

# Validation of the 1290 MHz wind profiler at Payerne, Switzerland, using radiosonde GPS wind measurements

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**ABSTRACT:** The validation of a 1290 MHz wind profiler using 3 years of collocated wind profiler and radiosonde wind measurements is presented. The radiosonde wind information is derived from global positioning system data and is vertically averaged to match the vertical resolution of the wind profiler measurements. The integration period of the wind profiler is chosen such that it is centred around the radiosonde measurement time. Periods where bird migration must be expected have been systematically excluded. The standard deviation of the differences between wind profiler and radiosonde in the wind components  $u$  and  $v$  is between 1.75 and 2 m s<sup>-1</sup> and the bias is smaller than 0.75 m s<sup>-1</sup> for heights below 6 km for both modes. Some part of the obtained standard deviation can be explained by the fact that radiosonde and wind profiler measurements are not representative for each other. In order to reduce the representativeness error, a subset of cases has been selected, for which the wind field was stationary during the measurement period and uniform across the sampled volume of the wind profiler. The standard deviation derived from the subset is between 1 and 1.5 m s<sup>-1</sup> while the bias changes only little. This reduction can be attributed to a reduction in the representativeness error and in the retrieval error of the wind profiler since atmospheric homogeneity is a basic assumption in the wind retrieval. The obtained value of 1.5 m s<sup>-1</sup> can be taken as an upper limit of the measurement uncertainty of the wind profiler in favourable measurement conditions.

**KEY WORDS** remote sensing; wind profiler; validation; atmospheric wind; measurement uncertainty

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## 1. Introduction

Wind profilers provide continuous measurements of the horizontal wind components from a few hundred metres up to the lower stratosphere depending on the used wavelength. Since measurements are possible under nearly all weather conditions including rain and snow, wind profilers are nowadays widely used in operational meteorological applications (Calpini *et al.*, 2011). Several operational wind profiler networks exist and data are routinely assimilated in numerical weather prediction (NWP) models. The positive impact of wind profiler observations on the forecast skills was demonstrated recently (Lorenc and Marriott, 2013). With the increasing use of wind profiler data in NWP and climate programmes, it is increasingly required to report and validate the measurement uncertainty.

Wind profilers with operating wavelengths from 50 to 1290 MHz in 3, 4 and 5 beam configurations have been extensively compared with tower measurements (Angevine *et al.*, 1998; Adachi *et al.*, 2005), radiosondes (Weber and Wuertz, 1990; Daniel *et al.*, 1999; Luce *et al.*, 2001; Hooper *et al.*, 2008), aircraft measurements (Cohn *et al.*, 2001) and Doppler lidar (Cohn and Goodrich, 2002). These studies report standard deviations of the differences between wind profiler and reference instrument between 1 and 5 m s<sup>-1</sup> in terms of wind speed. Cohn and Goodrich (2002) presented an assessment of the radial wind of a 915 MHz wind profiler by comparing with a Doppler lidar

minimizing sampling and consensus issues. A standard deviation of about 0.2 m s<sup>-1</sup> has been reported for a dwell time of 25 s, which translates into an uncertainty of <1 m s<sup>-1</sup> in horizontal wind speed.

The variety in these results can to a good extent be attributed to the representativeness error and the retrieval error. The representativeness error arises when the measurand of two measurement techniques is not the same. For example, the measurand of a cup anemometer is in very good approximation the instantaneous horizontal wind in an infinitely small volume. On the other hand, the measurand of a wind profiler is the average wind speed over a spatio-temporal domain of typically 1–5 km (horizontal) and 30–60 min. If the instantaneous wind in an infinitely small volume is associated to the wind profiler measurement, then the representativeness error would be equal to the standard deviation of the instantaneous wind over the integration period and domain of the wind profiler. The retrieval error arises when the basic assumption of atmospheric homogeneity during the wind profiler measurement is violated. This error depends on one side on atmospheric variability and on the other side on the scan strategy. It has been shown that the retrieval error can be reduced when 4 or 5 beams are used instead of only 3 (Adachi *et al.*, 2005).

There are two strategies to reduce the representativeness error when validating remote sensing data. First, to choose a reference method that measures in good approximation the same measurand. The arrival of Doppler lidars opened this possibility for the validation of wind profilers (Cohn and Goodrich, 2002). This needs to be explored more extensively. However, the observable range of Doppler lidars is often much smaller than the one of wind profilers and only a small portion of the wind profiler profiles can be validated. Second, to choose spatially and

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temporally homogeneous atmospheric conditions such that the measurands of both methods that shall be compared are reciprocally representative. This latter strategy has been chosen in this study to assess the uncertainty of the horizontal wind measurements of a wind profiler under ideal conditions.

The paper is structured as follows: A description of wind profiler and radiosonde is given in Section 2 followed by the presentation of the intercomparison method and results in Section 3. In Section 4, the results are discussed, and conclusions are presented in Section 5.

## 2. Instrument description

### 2.1. 1290 MHz Wind profiler

The Federal Office of Meteorology and Climatology MeteoSwiss operates three wind profilers that are part of a tool for the meteorological surveillance of the nuclear power plants (Calpini *et al.*, 2011). One of the wind profilers is operated at the aerological station of Payerne (7° E, 47° N, 491 m). Payerne lies on the Swiss plateau, which is ~50 km wide and stretches along a southwest/northeast axis between the Jura mountains (up to 1600 m) in the northwest and the Alps (up to 4500 m) in the southeast. The predominant wind direction at 2000 m is from the southwest (more than 50% of the time between 220° and 270°) and from the northeast (more than 10% of the time between 30° and 70°).

The 1290 MHz wind profiler is of type PCL-1300 (software version V5.41A) from Degréane and is operated in a five beam configuration with one vertical and four oblique beams with a zenith angle of 17°. The dwell time is automatically adjusted depending on the expected wind speed and is on the order of 40 s. The wind profiler is operated in a high and low mode configuration covering altitude ranges from 790 to 8500 m and from 590 to 3500 m, respectively. The data availability depends on the meteorological conditions and decreases with altitude. On average, the data availability drops below 50% at 4500 m for the high mode and at 3000 m for the low mode. A pulse length of 1000 ns is used for the low mode and 2500 ns for the high mode resulting in a vertical resolution of 150 and 375 m, respectively. Measurement scans are performed following

a vertical-northwest–southeast–northeast–southwest sequence alternating between high and low mode. A consensus is calculated based on a 40 min (60 min) time interval for the low mode (high mode). The consensus data undergo a thorough quality check based on temporal and spatial continuity before the wind components are calculated. The resulting wind components are further quality checked with a similar method as proposed by Weber *et al.* (1993). The manufacturer states a measurement uncertainty of 1 m s<sup>-1</sup> in horizontal wind speed.

### 2.2. Radiosonde

Routine radiosoundings are performed at Payerne twice a day, launched at 1100 and 2300 UTC. The digital radiosonde of type SRS-C34 from Meteolabor is equipped with a global positioning system (GPS), which allows the determination of horizontal wind speed and direction under the assumption that the balloon is moving with the wind. According to the manufacturer, the uncertainties in wind speed and direction are 0.12 ms<sup>-1</sup> and 2°, respectively, for an integration time of 3 s. Vertical wind speed is not derived routinely from the radiosonde data and is not considered in this study. Since the measurement uncertainty in horizontal wind speed is approximately one order of magnitude smaller than the one for the wind profiler, it is neglected in this study.

## 3. Comparison with radiosonde

The study is based on a data set of 3 years from 1 January 2011 to 31 December 2013. To achieve an optimal match in space and time between the radiosonde and the wind profiler, the measurement interval of the wind profiler is centred around the point in time when the sonde reached 2 km (5 km) for the low mode (high mode). Further, the radiosonde data are averaged over the vertical extent of the sampling volume of the wind profiler (150 m and 375 m for low and high mode, respectively). Figure 1(a) shows the histogram of the differences in wind speed between the wind profiler high mode and the radiosonde considering all available data points (30 000) using a bin size of 1 m s<sup>-1</sup>. It is well known

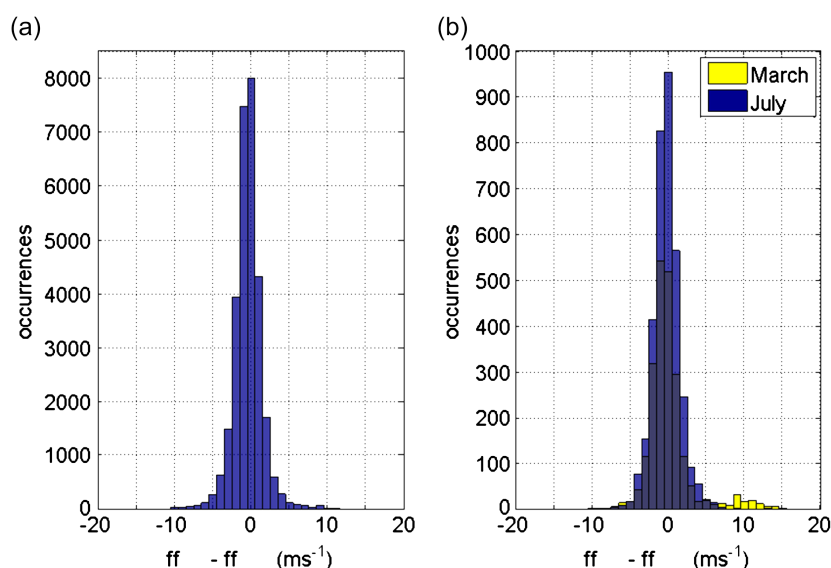


Figure 1. Histogram of the differences in wind speed between wind profiler high mode and radiosonde. (a) All data are shown. (b) The histograms of the data inside bird migration period (only March) and outside bird migration period (only July) are superposed.

that bird migration is a data quality issue, since bird echoes can be interpreted erroneously as atmospheric returns leading to wrong wind speed estimates in the data processing. Migration takes place from September until November when birds travel south to warmer regions to spend the winter and from March to May when they travel back north to their summer territory. Birds migrate preferably during night and rarely during day, at altitudes up to 4000 m. Data contamination due to bird migration is very variable since birds migrate only under favourable wind conditions, which can affect between 0 and 100% of the night time data. A special data quality filter is active during the migration period that detects and flags the contaminated data. It is, however, not possible to retrieve any wind information in the presence of migrating birds and the data availability can drop to 0% during night. Figure 1(b) shows the histogram for the migration period in spring (only March) superimposed by the histogram of data outside the migration period (only July). It is clearly visible that contaminated data are not perfectly filtered by the software and that during the bird migration period a secondary maximum at  $\sim 10 \text{ m s}^{-1}$  is visible, which corresponds to the air speed of birds. In the following analysis, periods where strong bird migration must be expected (months March, April, September and October) have therefore not been considered. Furthermore, since wind speed and wind direction are not normally distributed, all statistical analyses are performed on the horizontal wind components  $u$  and  $v$ .

Figure 2 shows the histograms of the differences between wind profiler high mode and radiosounding in  $u$  and  $v$  for different levels. The differences are in good approximation, normally distributed up to an altitude of  $\sim 6 \text{ km}$ . Above this altitude, not enough data points are available to obtain good statistics. A normal distribution of the differences has also been found for the low mode (not shown). The scatter plots between the radiosonde and wind profiler high mode measurements in terms of  $u$  and  $v$  are shown in Figure 3 in blue. A linear regression reveals an  $R^2$  value of 0.93 for both components and a slope of 0.9 and 1.0 for  $u$  and  $v$ , respectively. In the case of the low mode, the slopes are

identical and the  $R^2$  value is 0.91 for  $u$  and  $v$  (not shown). The profiles of the mean and the standard deviation of the differences between wind profiler high mode and radiosonde are shown in Figure 4(a). The bias is smaller than  $0.75 \text{ m s}^{-1}$  for high mode and low mode (not shown). The standard deviation is between  $1.75$  and  $2 \text{ m s}^{-1}$  for high and low modes up to  $6 \text{ km}$ . Above this, the sample is too small for a good estimate of the standard deviation.

As discussed in Section 1, an important assumption for the retrieval of the wind components from the radial winds is temporal and spatial homogeneity. Hence, some part of the obtained standard deviation can be explained by the fact that the wind field was not stationary and uniform across the sampled volume and during the integration period. This increases both the retrieval error and the representativeness error, since the sonde provides a measurement of the instantaneous wind and not a temporal and spatial average. In order to assess the contribution from atmospheric inhomogeneity, the differences between wind profiler and radiosonde have been analysed for cases where the atmosphere was stationary and uniform on scales of the wind profiler measurement. This subset has been selected based on the radial velocities obtained from individual dwells (40 s integration time). The atmosphere was considered stationary if the standard deviation, calculated over 120 min, of the radial velocities in each direction was smaller than  $0.5 \text{ m s}^{-1}$ . As an illustration, the instantaneous measurements of the radial velocity obtained from each dwell are shown in Figure 5. To test the spatial uniformity of the wind field, the standard deviation of the differences of the radial velocities of two opposite oblique beams over the integration period of 120 min must be smaller than  $0.5 \text{ m s}^{-1}$ . For this test, the radial velocities of the oblique beams have been corrected for the vertical speed using the vertical beam. The correction was, however, only applied if the vertical speed derived from each pair of oblique beams is consistent with the measurement of the vertical beam (agreement within  $0.5 \text{ m s}^{-1}$ ); otherwise, the data were rejected for further analysis. The test for atmospheric homogeneity (in space and time) reduced the

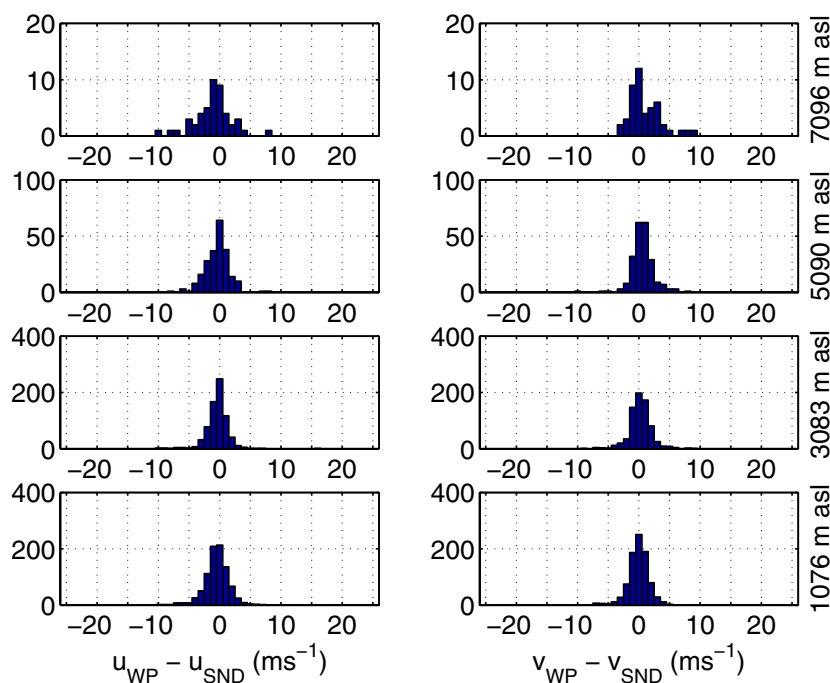


Figure 2. Histogram of the differences in  $u$  and  $v$  between wind profiler high mode and radiosonde for four different levels.

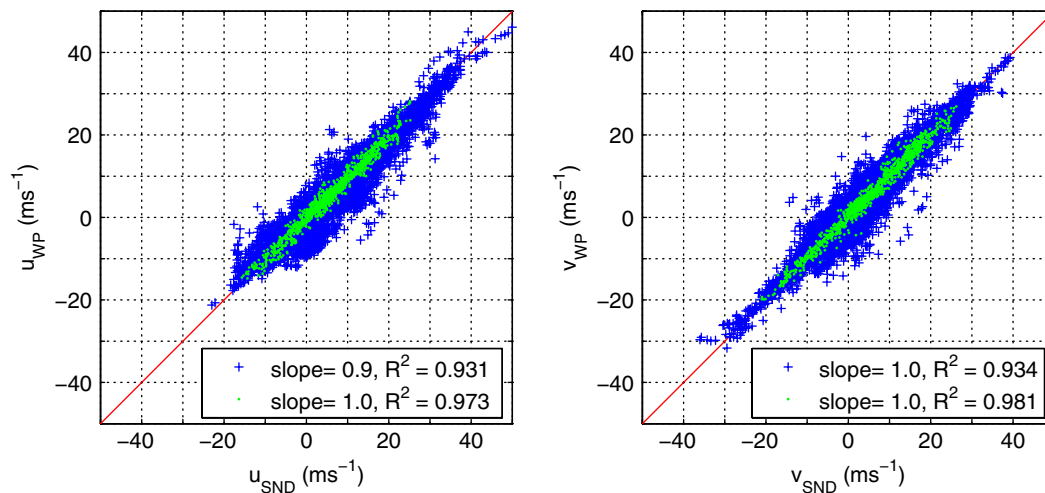


Figure 3. Scatter plots of the radiosonde data *versus* wind profiler high mode data for all data outside bird migration period (blue) and for cases outside bird migration period where the atmosphere was spatially and temporally homogeneous (green, see text).

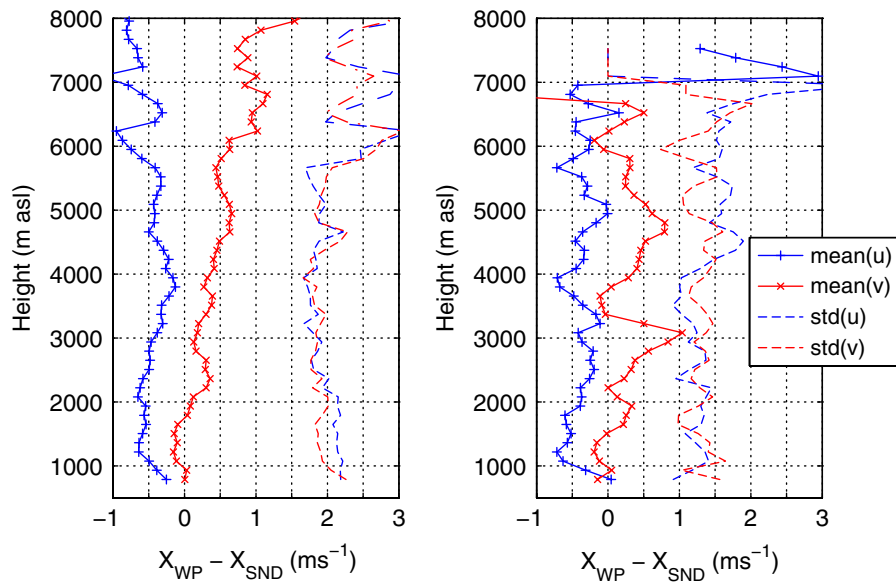


Figure 4. Profiles of mean and standard deviation of the differences between wind profiler and radiosonde. (a) Results taking into account all the data outside bird migration period, while the (b) shows data outside bird migration period for cases when the atmosphere was spatially and temporally homogeneous.

sample from over 800 to 40 profiles. All data points of the subset are shown in Figure 3. The slopes are now equal to 1 and the  $R^2$  value is 0.98 for both  $u$  and  $v$  for the high mode. In the case of the low mode, the slopes are unchanged and  $R^2$  values are 0.92 and 0.96 for  $u$  and  $v$ , respectively. The resulting means and standard deviations for the high mode are shown in Figure 4. While the biases remain essentially unchanged, the standard deviation lies between 1 and  $1.5 \text{ m s}^{-1}$  for this subset for both high and low modes.

#### 4. Discussion

The scatter plots of the wind profiler *versus* the radiosonde data in terms of wind components are shown in Figure 3 for the high mode. A linear regression revealed a slope of 0.9 and 1 and an  $R^2$  value of 0.93 for  $u$  and  $v$ , respectively, for the high mode, which demonstrates the generally good performance of the wind

profiler. The  $R^2$  values for the low mode are 0.91, being slightly lower. This lower quality in the low mode is due to the increased ground clutter compared with the high mode. The standard deviation of the differences between wind profiler high and low modes and the radiosonde in  $u$  and  $v$  has been found to be between  $1.75$  and  $2 \text{ m s}^{-1}$ . This value can be considered as an upper limit of the total uncertainty of the wind profiler for all weather conditions and under the assumption that the wind profiler measures the instantaneous wind. This figure has to be interpreted in the sense that in 50% of the cases, the true values of the wind components lie within  $2 \text{ m s}^{-1}$  of the wind profiler measurement. The uncertainty of the radiosonde measurement is, according to the manufacturer, almost one order of magnitude smaller and has been neglected. However, a part of this standard deviation is due to atmospheric inhomogeneities in space and time, which violate the basic assumption of the wind retrieval from radar data (retrieval error) and decrease the reciprocal representativeness

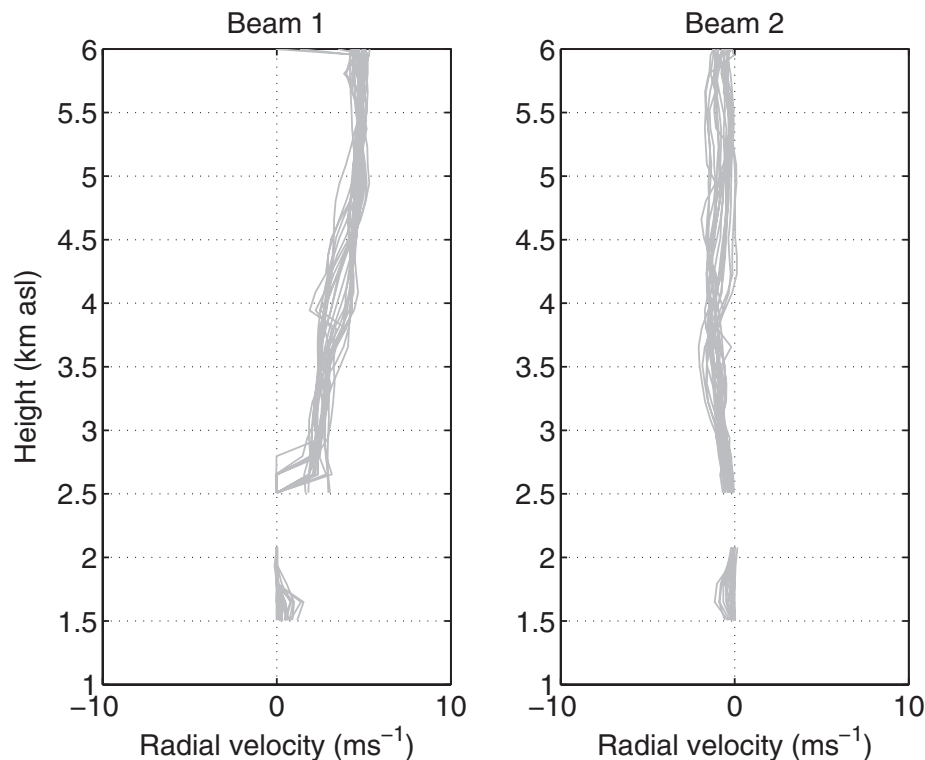


Figure 5. Radial velocity profiles obtained from individual dwells (40 s integration) for the northwest beam [beam 1 (a)] and the northeast beam [beam 2 (b)].

of the two measurements. The scatter plots of the subset of homogeneous cases are shown in Figure 3, which reveals that in particular the strong winds are rejected in the subset since these situations are usually characterized by increased variability. The standard deviation derived from the subset of measurements that have been taken under homogeneous conditions is between 1 and  $1.5 \text{ m s}^{-1}$ . It has to be noted that the subset has only 40 members and the derived mean and standard deviation are less robust. This can be seen by the increased noise in the profiles in Figure 4(b). The standard deviation derived from the subset can be interpreted as an upper limit of the measurement uncertainty under ideal weather conditions (homogeneous atmosphere). This translates into an uncertainty in wind speed of  $1.5 \text{ m s}^{-1}$  and  $10^\circ$  in direction at  $10 \text{ m s}^{-1}$  wind speed under the assumption that the errors in  $u$  and  $v$  are uncorrelated. These values are in general agreement with former studies that reported standard deviations ranging from 1 to  $5 \text{ m s}^{-1}$  (Weber and Wuertz, 1990; Daniel *et al.*, 1999; Luce *et al.*, 2001; Hooper *et al.*, 2008) and close to, but slightly higher than, the values stated by the manufacturer.

## 5. Summary and conclusions

The validation of the operational 1290 MHz wind profiler operated by the Federal Office of Meteorology and Climatology MeteoSwiss at Payerne, Switzerland, has been presented, using radiosonde global positioning system (GPS) wind measurements as reference. The radiosonde data have been vertically averaged to match the vertical resolution of the wind profiler, and the integration time of the wind profiler has been chosen such that the time interval is symmetrical around the point in time when the radiosonde reached 2000 m (5000 m) for the low mode (high mode). Periods when bird migration has to be

expected have been systematically excluded from the analysis. The standard deviation of the differences between wind profiler and radiosonde is between 1.75 and  $2 \text{ m s}^{-1}$ . This value can be reduced to 1 to  $1.5 \text{ m s}^{-1}$  if only cases are considered where the atmosphere was spatially and temporally homogeneous during the measurement process. This value is considered as an upper limit of the measurement uncertainty of the wind profiler in ideal, i.e. homogeneous, conditions. The bias of the wind profiler compared with the radiosonde is below  $0.75 \text{ m s}^{-1}$  for both high and low modes.

This study shows that the wind profiler under consideration provides good quality data. The measurement error was estimated by performing an intercomparison under homogeneous conditions minimizing the representativeness error and retrieval errors, i.e. effects coming from the violation of the assumption of atmospheric homogeneity in the wind retrieval. A distinction between representativeness error and retrieval error is not possible with the chosen approach and requires comparisons with measurement techniques that allow to perform the same temporal and spatial sampling as the wind profiler. Doppler lidars offer these possibilities, as has been shown successfully by Cohn and Goodrich (2002). Improvements of the data quality of the wind profiler under consideration can mainly be expected from better suppression of ground clutter and more efficient filtering of data that are contaminated by bird migration.

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