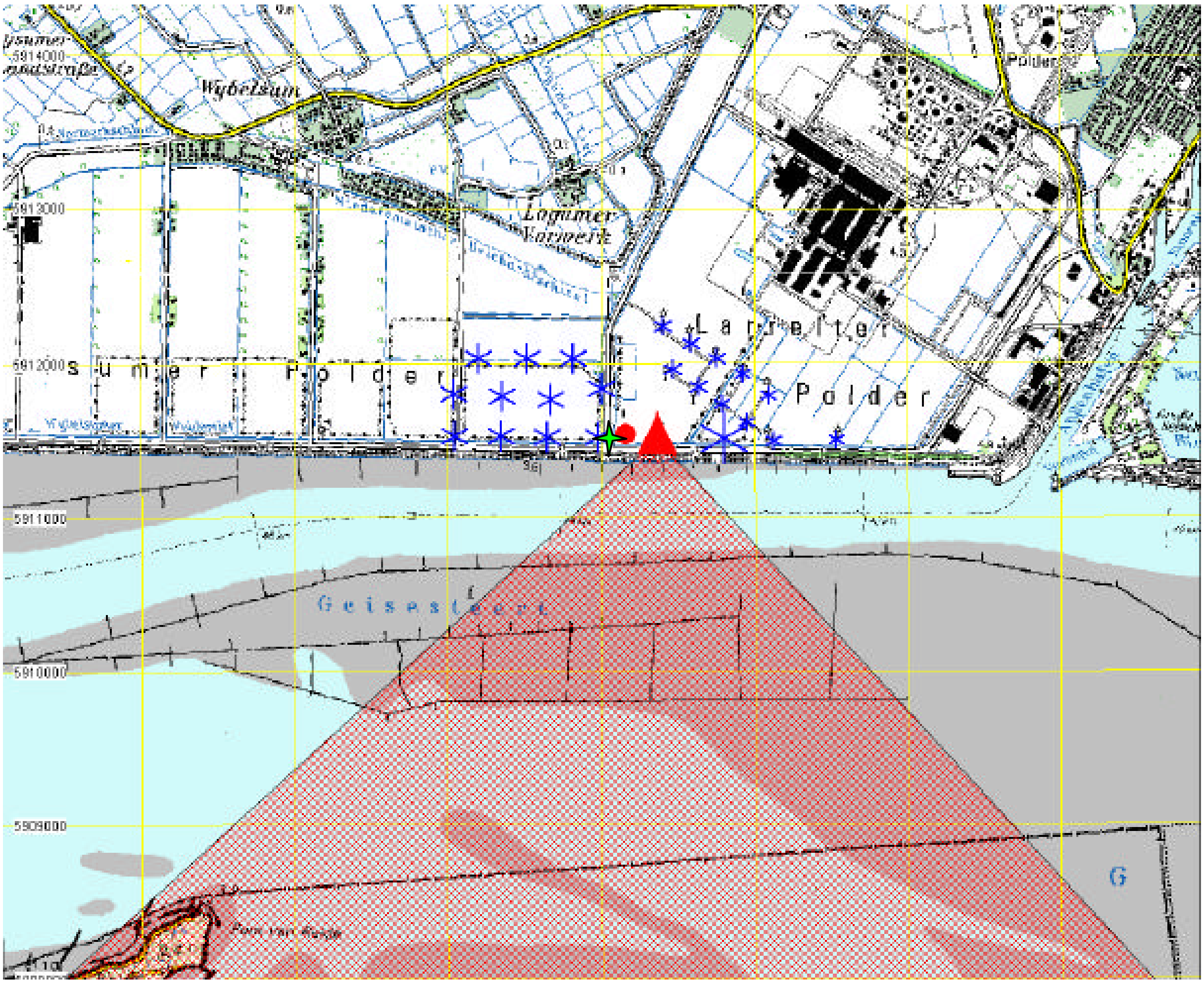

Figure 7: Map of the measurement site Emden. The red triangle marks the position of wind turbine E-112. The red circle marks the position of the met mast. The green cross marks the position of the ZephIR. The blue stars mark the position of neighbouring wind turbines. The measurement sector for the wind turbine power performance test of 136°-226° is indicated by red shading. For the test of the ZephIR this sector has been reduced to 136°-199°.

N=0° E=90°

E=90° S=180°

S=180° W=270°

W=270° N=360°

Figure 8: Photos of the measurement site Emden as taken from the nacelle of the wind turbine E-112.

3 Set-up of the ZephIR, Data Collection and Data Processing

3.1 Set-Up of the ZephIR

3.1.1 Set-Up of the ZephIR at Measurement Site Westdorf

The ZephIR has been set-up at 12/20/2005 by two staff members (Mr. Ian Locker and Mr. Adrian Coffey) from the manufacturer QinetiQ. During the installation of the ZephIR different staff members of Deutsche WindGuard have been introduced in the operation of the system. The key settings of the ZephIR have been chosen as follows:

- Measurement heights: 300 m, 65 m, 65 m, 65 m, 65 m
- Cloud correction: not activated.

In this mode the ZephIR measures the wind conditions successively in 300 m and four times in 65 m above ground. The measurement height of 65 m has been chosen in order to make the measurements comparable to the cup anemometer measurements at top of the met mast. The additional measurement height of 300 m has been chosen in order to be able to apply a cloud correction of the measurement data afterwards.

The vertical alignment of the ZephIR has been checked with a spirit level during the installation. The vertical alignment has been checked some days later with an electronic spirit level. The alignment did not change during the course of the measurements. The deviation from an ideal alignment has been found to be 0.5° in one direction and 0.1° in the transversal direction. According to QinetiQ this deviation is uncritical.

The ZephIR as well as the data acquisition system of the met mast have been synchronised to PTB time. The synchronisation has been checked during the course of the measurements.

3.1.2 Set-Up of the ZephIR at Measurement Site Emden

The ZephIR has been installed at the measurement site Emden at 01/10/2006 by two staff members of Deutsche WindGuard. The same settings of the ZephIR than at the site Westdorf have been chosen, except of that the measurement heights have been set to 300m, 124m, 124m, 124m in order to make the measurements comparable to the anemometers at top of the met mast in Emden.

The vertical alignment of the ZephIR has been checked with a spirit level during the installation and at any time the data was read out (every 6 days). The ZephIR as well as the data acquisition system of the met mast have been synchronised to PTB time.

3.2 Data Collection

The ZephIR stores the measurement data on a 4GB flashcard. On the flashcard the measured spectra (raw-files) as well as wind data averaged over three seconds (wnd-files) are stored. A 4GB flashcard can store about 6 days of raw-data and about 24 days of wnd-data. The data can in principle be read out via GSM, Ethernet link between a PC and the ZephIR or by removing (exchanging) the Flashcard. It has been found to be impractical to read out the raw-files and the 3-second-wnd-files via GSM. It was possible to read out the wnd-data pre-processed to 10-minute averages. However, as we wanted to store all raw-files and wnd-files for 3-second averages, we read out the flash card directly. We figured out, that the best way to collect the data is to remove the flash card and to read out the flashcard manually.

The data form the met mast in Westdorf/Emden is sampled with 1 Hz / 5 Hz and processed to statistics of 10-minute periods. The data is read out by GSM.

3.3 Data Processing

The ZephIR measures the wind conditions at each height over 3 seconds. Afterwards it shifts to the next measurement height. Due to the applied configuration of the ZephIR (see chapter 3.1) we measured at a height of 65 m (in Westdorf, 124 m in Emden) for 4 successive 3-second periods, followed by a measurement in 300 m over 3 seconds.

The wnd-files (wind data) have been processed in the following way:

- The data has been reloaded in the ZephIR operating software in order to convert the wnd-files from a binary format to ASCII-data.
- Unfortunately, the ASCII-output files produced by the ZephIR operating software has a quite unconventional format in respect to the stored time stamp. For this reason special software has been programmed (lidar_convert.exe) in order to convert the data to a more convenient format.
- In the next step the data (3-second-averages) has been filtered according to the measurement height by application of our internal standard software filter.exe 1.1. Other filtering of the data, apart from the filtering according to measurement height, would be possible at this step, but has not been applied.
- In the next step, for each full 10-minute period a statistic of the data from 65 m / 124 m height has been calculated by application of our internal software statistics.exe, version 1.3. The statistics contain the average, minimum and maximum value and standard deviation of each data channel for each 10 minutes. As the time between the ZephIR measurements is not exactly 3 seconds (between 3 and 4 seconds), the number of processed data within the 10-minute periods varies slightly. Due to this, the statistics.exe software had to be extended by an analysis of the time stamp, so that only data from full 10-minute periods is processed. The data logger used for the met mast collects also data from full 10-minute periods. As usually no measurement by the ZephIR falls exactly on the end of a full 10-minute period, the 10-minute periods evaluated from the ZephIR and evaluated from the mast can deviate up to a few seconds.
- The measurements by the ZephIR show some single data gaps, because the flashcard was removed for reading out the data. Furthermore, the voltage supply of the mast in Westdorf was interrupted for some hours. In order to evaluate data only from the same 10-minute periods, the 10-minute statistics from the ZephIR and from the masts have been synchronised by our internal software synchroniser.exe, version 1.0.

The ZephIR has been operated without cloud correction. In order to test the cloud correction, the raw-files (spectra) have been re-processed with the ZephIR operating software. Unfortunately, the wnd-data gained from this re-processing of raw-files does not contain valid timestamps. However, each data set of the raw-file is attributed to a data set of the wnd-file, which has been stored during the measurements, by a reference number. Thus, the timestamps stored with the wnd-files can be attributed to the data from the raw-files by an analysis of the reference number.

4 Results

4.1 Results from Measurement Site Westdorf

In this chapter the results gained from the measurement site Westdorf at a measurement height of 65 m in the period 12/20/2005 till 01/03/2006 are shown.

4.1.1 Availability of the ZephIR at Measurement Site Westdorf

The ZephIR was always in operation in the period 12/20/2005 till 01/03/2006, except at those time periods where the flashcard has been taken out for collecting the measurement data. The system never interrupted the operation by itself. In the test period 233568 data sets from 65 m height have been collected in wnd-files (3 seconds averages for each data set). From these data sets 232766 data sets showed valid and plausible wind values for 65 m height. Thus, the availability of the ZephIR was 99.7 %. This high availability is the more impressive as partly bad weather conditions with rain, snow and temperatures below 0°C was present. Once, during a period with heavy snow, the ZephIR has sent an SMS, indicating that it has been moved. We went immediately to the measurement site in order to check the ZephIR. We found the system with about 15 cm snow on the one corner of the optics pod. Despite the snow, the system still showed plausible measurement results, while the wiper was cut-on.

The raw-files contained only 208235 data sets from 65 m measurement height, although all raw data has been stored, i.e. no gap in the raw data is due to not reading out the flashcard. That means that the raw-data (spectra-data) has not always been stored on the flashcard. However, from the stored raw-data sets, again 99.7 % of the data sets show plausible wind data.

4.1.2 Comparison Between 10-Minute Averages of Wind Speed Measured by the ZephIR and the Cup Anemometer at Measurement Site Westdorf

At the site Westdorf the measurements of the horizontal component of the wind velocity with the ZephIR have been compared to measurements with the cup anemometer of type Thies First Class, which is positioned on top of the mast at a height of 65 m above ground. The comparison has been limited to the wind direction sector 235°-325°, in which the cup anemometer and the ZephIR are exposed to the same wind conditions, and to wind speeds above 4 m/s, because at low wind speeds uncertainties even of the cup anemometer measurements are relatively high. No other filtering of the data has been applied. The ZephIR was fully available when the wind direction was in the measurement sector. After filtering 725 10-minute periods are available for the comparison without cloud correction applied for the ZephIR (direct application of wnd-files stored by the system, see chapter 3.3). 635 10-minute periods are available for the comparison with the cloud correction applied for the ZephIR. The reason for the lower number of available data is due to the fact, that the raw-data, which had to be re-processed for the cloud correction, has some data gaps (see chapter 4.1.1).

According to reference [3] the Thies First Class anemometer measures the horizontal wind speed component with nearly no aerodynamic overspeeding or overspeeding caused by moment of inertia. Among the two cup anemometers on top of the mast, the Thies First Class anemometer has been chosen for the comparison with the ZephIR, because this anemometer also serves for testing the wind turbine power curve. The wind speed measurements between the two anemometers on top of the mast deviate by less than 1 percent. It has been checked that the cup anemometers are not influenced by icing.

Without cloud correction the ZephIR overestimates the cup anemometer on average by about 3 percent Figure 9. This is to be expected as during periods of cloud, the cloud velocity is generally higher than the wind speed at the measurement height of ZephIR. The correlation coefficient between both measurements is high R^2=0.982, while some outlier data are present. After application of the cloud correction the ZephIR measurements of the horizontal wind speed component are closer to the cup anemometer readings, now slightly underestimating the cup anemometer measurements, the correlation coefficient between ZephIR measurements and the cup anemometer readings increases to above 0.99, and most outlier data vanish. When the cloud correction is applied, the ZephIR agrees very well with the cup anemometer (average deviation -0.04 m/s, standard deviation of deviations 0.18 m/s).

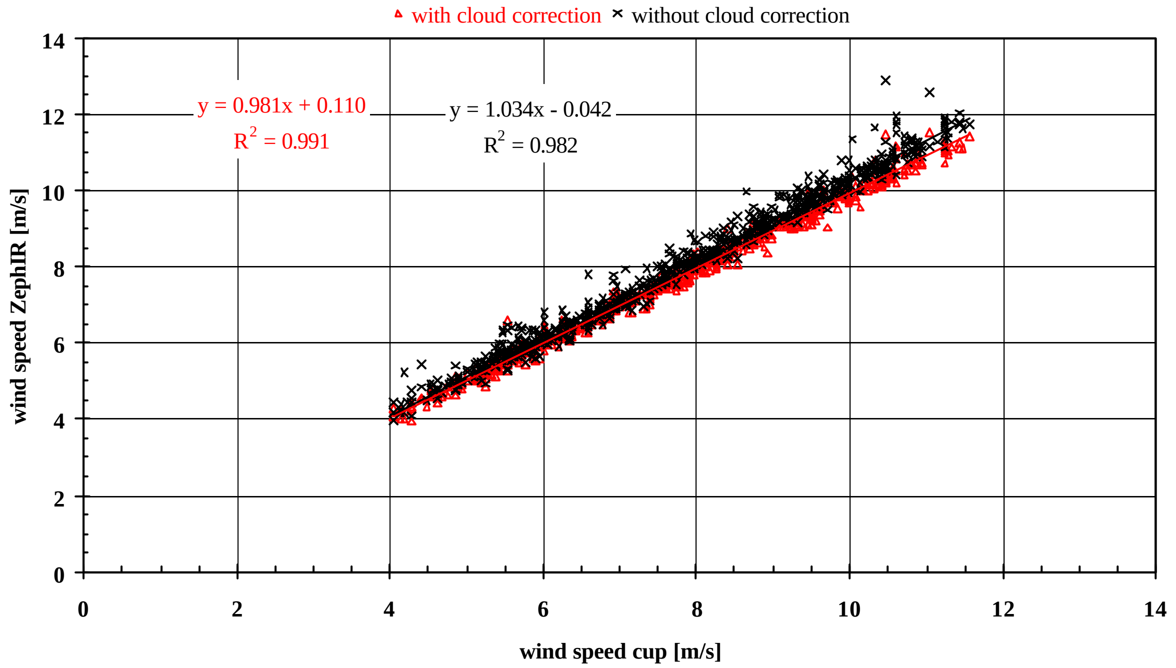

Figure 9: Scatter plot of horizontal wind speed component as measured by ZephIR against cup anemometer readings at 65 m height above ground. Every point represents a 10-minute average.

In Figure 10 the time series of the ZephIR, without application of the cloud correction, and the cup anemometer measurements are shown. It becomes evident that the overestimation of the wind speed is present especially during certain periods of time (certain events). Furthermore, from Figure 11 it becomes evident that this overestimation of wind speeds during these events is removed to a large extend by the application of the cloud correction. In order to find an explanation for the overestimation of wind speeds by the ZephIR (without cloud correction) during certain events, we analysed the percentage deviation between the ZephIR measurements and cup anemometer measurements in dependence of all variables measured with the ZephIR and the met mast. Also meteorological variables calculated from the measured variables, like turbulence intensity, vertical wind speed gradient and air density have been taken into account for this investigation. Only a dependency of the deviation between both measurements on the vertical wind speed gradient, i.e. the increase of wind speed with height above ground has been found. No dependency of the deviation between both measurements on any other measured or calculated variable has been observed. Figure 12 indicates that a high overestimation of wind speeds by the ZephIR (without cloud correction) in the order of 5-15 % occurs preliminary at vertical wind speed ratios below 1.3 (ratio of wind speeds in 65 m height and 31 m height below 1.3). Figure 12 further shows that any tendency to higher deviations between the ZephIR and the cup anemometer in dependency on the vertical wind speed gradient is removed by the application of the cloud correction. It has been found that the most severe deviations between the ZephIR (without cloud correction) and cup anemometer measurements occurred at 12/21/2005, 12/23/2005 and 12/29/2005. At these days very cloudy and partly wet weather was present.

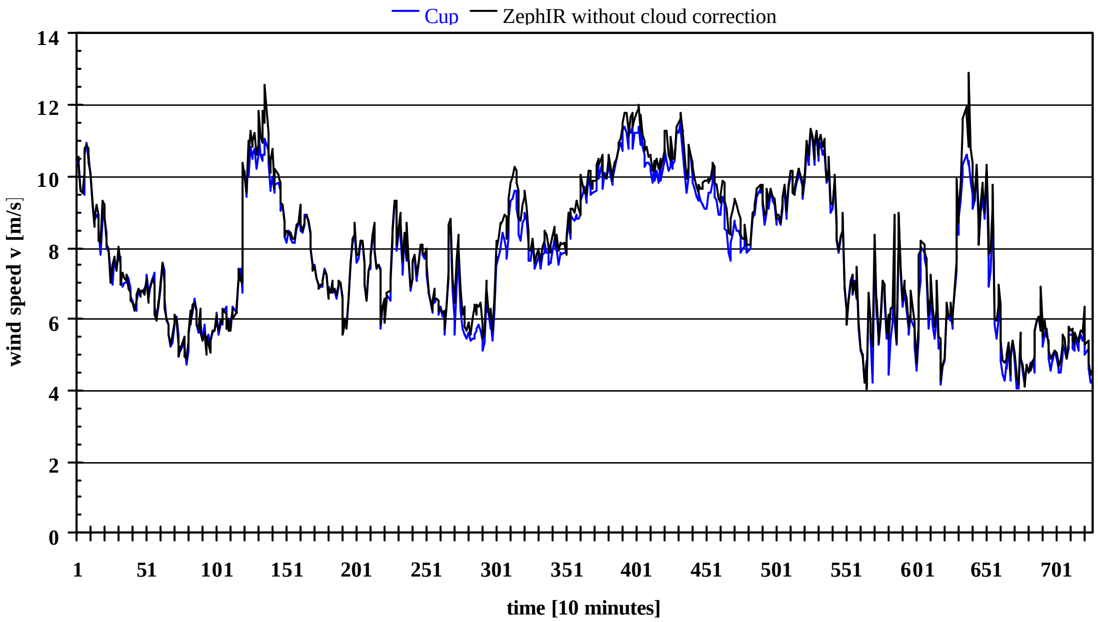

Figure 10: Comparison of time series of horizontal wind speed component as measured with the ZephIR without cloud correction and the cup anemometer at 65 m height above ground.

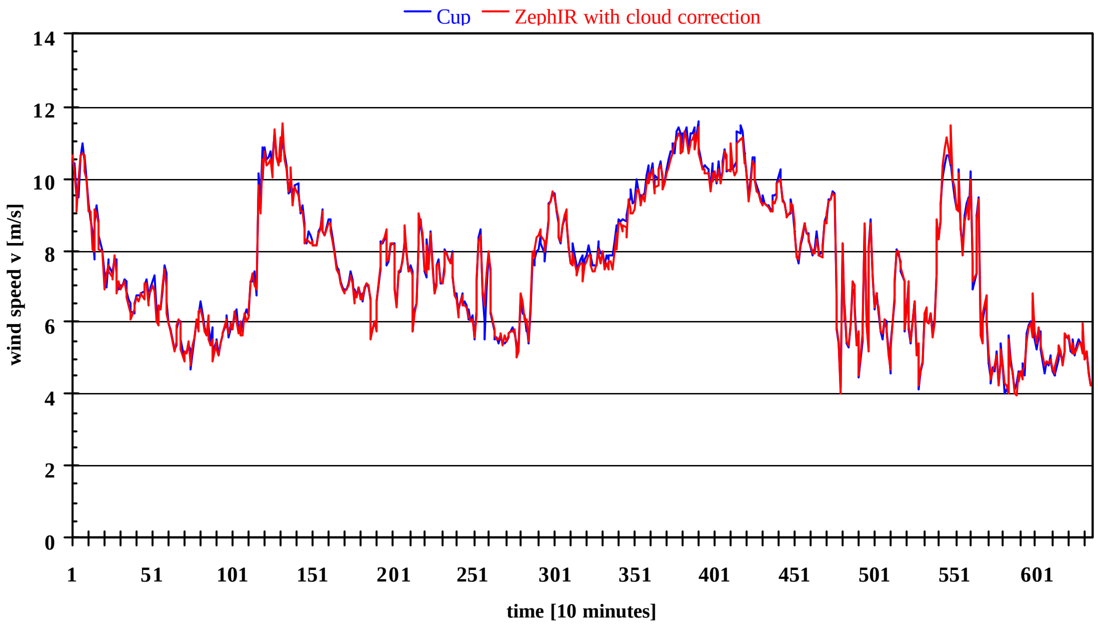

Figure 11: Comparison of time series of horizontal wind speed component as measured with the ZephIR with cloud correction and the cup anemometer at 65 m height above ground.

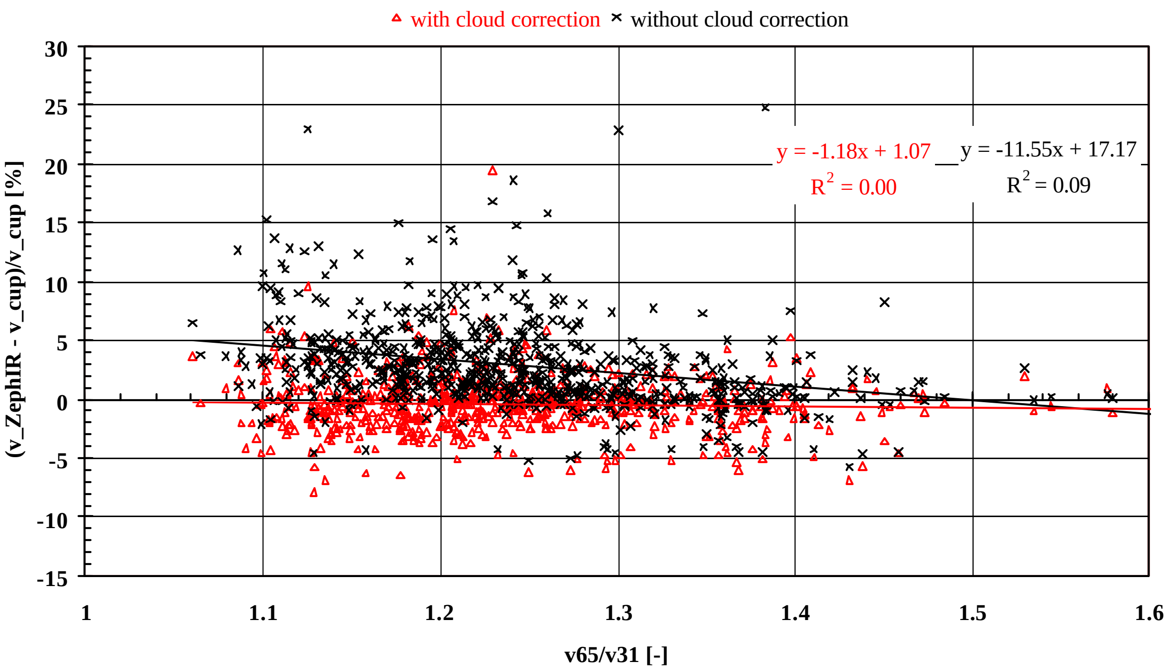

Figure 12: Percentage deviation between measurements of the horizontal wind speed component by ZephIR and the cup anemometer at 65 m height above ground as function of the vertical wind speed gradient. The vertical wind speed gradient is expressed as ratio of cup anemometer measurements at 65 m height and 31 m height.

4.1.3 Comparison of Extreme Values and Standard Deviation at Measurement Site Westdorf

In Figure 13 the extreme values of the horizontal wind speed component as measured by the ZephIR and by the cup anemometer are compared. Obviously, the ZephIR measures a higher minimum wind speed and a lower maximum wind speed per 10-minute interval than the cup anemometer. Furthermore, the standard deviation of wind speeds per 10-minute interval as measured by the ZephIR are smaller than measured by the cup anemometer (Figure 14). The observations can be understood by the following facts:

- For the ZephIR the extreme values and standard deviation have been gained from 3-second averages of the wind speed, while from the cup anemometer 1-second averages have been applied. This leads to less extreme maximum and minimum values of the wind speed as well as to lower standard deviations. According to reference [4] the expected reduction of wind speed standard deviations of 3-second averages compared to 1-second averages is 0.94.
- The focussing of the ZephIR beam leads to a spatial averaging over a significant probe length with the sensitivity decreasing symmetrically as a Lorentzian function away from the focus. In contrast, the cup anemometer represents more a point measurement. The spatial averaging is linked to a decrease of wind speed variances.
- Furthermore, the ZephIR measurements represent another spatial averaging, as the measurements are taken from a circle with significant diameter.

For the comparison of extreme values and standard deviations the data from the ZephIR with cloud correction has been applied, as this data seems to be more accurate according to chapter 4.1.2.

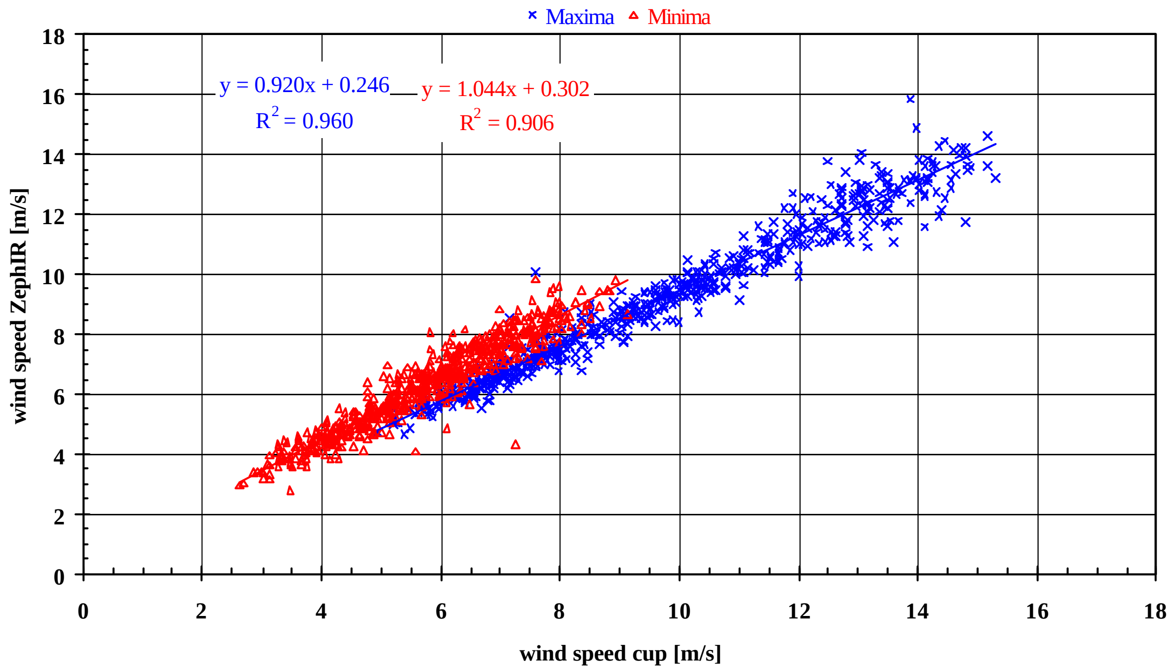

Figure 13: Comparison of extreme values of wind speed within 10-minute periods as measured by ZephIR and the cup anemometer at 65 m height above ground.

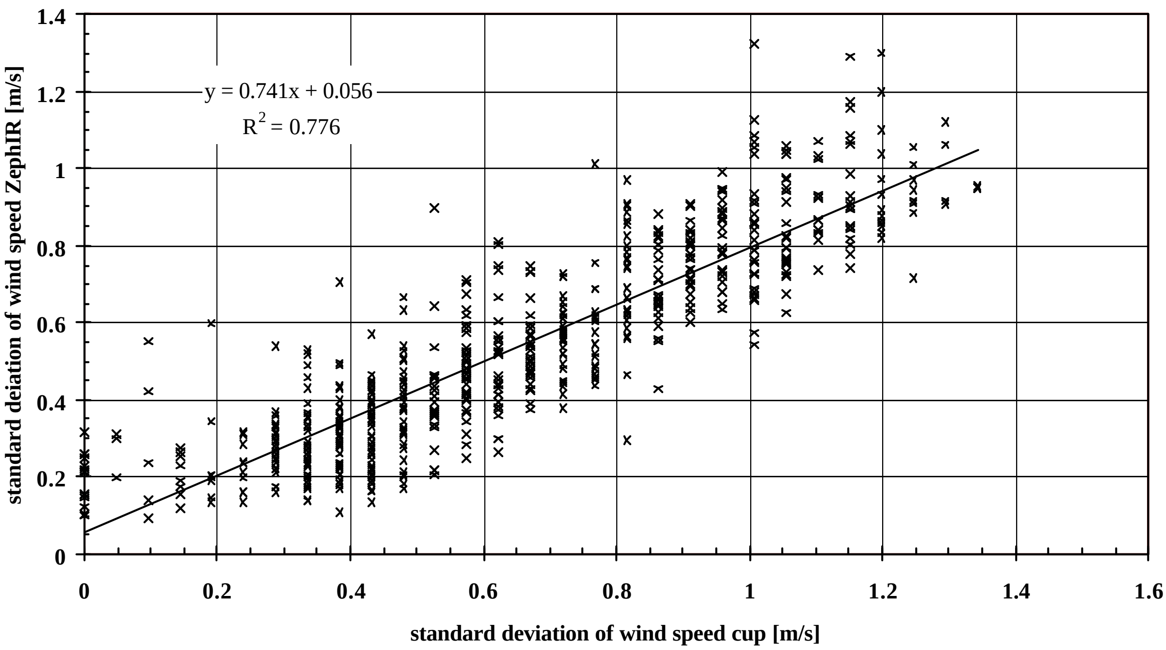

Figure 14: Comparison of standard deviation of wind speed within 10-minute periods as measured by ZephIR and the cup anemometer at 65 m height above ground.

4.1.4 Comparison of Wind Direction Measurements at Measurement Site Westdorf

The wind direction measurements of the ZephIR at 65 m above ground are compared to the measurements by a vane (mounted on the mast at about 63 m above ground) in terms of 10-minute averages in Figure 15. The direction measurements correlate well. However, there is a significant offset of about 30 °on the measurements of the ZephIR. The reason for this offset was later found to be the incorrect adjustment of the direction offset potentiometer upon initial installation. The northing of the ZephIR has been checked during the installation.

A detailed investigation of the direction measurements stored by the ZephIR as 3-second averages has shown, that quite often the wind direction is misinterpreted by 180°. These incidents might have to do with interim misreading of the wind direction by the multi sensor on the mast of the ZephIR. However, the misinterpretation by the ZephIR of 180° has also been observed, when the multi sensor showed no error.

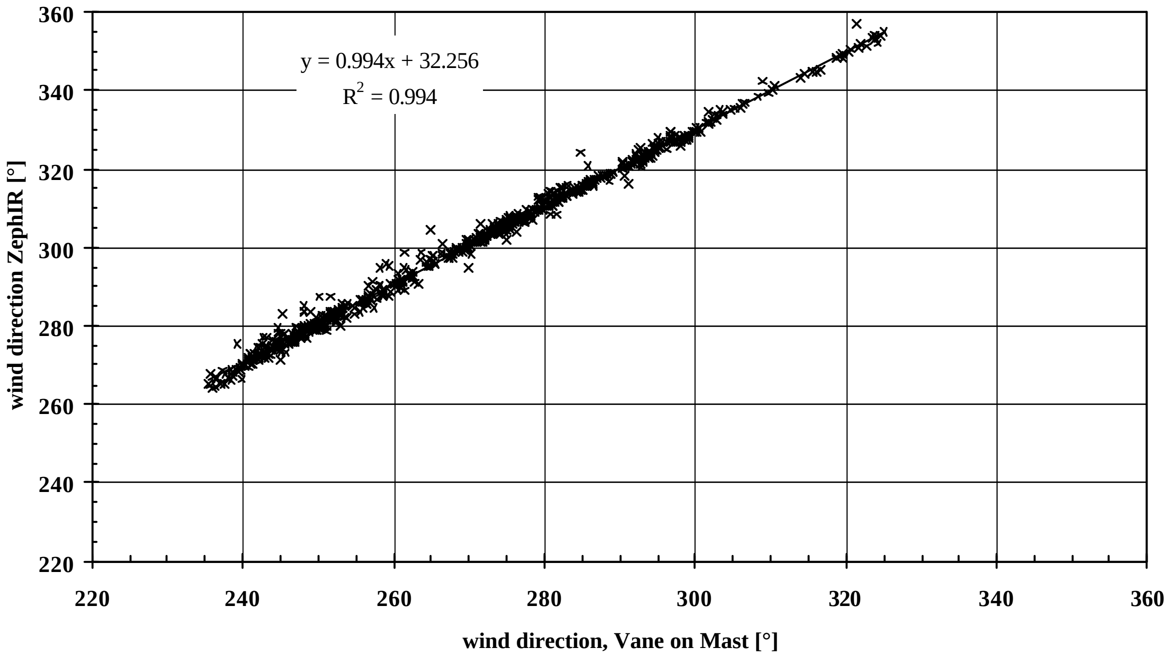

Figure 15: Comparison of wind direction measurement performed by the ZephIR at 65 m height above ground and by a vane near the top of the met mast in Westdorf. Each data point represents a 10-minute average.

4.1.5 Comparison of Wind Turbine Power Curve based on ZephIR and the Met Mast at Measurement Site Westdorf

The power curve of the wind turbine Enercon E-70 E4 has been evaluated based on the wind speed measurements by the ZephIR and based on the wind speed measurements by the met mast. The data evaluation has been done according to the standard IEC 61400-121 [2]. For the evaluation of the power curve the cloud correction of the ZephIR has been applied, because according to 4.1.2 this seems to lead to much more accurate wind measurements.

The power curve raw data is shown in Figure 15. The raw data as evaluated from the ZephIR agrees well with the raw data as evaluated from the mast data. However, at wind speeds around 11-12 m/s the power curve raw data as evaluated with the ZephIR shows some outlier data, which is not present by the use of the met mast. The bin-averaged power curves evaluated from the ZephIR and the met mast agree very well (Figure 17). Finally, the annual energy production (AEP) has been calculated from the bin-averaged power curves for different annual average wind speeds according to the IEC 61400-121 [2] (assuming a Rayleigh wind speed distribution). The AEPs evaluated from the power curve as gained from the ZephIR measurements are less than two percent higher than the AEPs evaluated from the met mast based power curve. The deviations of the wind turbine power curves gained from the ZephIR and the met mast are by far lower than the standard uncertainty of the cup anemometer based power curve.

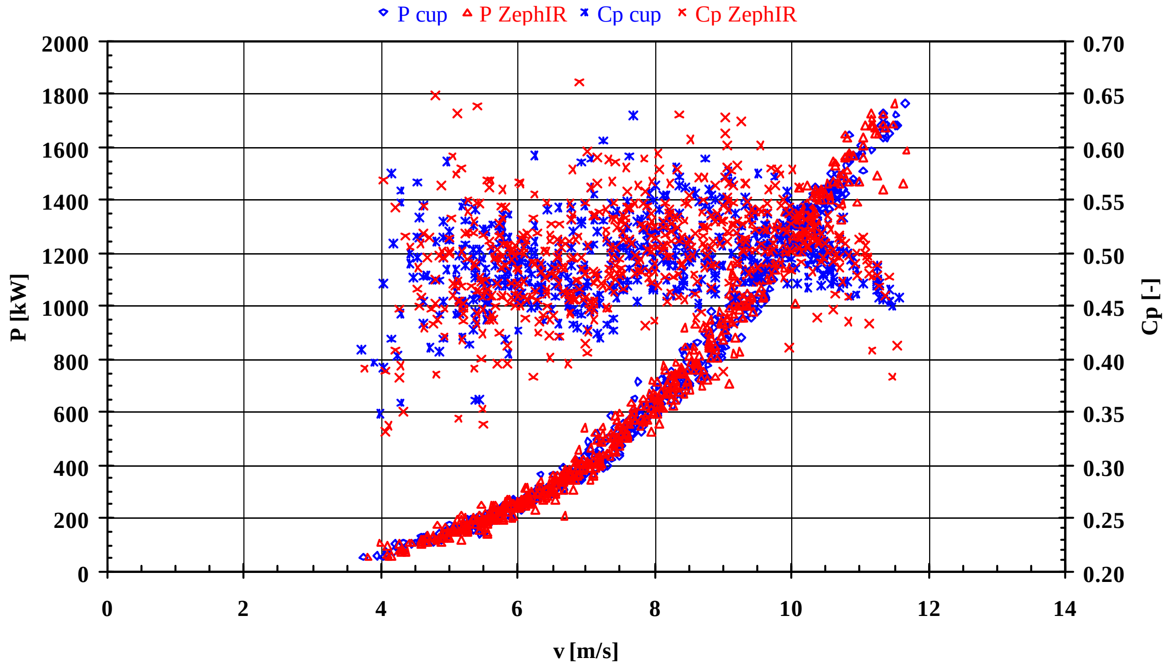

Figure 16: Power curve raw data of the Enercon E-70 E4 evaluated by application of the ZephIR and the met mast. Each data point represents a 10-minute average.

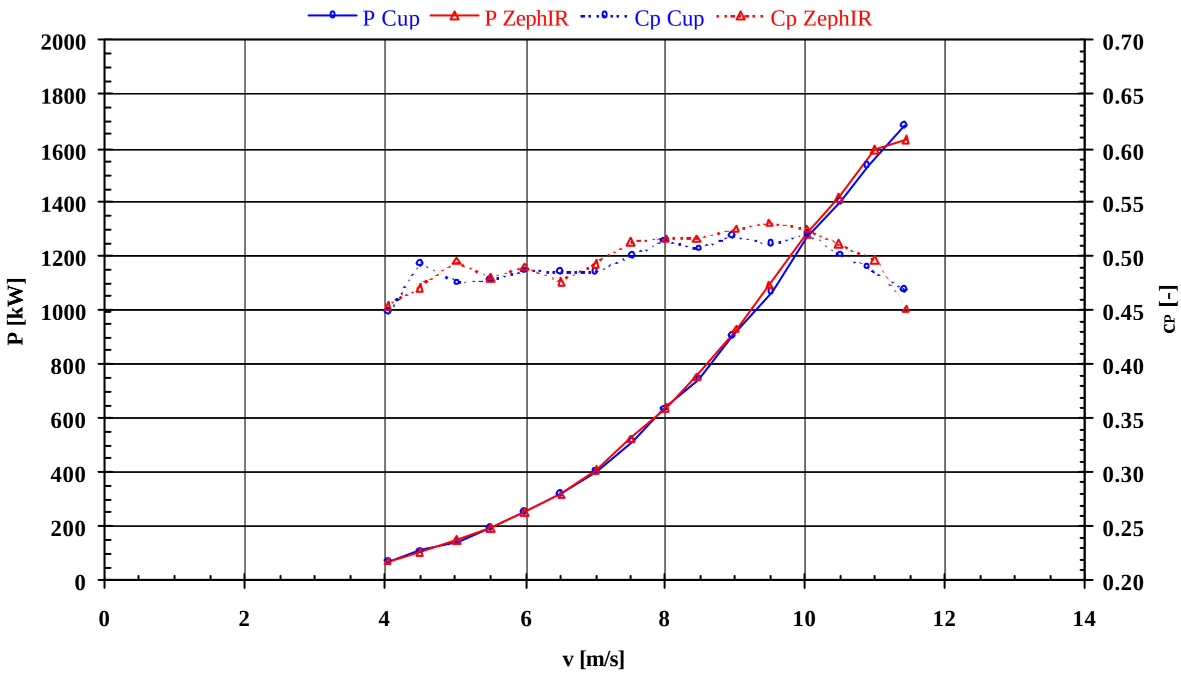

Figure 17: Bin-averaged power curve of the Enercon E-70 E4 evaluated by application of the ZephIR and the met mast. The power curves have been normalised to the air density of 1.225 kg/m³.

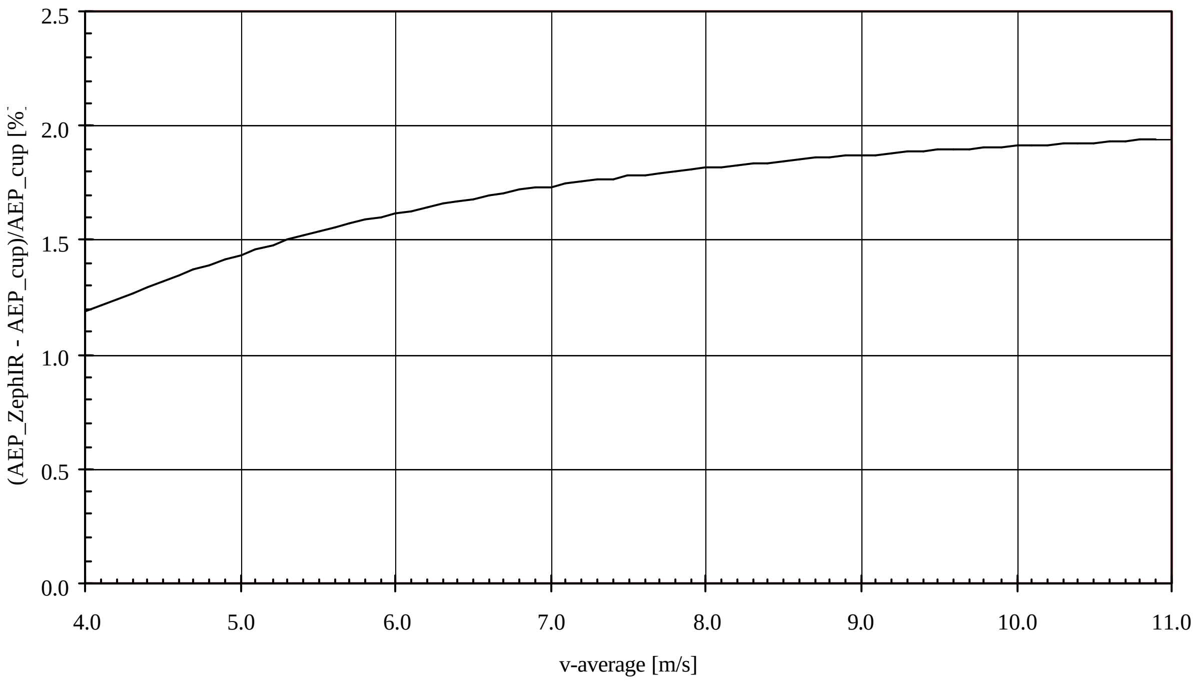

Figure 18: Percentage deviation in annual energy production of the E-70 E4 power curves as function of the annual average wind speed as evaluated from the ZephIR data and the cup anemometer data.

4.2 Results from Measurement Site Emden

In this chapter the results gained from the measurement site Emden at 124 m above ground in the period 01/10/2006 till 01/24/2006 are shown.

4.2.1 Availability of the ZephIR at Measurement Site Emden

The ZephIR was always in operation in the period 01/10/2006 till 01/28/2006, except at those time periods where the flashcard has been taken out for collecting the measurement data. The system never interrupted the operation by itself. In the test period 323702 data sets from 124 m height have been collected in wnd-files (3 seconds averages for each data set). From these data sets 310988 data sets showed valid and plausible wind values for 124 m height in respect to the horizontal and vertical wind speed component. Thus, the availability of the ZephIR was 96.1 %. Taking into account the bad weather conditions with partly mist, rain, snow and temperatures below 0°C the availability is considered as high.

Unfortunately, until 01/16/2006 no raw-data was stored by the system. Thus the raw-files contained only 215695 data sets from 124 m measurement height. From this data sets 99.5 % of the data showed valid data of the horizontal wind speed component. However, only 71.8 % of the raw-data showed valid values of the vertical wind speed component. During periods of precipitation the vertical wind speed component is not considered valid, unlike the horizontal one. ZephIR identifies this and automatically flags the vertical wind speed as 9999 under these conditions. We would therefore expect that the availability of vertical speed data to be heavily reduced compared to the horizontal availability.

4.2.2 Comparison Between 10-Minute Averages of Wind Speed Measured by the ZephIR and the Cup Anemometer at Measurement Site Emden

At the site Emden the measurements of the horizontal component of the wind velocity with the ZephIR have been compared to measurements with one of the cup anemometer of type Thies First Class, which is positioned on top of the mast at a height of 124 m above ground. According to reference [3] the Thies First Class anemometer measures the horizontal wind speed component with nearly no aerodynamic overspeeding or overspeeding caused by moment of inertia. Among the two types of cup anemometers on top of the mast, the Thies First Class anemometer has been chosen for the comparison with the ZephIR, because this anemometer also serves for testing power curve of the wind turbine Enercon E-112. The wind speed measurements between the anemometers on top of the mast deviate by less than 1 percent.

The comparison between the ZephIR and the cup anemometer has been limited to the following data:

- Wind direction sector 136°-226° in which the cup anemometer on the mast, the ZephIR and the Enercon E-112 were believed to be exposed to the same wind direction. However, there are indications that the ZephIR might be influenced by the wake of the next neighbouring wind turbine of type Enercon E-66/15.66 in the sector 199°-226°. Hence the sector for the evaluation of the ZephIR has later been changed to 136°-226°.
- Wind speeds above 4 m/s, because at low wind speeds uncertainties even of the cup anemometer measurements are relatively high
- Events with icing of cup anemometers have been identified and have been excluded from the evaluation.
- ZephIR measurements of the horizontal wind speed component show no error code of 9999 during no single 3-second period within each 10 minute period.
- At 01/14/2006 there were 6 10-minute periods where the horizontal wind speed component as measured by the ZephIR was implausible high. During all these events there were 3-second averages present with a low number of data points (less than 68). However, data filtering according to the number of points has been avoided, because there are also data sets available with a low number of data sets and plausible wind speed measurements. It has been found that a more proper filter criterion is the turbulence parameter stored by ZephIR for each 3-second average. Only such 10-minute periods have been considered for the ZephIR evaluation, which did not contain 3-second data with a turbulence parameter above 1000. By this filtering exactly the 6 critical 10-minute periods were eliminated.

The time series of the horizontal wind speed component as measured by the ZephIR and the cup anemometer at 124 m height above ground remaining after this filtering within the wind direction sector 136°-226° are compared in Figure 19. There is an event over about 4.5 hours at 01/19/2006, were the ZephIR measures a wind speed about 20 %-50 % lower than the cup anemometer (see data set 830-860 in Figure 19). This strong underestimation of wind speeds by the ZephIR is present also in case the cloud correction is applied to the measurement data. The strong underestimation of wind speeds during 01/19/2006 is believed to be due to the following reasons:

- During the event inversion was present. The air temperature at 122 m height was about 0.5 ° higher than at 10 m height. Furthermore, it was cloudy near ground (maybe even misty weather). Due to the weather conditions it is possible that at 124 m height a much lower cloud density was present than at lower heights. Under such conditions it is thinkable that the ZephIR measurements are influenced by a stronger reflection of the laser beam at much lower heights than the focussing height.

- During the event the wind direction was in the range 203°-225°. In the wind direction range 199°-226° a part of the measurement circle of the ZephIR at 124 m measurement height may interfere with the wake of the next neighbouring wind turbine of type Enercon E-66/15.66. Thus the ZephIR measurements could be influenced by the lower wind speeds within the wake. There are time series available within the sector 199°-226°, where the ZephIR does not underestimate the cup anemometer measurements significantly. However, under the inversion conditions present during the event at 01/19/2006 it is possible that the wake relaxation is inhibited by reduced mixing with the airflow in upper heights, and thus the wake might extend to a larger sector than under other weather conditions.

As an influence of the wake of the next neighbouring wind turbine of type Enercon E-66/15.66 on the ZephIR measurements cannot be excluded at wind directions northerly than 199° according to reference [2], the wind direction sector has been reduced to 136°-199° for the evaluation of the ZephIR. After filtering 810 10-minute periods are available for the comparison without cloud correction applied for the ZephIR (direct application of wnd-files stored by the system, see chapter 3.3). 350 10-miute periods are available for the comparison with the cloud correction applied for the ZephIR. The reason for the lower number of available data is mainly due to the fact, that the raw-data was not stored till 01/16/2005 (see chapter 4.2.1).

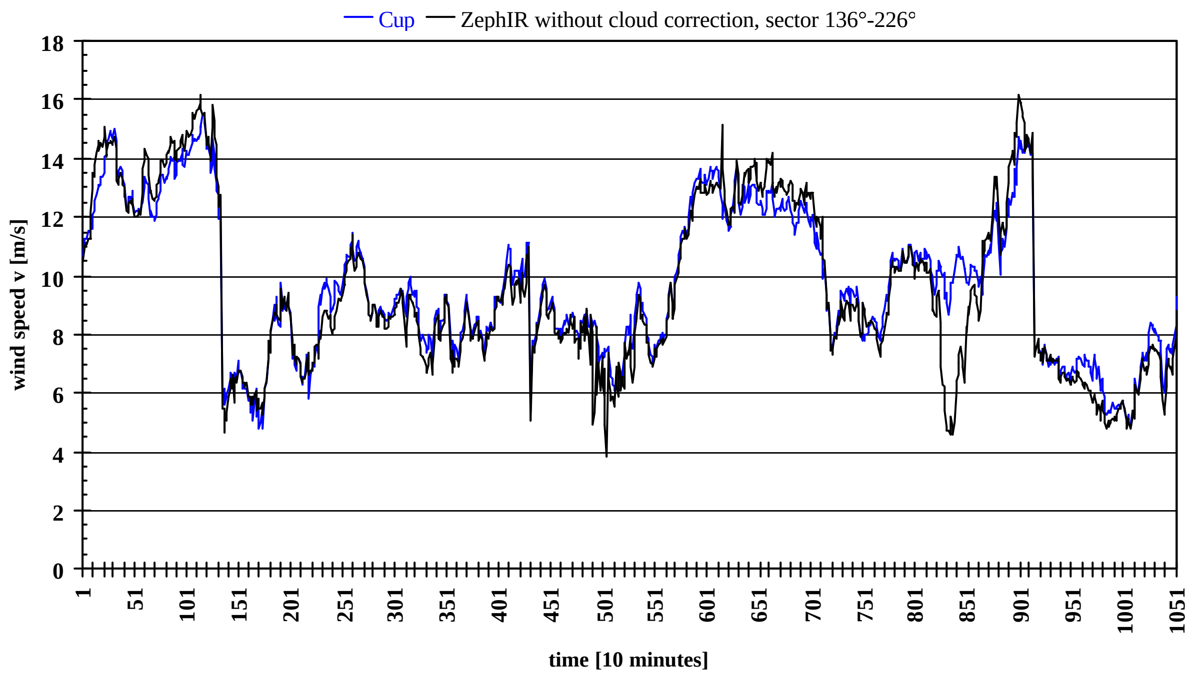

Figure 19: Comparison of time series of horizontal wind speed component as measured with the ZephIR without cloud correction and the cup anemometer at 124 m height above ground. Wind direction sector 136°-226°.

Without cloud correction the scatter plot between ZephIR measurements and cup anemometer measurements of the horizontal wind speed component at 124 m height above ground clearly shows outlier data. Furthermore, at high wind speeds the ZephIR clearly overestimates the wind speed. A regression line between the ZephIR measurements and cup anemometer measurements has a slope much higher than unity and a large negative offset. The squared correlation coefficient between both measurements is 0.95 (Figure 20). After application of the cloud correction the ZephIR measurements agree much better with the cup anemometer measurements (average deviation -0.39 m/s, standard deviation of deviations 0.30 m/s). The squared correlation coefficient increases to 0.986. The slope of a regression line is much closer to unity than without cloud correction, and the offset of the regression line is much closer to zero than without cloud correction. Indeed the regression slope of 0.982 in Emden at 124 m height is very close to the slope in Westdorf at 65 m height. However, the regression offset changed from +0.1 m/s in Westdorf to –0.3 m/s in Emden, i.e. on average a 4 % underestimation of wind speed by the ZephIR is present in Emden (compare Figure 9).

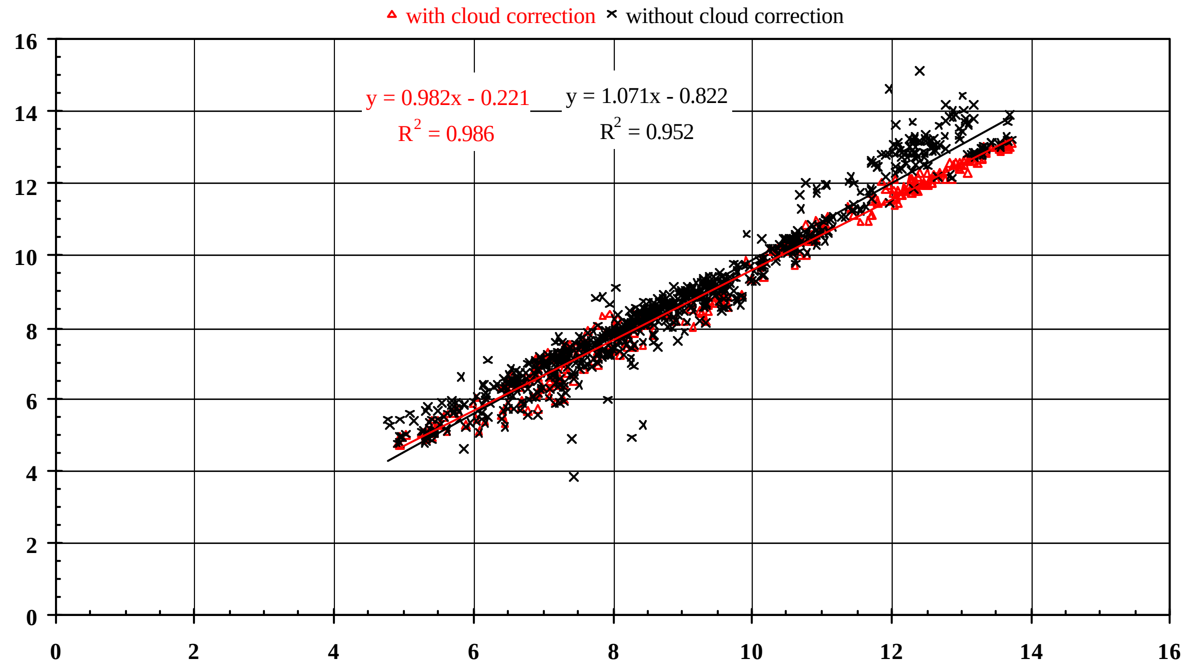

Figure 20: Scatter plot of horizontal wind speed component as measured by ZephIR against cup anemometer readings at 124 m height above ground. Every point represents a 10-minute average. Wind direction sector 136°-199°.

In Figure 21 the time series of the ZephIR, without application of the cloud correction, and the cup anemometer measurements are shown for the site Emden. During certain periods a clear overestimation on wind speeds by the ZephIR is seen, while during other periods a clear underestimation of wind speeds is found. From Figure 22 it becomes evident that the overestimation of wind speeds during some events is removed to a large extent by application of the cloud correction, while the underestimation during other events is still present after application of the cloud correction.

In order to find an explanation for the underestimation of wind speeds by the ZephIR (with cloud correction) during certain events, we analysed the percentage deviation between the ZephIR measurements and cup anemometer measurements in dependence of all variables measured with the ZephIR and the met mast. Also meteorological variables calculated from the measured variables, like turbulence intensity, vertical wind speed gradient, indicators for atmospheric stability and air density have been taken into account for this investigation. A clear dependency of the deviation between both measurements on the vertical wind speed gradient, i.e. the increase of wind speed with height above ground and a less pronounced dependency on the atmospheric stability has been found (Figure 23). No dependency of the deviation between both measurements on any other measured or calculated variable has been observed. According to the regression lines in Figure 23 the deviation between the ZephIR measurements and cup anemometer measurements at 124 m height vanishes if no increase of wind speed with height is present. At high wind speed gradients (e.g. ratio of cup anemometer measurements at 124 m and 95 m height between 1.2 and 1.3) the ZephIR underestimates the wind speed by over 10%. This property might be linked to the relative large probe lengths of the ZephIR at 124 m measurement height. A solution of this problem could a correction of measurement data according to the measured vertical wind speed gradient.

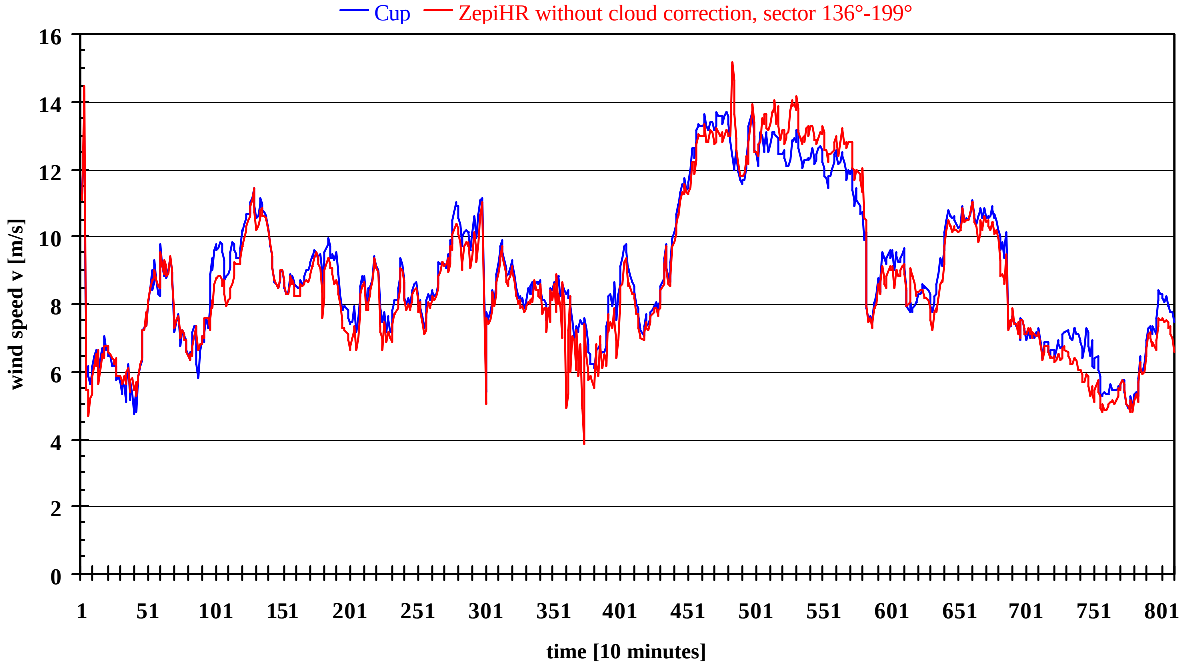

Figure 21: Comparison of time series of horizontal wind speed component as measured with the ZephIR without cloud correction and the cup anemometer at 124 m height above ground. Wind direction sector 136°-199°.

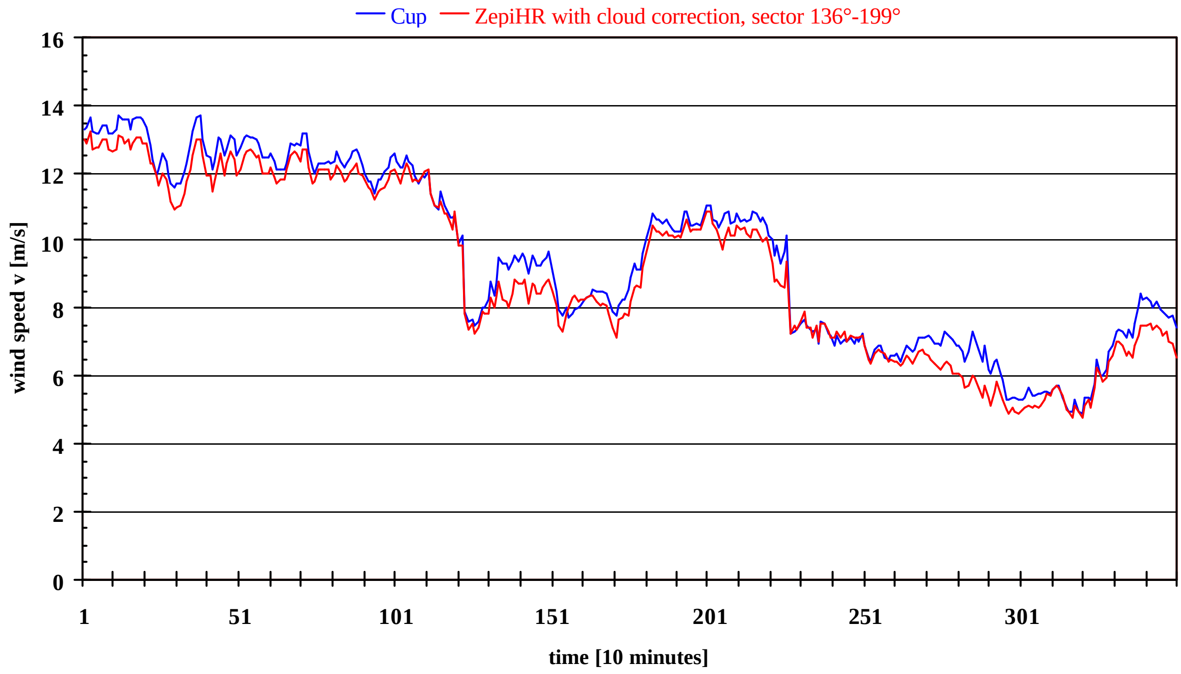

Figure 22: Comparison of time series of horizontal wind speed component as measured with the ZephIR with cloud correction and the cup anemometer at 124 m height above ground. Wind direction sector 136°-199°.

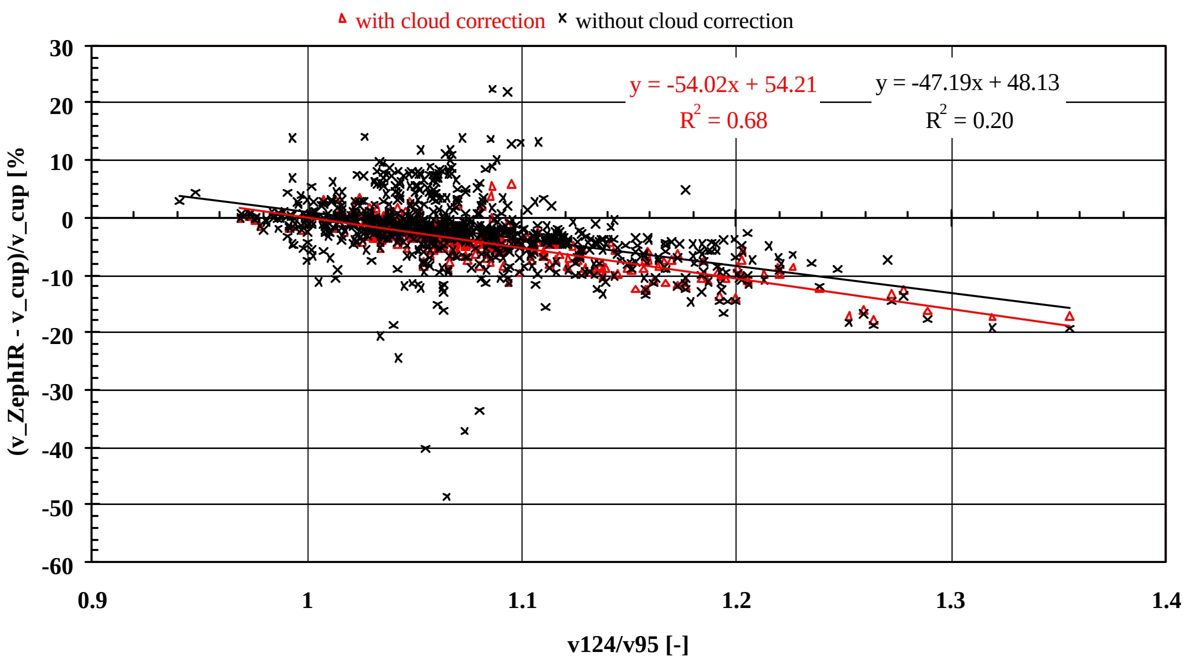

Figure 23: Percentage deviation between measurements of the horizontal wind speed component by ZephIR and the cup anemometer at 124 m height above ground as function of the vertical wind speed gradient. The vertical wind speed gradient is expressed as ratio of cup anemometer measurements at 124 m height and 95 m height.

4.2.3 Comparison of Extreme Values and Standard Deviation at Measurement Site Emden

In Figure 24 and Figure 25 the extreme values and the standard deviations of the horizontal wind speed component measured by the ZephIR (with cloud correction) and by the cup anemometer within each 10-minute period at 124 height above ground are compared. The results are very similar to the measurements at 65 m height (see chapter 4.1.3). At 124 m height the ratio of the standard deviation of wind speed as evaluated with the ZephIR and gained from the cup anemometer is smaller than at 65 m height. The reason can be found in the larger probe lengths and the larger measurement circle of the ZephIR at 124 m height than at 65 m height (larger volume for spatial averaging).

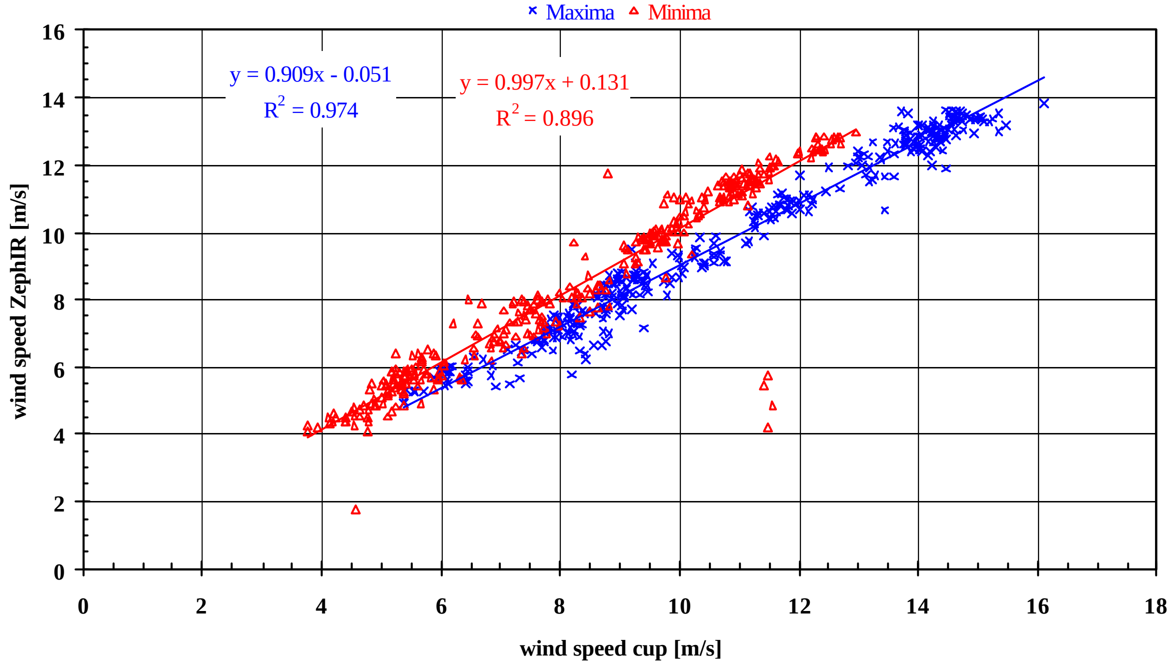

Figure 24: Comparison of extreme values of wind speed within 10-minute periods as measured by ZephIR and the cup anemometer at 124 m height above ground.

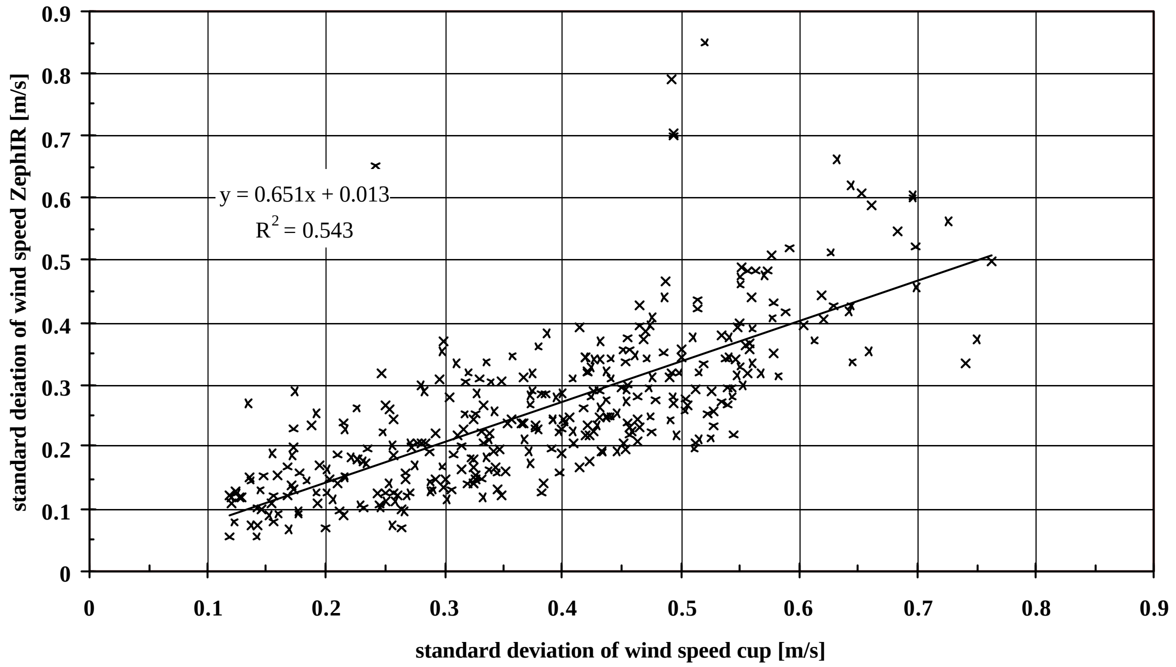

Figure 25: Comparison of standard deviation of wind speed within 10-minute periods as measured by ZephIR and the cup anemometer at 124 m height above ground.

4.2.4 Comparison of Wind Direction Measurements at Measurement Site Emden

The wind direction measurements of the ZephIR at 124 m above ground (with cloud correction) are compared to the measurements by a vane (mounted on the mast at about 122 m above ground) in terms of 10-minute averages in Figure 15. The direction measurements correlate well. In Emden a much bigger Offset is seen between the measurements by the ZephIR and the vane. This is due to the fact that in Emden the met station of the ZephIR was not in operation till 01/28/2006. Since the met station has been put back to operation at 01/28/2006, the offset between both wind direction measurements is again in the order of 30 °, like in Westdorf at 65 m height.

As in Westdorf, in Emden a detailed investigation of the direction measurements stored by the ZephIR as 3-second averages has shown that quite often the wind direction is misinterpreted by 180°.

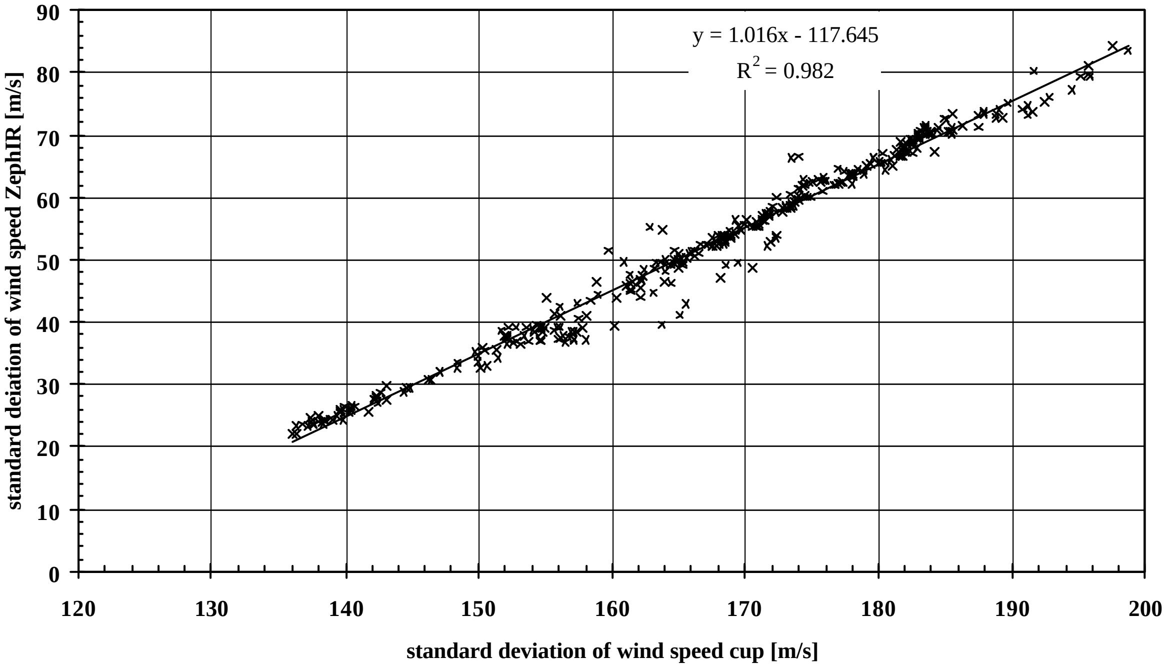

Figure 26: Comparison of wind direction measurement performed by the ZephIR at 124 m height above ground and by a vane near the top of the met mast in Emden. Each data point represents a 10-minute average.

4.2.5 Comparison of Vertical Wind Speed Component at Measurement Site Emden

The vertical wind speed component as determined with the ZephIR has been compared with the measurements of an ultra sonic anemometer (USA) of type Gill Windmaster, which is installed at the mast in Emden at 122 m height (Figure 27). For this evaluation data with rain has been filtered out.

The vertical wind speed measured by the ZephIR in tendency increases with increasing vertical wind speed as measured by the USA. However, some outlier data points are clearly present. The average deviation between the measurements of the vertical wind speed component is 0.06 m/s with a standard deviation of deviations of 0.08 m/s.

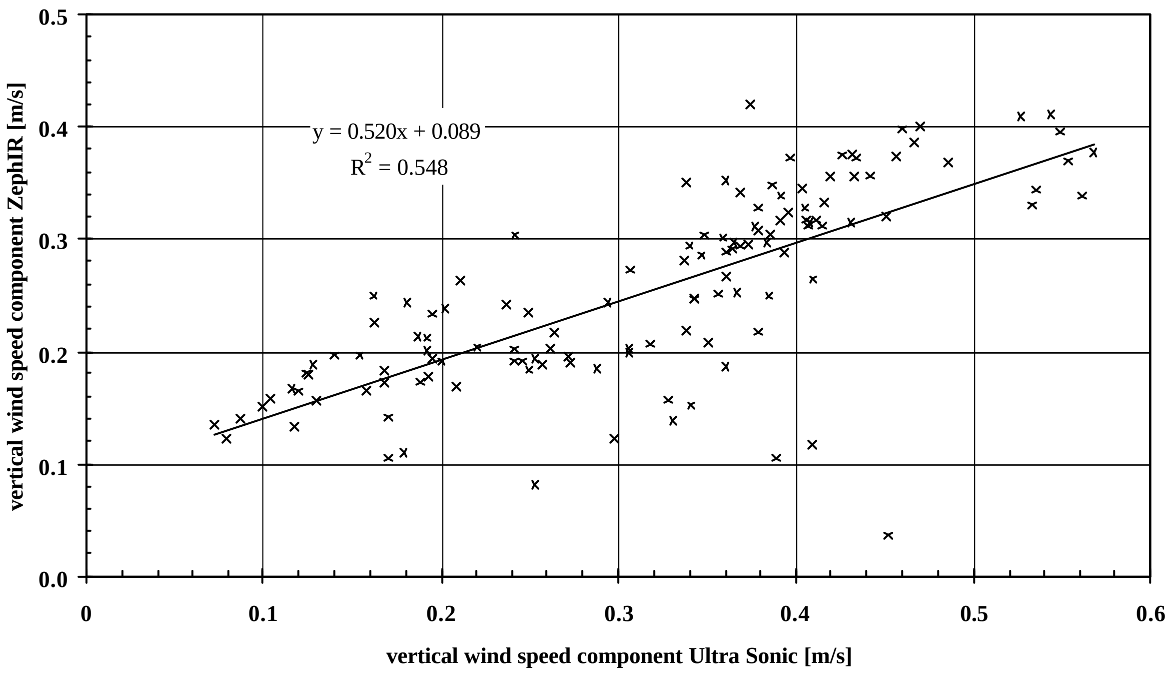

Figure 27: Comparison of vertical wind speed component measured at 124 m height above ground by the ZephIR and measured at 122 m height above ground by an ultra sonic anemometer. Each data point represents a 10-minute average.

4.2.6 Comparison of Wind Turbine Power Curve based on ZephIR and the Met Mast at Measurement Site Emden

The power curve of the wind turbine Enercon E-112 has been evaluated based on the wind speed measurements by the ZephIR and based on the wind speed measurements by the met mast. The data evaluation has been done according to the standard IEC 61400-121 [2]. For the evaluation of the power curve the cloud correction of the ZephIR has been applied, because according to chapter 4.2.2 this seems to lead to much more accurate wind measurements.

The power curve raw data is shown in Figure 28. The raw data as evaluated from met mast shows some outlier data points at wind speeds between 6-7 m/s, what indicates that not all data with anemometer icing has been fully removed. However, the raw data from the ZephIR shows outlier data and partly implausible data in the entire wind speed range up to wind speeds of 10 m/s, also during periods where icing is impossible. This is reflected also in an unrealistic bin-averaged power curve gained with the ZephIR measurements Figure 29 and high deviations between the AEPs as calculated from the mast based power curve and the ZephIR based power curve Figure 30.

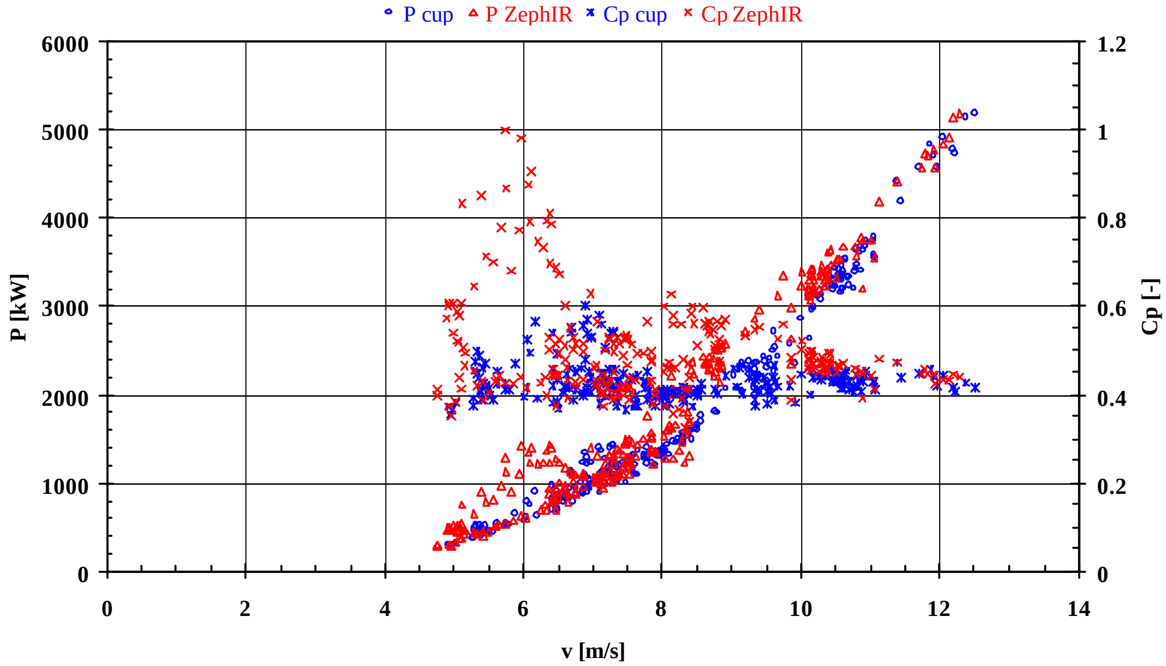

Figure 28: Power curve raw data of the Enercon E-112 evaluated by application of the ZephIR and the met mast. Each data point represents a 10-minute average.

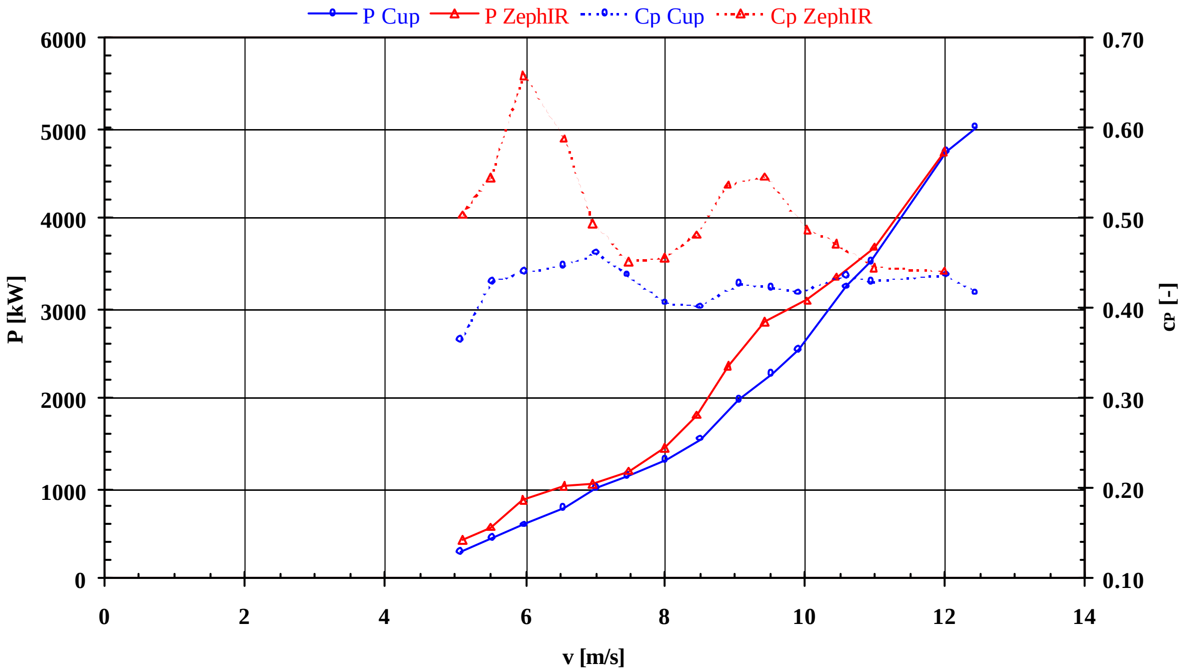

Figure 29: Bin-averaged power curve of the Enercon E-112 evaluated by application of the ZephIR and the met mast. The power curves have been normalised to the air density of 1.225 kg/m³.

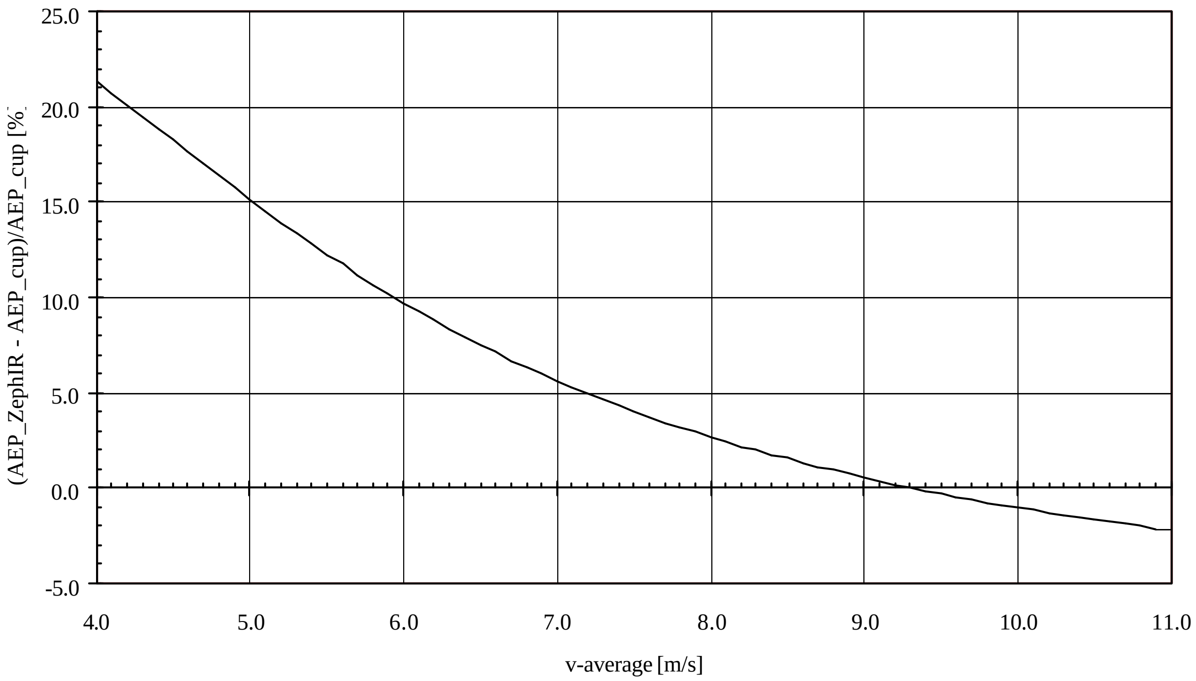

Figure 30: Percentage deviation in annual energy production of the Enercon E-112 power curves as function of the annual average wind speed as evaluated from the ZephIR data and the cup anemometer data (assumptions: Rayleigh wind speed distribution, measured power curve not extended over wind speed range covered by the measurements).

5 Conclusions

The ZephIR has so far shown a very good agreement to cup anemometer measurements at 65 m height above ground, if the cloud correction is applied. Without cloud correction, there seem to occur unacceptable high misinterpretations of the wind speed during certain events at 65 m measurement height. There exist indications that such events might more likely occur during periods with low vertical wind speed gradients and high cloud coverage.

At 124 m height above ground a clear tendency to underestimations of the wind speed is found, if the cloud correction is applied. The underestimation of wind speeds at 124 measurement height is on average 4% and has been found to strongly increase with increasing vertical wind speed gradient (same tendency of deviation between ZephIR measurements and cup anemometer measurements than at 65 m height without application of the cloud correction). In the absence of a vertical wind speed gradient the deviation between the ZephIR and cup anemometer reading nearly vanishes. Without cloud correction the data at 124 m height shows deviations to the cup anemometer (overestimations and underestimations).

As one application for the ZephIR is seen for measurements at heights larger than 100 m above ground, it becomes clear that improvements of the ZephIR performance at heights above 100m would be beneficial. From the gained experience, we believe that the introduction of further data correction, eventually dependent on the measured wind speed gradient, would offer a potential performance improvement.

The system availability throughout the evaluation period has been excellent with the horizontal wind speed data availability approaching close to 100%.

6 Acknowledgement

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7 References

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