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Wessels' wind measurement corrections : Applied to rigs on the North Sea

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Abstract

In this report, wind measurements of the platform AWG1 are analyzed and compared to good measurement sites (MMIJ, OWEZ). The measurements of AWG1 initially do not comply with WMO/ICAO accuracy requirements. Correction formulae derived by Wessels are applied to the measurements. [7] They take into account the presence of a vent stack which supports the wind measuring devices. Furthermore, optimal schemes to combine the different measurement sets into one set are analyzed. The aim of all of the above was to improve the measurements.

Before correcting, the wind direction dependent biases of the AWG1 2012 and 2013 measurements w.r.t. KNW-atlas data are smaller than 1.8 m/s and 21 degrees. The corrected values for the wind speed all have a bias smaller than 1.3 m/s. For the wind direction, a bias of at most 13 degrees is found when the wake cause by the vent stack comes close to the wind vane. While the biases of the measurements are reduced significantly by applying Wessels' corrections and the introduced schemes, they still do not comply with WMO/ICAO standards.

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1 Introduction

In 2006 a few of weather stations were installed on rigs in the North Sea because the Royal Netherlands Meteorological Institute (KNMI) was going to start making weather forecasts to facilitate helicopter flights to and from these rigs.

In response to a request of the Nederlandse Aardolie Maatschappij (NAM), Wiel Wauben (KNMI) analyzed wind measurements from 5 of the 9 rigs. The conclusion of his analysis was that these measurements did not comply with the World Meteorological Organization's (WMO) requirements. The purpose of this project is to improve the measurements on these rigs. This will be done by comparing them to the KNMI Noordzee Wind-atlas (KNW-atlas).

The KNW-atlas is a dataset containing hourly wind data at several heights in the boundary layer. The dataset is composed of series of the first 6 hours of HARMONIE runs initialized with the 6-hourly analyses of ECMWF's ERA-Interim. Averages over multiple years of wind speeds in the KNW-atlas deviate only 2 percent from good, uninfluenced measurements. [4]

The measurements at Meteomast IJmuiden (MMIJ) and Offshore Windpark Egmond aan Zee (OWEZ), as located in Fig. 1, are considered to be good measurements and are therefore used to quantify the errors of poor measurement sites. One such poor measurement site is AWG1, which is also shown in Fig. 1. The other poor measurement sites with instruments mounted on the vent stack are D15, F16, J6, K14 and L9.



Figure 1: The location of the measurement sites considered in this report.

This report is not only focused on explaining the results produced during the author's internship at KNMI, but also tries to provide enough information for follow up research and therefore includes explanations of methods used, mathematical tools utilized and in-depth documentation of the codes such that the results can be reproduced.

Firstly, theoretical background on directional statistics and the method of correction described by Wessels will be introduced. Thereafter, the KNW wind data will be verified against the high quality measurements from MMIJ and OWEZ and a selection of the most accurate KNW data will be used as a reference to assess the AWG1 measurements. The code will be described fully and evaluated for an artificial test case to see if it functions correctly. Following this, results are presented and recommendations are made.

This report is part of T.H. Joosten's industrial internship at the KNMI, which took place from September 1st - November 30th 2017. An internship is part of the Research and Development orientation of the MSc Applied Physics at Delft University of Technology.

2 Theoretical background

2.1 Wind direction computations

2.1.1 Computing the mean

When averaging certain angles, one can see that a problem will occur. If two angles of, for example, 1^{*o*} and 359^{*o*} are averaged, the regular average would not give a satisfactory result. However, by converting the angles to complex numbers with unit length, one avoids this problem. Suppose we have *n* wind direction measurements $\vec{a} = (a_1, ..., a_n)$ (in radians). We can then define

$$C = \sum_{j=1}^{n} \cos(a_j)$$
 and $S = \sum_{j=1}^{n} \sin(a_j)$,

which are just the sums of projections on respectively the real and imaginary axis of the complex numbers $e^{ia_j} = \cos a_j + i \sin a_j$. When adding complex numbers, one does not suffer from the discontinuity that angles suffer from. Using simple trigonometric formulae, one can compute the phase of the summed complex numbers and hence

$$a_{\rm avg} = \arctan 2 \left(\frac{\bar{S}}{\bar{C}} \right).$$

where an overbar in the variable name denotes that the given value has been divided by the number of data *n*. Note: When computing this value with computational software, one should be aware of the differences between arctan and arctan2.

Furthermore, these summations give rise to a mean resultant length

$$\bar{R} = \sqrt{\bar{C}^2 + \bar{S}^2},$$

which is a measure for how concentrated the data is. Note that $\bar{R} \in [0, 1]$ since the vectors are unit vectors. \bar{R} will be close to 1 if the angles are packed together, whereas it will be close to 0 if they are widely dispersed. [3, p. 15]

2.1.2 Computing the standard deviation

The standard deviation also suffers from the discontinuity in the angles. If the same example is taken, two angles of 1° and 359° respectively, the angles are only 2° apart. However, when computing the regular standard deviation metric, the difference |359 - 1| is enormous. One can also define an analogue for circular data of the standard deviation. This can be achieved by transforming the circular variance $V \equiv 1 - \bar{R}$. The circular standard deviation σ is then given by

$$\sigma = \sqrt{-2\log\left(1-V\right)} = \sqrt{-2\log\bar{R}},$$

where log denotes the natural logarithm with base *e*. This can be approximated (for small *V*) by a first order Taylor expansion that has been given in Wiel Wauben's report [6]

$$\sigma \approx \sqrt{2\frac{n}{n-1}\left(1-\sqrt{\bar{C}^2+\bar{S}^2}\right)}.$$

However, this approximation is not used here in this report. This measure of standard deviation does not suffer from the problem that the angles have a discontinuity. Furthermore, the circular and regular standard deviations are equal when the regular standard deviation behaves well (numerical differences of 180 degrees or less). [3, p. 17-19]

2.1.3 Directional interpolation

The KNW-atlas offers data computed at certain heights above sea level, e.g. 40 m and 60 m. However, measured data may not coincide with these heights. A suitable approach to compute wind speeds that can be compared is to linearly interpolate between the two heights $h_1 \le h_2$ at which the KNW-atlas is given, to the measurement height h by computing

$$WS_h \approx \frac{h_2 - h}{h_2 - h_1} WS_1 + \frac{h - h_1}{h_2 - h_1} WS_2.$$

Luckily, this is straightforward for the directions as well if one grasps the concept of projection on the real and imaginary axes explained above. The formula to compute this will include weights and therefore:

WR_h
$$\approx \arctan \left(\frac{\frac{h_2 - h_1}{h_2 - h_1} \sin WR_1 + \frac{h - h_1}{h_2 - h_1} \sin WR_2}{\frac{h_2 - h_1}{h_2 - h_1} \cos WR_1 + \frac{h - h_1}{h_2 - h_1} \cos WR_2} \right)$$

where we need to take into account that the value computed is "placed back" into the proper interval by means of a modulus operation. That is, the directions in [0,360) are equivalent to the directions in [360,720). A wind direction of 370 degrees in the first interval is equivalent to a wind direction of 10 degrees the latter interval.

2.2 Wessels' corrections

When a fluid flows around an object, one can expect the flow pattern to be distorted. The flow around such an object can be exactly solved for simple cases. In this report, the flow around a vent stack is studied. The vent stack is approximated by a perfect cylinder in order to derive correction factors at every point in space. [7] will be followed closely and information will be added or left out whenever appropriate.



Figure 2: A wind-measuring device is placed at point *P*. The point *P* is defined by the clockwise increasing angle α it makes with the incoming wind which is illustrated by the red arrow. Furthermore, the distance to the origin is r/R where the wind is distorted by a cylinder with radius *R*.

The flow around a cylinder can be described by a superposition term of $u \cdot x \cdot \frac{R^2}{r^2}$ on the main flow potential $u \cdot x$ resulting in:

$$\phi = u \cdot x \left(1 + \frac{R^2}{r^2} \right),\tag{1}$$

where *R* is the radius of the cylinder as shown in Fig. 2 and *u* the scalar wind velocity. Taking the derivative of this potential now yields the respective *x*- and *y* components of the horizontal wind speed, i.e.: (See Appendix A for an elaboration.)

$$u_x = \frac{\partial \phi}{\partial x} = u \left(1 - \frac{R^2}{r^2} \cos 2\alpha \right) \tag{2}$$

$$u_y = \frac{\partial \phi}{\partial y} = u \frac{R^2}{r^2} \sin 2\alpha.$$
(3)

However, we are interested in the relative error of the length of the velocity vector, which is given by

$$\frac{\Delta u}{u} = \sqrt{1 - 2\frac{R^2}{r^2}\cos 2\alpha} + \frac{R^4}{r^4} - 1,$$
(4)

and the angular deviation in the flow direction

$$\Delta\delta = \arctan\left(\frac{\sin 2\alpha}{r^2/R^2 - \cos 2\alpha}\right).$$
(5)

Please note that a measurement of the wind direction δ_{meas} is defined as

$$\delta_{\text{meas}} = \delta + \underbrace{\Delta \delta}_{\text{from Wessels}}, \tag{6}$$

where δ is the true wind direction. Therefore, the deviation needs to be subtracted from the measured value. For the multiplicative correction factor of the wind speed, a similar statement holds. The value computed by Wessels' formula gives an alteration of the true wind speed by the presence of the cylinder, i.e.:

$$u_{\text{meas}} = u \underbrace{\left(1 + \frac{\Delta u}{u}\right)}_{\text{from Wessels}},\tag{7}$$

such that a value of 0.9 means that the measurement will have a 10 percent lower value than the "true" wind speed which would be measured if the cylinder was absent. A more appropriate name for Wessels' correction formulae would be Wessels' distortion formulae.

The final destination hasn't been reached yet. Till this point, the wake (Dutch: zog) has been disregarded behind the cylinder. In the wake, flow can behave very differently compared to other areas around the cylinder, e.g. flow in the reverse direction. Therefore, wind vanes and anemometers measure a flow in the wake that is entirely different from the undisturbed flow.

One can describe the wake by superposition of a dipole source at the origin and sink at x = d, where their respective source strengths are denoted by s_1 and s_2 . Then, the complex potential is

$$\phi + i\psi = u\left(z + \frac{s_1}{\pi}\ln z - \frac{s_2}{\pi}\ln(z - d)\right). \tag{8}$$

Thereafter, the velocity potential is the real part where *z* has been replaced by its complex representation $z = r \exp[i(\pi - \alpha)]$, such that

$$\phi = u \left[x + \frac{s_1}{\pi} \ln r - \frac{s_2}{2\pi} \ln \left\{ (r \cos \alpha + d)^2 + r^2 \sin^2 \alpha \right\} \right], \tag{9}$$

and the relative velocity components are

$$\frac{u_x}{u} = 1 - \frac{1}{\pi} \left(\frac{s_1}{r} \cos \alpha - s_2 \frac{r \cos \alpha + d}{r^2 + 2dr \cos \alpha + d^2} \right),$$
(10)

$$\frac{u_y}{u} = -\frac{1}{\pi} \left(\frac{s_1}{r} \sin \alpha - s_2 \frac{r \sin \alpha}{r^2 + 2dr \cos \alpha + d^2} \right). \tag{11}$$

For this case, the values d = R/2, $s_1 = 4R$ and $s_2 = 3R$ have been chosen. Furthermore, to avoid the area where the wake effects are much stronger than this theory suggests, only corrections for $|\alpha| < 120^{\circ}$ are considered.

The values of both correction factors have been plotted in Fig. 3. The values for the wind direction are with respect to the clockwise increasing angle α (wind veering) as shown in Fig. 2. Therefore, negative values denote a counterclockwise deviation.



(a) Wind speed change in percentages

(b) Wind direction change in degrees

Figure 3: The values of Wessels' corrections showing the change in wind speed and direction due to the presence of a cylinder. The spatial positions are given in terms of r/R. The hatched area is not used due to stronger than modeled wake effects.

3 Determining parameters

In [4], the wind speed of three different measurement sites has been compared with the predicted KNWatlas wind speed. However, this has not been done for the wind direction. A comparison and further analysis of the directional distribution of the biases of these two wind speeds resulted in the selection of the hours in {3,4,15,16,17,22} UTC. Here a threshold of ≤ 0.2 m/s was used. However, it may be the case that not all of these hours have a low bias when considering the wind direction.

Therefore, an analysis of the sites Meteomast IJmuiden (MMIJ) and Offshore Windpark Egmond aan Zee (OWEZ) has been conducted. The measurements at these two sites are considered to be of good quality. For each hour of the day the bias between the KNW-atlas and the measured data has been determined. For MMIJ, the whole period of 2012 has been used. For OWEZ, data was supplied starting 01-07-2005 and ending 30-06-2006. This data does not include 01-01-2006. At both measurement sites, two heights have been analyzed. For MMIJ these were 58 m and 86 m. For OWEZ these were 70 m and 116 m.

It is worth noting that at the 86 m measurements of MMIJ are in fact from anemometers located at 85 m and wind vanes located at 87 m. In this research, both were treated as if they were situated at a height of 86 m. This is unlikely to have a significant effect on the results. However one analysis where some small effect might be felt is when determining if the wind speed is sufficient to ensure that the wind vane works properly. In this research a cut-in speed of 2 m/s for the wind vanes has been used. Whether the KNW-atlas data (86 m) or the measured values were used to check for this criterion depends on the purpose of the analysis.

3.1 Hours at which the KNW-atlas is accurate

When selecting the hours that are considered accurate, a maximum acceptable level for the differences needs to be established. Firstly, taking a look at the equipment that is used to determine the wind direction, it can already be seen that some 2.5 - 3.0 degrees of uncertainty is present. Additionally, the World Meteorologic Organization (WMO) dictates that wind direction measurements should be measured with an accuracy of 5 degrees. [1]

Using a threshold of $\leq 0.2 \text{ m/s}$ for the wind speed does not yield enough hours where both the wind direction and wind speed of the KNW-atlas and measurements are sufficiently close together, only the hours in {15, 16, 17} UTC. Therefore, the threshold has been doubled to 0.4 m/s for the wind speed. Further investigation reveals a level of 7 degrees for the wind direction. Taking a level of 6 degrees would leave us with 2 hours less and going to 9 degrees would only increase the number of hours by 1, therefore using 7 degrees would seem to be an optimal choice. Fig. 4 shows for each individual hour of the day the bias in the measured wind direction w.r.t. the KNW-atlas wind direction. All four measurements (from two sites at two heights) should be below our thresholds. The hours in {2,9,11,13,14,15,16,17} have been used throughout this report, if not mentioned otherwise.



Figure 4: The bias in the wind direction of measurements w.r.t. the KNW-atlas. The biases are all made positive for the purpose of presentation. The 7 degree selection threshold is also shown.

3.2 Averaging time

In order to compute the averages which compare best to the hourly data (01:00, 02:00 UTC, etc.) provided by the KNW-atlas, an averaging time needs to be chosen such that the fluctuations of the measurements and the KNW-atlas are comparable and/or the differences minimal. The measure which has been minimized to find an optimal averaging time is the standard deviation of the differences as described in Ch. 2.1.2. Something similar has been done in [4], but solely for the wind speed, looking at extremes with an average of 28 ms^{-1} . One could argue that to compare well to these extremes a smaller averaging time should be used for the measurements than for more common lower wind speeds. This is logical when one considers that the KNW-atlas data are instantaneous spatial averages of volumes of space of $2, 5 \times 2, 5$ km and a few tens of meters tall, referred to as a gridbox. This spatial averaging smooths the variations in the wind. In a similar way temporal averaging of measurements smooths the variations. A shorter temporal averaging time should give an optimal match to the KNW-atlas data at high wind speeds and a longer time at lower speeds. At high wind speeds it takes the air less time than at low wind speeds to cover a distance comparable to the dimensions of the KNW-atlas' gridbox. An averaging time of 60 minutes was found. In this research averaging times have been tested from 10 to 1000 minutes since we are less focused on extremes. Results are presented for averaging times up till 2 hours.

In Fig. 5 the measurements of November 1st 2012 at MMIJ have been plotted. This is done to illustrate that the bias will never go to zero as the averaging time is varied. It can be seen that for the wind speed the KNW-atlas at times has large differences compared to the measurements. The KNW variations are most similar to the 10 minute measurements but the timing of the variations is incorrect. The standard deviation of the differences will decrease when a longer averaging period is used which smooths the 10 minute variations in the measurements. That is why one can see in Fig. 5 that the longer averaging period follows the KNW-atlas data more closely, with fewer and smaller errors.



Figure 5: Measurements with different averaging times, taken November 1st 2012 at the 58 m height of the MMIJ and the hourly KNW-atlas data. On the left wind speed (WS) and on the right wind direction (WR).

Selecting the right averaging time is a bit of a struggle. The parameter space as a whole can't be bruteforced as it needs to be taken into account that not every combination of hours of the day can be selected. Earlier research as mentioned above, concluded that the optimal wind speed averaging time for extremes is 60 minutes. In this case, however, it is necessary to find a trade-off picking the best averaging time to minimize wind speed bias, wind speed standard deviation, wind direction bias and wind direction standard deviation.

In Fig. 7 the standard deviation of the wind direction differences between the measurements and the KNW-atlas data have been plotted. For increasing averaging times, the standard deviation decreases and then increases. This is to be expected: smoothing out the variations in the measurements improves the comparison at first, but too much smoothing removes the variations that KNW most often models correctly (correct value, at the correct time). One can observe a small jump just before an averaging time of 400 minutes in all the sets. Fig. 6 shows that the jump can also be seen in 2 of the hours of the day selected for the comparisons. The left plot shows the second hour of the day.

This hour is picked as it furthest away from any of the other hours selected as being good hours. In this manner there is no overlap with other selected hours. At a height of 58 m, the same phenomena is

observed as searched for. Hour 15 was analyzed in the right plot because there are several hours close to it but a small jump around the 400 minutes mark is observed here too. The position of the minimum is, as observed in Fig. 7, somewhere around 400 - 600 minutes. No explanation for the jump at 400 minutes has been found but since it is small no further attention is paid to it.



Figure 6: Standard deviation of the differences in the wind direction for two hours of the day.

In Fig. 8 the standard deviation of the differences in the wind speed has been plotted: on the left for a few individual hours and on the right for all selected hours together. Computing the minimum that is present in these curves and averaging them gives an estimate of the optimal averaging time. Taking the mean of the minima results in an average of 449 minutes for the wind speed (Fig. 8b), and an average of 484 minutes for the wind direction. These two estimates result in a choice for an averaging time of 440 minutes and 480 minutes respectively. The fact that the minima are quite broad leaves us with some room to choose from and 460 minutes has been chosen to be applied uniformly for both wind speed and direction.

As 10-minute average measurements were available, only averaging times multiples of 20 minutes are considered (10 minutes on either side of the KNW-atlas data time stamp). All wind speeds above 2 ms^{-1} are considered at the hours selected in Ch. 3.1. Due to higher averaging times being computationally more demanding, fewer averaging times have been plotted in the range 400 - 1000 minutes than in 10 - 400 minutes.

It can be seen in Fig. 7 that most wind speed bias (measurements minus KNW) plots militate in favour of longer averaging times but that the wind direction bias plots are in favour of short averaging times. The wind direction results are as one would expect because a longer averaging period for measurements weakens the correlation with the KNW value for a given hour. In App. B the bias for various wind speed bins is presented and this shows that the unexpected result for wind speed originates in the bin for extremely high wind speeds. This can be explained by the fact that high KNW wind speeds have lower speeds before and after those hours and that lengthening the averaging period of the measurements must lower the measured average.

All of the standard deviation plots show some sort of parabolic behavior and show minima, which are the optimal averaging times. Values of approximately 6 to 8 hours are seen, which is long compared to the hourly output of weather forecasting models as used to make the KNW-atlas. However, this does agree with the statements the KNMI scatterometer group makes about the resolution of weather models: the real resolution of numerical weather forecasting models is 5-7 times the size of the gridbox. [5, p. 47]

As the former research was conducted for extreme wind speeds, one might think that the optimal averaging time is wind speed dependent. To check this the MMIJ and OWEZ measurements have been divided into four wind speed bins that have approximately equal amounts of measurements. These intervals are $2 - 7 \text{ ms}^{-1}$, $7 - 9 \text{ ms}^{-1}$, $9 - 14 \text{ ms}^{-1}$ and $> 14 \text{ ms}^{-1}$. Data is placed in a certain bin if the KNW-atlas wind speed at the time of the data falls in that bin. The results are shown in Fig. 9 where all four site-height combinations have been grouped together. It can be seen that indeed, for higher wind speeds the minima of the standard deviation of the differences move towards lower averaging times



Figure 7: The bias (measurements minus KNW) of wind speed and wind direction between measurements and KNW-atlas and the standard deviation of their differences for four measurement sets, for different averaging times.



Figure 8: Standard deviation of the differences in the wind speed.

for both wind speed and wind direction. Separate plots for each site-height combination are shown in Appendix B.



(b) Wind direction

Figure 9: Standard deviation of the differences where the data have been divided into four wind speed bins. A vertical line has been added to indicate the chosen averaging time of 460 minutes which works well for all but the highest wind speeds.

The standard deviation of the KNW-atlas data should ideally be comparable to the standard deviation of the measurements. The standard deviation of the KNW-atlas is a constant value for different averaging times of the measurements. In Fig. 10 the difference of the KNW-atlas data standard deviation and the measurement standard deviation is plotted for a range of averaging times. The general trend in these plots is that the measured standard deviation increases as the averaging time decreases and approaches the relatively high standard deviation of the KNW-atlas data. This means that the KNW-atlas displays variations that are comparable to those seen in measurements with an averaging time of a few minutes for wind speed and tens of minutes for wind direction. However, it has been shown earlier in this chapter that these high frequency variations in the KNW-atlas data do not occur at the right time and

place and that lower frequency variations, comparable to measurements averaged over several hours, is what the KNW-atlas data best represent.



(a) Standard deviation of the wind speed at MMIJ





(b) Standard deviation of the wind direction at MMIJ



(c) Standard deviation of the wind speed at MMIJ

(d) Standard deviation of the wind direction at OWEZ

Figure 10: The standard deviation of the measurements in wind speed (left) and wind direction (right) at MMIJ (top) and OWEZ (bottom) compared to the standard deviation of the KNW-atlas data.

Despite the conclusion, the averaging time has been chosen to be 60 minutes and not 460 minutes because 460 minutes is not commonly used in meteorology. Hourly measurements and weather forecasting model output are standard in meteorology so the remaining analyses will be based on hourly averages.

4 Data handling

4.1 What measurements are used to compare to KNW?



Figure 11: A schematic illustration of the measurements used per KNW-data point for the AWG1-site.

The KNW-atlas data are presented every hour. For information on what this hourly value represents (what kind of temporal averaging of point measurements is most appropriate), we refer to Ch. 3.2. In order to compare measurements with the KNW-data and determine the bias and standard deviation of the differences, a suitable average of these measurements has to be taken. The measurements closest in time to the time stamp of the KNW-atlas data point are used. Each measurement tells us something about the time-interval prior to the reported measurement-time. So, if *m* measurements are used, the closest measurements in the range m/2 - 1 before the time stamp up to and including m/2 after the time stamp are used. This process called aggregation is illustrated in Fig. 11.

For example, the AWG1-site generates 1 minute averages every minute. In order to compute an average which can be compared to the hourly KNW-atlas data, the 29 measurements prior to the KNW-atlas time stamp, the one with that time and the 30 measurements after the KNW-data time are used.

4.2 Identifying measurements made in the wake

Wind-measuring devices are in general mounted on some sort of support structure. The presence of this structure has an effect on the air flow in the neighborhood and the effect is greatest in the wake downwind of the object. To determine whether or not a wind measurement device is in the wake of an object is problematic, as the measurement device then produces unreliable measurements. Hence, the values of the KNW-data are used initially for the wind direction to determine whether or not the AWG1 wind measurement is in the wake of the vent stack. Once more is known of the reliability of the measurements they are interpreted in such a way as to reveal if the measurements are in the wake or not.

4.3 Directional input for Wessels' corrections



Figure 12: Schematic top view of the AWG1 measurement site. For both sets, $r/R \approx 3.671$. It should be noted that the angles depicted are for the anemometers. The wind vanes have slightly different angles because they are mounted a short distance from the anemometers to avoid interference.

In order to compute the Wessels' corrections, there needs to be some input wind direction. As one can not be sure which one of the two available measurements (see Fig. 12) is trustworthy, some intelligent scheme in order to pick a best value of the wind direction which is best for every measurement has to be thought of. Of course, "best" has to be defined. This is done by taking the value of the measurements and comparing them to the KNW-atlas data.

In Fig. 13 a set of measurements and KNW-atlas data are plotted for a randomly chosen 5-day period. Please note that the peaks in Fig. 13b on November 5th are present due to the fact that there is a discontinuity in the wind direction at 360°. Also note the high variance in the measurements for measurement



(b) Wind direction

Figure 13: The wind speed and wind direction measured in a randomly chosen week. The reference KNW-atlas data is also plotted.

set 2 around November 2nd in both figures (upper plot of wind speed, lower plot of wind direction). It can be seen that both the KNW-atlas and the other measurement set are in better agreement and that the KNW wind direction is somewhat higher than 210° , so apparently the wind comes from such a direction that the second measurement is in the wake area of the vent stack as it is located at an angle of 70° and the wake should be centered somewhat higher than 30° ($210^{\circ} - 180^{\circ}$).

In order to check the directional dependence of the trustworthiness of the measurements, [0, 360) is divided into bins of 10° centered around every whole 10 degrees (0, 10, 20 etc.). The measurements are distributed into the bins according to the KNW-atlas value closest in time to the measurement time. The measurements are aggregated according to the procedure described in Ch. 4.1. Thereafter, they are compared to the KNW-atlas by analyzing their differences on the selected hours {2,9,11,13,14,15,16,17}, as described in Ch. 3.1.

In order to decide which of the two AWG1 measurements to use, some criteria need to be defined that are deduced from how "good" measurements compare to KNW-data. If similar values for the AWG1 measurements are acquired, these measurements are also considered "good". The MMIJ and OWEZ are considered to be good. The measurements have been divided into two wind speed bins, such that extremes can be treated separately. The other bin (0-14 m/s) covers 7/8th of the measurements and has more than 10 data pairs in each bin so the analysis will focus on these values.

In Fig. 14-17 (left MMIJ, right OWEZ), the differences (defined as $WS_{meas} - WS_{KNW}$ and $WR_{meas} - WR_{KNW}$) are plotted as average biases, as well as their standard deviations. By inspecting these plots, values of these parameters can be determined which we can later use to sort good measurements from bad.

In Fig. 14, it is observed that the wind speed bin biases of the 0-14 m/s group are almost always smaller than 0.8 ms^{-1} . Similarly, in Fig. 15 a worst case value of 2.2 ms^{-1} for the standard deviation of the wind speed differences is observed.



Figure 14: The biases in the wind speed for different directions at good measurement locations.

For the wind direction a similar analysis can be conducted and in Fig. 16 it can be seen that the bias of a good measurement should be smaller than approximately 8 degrees. Furthermore, in Fig. 17 a maximum standard deviation of approximately 30 degrees is found.

4.3.1 Analysis of AWG1

Now that values for the biases and standard deviations which define good measurements have been determined, an analysis of the "bad" AWG1-measurements from the year 2012 is conducted to determine what the input wind direction for the Wessels' corrections should be. Firstly, some general aspects of these measurements and the plots used to describe them are discussed.

In Fig. 18-20, two measurement sets are plotted. One set with an anemometer at 70 degrees and a wind vane at 58.5 degrees with respect to north, denoted by the red crosses. (Set 2 in Fig. 12) Another set, which is denoted by the blue dots, has an anemometer at 245 degrees and a wind vane at 233.5 degrees. (Set 1 in Fig. 12) One can also see two areas of large decrease in wind speed in Fig. 18b, one for each of the two measurement sets. These are where the vent stack wake affects the anemometer and they are denoted by the blue (set 1 in Fig. 12 is affected) and red (set 1 in Fig. 12 is affected) areas.



Figure 15: The standard deviation of the wind speed differences for different directions at good measurement locations.



Figure 16: The biases in the wind direction for different directions at good measurement locations.



Figure 17: The standard deviation of the wind direction differences for different directions at good measurement locations.

Generally speaking, blue measurements in the blue area are not trusted and similarly in the red area red measurements are not trusted. Interesting to see is that also when the anemometer is not in the wake, but on the opposite side, pointing approximately in the direction the wind is coming from, the wind speed is also lower than the KNW wind speed (Fig. 19a). This is due to the fact that the air is obstructed by the vent stack.



(a) The occurrence of different wind directions

(b) The average wind speed for different wind directions

Figure 18: Some general information about the AWG1 measurements.



(a) Bias in the wind speed for different wind directions.



Figure 19: The bias and standard deviation of the wind speed differences for different wind directions at AWG1.

In order to determine what wind direction to use as input for Wessels' corrections, the first quality criterion that needs to be met (the wind direction bias should be smaller than 8 degrees) is applied in Fig. 20a. Furthermore, measurements that have a background-color similar to the measurement should not be considered because they are in the wake. Please also note the absence of some data, e.g. the blue dots of 30 - 60 degrees in Fig. 20. These values were too high and made the plot less clear. The criteria that have been derived in Ch. 4.3 are also plotted as horizontal lines.

Starting out in the blue wake area, where only measurements from set 2 are trusted, it can be seen that in bins 10, 20 and 60 set 2 can be used. For the leftover bins (30 - 50 and 70 - 100) the KNW-atlas data is used. Moving on, the average of the two measurements can be used (110 - 180). From bin 190 and on it is seen that set 1 is in the wake of the cylinder and the measurements of set 2 do not meet the quality criteria. Therefore, the KNW-atlas data is used for bins 190 - 260. Assuming that the wake is somewhat smaller than depicted here, it is chosen to use the average of the two measurements in bin 270 - 320. This is justified by the fact that the standard deviations of the differences of the two wind vanes (w.r.t. KNW-atlas data) are almost equal for these bins. Finishing off with the last four bins, the measurements of set 1 can be used for bins 330 - 350, but not for bin 0, where the KNW-atlas data is used.



(a) Bias in the wind direction

(b) Standard deviation in the wind direction

Figure 20: The bias and standard deviation in the wind direction for different directions at AWG1.

$$WR_{init} = \begin{cases} WR_{KNW} & -5^{\circ} \leq WR_{KNW} < 5^{\circ} \text{ or } 25^{\circ} \leq WR_{KNW} < 55^{\circ} \text{ or } \\ & 65^{\circ} \leq WR_{KNW} < 105^{\circ} \text{ or } 185^{\circ} \leq WR_{KNW} < 265^{\circ} \\ WR_{2} & 5^{\circ} \leq WR_{KNW} < 25^{\circ} \text{ or } 55^{\circ} \leq WR_{KNW} < 65^{\circ} \\ \frac{1}{2}(WR_{1} + WR_{2}) & 105^{\circ} \leq WR_{KNW} < 185^{\circ} \text{ or } 265^{\circ} \leq WR_{KNW} < 325^{\circ} \\ WR_{1} & 325^{\circ} \leq WR_{KNW} < 355^{\circ} \end{cases}$$
(12)

Please note that one needs a certain number of measurements for every KNW-atlas time t_{KNW} , as illustrated in Fig. 11. Therefore, the number of values in the vector representation of WR_{init} is equal to the number of the measurements. Intervals are filled with either a copy of the nearest KNW-atlas value or, if measurements are used, the respective measurement at that time.

5 Code details

In this section the requirements to run the code successfully in the correct manner are explained such that the results of this report can be reproduced. As the choice of what to plot is subjective, how to plot the results is mainly omitted.

5.1 Required data

KNW-atlas data This .CSV-file should have the name data_site\KNW-1.0_site.csv where "site" should be replaced with the respective site (e.g. "AWG1"). This .CSV-file is downloaded from the KNMI-datacentre (October 2017: https://data.knmi.nl/datasets/KNW-CSV-TS/1.0). One should select the grid point of the KNW-atlas nearest to the site (see Table 1). Furthermore, the relevant time period should be selected as the KNW-atlas contains data for 35 years. Once this has been done, the read_data.py Python script should be run in "KNW" mode to produce data at the correct height, ready for further analysis.

Site	E-W	N-S
AWG1	119	140
D15	039	175
F16	067	166
J6	040	152
K14	058	128
L9	093	144

Table 1: The KNW-atlas grid points closest to the platform locations.

Measured data For the years 2012 and 2013 .log-files for each location exist. read_data.py can handle this format. One has to write a script (see read_data.py for examples) to deal with files with other formats correctly. It is common practice to record measurements in non-standard formats. However, uniform input is required for our code.

How to get uniform input? This is facilitated by using the read_data.py Python script. When introducing a new measurement site, one just has to create a new elif statement checking for the file containing the measurements. Thereafter, import the data (wind speed goes in WS_meas, wind direction goes in WR_meas and the time goes in t in the format numpy.datetime64. After setting these variables, read_data.py automatically saves the file. The file containing the measurements should be in the same folder as the KNW-atlas data.

5.2 Files

These are brief descriptions of the files used in evaluating measurements.

- **libFuncs.py** Includes all functions used in the scripts. It has to be imported in every script written by including the line import libFuncs in the Python-script. Note that all functions have a docstring with information about the function, which can be accessed after importing the functions. E.g. by typing libFuncs.aggregate? in an iPython-notebook to get information about the function aggregate().
- **read_data.py** Converts any given measurement file to the convention used for the Python-scripts used in this project. Wind speed goes into the variable WS_meas, wind direction into WR_meas and time into t.
- **aggregate_measurements.py** This is used to compare uncorrected measurements to KNW-atlas times. These measurements have to be aggregated, which is done by this Python-script.
- **calculate_wessels_input.py** Calculates a file of wind directions suitable as input to Wessels' correction formulae.
- **apply_wessels.py** Applies Wessels' corrections to the given measurements, it requires the file created in calculate_wessels_input.py.
- **evaluate_awg1.py** The corrected measurements are compared to KNW-data. In this file, two measurement sets can be combined to one optimal series of measurements. Results can also be plotted by using this script file.

5.3 Running the codes

In this section, the proper order of running the Python-scripts is documented. Commands to be executed in the terminal are started by a dollar sign \$. In order to apply Wessels' corrections to measurements, in this case from AWG1, the Python-scripts <code>aggregate_measurements.py</code>, <code>apply_wessels.py</code>, <code>calculate_wessels_input.py</code>, <code>evaluate_awg1.py</code>, <code>libFuncs.py</code> and <code>read_data.py</code> should be present in some directory. There should also be a folder called <code>data_AWG1</code> which contains the .logfiles with the measurements and the KNW-atlas data as .csv-file.

- 1. Open a terminal and navigate to the directory the Python-files are located by using the cd command.
- 2. Open read_data.py in a text-editor such as Spyder or VI, set KNW = True and save the file.
- 3. \$ python3 read_data.py
- 4. Set KNW = False and run the previous shell command in step 3 twice, once for every measurement set. As both of the measurement sets are to be processed, set measurementSet = 1 in read_data.py, save and run the command. Thereafter, repeat with measurementSet = 2.
- 5. It is now a sensible idea to run aggregate_measurements.py as this process takes a while to complete. As before, change the measurementSet variable in aggregate_measurements.py, save and run:
- 6. \$ python3 aggregate_measurements.py &

Please note the ampersand at the end of the shell command. Using the ampersand stops the terminal from freezing, such that a second instance of the aggregate_measurements.py-script can be run parallel.

7. Computing the most suitable input wind direction for Wessels' corrections is done by running calculate_wessels_input.py. This is a very straight-forward processing of both measurement sets in one go, again with ampersand as it takes quite some time to complete.

\$ python3 calculate_wessels_input.py &

8. We have now arrived at a point where Wessels' corrections can be applied to the measured data. This process needs to be completed for both measurement sets, so open apply_wessels.py and change measurementSet accordingly. Run the code twice by executing

```
$ python3 apply_wessels.py &
```

9. As a final step, the Wessels corrected measurements are combined by the use of a scheme. An aggregation step can be included in here as well in order to compare the results to the KNW-atlas data. This is done in evaluate_awgl.py, where in addition to that plots are created.

6 Proof of principle: Code

In order to validate if the code works according to our expectations, an artificial data-set has been generated of which the parameters are known. In this manner, it can be checked if the code functions properly.

Over a time of one day, it is assumed that a constant wind speed of 10 m/s is present from a direction of 260 degrees. It is also assumed that the KNW-atlas offers a perfect recording of these values.



Figure 21: The setup as used in the proof of principle study, there are two measurement sites, located at r/R = 4 and with an angle of 0 degrees and 180 degrees w.r.t. north respectively. The wind is coming in at an angle of 260 degrees w.r.t. north.

The wind is measured at two measurement sites, which are located at r/R = 4 where R is the radius of the vent stack. Measurement site 1 and site 2 have an angle of 0 degrees and 180 degrees w.r.t. north respectively, as depicted in Fig. 21. Please note that the nonphysical assumption that anemometer and wind vane are in exactly the same position is also used for convenience.

We wish to validate the code, not Wessels' corrections. Therefore, the Wessels correction formulae as mentioned in Eq. 10 and Eq. 11 have been used to determine which wind speed and wind direction would be measured at site 1 and 2 if Wessels' corrections work perfectly. The wind speeds for measurement site 1 and 2 have been increased by a factor 1.046 and 1.016 respectively. The wind direction for set 1 has been reduced by 3.93 degrees and for set 2 it has been increased by 5.16 degrees. Furthermore, some noise has been added as it would be present in real data too. The input signals can be seen in Fig. 22.



Figure 22: The KNW and artificial uncorrected measurement values over the course of one day.

In order to compare the measurements to KNW-data, the code includes an aggregation step as described in Ch. 4.1, which yields the signals as shown in Fig. 23. The aggregated measurements are made up out of 60 data points as described in Ch. 4.1.

The code applies Wessels' corrections to each single measurement value of every measurement set. The result of this can be seen in Fig. 24.



Figure 23: The uncorrected and aggregated artificial measurement and KNW values over the course of one day.



Figure 24: The corrected artificial measurement values over the course of one day.

In the last step, the corrected measurements are aggregated in order to compare to the KNW-atlas values. It can be seen in Fig. 25 that applying the corrections has resulted in measurements with a bias of zero compared to the KNW values. This is what we expect if the code works properly.



Figure 25: The corrected and aggregated artificial measurement values over the course of one day compared to the KNW data.

7 Results and conclusions

7.1 Optimizing combining the corrected measurements

We wish to find a scheme in order to minimize the biases. For this case, the input wind direction for Wessels' correction formulae was taken as described by Eq. 12. The results are shown in Fig. 26 where corrected and uncorrected measurements are binned according to wind directions determined with Eq. 12 and the bias w.r.t. KNW-atlas data is presented. The bias of measurements made in the wake of the vent stack are not presented. The wake of instrument set 1 was considered to be 30 - 90 degrees and for set 2 200 - 260 degrees.



Figure 26: The biases of AWG1-measurements before and after Wessels' correction formulae have been applied. Whenever both measurements were available, i.e. both measurement sets were not in the wake of the vent stack, an average of the two biases is also supplied.

Looking in Fig. 26 at the wind speed of measurement set 1, out of 36 bins of 10 degrees there are 7 bins in which Wessels' correction formulae deteriorate the bias: {20, 100, 110, 180, 190, 320, 330}. For measurement set 2 there are 5 such bins: {120, 130, 140, 270, 350}. It is interesting to see what happens if the directions which have two measurements, i.e. where both measurement sets are not in the wake of the vent stack, the biases are averaged. (See Fig. 26b and Fig. 26d)

This method results in 5 directions where the speeds are not improved by Wessels' formulae, of which one is newly introduced: {10, 100, 120, 130, 350}. By averaging the two measurement sets, 7 bad corrections are removed.

Now, if the wind direction in Fig. 26c is considered, for measurement set 1 and 2 the "bad" directions {0, 10, 20, 60, 100, 110, 120, 240, 250, 280, 340, 350} and {50, 100, 270, 280, 290, 300, 310, 320} are found respectively. Following the same procedure as above for the wind speed the averaged bias of the directions in the set of directions {60, 100, 110, 120, 130, 270, 280, 290, 300, 310, 320} are still increased instead of the desired decrease. (See Fig. 26d)

Analyzing these results, a scheme of which combination of measurements should be used to optimize

the combined series of corrected measurements when the wind has a certain direction was established:

$$Measurement = \begin{cases} Set 1 & 125 \le WR < 135 \text{ or } 195 \le WR < 325 \\ Set 2 & 25 \le WR < 95 \text{ or } 105 \le WR < 125 \\ AVG & 0 \le WR < 25 \text{ or } 95 \le WR < 105 \text{ or } 135 \le WR < 195 \text{ or } \\ 325 \le WR < 360 \end{cases}$$
(13)

7.2 Measured input for Wessels' correction formulae

The scheme in Eq. 12 tells us which combination of wind directions is the best to use as input wind direction for Wessels' correction formulae for different wind directions. However, Eq. 12 is like an ouroboros, it bites its own tail. Accurate wind direction data are required in order to determine what wind direction should be used as input for Wessels' correction formulae.

The accurate wind directions for input to Eq. 12 are provided for half of the wind directions by the KNW-atlas. The KNW-atlas data is not available to help correct operational measurements in near real time. For this application an optimum combination of the uncorrected wind direction measurements will have to be found.



Figure 27: The wind speed and direction plotted for a single day of measurements at the AWG1-site. It can be seen that at approximately 18 UTC, instrument set 2 moves into the wake of the vent stack.



Figure 28: The wind speed (left) and direction (right) standard deviations of the 10 minutes preceding the time stamp and updated every minute. The wake of the vent stack can be clearly observed as the vane 2 wind direction standard deviation increases sharply. It can also be seen in the wind speed standard deviation, but less clearly.

In order to determine the most accurate combination of uncorrected wind directions to use, the 1 minute wind speed and direction have been analyzed, as well as the 10 minute wind speed and direction standard deviation. From these measured quantities a reliable indication will be found for situations

where a measurement is affected by the wake of the vent stack and should therefore not be used. As the average wind direction and standard deviation of the wind speed did not turn out to be good discriminators, their results will not be discussed. A (boolean) indicator for the wake which does work well is the one based on the one minute average wind speed which is defined as

$$I_{\rm WS} = \begin{cases} (WS_{\rm min}/WS_{\rm max} < 0.8) & WS_{\rm max} > 5 \text{ ms}^{-1} \\ (WS_{\rm max} - WS_{\rm min} > 0.8 \text{ ms}^{-1}) & WS_{\rm max} \le 5 \text{ ms}^{-1} \end{cases}$$
(14)

where the larger of the two wind speeds, WS_1 and WS_2 , is WS_{max} and the other is WS_{min} . The reason to for using the ratio of wind speeds rather than the difference is that higher wind speeds show larger differences. The reason for using two cases is that for lower wind speeds small random differences have a relatively big influence on the ratio.



Figure 29: The ratio of the minimum to maximum wind speed (left) and the difference (right). (maximum minus minimum)

It can be seen from Fig. 27 and Fig. 28 that whenever a set of instruments is in the wake (in this case set 2), the wind vane starts to rotate and therefore the standard deviation increases. Furthermore, whenever the two sets are out of the wake, the two standard deviations are almost equal. Therefore, it makes sense to define another (boolean) indicator, this time based on the difference between the standard deviation of the wind vanes (updated every minute):

$$I_{\text{STD, WR}} = (|\sigma_{\text{WR,1}} - \sigma_{\text{WR,2}}| > 5).$$
(15)

The values present in Eq. 14 and Eq. 15 were decided on after a visual inspection of Fig. 28 and Fig. 29. Whenever one or both of the two indicators defined in Eq. 14 and Eq. 15 has a True value, it should be decided which set of measurements is trusted most. This decision can either be based on the standard deviation of the wind direction or the value of the wind speed. Fig. 27 shows that wakes can be distinguished very well by analyzing the average wind speed. However, as seen in Fig. 28, the standard deviation of the wind direction is also a very good discriminator. Because the standard deviation has a 10 minute memory, it has been decided to use the measurements of the instrument set which reports the highest average wind speed as it is known that in the wake the wind speed is severely reduced and this provides information over the same period as the measurements that it selects.

The wind direction measurements of this indicator set are used to substitute for KNW-atlas data in Eq. 12 to decide which combination of wind direction measurements can best be used as input for Wessels' correction formulae.

7.3 Applying Wessels' correction formulae

The scheme in Eq. 12 is used to determine which combination of measurements should be used in order to get the best input wind direction for Wessels' correction formulae with measured inputs decided by indicator I_{WS} . Continuing, Wessels' correction factors are computed as shown in Fig. 3 and applied to the measurements.



Figure 30: The input wind direction for Wessels' correction formulae obtained by applying the indicators and Eq. 12.

It can be seen from Fig. 30 that the wake is completely removed by the use of the indicator functions. The corrections are applied to each individual measurement, but this does not fix the problem of having two measurements which has to be combined to one real measurement.

The scheme of Eq. 13 is applied to optimize the two corrected measurement sets to one signal. Thereafter, the combined time series is compared to the KNW-atlas data to determine how well the correction has performed. This is done for the years 2012 and 2013. The year 2013 is chosen because all of the analyses used to develop and test the method are based on the year 2012 and the verification of the results requires an independent year (2013).

The results (bias w.r.t. KNW-atlas data averaged over 36 wind direction bins) of applying the method described above to the measurements of AWG1 are shown in Table 2. These are 60 1-minute averages, where if there are missing measurements, less samples have been taken. The uncorrected values are checked for the same KNW data time stamps, however some measurements will not be removed from the data as Wessels' correction formulae are not applied to these measurements.

	2012	2013
Uncorrected WR [deg]	9.76	9.20
Corrected WR [deg]	0.75	0.05
Gain [deg]	9.01	9.15
Uncorrected WS [ms ⁻¹]	-1.52	-1.56
Corrected WS [ms ⁻¹]	-0.30	-0.26
Gain [ms ⁻¹]	1.22	1.30

Table 2: The results of applying Wessels' correction formulae to the measurements and combining these afterwards to form a single time series. The corrected and uncorrected values are averages of the biases of the 36 wind direction bins. The "gain" is the amount the average bias has improved by.

The directional dependence of the biases can be seen in Fig. 31. Here, the input (uncorrected measurements of instrument set 1 and 2) has been binned as before with the KNW-atlas wind direction, together with the corrected and combined measurements. It can be seen that the measurements of both 2012 and 2013 exhibit approximately the same behavior. Before correcting, the biases (excluding wakes) are smaller than 2.0 m/s for the wind speed and at most 21 degrees for the wind direction. The corrected values for the wind speed all have a bias of less than 1.3 m/s. For the wind direction, a maximum bias of 13 degrees is observed at 130 degrees near the wake. Despite the decrease in bias, WMO/ICAO standards are still not met. [2, p. 5-7]

Possible explanations for the imperfect corrections are that the measured radius of the vent stack insufficiently describes the physical object causing the wakes. At the AWG1-site, a fenced platform with a hole in it to facilitate people using the ladder is present. This might make the effective radius of the objects causing the wake to be bigger than the vent stack radius.



Figure 31: The directional dependence of the bias w.r.t. KNW-atlas data of the measurements of wind speed and direction (corrected, then combined) for two years. The bias of the two uncorrected measurement sets are also plotted as a reference. The plots have been cut off to exclude more extreme wake biases.

Using an effective radius R_{eff} which is bigger than R will decrease the value of r/R and therefore Wessels' correction factors will be bigger and bring the bias closer to 0. (See Fig. 3) Investigating what an optimal r/R is for each vent stack measurement set-up seems like a sensible thing to do, but is not done in this report due to time constraints.

8 Recommendations

As author's internship only lasted for three months, lots of things that were observed did not receive an in-depth analysis. Some of these recommendations for further research are listed below.

- Wake It has been observed that the wake is smaller than the 120 degrees advised by Wessels and used in this report. A quick analysis yielded a wake size of approximately 80 degrees. The AWG1 measurements should be compared to the KNW-atlas data. In this manner, not only the size but also the location can be determined. Binning of the 1 minute measurements could be done by interpolating between two successive hourly KNW-atlas datapoints. As with the indicators devised in Ch. 7.2, the standard deviation of the wind direction or the wind speed can then be analyzed in detail.
- Averaging time The value of the measurement averaging time that corresponds to the KNW-atlas spatially averaged data. What does the value the KNW-atlas returns every hour actually represent? What kind of variations are captured by the KNW-atlas? Relatively high frequency variations seem to be described (some few minutes). It is possible to use high-frequency measurements of the Cabauw site to compare to the KNW-atlas.
- Effective r/R Because there are more obstacles than just the vent stack, such as a fenced platform, the true radius *R* of the vent stack might not represent what is physically present. Finding an optimal value of *R* which optimizes the corrections should further decrease the bias of the corrected measurements.
- Include 10 minute standard deviation In the current data format produced by read_data.py, the 10 minute standard deviation (of the wind direction) is disregarded. During the research this turned out to be a valuable measurement which is also returned in the .log-files. By extracting it from these files, some computational time can be saved.
- **Improve the measurement set-up** The instruments measuring the wind at AWG1 are at the same height as the fence around the platform. Raising the instruments out of the wake of the fence should improve the measurements. Also, longer support beams would increase *r* and therefore improve the measurements.
- More platforms Repeat this research for the other oil and gas production platforms on the North Sea with similar measurement set-ups (D15, F16, J6, K14, L9). The instruments on D15 and K14 measure above the height of the fence around the platform and could be used to prove conclusively that such a set-up provides better measurements. The r/R of K14 is the largest (3 times larger than AWG1's) so an analysis of the K14 measurements could show clearly the effect of lengthening the support beams.
- Dutch Offshore Wind Atlas In December 2018 an improved KNW atlas (DOWA, Dutch Offshore Wind Atlas) has become available. After validation of the new atlas proves conclusively that the data are indeed an improvement on the KNW-atlas data, it is recommended that for future research DOWA be used instead of KNW.

8.1 Differences between KNW and our schemes

Some further research was conducted in order to determine whether or not the schemes represented what we want it to represent. Therefore, the probability density functions in the form of histograms are given in Fig. 32. It can be seen that the KNW-atlas and our corrected AWG1 measurements (2012) do not have the same distribution, which is not desirable. Therefore, some further research into these schemes could be done.



Figure 32: The two probability functions should be (approximately) the same. However, this is certainly not the case. The measurements have been binned in bins of 1 degree.

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A Elaboration of formulae

Because the derivations of the equations Eq. 10 and Eq. 11 are not straightforward, they are presented here.

$$\begin{split} u_x &= \frac{\partial \phi}{\partial x} = \frac{\partial}{\partial x} \left(u \cdot x \cdot \left(1 + \frac{R^2}{r^2} \right) \right) \\ &= \frac{\partial}{\partial x} \left(u \cdot x \cdot \left(1 + \frac{R^2}{x^2 + y^2} \right) \right) \\ &= u + \frac{\partial}{\partial x} \left(u \cdot x \cdot \left(\frac{R^2}{x^2 + y^2} \right) \right) \\ &= u \left(1 + R^2 \frac{\partial}{\partial x} \left(\frac{x}{x^2 + y^2} \right) \right) \\ &= u \left(1 - R^2 \left(\frac{r^2 - 2y^2}{r^4} \right) \right) \\ &= u \left(1 - R^2 \left(\frac{r^2 - 2y^2}{r^4} \right) \right) \\ &= u \left(1 - \frac{R^2}{r^2} \left(1 - \frac{2r^2 \sin^2 \alpha}{r^2} \right) \right) \\ &= u \left(1 - \frac{R^2}{r^2} \left(1 - 2\sin^2 \alpha \right) \right) \\ &= u \left(1 - \frac{R^2}{r^2} \left(1 - 2\sin^2 \alpha \right) \right) \\ &= u \left(1 - \frac{R^2}{r^2} \cos 2\alpha \right) \\ u_y &= \frac{\partial \phi}{\partial y} = \frac{\partial}{\partial y} \left(u \cdot x \cdot \left(1 + \frac{R^2}{r^2} \right) \right) \\ &= u \cdot x \cdot \frac{\partial}{\partial y} \left(\frac{R^2}{r^2} \right) \\ &= u \cdot x \cdot \frac{\partial}{\partial y} \left(\frac{R^2}{r^2} \right) \\ &= u \cdot x \cdot R^2 \cdot \frac{2y}{r^4} \qquad \text{use that } y = r \sin \alpha \text{ and } x = r \cos \alpha \\ &= u \cdot R^2 \cdot \frac{2r^2 \sin \alpha \cos \alpha}{r^4} \qquad \text{use that } 2 \sin \alpha \cos \alpha = \sin 2\alpha \\ &= u \cdot \frac{R^2}{r^2} \sin 2\alpha \end{split}$$

B Figures





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