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Comparison of wind measurements between a Mini-SODAR PA0, a METEK-SODAR and a 99 m tower

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ABSTRACT

Doppler-SODAR measurements are commonly used to derive the vertical wind profile. One main advantage of the Mini-SODAR (from the company Remtech) is its small size and weight and therefore it is easy to handle and set up in short time. Two long-term measurements were operated in September and October 2009. A statistical comparison was made between the Mini-SODAR, the tower and the DWD-SODAR (from the company METEK) for the two measurement periods. It is presented here that the Mini-SODAR overestimates the tower measurements and also the measurements of the DWD-SODAR. It is also shown, that the Mini-SODAR is able to determine the mean flow conditions in the lower boundary layer (up to 200 m).

1. INTRODUCTION

For the understanding and the research of the planetary boundary layer it is necessary to provide a validated knowledge about the flow and stratification characteristics of the lower atmosphere (up to 1000 m). Therefore the SODAR (**SO**nic **D**etecting **A**nd **R**anging) as an acoustic remote sensing method is a reasonable entrancement of the conventional measurements of the wind vector with a tower. In the SODAR method, pulses of audible sound are emitted into the atmosphere by an antenna. They get scattered on turbulent structures in the atmosphere and the backscattered signals are received by the same antenna (monostatic SODAR) or by a second antenna (bistatic SODAR). Just a fraction of the emitted sound energy is detected. The SODAR instrument allows measurements of the wind components and their standard deviation as a function of height.

First applications of SODAR systems started in the early 1970s (Kallistratova and Coulter, 2004) but the theoretical background about the turbulent scattering of sound were done in the 1940s by Obukhov (1941) and Kolmogorov (1941) and in the late 1950s and the early 1960s by Kallistratova (1959 and 1961), Tatarskii (1961) and Monin (1969). While the first SODAR gadgets just received the backscattered sound intensity to determine the thermal stratification, the development of SODAR systems leads to Doppler-SODAR and multi-frequency SODAR systems.

Details of the principles and the signal analysis are given by VDI (1994) and Bradley (2008).

SODAR systems are used for the investigation of the meso-scale and micro-scale flows and wind systems as well as turbulent and wave-like structures under stable and unstable conditions.

There are some intercomparisons between SODAR and tower measurements (e.g. Reitebuch, 1999, Vogt and Thomas, 1994) or even between two SODAR systems (e.g. Vogt and Thomas (1994)) which can be found in the literature. Some authors, e.g. Bradley et al. (2005), were engaged with the calibration of SODAR systems and their sources of error.

Recently, Pietschmann (2007) operates some first short test-measurements at the boundary layer field site Falkenberg that belongs to the Meteorological Observatory Lindenberg of the German Weather Service and concentrates on the features given by the Remtech Mini-SODAR. The question of the performance of a long-term measurement with the SODAR and therefore the comparison with measurements of the tower and the DWD-SODAR is still unknown and shall be investigated here.

2. SETUP AND MEASUREMENT PRINCIPLE OF THE MINI-SODAR PA0

The Mini-SODAR PA0 of the French company Remtech is a monostatic system with an antenna size of 0.4 x 0.4 m^2. Because of the antenna weight of only 12 kg (including supporting equipment) it offers a high agility and it is built up in a short time. After the installation it is important to determine the azimuth angle α (angle against north clockwise).

The PA0 consists of a phased-array antenna with 52 loudspeakers. It features a 5-beam system with one beam aimed vertically the other four beams are inclined with an angle $\theta = 30°$ and their azimuth angles are 90° apart.

The signal of the PA0 consists of several frequencies. During one pulse duration it emits up to nine different frequencies between 600 Hz and 18 kHz. Thereby the most frequent frequency is 3.5 kHz. Because of the use of several frequencies the detection of the backscattering signal out of the background noise is much easier according to the manufacturer Remtech.

In addition to the main system (antenna) there exists a sound protection which is lined with an absorbing material. This sound protection, with a height of 1.60 m, reduces fixed echoes (reflection of sound on fixed obstacles, e.g. houses or trees) and also serves as a noise protection for the environment. The acoustic power of the PA0 is 1 W and the manufacturer offers an average vertical range under typical conditions of 600 m. It operates over the power network (20 V) or with the help of batteries (12 V).

After emitting a sound pulse, the monostatic SODAR switches into the receive mode to detect the backscattering signal from the atmosphere. Thereby the Doppler spectrum (it shows the spectral power against the frequency) is recorded. From this the Doppler parameters are calculated: (i) the backscattering amplitude A, (ii) the shift in frequency Δf_d and (iii) the width of the Doppler spectrum σ_f. The shift in frequency is the result of the so called Doppler effect (which is just mentioned here; for more information see Bradley, 2008 and Pierce, 1989). The radial wind velocity (v_{rad}) along one sound beam can be determined with the help of the Doppler effect:

$$v_{rad} = \frac{c}{2}\frac{\Delta f_d}{f_0}. \tag{1}$$

In Equation (1) c is the speed of sound, f_0 is the emitted frequency and Δf_d is the shift in the Doppler frequency. A positive (negative) radial wind velocity means that the scattering volume moves toward (away from) the antenna. With the help of the width of the Doppler spectrum, it is possible to achieve the standard deviation of the radial wind. In nature the speed of sound depends on the temperature. But in practice the SODAR uses a constant surface value. This leads to a systematic error in determining the radial wind velocity and the height of the backscattering volume.

3. DESCRIPTION OF MEASURING FIELD AND INSTRUMENTS

The measurements took place at the boundary layer field site (in German: Grenzschichtmessfeld, GM) Falkenberg which is controlled by the Richard-Aßmann Observatory - Meteorological Observatory Lindenberg (RAO-MOL) of the German Meteorological Service (in German: Deutscher Wetterdienst, DWD). The GM (Figure 1) is located 5 km to the south of the MOL near the village Falkenberg in the north-east of Germany (52° 10’ N and 14° 07’ E, 73m above sea level). It was established as a central base point for field studies of land surface and boundary layer processes (Neisser et al., 2002). The terrain around the GM is flat and slightly slanted from NNE towards SSW with hight differences of less than 5 m over a distance of about 1 km. The surrounding area of the GM is dominated by forests and agricultural fields (more than 40% each) and the rest of the area is covered by lakes, traffic roads and villages (Beyrich and Mengelkamp, 2006). For more information see also Neisser et al. (2002) and Beyrich and Foken (2005).

The DWD operates a 99 m tower and a SODAR-system of the type METEK DSDPA.90-64 on the GM. The tower is equipped with three crossarms mounted at each level pointing towards S, W and N. The wind sensors are mounted on each of the three crossarms at the heights of 10, 20, 40, 60, 80 and 98 m in order to ensure that there is always at least one sensor not influenced from the structure of the tower (Neisser et al., 2002). The SODAR-system is a monostatic phased-array antenna (like the Mini-SODAR PA0) with an array aperture of 1 x 1 m^2. It works with a 5-beam system and transmits a single frequency of 1598 Hz. For more details see Engelbart et al. (1999).

The Mini-SODAR was build up in the middle of the connecting line between the DWD-SODAR and the tower (see Figure 1) during two measurement periods. The Mini-SODAR was directed to the north ($\alpha = 0°$), so that one beam was vertically directed and two beams were directed to the north and to the west with a zenith angle of $\theta = 30°$. There were some small trees and bushes along a country road in the northern direction. But the distance between these obstacles and the Mini-SODAR was big enough (~ 50 m) to avoid strong fixed echoes. During both measuring periods the sound protection of the manufacturing company REMTECH was used.

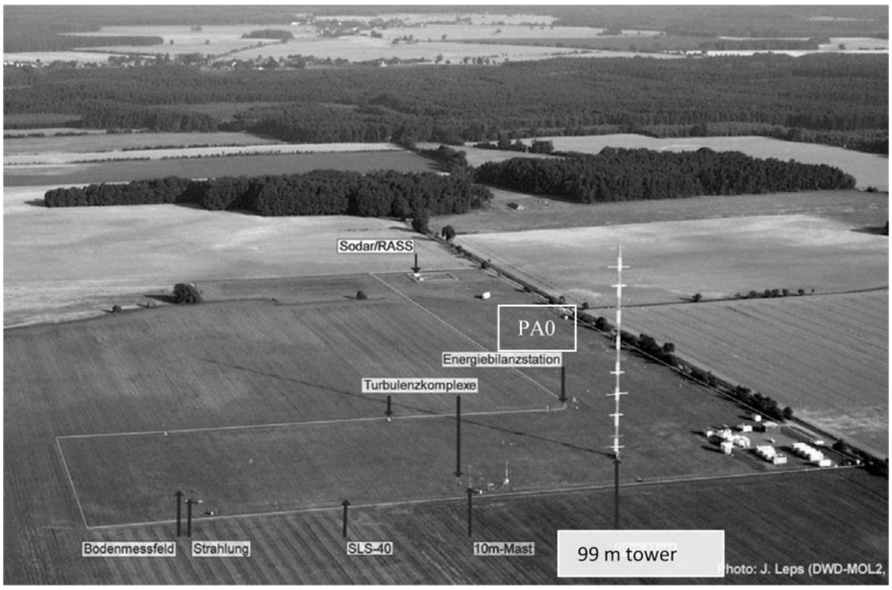

Figure 1: *Boundary layer field site Falkenberg, modified from [Beyrich and Foken, 2005].*

The settings of the Mini-SODAR were tried to match with the settings of the DWD-SODAR and the tower (see Table 1).

Parameter	Mini-SODAR	DWD-SODAR	Tower
Averaging period	10 min	15 min	10 min
Minimum height	20 m	40 m	10 m
Thickness of each gate	20 m	20 m	20 m
Maximum height	880 m	700 m	98 m

Table 1: *Comparison of the settings between DWD-SODAR, Mini-SODAR and the tower.*

4. INTERCOMPARISON OF DATA

The Mini-SODAR was operated at the GM Falkenberg during two measurement periods. The first period took place from the 7th September to 16th September 2009. For a direct comparison, the SODAR and the tower data are plotted versus the time. An example of the wind speed and direction at 100 m agl on the 14th September 2009 are given in Figures 2. The following conclusions can be drawn from the time series:

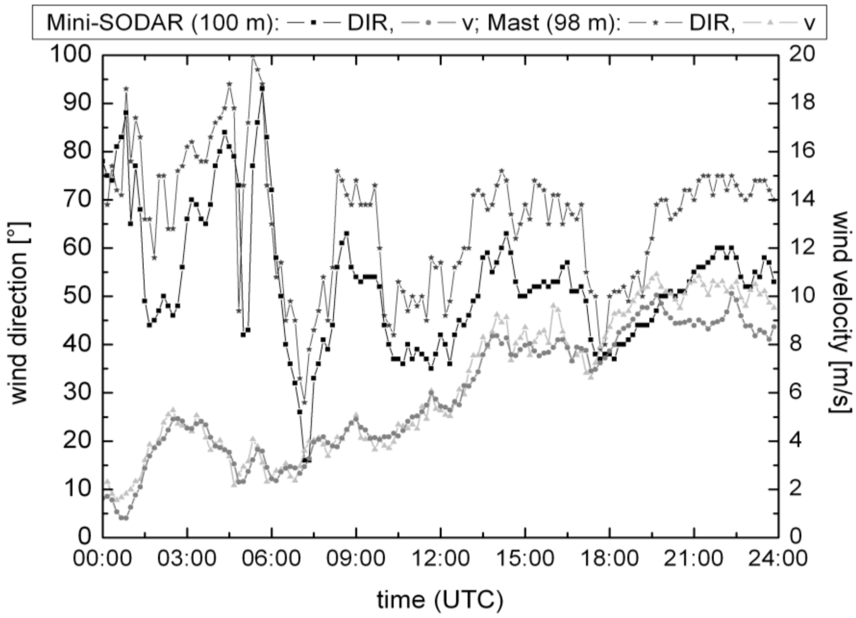

Figure 2: *Comparison of wind direction (DIR) and the horizontal wind velocity (v) between the Mini-SODAR (black square, grey dot) and the tower (dark star, triangle) for the 14.09.2009 at a height of 100 m altitude; the averaging time was 10 min.*

(1) The wind speed measured by both instruments is well comparable. The temporal behavior of the wind speed is shown by both instruments in a similar manner. In the second half of the day the discrepancies between the tower and the Mini-SODAR become greater.

(2) The wind directions measured with both instruments are not well comparable. Both instruments represent a similar time behavior but the tower measures wind directions with a difference of about 10-15° compared to the Mini-SODAR. A probably reason for this discrepancy could be due to uncertainties in the orientation of the Mini-SODAR and the accuracy of the SODAR itself.

The scatter diagrams of the horizontal wind velocity of the tower and the SODAR data are represented in Figures 3 for two different heights (20 m, left panel and 100 m, right panel) over the whole first measurement period. The dashed lines of these diagrams represent the perfect fit lines and the black lines represent the linear regression lines. Figure 3 (left panel) clearly shows that the Mini-SODAR overestimates the wind speed of the tower at the 20 m level. In contrast the Mini-SODAR results in Figure 3 (right panel) underestimates the wind velocity for wind speeds less than 3 m/s and for wind speeds more than 8 m/s. For wind speeds more than 3 m/s and less than 8 m/s the Mini-SODAR overestimates the wind speed a little.

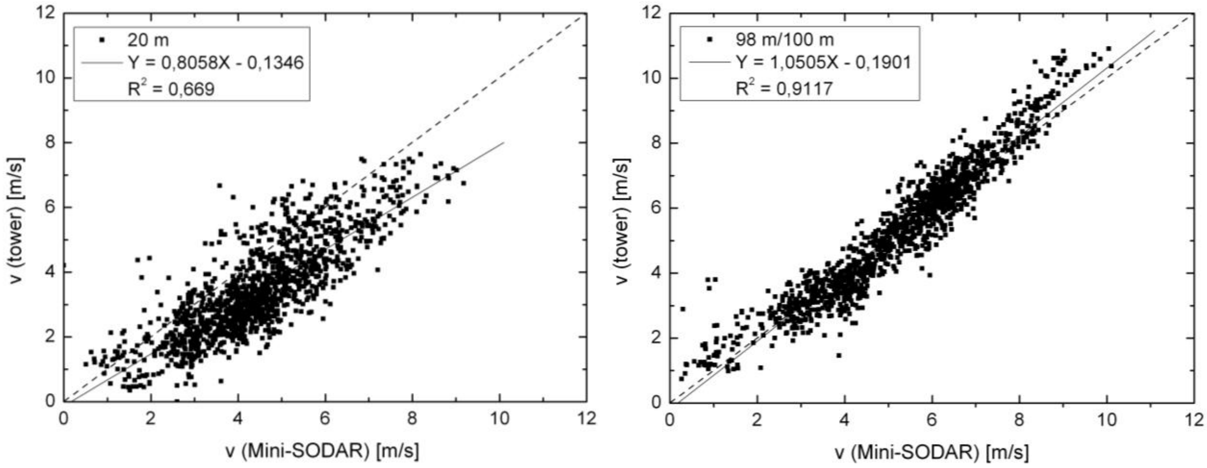

Figure 3: *Correlation between Mini-SODAR (20 m) and tower (20 m) (left panel) and between the Mini-SODAR (100 m) and the tower (98 m) (right panel) for the period 7.09. – 16.9.2009 regarding the horizontal wind velocity.*

For the second measurement period at the GM Falkenberg the data of the DWD-SODAR were additionally available. For a direct comparison, the Mini-SODAR, the DWD-SODAR and the tower data are plotted versus the time. Examples of the wind speed and direction at 100 m agl on the 22nd October 2009 are given in Figure 4. Following conclusions can be drawn:

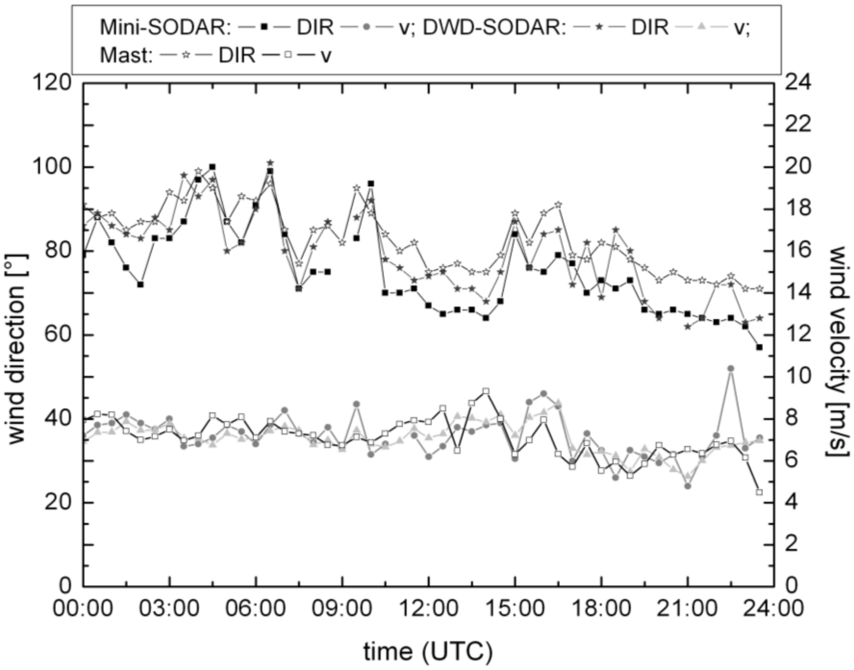

Figure 4: *Comparison of wind direction (DIR) and the horizontal wind velocity (v) between Mini-SODAR (black square, diamond), DWD-SODAR (black star, triangle) and tower (white star, white square) for the 22.10.2009 in a height of 100 m altitude. Values of each hour and half hour are plotted.*

(1) The wind speed measured by all three instruments is well comparable. The temporal behavior of the wind speed is shown by all three instruments in a similar manner.

(2) The wind directions measured with all three instruments are also well comparable. But in the second half of the day the DWD-SODAR data fluctuates a bit more then the Mini-SODAR data.

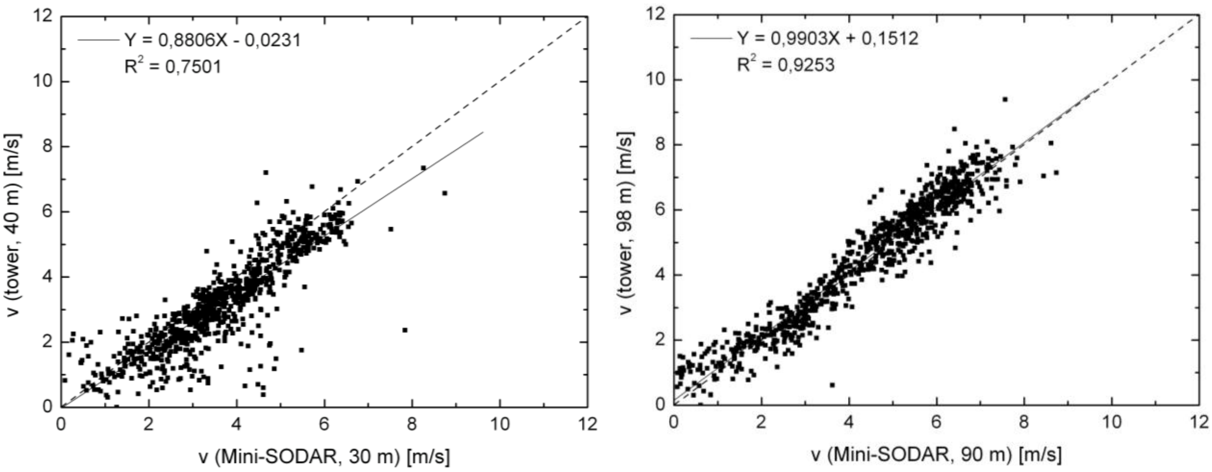

Figure 5: *Correlation between Mini-SODAR (30 m) and tower (40 m) (left panel) and between the Mini-SODAR (90 m) and the tower (98 m) (right panel) for the period 23.09. – 29.10.2009 regarding the horizontal wind velocity.*

The scatter diagrams of the horizontal wind velocity of the tower and the SODAR data are represented in Figures 5 for two different heights (40 m and 100 m) over the whole second measurement period. The dashed lines of these diagrams represent again the perfect fit lines and the black lines represent the linear regression lines. It must be stated that in Figure 5 the tower level of 40 m (98 m) agl is plotted versus the 30 m (90 m) level of the Mini-SODAR data. This is because the settings (minimum height: 30 m) of the Mini-SODAR were changed. Figure 5 (left panel) show that the data of the lower levels of the Mini-SODAR overestimates the tower data. While the data of the higher level (Figure 5 right panel) show an adequate agreement between the two systems.

For the second measurement period the data sets of the horizontal wind velocity of the three instruments were averaged for the time of 23.10. to 29.10.2009 up to an altitude of 110 m. These three vertical profiles are plotted in Figure 6. The vertical gradients of the wind velocity measured by the DWD-SODAR and the Mini-SODAR are not well comparable. There are greater discrepancies for lower altitudes and these discrepancies get less up to 100 m. But over the whole vertical profile the Mini-SODAR measures a higher wind velocity then the DWD-SODAR. Also the tower measures a higher wind velocity over the whole vertical profile then the DWD-SODAR. The wind velocity

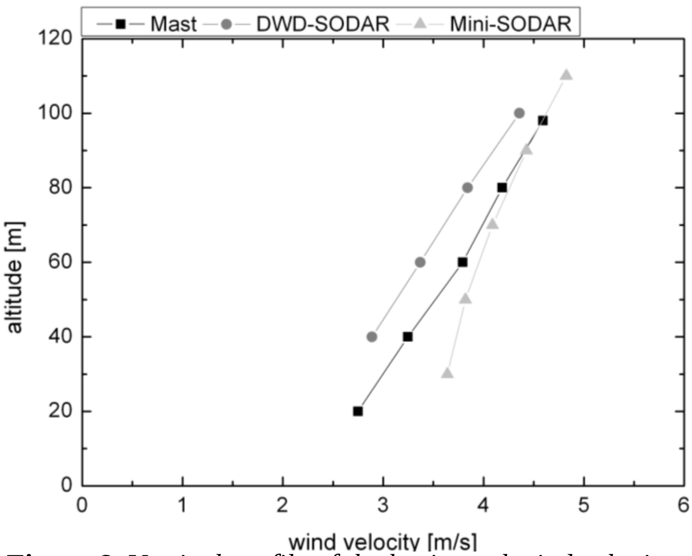

Figure 6: *Vertical profile of the horizontal wind velocity of the Mini-SODAR, the DWD-SODAR and the tower for the period 23. – 29.10.2009.*

measured by the tower and the Mini-SODAR is in good accordance for higher altitudes. But for lower altitudes the Mini-SODAR measures higher wind speeds then the tower. For a statistical comparison between the three instruments see the section about the $BIAS$ and Tables 2 and 3.

To see how comparable the measurements of the two SODAR systems are, Figure 7 shows a plot of the vertical profiles of the wind velocity up to an altitude of 510 m. These profiles were averaged over the time from 23.10. to 29.10.2009. Up to an altitude of 60 m agl there are little discrepancies between these two systems. But above 60 m up to 200 m there is an adequate accordance between the two SODAR systems. In the next range gate between 200 m and 450 m there is a big difference between both systems. The reason for this is not clear up to now. Furthermore there is a good accordance between both measurements for the altitudes from 450 m up to 510 m.

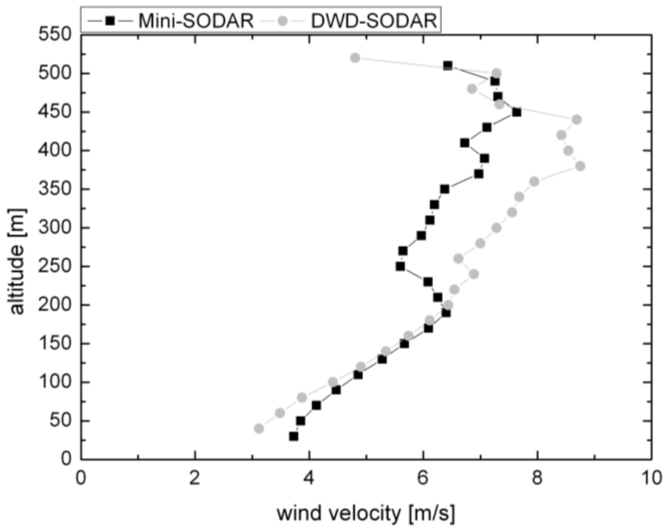

Figure 7: *Vertical profile of the horizontal wind velocity of the Mini-SODAR and the DWD-SODAR for the period 23. – 29.10.2009.*

The systematic deviation $BIAS$ is calculated to compare the three different data sets. The $BIAS$ is the difference between the mean values of the Mini-SODAR and the tower data and can be expressed by the Equation (2) and also the standard deviation (Equation (4)) of $BIAS$ the is calculated.

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i) = \hat{Y} - \hat{X} \tag{2}$$

$$\sigma_{BIAS}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left[(Y_i - X_i) - \frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)\right]^2 \tag{3}$$

$$STD = \sqrt{\sigma_{BIAS}^2} \tag{4}$$

In this Equation (2 and 3) the Mini-SODAR data are indicated by Y_i, whereas X_i presents the data of the tower. The fact that this comparison is done between two different measurement methods and each of them got his own uncertainties, the true $BIAS$ will not be equal zero.

Horizontal wind [m/s] /Height	20 m	40 m	60 m	80 m	98 m/100 m
$BIAS$	0.99	0.37	0.01	-0.09	-0.08
STD	1,00	0,63	0,59	0,67	0,68

Table 2: *Summary of the statistical parameter BIAS and the standard deviation for the comparison of the horizontal windspeed [m/s] between the tower and the Mini-SODAR for the first measurement period (08.09.-14.09.2009).*

The $BIAS$ between measurements of the tower and measurements of the Mini-SODAR in the first period regarding the horizontal wind velocity is listed in Table 2. It is noticeable that for heights up to 60 m the $BIAS$ is positive which means that the Mini-SODAR detect higher wind speeds then the tower. This is differs from the theory and therefore some other factors must be relevant. Bradley et al. (2005) listed some possible factors for the uncertainties in the measurements with a SODAR: (1) an inexact horizontal orientation of the Mini-SODAR, (2) uncorrected effects of the temperature (influence of the temperature field on the sound path through the atmosphere) and (3) turbulent widening of the beam because of multiple scattering. For the two higher altitudes the $BIAS$ is negative which is consistent with the theory.

The Table 3 shows the $BIAS$ for the comparison between the three measurement systems for the second measurement period. There is a positive systematic deviation for all altitudes up to 100 m. Possible reasons were already discussed. It should be mentioned that there is a difference ($\Delta h = 10\ m$) between the heights which are compared because of a little rearrangement in the settings of the Mini-SODAR. But it can be seen that the systematic deviation decreases with height. This could be because of the fact that the mechanical turbulence decreases with height and therefore the measurement over a volume with a SODAR might be more precise.

The comparison between the tower and the DWD-SODAR leads to a negative $BIAS$ which is consistent with the above mentioned reasons and be caused by the effect of "overspeeding",

Horizontal wind [m/s] / Height	20 m	40 m	60 m	80 m	98 m/100 m
$BIAS$ Mini-S. (Y) vs. tower (X)	0.89	0.57	0.29	0.24	0.23
STD	-	0,83	0,62	0,45	0,46
$BIAS$ DWD-S. (Y) vs. tower (X)	-	-0.36	-0.42	-0.35	-0.24
STD	-	1,71	1,34	0,59	0,87
$BIAS$ Mini-S. (Y) vs. DWD-S. (X)	-	0.93	0.72	0.59	0.47
STD	-	1,93	1,49	0,70	0,93

Table 3: *Summary of the statistical parameter BIAS for the comparison between the tower, the Mini-SODAR and the DWD-SODAR for the second measurement period (23.10.-29.10.2009).*

through to none filtering of fixed echoes or because of differences in the averaging method.
The third comparison is provided between the Mini-SODAR and the DWD-SODAR. The first two comparisons have shown that the Mini-SODAR overestimates the measurements of the tower and the DWD-SODAR underestimates the tower measurements regarding to the horizontal wind velocity. Thus a larger deviation results between the two SODAR systems.
For the first measurement period these overestimation of the tower measurement was only found in altitudes of 80 m and 100 m. In the altitudes of 20 m to 60 m the SODAR measurement overestimates the wind velocity. In the second measurement period the Mini-SODAR overestimates the tower measurement over all altitudes. The comparison between the DWD-SODAR and the tower leads to a negative $BIAS$. This implies an overestimation of the wind velocity by the tower. It is noticeable that the $BIAS$ between the systems decreases with height.

The systematic deviation is also calculated with regard to the wind direction. The $BIAS$ between the Mini-SODAR and the tower for the first period showed that the values of the Mini-SODAR deviate from the values of the tower with an absolute value of about 7° (in an altitude of 40 m agl) and 9.8° (in an altitude of 100 m/98 agl). The deviation between these two instruments is for the second period half as much as for the first period. The absolute value of about 3.5° is in an acceptable range. A reason for the differences of both periods could be due an inexact orientation to the north ($\alpha \neq 0°$). It was tried that the installation in both periods was the same but it was not possible to orientate it exactly the same.
The comparison between the tower and the DWD-SODAR leads to much better systematic deviations then the comparison between the tower and the Mini-SODAR. The deviation of an absolute value of less than 1° is negligible.
The third comparison for the second period was provided between the two SODAR systems. In an altitude of 100 m the absolute value of the deviation is comparable with the deviation between the tower and the Mini-SODAR. Just in an altitude of 40 m the deviation is a bit greater for the comparison between the two SODAR systems than between the tower and the Mini-SODAR.

5. CONCLUSION AND OUTLOOK

The comparisons during the first measurement period resulted in an overestimation in the wind velocity of the Mini-SODAR in the lower altitudes up to 60 m and to an overestimation by the tower measurements in the higher altitudes of 80 m and 100 m. The comparison between the tower and the Mini-SODAR leads to an overestimation of the horizontal wind velocity by the Mini-SODAR during the second measurement period. Possible reasons are not clear yet. The difference between the Mini-SODAR and the DWD-SODAR is greater because the DWD-SODAR underestimated the horizontal wind velocity compared to the tower. But the measurements of the Mini-SODAR are quite comparable with the tower measurements for the heights from 60 m up to 100 m ($BIAS$ of 0.2 – 0.3 ms^{-1}). The measurement with the Mini-SODAR is in adequate agreement with the measurement of the DWD-SODAR for a range gate from 60 m up to 200 m. The comparisons between the Mini-SODAR and the DWD-SODAR above an altitude of 500 m are possible but the reliability of the results is limited due to the weak data availability. The data availability amounts nearly 70 % at a height of 330 m. Furthermore, the data availability of the Mini-SODAR decreases distinctively for height levels above 400 m. Therefore it is not very useful to compare these two systems above 500 m.

It is not possible to get inside of the software of the Mini-SODAR to customize the SODAR to different environmental conditions. Nevertheless it is possible to get an overview about the mean flow conditions for the lowest 60 m to 200 m of the planetary boundary layer.

In further work the dependence of the data availability of the Mini-SODAR on the stratification will be investigated. There will be also investigations about the development of low-level jet events, the development of the stable boundary layer and a possible connection between these two atmospheric phenomenons.

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