

WIND TUNNEL AND FIELD TEST OF THREE 2D SONIC ANEMOMETERS

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ABSTRACT

Three 2D sonic anemometers (so-called sonics) have been selected by KNMI and have been subjected to tests in order to establish whether they are suitable for operational use. The three sonics are the Thies 2D, the Gill Windobserver 2 and the Vaisala WAS425. The sonics have been compared to the KNMI cup anemometer and wind vane that are used operationally. After some initial tests, during which all three sensors showed some problems, all sensors were upgraded and the tests commenced. Wind tunnel tests were performed for wind speeds up to 75m/s. Overall the agreement of all sensors is within the WMO requirements, although in detail all three sensors have strong and weak points. The field test showed that all 3 sonics worked properly although the Thies showed some signs of wear and the Vaisala occasionally missed a measurement. Overall the sonics agree very well with each other. The differences between the sonics and the conventional cup and vane are larger. The differences for the 10-minute averaged wind speed show a strong directional dependence that is probably related to surface roughness. The results also show a dependency on precipitation intensity. Overall the sonics seem suitable for operational use, but the use of sonics instead of the conventional wind sensors requires the construction of transfer functions for the homogenization of the climatological measurements.

1. INTRODUCTION

The Royal Netherlands Meteorological Institute (KNMI) uses conventional cup anemometers and wind vanes to measure wind speed and direction. Although the KNMI cup and vane meet WMO and ICAO requirements concerning the accuracy of wind measurements, the sensors require a large amount of maintenance and occasionally some anemometer freeze during calm winter conditions. Therefore, the usage of alternative wind sensors is considered. Sonic anemometers, in this report referred to as sonics, have no moving part, which makes them robust and almost maintenance free. In addition, the sonics have virtually no detection limit and detect changes almost instantly, whereas cup and vane have a threshold speed and need some time to adjust to the prevailing conditions. Furthermore sonic anemometers can optionally be equipped with a heater in order to prevent malfunctioning due to icing. Sonic anemometers have been available for several years. These sensors are generally used for scientific research, particularly because the 3-D sonics also measure the small vertical wind component very accurately and with a high temporal resolution. In recent years new measurement techniques and especially by more advanced processing of the raw data make the measurements of new sonic anemometers more reliable under all weather conditions. Therefore KNMI considered it a good moment to perform a test of sonic anemometers in order to find out whether they are suitable for use in the operational meteorological network. The test is restricted to commercially available 2-D sonic anemometers since the more expensive 3D sensors are not required in the operational network.

In this paper some preliminary results of the data analysis will be presented. Details of this study will be reported in a forthcoming KNMI technical report (Wauben 2005).

2. WIND SENSORS

KNMI uses conventional cup anemometers and wind vanes that have both been developed indoors. An overview of the sensor characteristics is given in Table 1. The cup anemometer and the wind vane are both connected to a sensor interface that reads the instruments with a 4Hz-sampling rate. The sensor interface calculates running averages for wind speed (scalar) and direction (unit vector), computes the wind gust (highest 3-second averaged speed) and takes care of marked discontinuity according to WMO and ICAO regulations (WMO, 1994). The sensor interface outputs a measurement string every 12 seconds that includes the sample values, 1-minute and 10-minute averages and extremes as well as the 10-minute standard deviation. Sonic anemometers determine wind speed and direction from the travel time of sound pulses. Three 2D sonic anemometers have been selected for the test. The specifications of these sensors meet the requirements (cf. Table 1) and the sensors are already extensively used, albeit not operationally by the meteorological community, although some tests have been performed. The selected sonics are the Thies 2D ultrasonic anemometer (Thies Clima, 2001), the Gill Solent WindObserver II ultrasonic wind sensor (Gill Instruments, 2000) and the Vaisala WAS425 ultrasonic wind sensor (Vaisala, 2000).

Table 1: An overview of the general characteristics of the wind sensors considered in this study and the WMO requirements.

General sensor characteristics					
<i>Parameter</i>	<i>KNMI cup</i>	<i>KNMI vane</i>	<i>Thies</i>	<i>Vaisala</i>	<i>Gill</i>
Name	KNMI cup anemometer	KNMI wind vane	Ultrasonic Anemometer 2D	Ultrasonic wind sensor WAS 425 AH	Solent WindObserver II
Software version	4.0	4.0	1.90	6.04	2.01
Operating Frequency	N.A.	N.A.	250kHz	100kHz	± 180kHz
Output rate	1/12Hz	1/12Hz	10Hz	1Hz	1, 4 or 10Hz

Wind direction					
<i>Parameter</i>	<i>WMO</i>	<i>KNMI</i>	<i>Thies</i>	<i>Vaisala</i>	<i>Gill</i>
Range	360°	0 to 359.9°	1 to 360°	0 to 359°	0 to 359° or 1 to 360°
Resolution	3°	1°	1°	1°	1°
Accuracy	±5°	±3°	±1.5°	±2°	±2°
Sample rate	4Hz	4Hz	400Hz	1Hz	40Hz
Running average	3sec	3sec	0, 1, 10sec or 2min (3sec in SW upgrade end 2000)	1 to 9sec (RS232)	0 or 1 to 3600sec
Detection limit	0.5m/s	0.4m/s	0.01m/s	virtually zero	below 0.5m/s no direction reported, but u,v in 0.01m/s
Damped wavelength	< 10m	3.8m	N.A.	N.A.	N.A.
Damping ratio	0.3 to 0.7	0.36	N.A.	N.A.	N.A.
Time constant	1sec	?	meas. time 0.0025sec, response time 0.1sec	meas. time 0.2sec, response time 0.35sec	< 0.1sec

Wind speed					
<i>Parameter</i>	<i>WMO</i>	<i>KNMI</i>	<i>Thies</i>	<i>Vaisala</i>	<i>Gill</i>
Range	0.5 to 75m/s	0.5 to 75m/s	0 to 60m/s (above value)	0 to 65m/s	0 to 65m/s (above value or error)
Resolution	0.5m/s	0.01m/s	0.1m/s	0.1m/s	0.01m/s
Accuracy	Max of ±0.5m/s and ±10%	±0.5 m/s	Max of ±0.1m/s and ±2%	Max of ±0.135 m/s and ±3%	±2%
Sample rate	4Hz	4 Hz	400Hz	1Hz	40Hz
Running average	3sec (gust)	3 sec	0, 1, 10sec or 2min (3sec in SW upgrade end 2000)	1 to 9sec (RS232)	0 or 1 to 3600sec
Threshold speed	0.5m/s	<0.5m/s typically 0.3m/s	0.001m/s	virtually zero	0.01m/s
Response length	2 to 5m	2.9m	0.20m	0.40m	0.15m
Time constant	1sec	?	meas. time 0.0025sec, response time 0.1sec	meas. time 0.2sec, response time 0.35sec	< 0.15sec

The basic quantity, which is needed for the measurement of wind gust in particular, are running 3-seconds averages with an update frequency of 4Hz as recommended by WMO (1987). Since not all three sonic anemometers facilitate running 3 seconds averages and 4Hz updates it was decided to poll all three sensors identically with 1Hz during which the 1-second averaged wind is obtained.

The three sonic anemometers have different mounting mechanism, power and signal connectors, dimensions and alignment methods. A coupling device was developed in order to facilitate the installation of each of these sensors. This device allows the mounting of the sensor to the standard 9-pole plug of the KNMI cup anemometer and wind vane. A reference pin in this plug is used for the orientation of the sensor. Tests showed that the alignment of the sonics agreed within $\pm 1^\circ$.

3. WIND TUNNEL TESTS

Wind tunnel tests were performed in the Low Speed Tunnel (LST) of the Dutch National Aerospace Laboratory (NLR) that is operated by DNW (German-Dutch Wind Tunnels). The LST is an atmospheric, closed-circuit wind tunnel with a $3 \times 3 \times 2.25$ m test section. The wind speed range of the tunnel is 1.5m/s to 80m/s. The absolute accuracy of the tunnel wind speed calibration is 0.11m/s at 2.0m/s, decreases to 0.05m/s at 5.0m/s, remains 0.05m/s up to 10.0m/s and increase to 0.15m/s at higher wind speeds. The blocking factors applied for the cup, Gill/Thies and Vaisala were determined to be 2.1, 2.5 and 2.7%, respectively. The variation in wind speed across the test section is less than 0.2% and turbulence is below 0.03%. The horizontal and vertical flow angularities are within 0.1° . The sensors are mounted on a unipod with a height of 1.1m that is equipped with a standard 9-pole plug and brings the sensor near the middle of the test section. The unipod is fixed to the centre of the turntable in the floor of the test section that can be rotated over 360° with accuracy well below 0.1° . At each of the wind speeds 2, 3, 5, 10, 20, 50, 60, 75, 70, 30, 15, 7, 5m/s azimuth scans are taken with a constant angular speed of the turntable of $0.5^\circ/\text{sec}$.

Some results of the azimuth scans are shown in Figure 1. For that purpose the 1-second sensor and tunnel readings are averaged over 2-degree interval of the turntable and presented as a function of the azimuth angle of the turntable. Note that a discontinuity at about -60° is the result of the angular offset between the North directions of the turntable and the sonic. Also note that the full scale of the figure corresponds to the accuracy required by WMO, i.e. $\pm 5^\circ$ for direction and the maximum of $\pm 0.5\text{m/s}$ and $\pm 10\%$ for the wind speed. Overall the agreement of all sensors is within the WMO requirements. The results of the Vaisala are fine at high wind speeds. For wind speeds of 50m/s and more a small disturbance caused by the transducer arms can be observed. At low wind speeds ($< 5\text{m/s}$) the results are bit noisy, but well within WMO limits. The results of the Thies clearly show that the sensor compensates for the disturbance caused by the transducer arms, although a small effect can still be observed at wind speeds below 15m/s. The Thies results for all wind speeds are close to the reference, but the Thies failed to give good measurements above 50m/s. Inspection of the sensor by Thies showed that this was a result of bird-inflicted damage during the field test, whereby moisture entered the sensor. The Gill measurements are very consistent even at low wind speeds. Gill does not correct for the disturbance of the transducer arms. Especially at high wind speeds ($> 30\text{m/s}$) the disturbance is very pronounced and above 60m/s the differences induced by the transducer arms even exceeds the WMO limits at some orientations.

All azimuth scans were used to calculate the azimuthally averaged differences in the measured wind speed. The deviations of these averaged wind speeds from the tunnel wind speed are shown in Figure 2 as a function of the tunnel wind speed. Two KNMI cup anemometers are also included in this figure. For that purpose the cups were placed in the wind tunnel and sampled for about 2 minutes at each of the tunnel speeds. During these measurement the turntable was not operated and delays were included in order to allow the tunnel and the cup anemometer to adjust to the new speed. Figure 2 shows that the azimuthally averaged wind speeds of all sensors agree with the tunnel reference speed within the accuracy of $\pm 10\%$ required by WMO. All sensors give lower averaged wind speed values at low tunnel speeds. The cup anemometers measurements are close to the tunnel values in the middle wind speed range of 5 to 30m/s, but underestimate the wind speed at low and high wind values. The sonic anemometers generally show the largest relative differences at low wind speed values and the differences decrease for higher wind speed values. The Vaisala and Thies generally give the best results. The Vaisala slightly overestimates the wind speed above 5m/s whereas the Thies always reports slightly lower values. The Gill generally differs more from the tunnel reference values than the other 2 sonics and also shows larger fluctuations between the differences at neighboring wind speed values. Note that the successive wind speed values were measured alternatively in the upward and downward sweep through the full wind speed range.

Tests were also performed in the KNMI wind tunnel with a closed measurement section of about 0.4m and a wind speed range of 0.2m/s to about 27m/s. Due to the rather small dimensions the KNMI tunnel is not suitable for absolute calibrations of the sonics. However, tests revealed that the KNMI tunnel could be used for verification of the alignment and the azimuth response as well as for checking the wind speed although the magnitude and sign of the differences shows a different behaviour than was observed in the LST tunnel tests. The different behaviour observed in the KNMI tunnel cannot be explained by a single correction factor. However, all sensors agree within WMO limits with the KNMI tunnel over the full wind speed range.

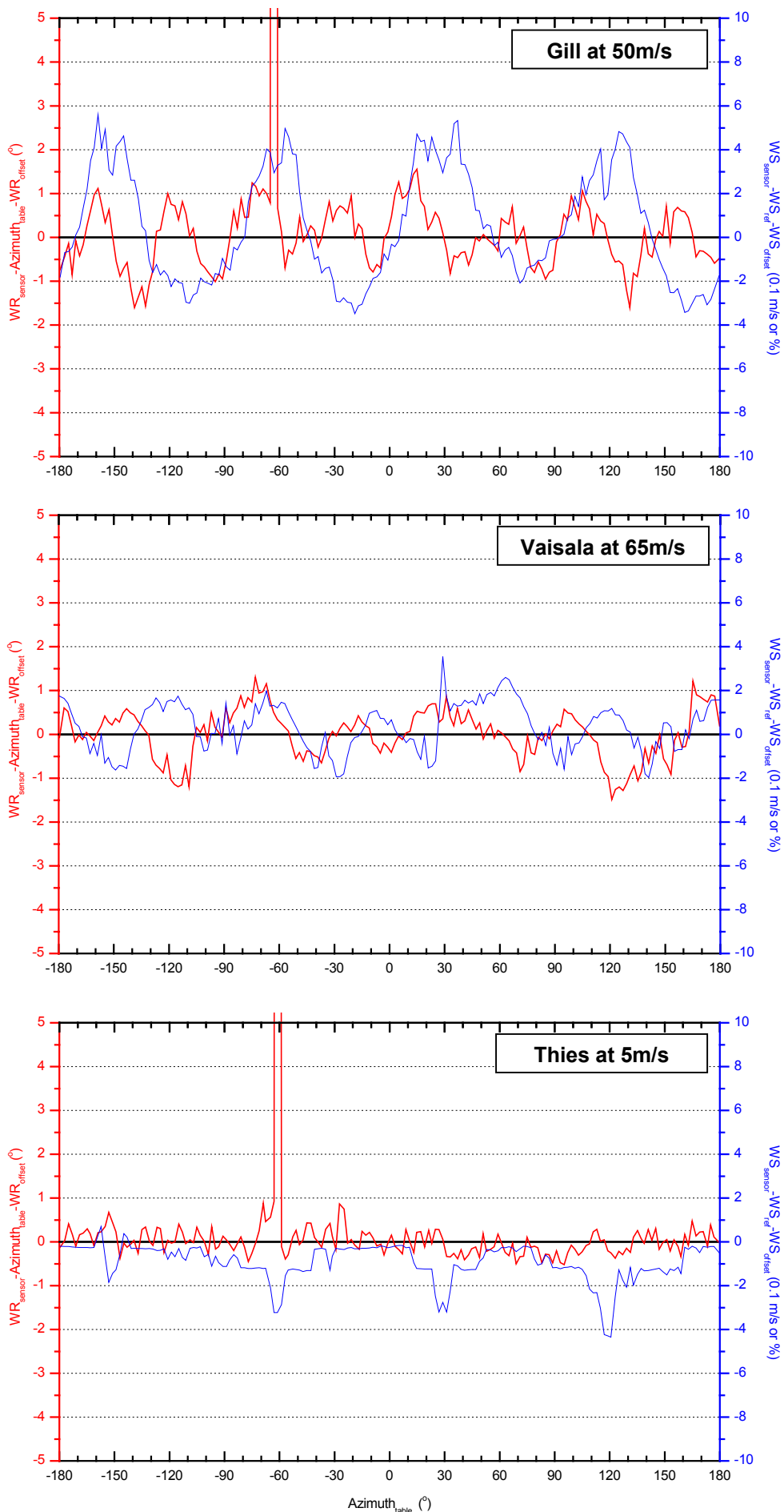


Figure 1: Differences between the LST tunnel wind speed and turntable direction and the values reported by the three sonics during azimuth scans with a fixed tunnel speed.

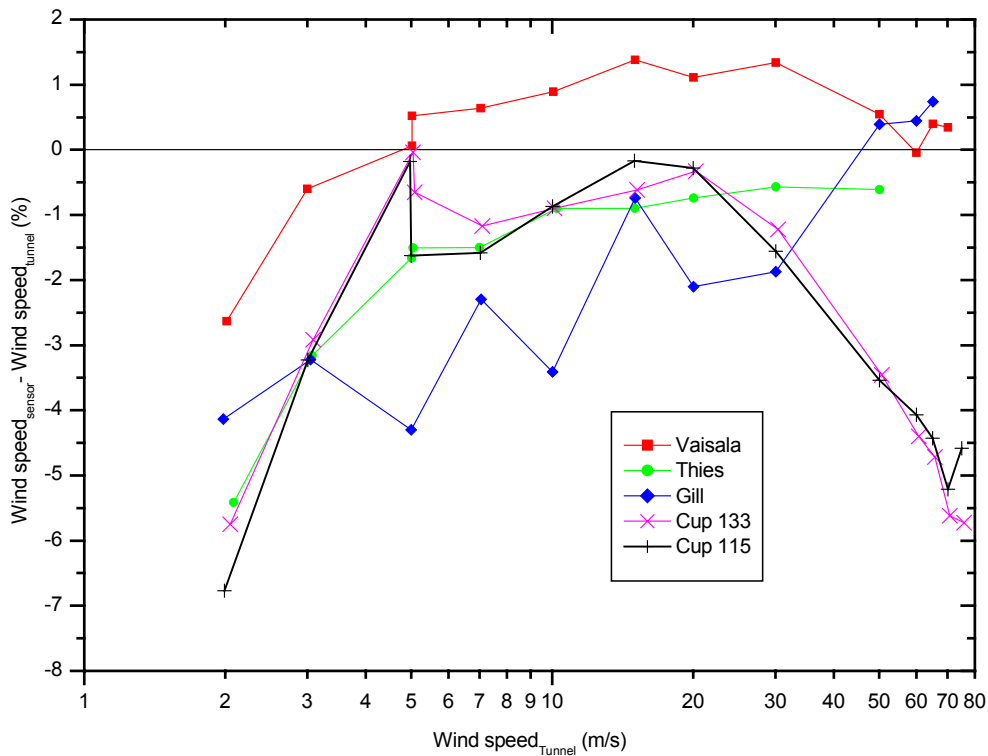


Figure 2: Relative differences between the LST tunnel wind speed and the sensor speed averaged over all angles as a function of the tunnel wind speed.

4. FIELD TEST

The field test was conducted at the test site in De Bilt between June 15, 2002 and July 2003 after all three sensors were upgraded. The 3 sonics were mounted on a 10m mast using a head that separated the sonics 1m. The mast was located 20m to the south-southwest of the 10m mast containing the KNMI cup and vane. The 3 sonics Gill, Thies and Vaisala were oriented ENE to WSW. During the period of the field test 12-second data of the KNMI sensor set and 1sec values of the sonics were archived. The sonic data was later processed into running 3-second averages from which the 10-minute averaged values and extremes were derived. The analysis below is based on 10-minute data.

A histogram of the 10-minute averaged wind speed data clearly show that the cup anemometer reports more cases where the wind speed is below 0.5m/s and generally also reports more cases when the speed is above 5m/s. The first is related to the detection threshold of the cup anemometers whereas the latter is probably related to the so-called speeding. Speeding was clearly observed during a storm when the cup and sonics showed good agreement for the wind gusts up to 28m/s, whereas for the 10-minute averaged wind speed up to 12m/s the sonics generally reported lower values. A scatter plot of all 10-minute wind speed data of the cup anemometer versus a sonic have a correlation of 0.992, the slope of a linear fit is about 0.95 and the standard deviation is 0.19m/s for all three sonics. Although the overall agreement is quite good some cases with large differences that exceed WMO criteria do occur. Most striking are the cases where all 3 sonics reported wind speeds between 0.5 and 2m/s while the cup anemometer was probably frozen and reported 0m/s. Comparison between the 3 sonics shows much better agreement with a correlation of 0.999, slope of the linear fit of 0.98 and the standard deviation is 0.06. Similarly the 10-minute averaged wind direction of the vane and a sonic have a correlation coefficient of 0.94, the linear fit has a slope of 0.94 and the standard deviation is 11°. Again cases occur when the differences exceed the WMO criteria and some even reach 180°, but that is during low wind speeds. The agreement between the 3 sonics is again much better with a correlation of 0.97, a slope of 0.96 and a standard deviation of 4°.

Next only cases where the cup anemometer reports wind speeds above 0.5m/s are considered in order to overcome the large differences at low wind speeds. The observed differences in the 10-minute averaged wind speed are next studied as a function of wind direction reported by the vane in Figure 3. At all bins about 1000 cases or more are available. The figure shows larger differences near 0, 90, 180 and 270° that are probably caused by the disturbance of the transducers. Furthermore a large increase can be observed near 250° with elevated values between 210 and 360°, which is the roughly in the direction of a line of 20-25m trees at a distance of about 150m, but also coincides with the direction of the highest wind speeds. Figure 4 shows the same results, but indicates the fraction of cases were the wind speed agrees within the WMO limits. Overall in about 98% of the cases the sonics agree within the WMO limits with the cup anemometer, but at 250° this applies only for about 87% of the cases. When the sonics are compared to each other the

averaged absolute differences per wind direction bin are much less and nearly independent of wind direction. The wind speed of the sonics is in nearly 100% of the cases within the WMO limits. Figure 3 and Figure 4 show that the results of the Thies deviate slightly more from the cup anemometer than the other 2 sonics.

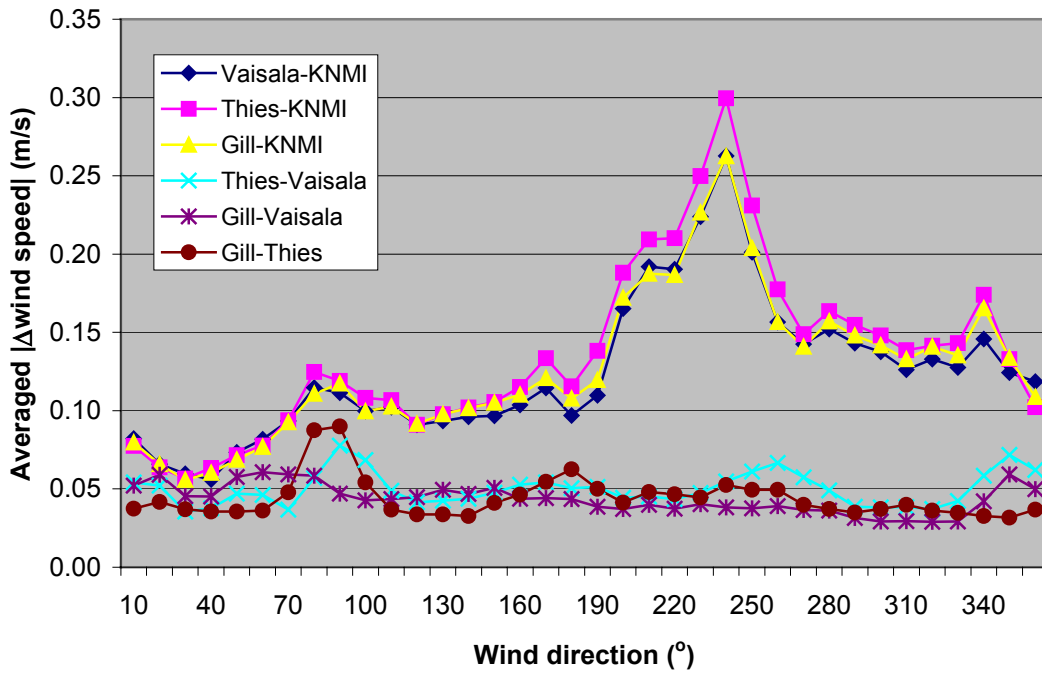


Figure 3: Averaged absolute differences in 10-minute wind speed as a function of the wind direction in bins of 10°.

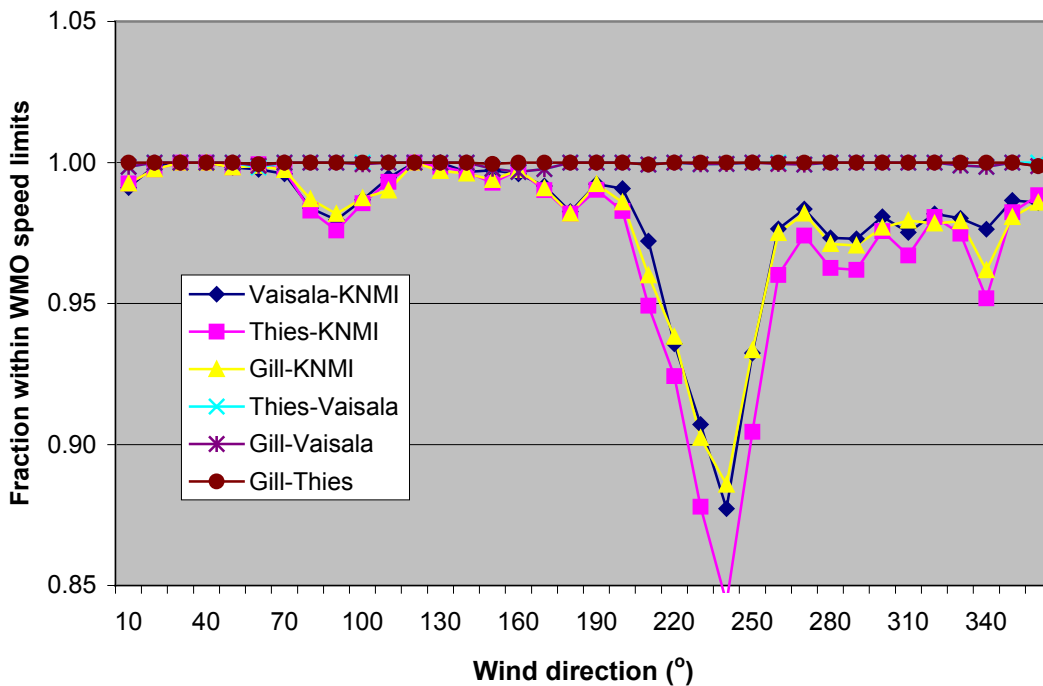


Figure 4: Fraction of the cases per wind direction bin of 10° where the wind speed agrees within the WMO limits of $\pm 0.5\text{m/s}$ or $\pm 10\%$.

The differences in wind direction are shown as a function of wind speed in Figure 5. Below wind speeds of 5m/s the number of cases per wind speed bin is larger than 1000, but the number decreases rapidly with increasing wind speed and is less than 100 at 7m/s and is even less than 10 above 8.5m/s. At low wind speeds the fraction of cases where the wind direction is outside the WMO limits of the wind vane is rather large, but the agreement gets gradually better at higher wind speeds. The Gill compares better to the KNMI

wind vane than the other 2 sonics. The averaged absolute differences in wind direction shows hardly any dependency with wind speed, except a sharp increase at wind speed values below about 2m/s.

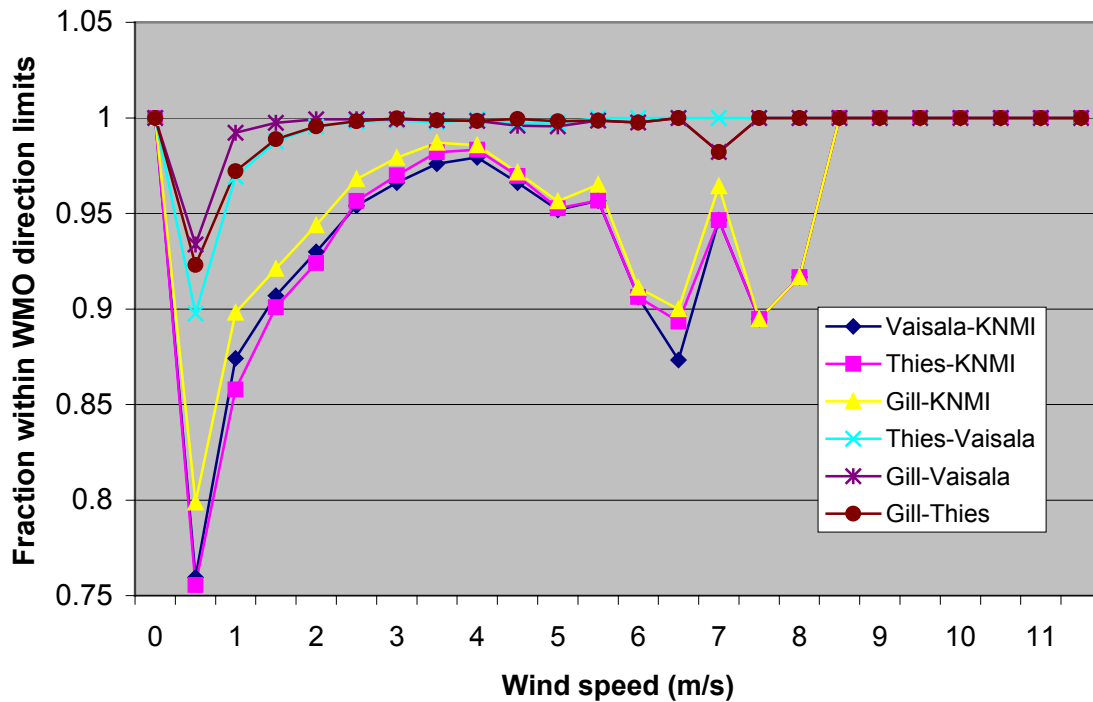


Figure 5: Fraction of the cases per wind speed bin of 0.5m/s where the wind direction agrees within the WMO limits of $\pm 5^\circ$.

Next the differences are studied as a function of the precipitation class. The precipitation intensity and type as measured by a FD12P present weather sensor is used for the purpose. The 10-minute averaged precipitation intensity and the ‘maximum’ precipitation type observed in the previous 10 minutes are used for that purpose. The precipitation classes considered are, respectively, no precipitation (NP), traces (TR with 10-minute averaged intensity below 0.05mm/h) and intensity classes rounded to mm/h in the range 0-10 where the last bin also contains all cases with higher intensity values. Next all cases with precipitation are summed (AP) and a distinction is made between the precipitation types liquid (LP), solid (SP) and unknown precipitation (UP). Finally the results are given independent of precipitation (All). In all classes the number of cases is above 100, except for the classes for intensity larger than 5mm/h. The averaged absolute differences of the wind direction show a dependency on precipitation class, although the statistics is poor, the averaged differences increase from about 2° for intensities below 3mm/h to about 4° at intensities of 10mm/h. The same behaviour can be observed in the fraction of cases the sonics agree within the WMO limits with the KNMI vane, which is generally above 90% and decreases below 80% at the highest intensities. The averaged differences between the three sonics and the KNMI wind vane for solid precipitation are less (1.5°) than for liquid precipitation (2.5°). The differences in wind direction between the sonics themselves show no clear dependency on precipitation class and are about 1.5° . The averaged absolute differences of the observed wind speed as a function of the precipitation class (cf. Figure 6) show a clear dependency on the precipitation intensity and increase from about 0.15 to 0.25m/s. The same behaviour again holds for the fraction of cases the sonics are within WMO limits from the cup anemometer which is about 95%, but decreases to about 85% at high intensity values. Again solid precipitation seems to have less effect on the differences that liquid precipitation. The results indicate that the Thies is slightly more affected by precipitation than the other 2 sonics when compared to the KNMI cup anemometer. When the sonics are compared to each other the wind speed of the Thies and Gill agree almost in 100% of the cases within the WMO limits, whereas the Vaisala shows a slightly reduced agreement of about 98% at mid and high intensity levels. It should be noted that the observed differences between the sonics and the conventional cup anemometer and wind vane during precipitation can also be the result of a deterioration of the performance of the conventional sensors since the precipitation will attach to these sensors and affects their dynamical properties.

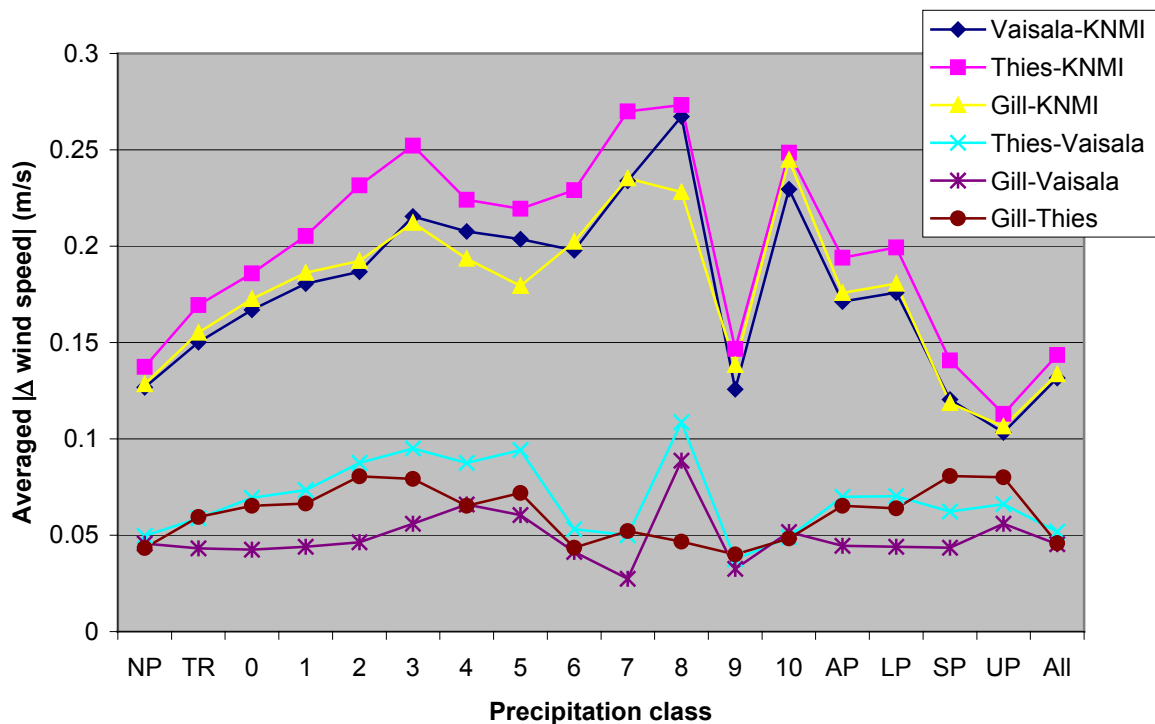


Figure 6: Averaged absolute differences in 10-minute wind speed as a function of the precipitation class.

5. CONCLUSIONS AND OUTLOOK

Three sonics, i.e the Thies 2D, the Gill Windobserver 2 and the Vaisala WAS425 have been compared to the KNMI cup anemometer and wind vane. Wind tunnel tests were performed for wind speeds up to 75m/s. Overall the agreement of all three sonics and the KNMI cup anemometers is within the WMO limits when compared to the tunnel reference. The Vaisala compares well with the reference over the full angular and wind speed range, although the signal is a bit noisy at low wind speeds (<5m/s). The Gill measurements are very consistent, but the differences generated by disturbances by the transducer arms, which are not corrected for in the software, exceed the WMO limits at some orientations for high wind speeds (>60m/s). Furthermore, the wind speed reported by the Gill is generally smaller than the tunnel reference, although within WMO limits. The Thies compensates for the disturbances caused by the transducer arms and is close to the reference, but it failed to give good measurements above 50m/s as a result of damage obtained during the field test. The field test showed that all 3 sonics worked properly although the Thies showed some signs of wear and the Vaisala occasionally missed a measurement. Overall the sonics agree very well with each other. The differences between the sonics and the conventional cup and vane are larger. The differences for the 10-minute averaged wind speed show a strong directional dependence that is probably related to surface roughness. The differences show a dependency on precipitation intensity. The sonics seem suitable for operational use, but the introduction of the sonics requires the construction of transfer functions for climatological purposes. A more detailed analysis of the data is required before KNMI can make a definite choice for a specific sonic anemometer. After this selection KNMI will perform further tests with some sonic anemometers in 2005 at selected locations such as airports, coastal stations, platforms and possibly at the 200m research tower, in order to get more operational experience with these sensors.

6. REFERENCES

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