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Performance Verification of Vaisala Anemometers

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Authorisation

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15 Pages

1. AIM

As part of a larger study of anemometers, a Vaisala WAA151 (S/N S45504) and a Vaisala WAA251 (S/N 803408) anemometer were tested to determine whether they met the Bureau of Meteorology Specification [1], [3] for accuracy and functionality. The WAA251 anemometer was installed over the winter of 1998 at Mt Hotham while the WAA151 anemometer was a new unit.

2. TEST PROCEDURE

The Vaisala model WAA151 is the standard unit used on Milos AWS for use in non-freezing conditions. The model WAA251 is designed for use in cold climates as it has heating elements for the bearings, shaft and cups to minimise ice accretion.

The anemometers were tested using the American Standard Test Method ASTM D5096-96 (Standard Test Method for Determining the Performance of a Cup Anemometer or Propeller Anemometer) [2] to determine the uncertainty of the unit and its rundown time. The results were assessed against the Bureau of Meteorology Specification ES 835 Anemometer Cup Contact Type [1] and Bureau of Meteorology Specification ES A2659 Guidance Specification (Functional) for a General Purpose Automatic Weather Station (AWS) [3]. These tests were carried out at the Monash University Civil Engineering Wind Tunnel on 17 December 1998.

Calibration of the wind tunnel was derived from the output of the Pitot tube analogue pressure transducer and amplifier system. Two Pitot tubes were mounted in the tunnel, one in the main section adjacent to where the test barometers were installed and the other further down the tunnel in the high-speed section. The tubes were connected to the pressure transducer and the output measured by a Hewlett Packard digital multimeter (HP3457A S/N 3114A14559). The output was compared to a differential water manometer.

Calibrated Rosemount Slimline RTD temperature sensors were installed in the tunnel and the room outside the tunnel. Both were connected to an ALMOS AWS and logged on a computer along with the atmospheric pressure (Paroscientific 760-16B S/N 55745), the reference voltage from the Pitot tube and the output of the test anemometer. Two in-house developed LabView programs (WINDT08.VI and AWS1SGET.VI) were used to collect the data. See Figure 1 for experimental arrangement.

The voltage output from the HP3457A multimeter was converted to pressure and corrected for the air density changes due to changes in the ambient air pressure and the tunnel air temperature and for zero drift in the output voltage of the pressure transducer. (See Appendix 1 for conversion details). The output of the anemometers was fed through a HP53131A Universal Counter (S/N 3736A23981) into the personnel computer. Below 9 m/s the period of the anemometer was measured and above 9 m/s the frequency of the output was measured. This experiment was an assessment of the performance of the anemometer against the specification thus the period was converted to frequency and the standard Vaisala algorithm used to convert the wind in hertz to m/s.

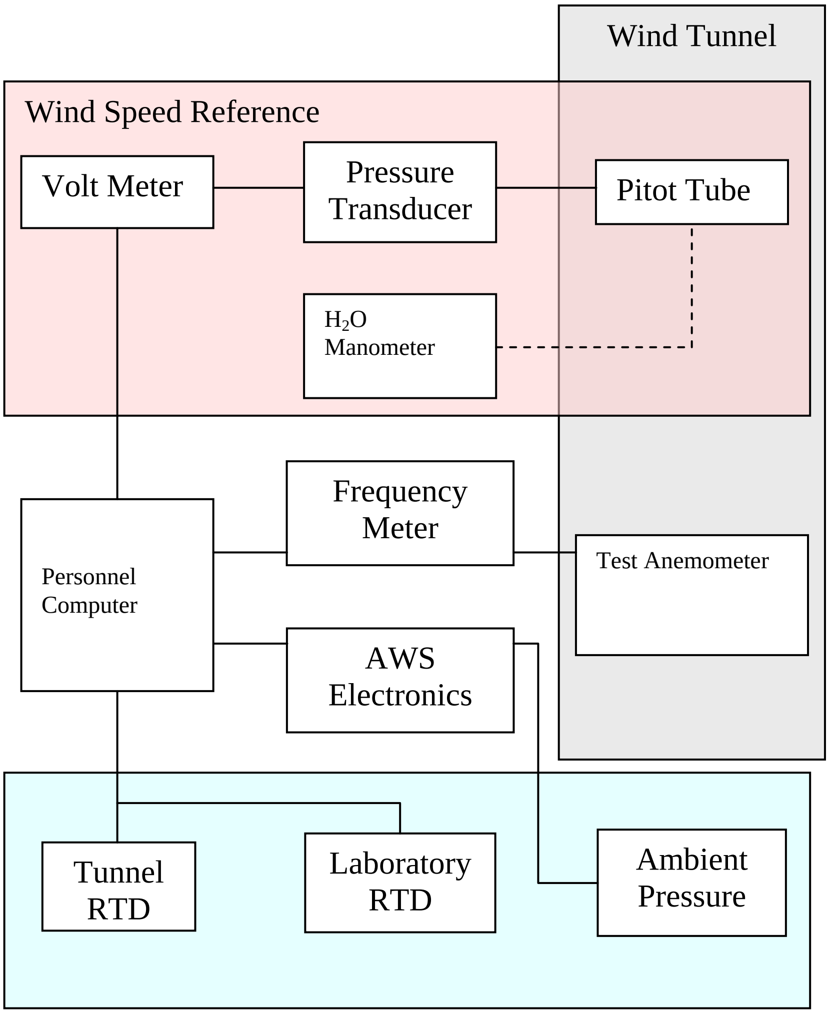
Wind Speed (m/s) = 0.4054 + 0.09853 * Signal (Hz)

This was compared the reference wind speed. There was no attempt to determine the calibration of the anemometer.

The anemometers were subjected to two different tests. The first was measurement of the response of the anemometer against wind speed. The speed of the wind tunnel was raised in approximately 2 m/s steps to 5 m/s then in 5 m/s steps to 25 m/s and held at each wind speed for 120 s. The wind speed in the tunnels was then reduced in 5 m/s steps to 5 m/s and in 2 m/s steps to 0 m/s; once again at each stage the wind speed was held constant for 120 s.

The second test was determination of the rundown time of the anemometer. This is the time it takes for the anemometer to slow from a known wind speed of 10 m/s to 0 m/s. The anemometer with the cups attached was manually spun up to a speed greater than 10 m/s. The time taken for the anemometer to slow from 10 m/s to when the cups stopped spinning was noted; this is the rundown time.

Figure 1 The layout of the experimental equipment. Doted lines indicate alternate connections for data flow.



3. RESULTS

Table 1 gives the summarised results and specifications against which the anemometers were assessed. Threshold wind speed has not been determined for either anemometer because of the poor sensitivity of the tunnel at low wind speed. In all figures the uncertainty limits shown on individual points are those calculated in Appendix 2.

3.1 ESTIMATION OF THE UNCERTAINTY

The estimation of the uncertainty of the measurements is given in Table 2, 3 and Appendix 2. Table 2 is a summary of the sources of error, the typical magnitude of these errors, and Appendix 2 provides the estimate of uncertainty.

From the raw data the uncertainty of the wind tunnel at low wind speeds is high, due to the use of a water manometer in the determination of the tunnel's wind speed. As a consequence, this component of uncertainty was broken into two components one associated with the resolution of the manometer and a second resulting from the stability of the water manometer and fit of the water manometer to the voltage output of the pressure sensor. The former was incorporated into the specification limits for ES A2659 [3] and ES 835 [1][1].

3.2 VAISALA WAA151 ANEMOMETER

Figure 2 shows that the Vaisala WAA151 anemometer corrections to the reference wind speed were relatively constant, having a gradient of 0.00069 with a standard error of 0.00072, over the range of wind speeds 5 to 25 m/s. Over this wind speed range the anemometer over-estimated the wind speed by approximately 0.4 to 0.5 m/s (As indicated in Table 3). Below 5 m/s the over-estimation of the anemometer increases to 1.6 m/s at <0.3 m/s. The anemometer displays negligible hysteresis of less than the uncertainty of measurement for this test. Approximately 0.5 m/s of this bias is attributable to the non-linearity and 1.1 m/s is attributable to the overrun or rundown characteristics of the anemometer at very low wind speeds, below 0.3 m/s.

The rundown time test of the anemometer was carried out 3 times. This resulted in a rundown time of approximately 45 ± 14 s (see Table 1).

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[1] It is noted that as the specifications were drafted in 1969 and 1989, a determination of the understanding of the sources of the testing uncertainty of this level of complexity was unlikely to have been applied leading to an optimistic interpretation of the likely accuracy of anemometers.

Table 1. Summary of Speed and Rundown Time Tests.

	Specification	**Vaisala WAA 151 (S/N S45504)**		**Vaisala WAA 251 (S/N 803408)**	
[2]3.7 to 7.7 m/s	± 0.52 to 0.5 m/s	-0.6 to – -0.3 m/s	P[3]	-0.29 to 0.26 m/s	P
7.7 to 13 m/s	± 1 m/s	-0.6 to – -0.2 m/s	P	0.12 to 0.30 m/s	P
13 to 52 m/s	± 10%	-6 to -2.5%	P	1.7 to 7%	P
Threshold	1.5 m/s	< 1 m/s	P	< 1 m/s	P
Rundown Time	>60 s	45.3 s	F	7.5 s	F
-ve to +ve change in uncertainty	Between 5 & 13 m/s	0.44	P	1.0 m/s	P
Max difference in uncertainty for any 5 m/s range	0.8 m/s	0.6 m/s	P	0.9 m/s	F
	Specification	**Vaisala WAA 151 (S/N S45504)**		**Vaisala WAA 251 (S/N 803408)**	
[4]0 to 10 m/s	± 1.84 to 1 m/s	-1.7 to – 0.3 m/s	P	-1.0 to 0.85 m/s	P
>10 m/s	10%	-3.1 to -6.1%	P	7.0 to 8.7%	P
Rundown Time Constant	> 30 s	45.3 s	P	7.5 s	F
Distance Constant	2 to 5 m/s	Not determined	-	Not determined	-
Threshold	0.5 to 1 m/s	< 1 m/s	P	< 1 m/s	P

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[2] The actual specification for ES835 is 0.5 m/s for the range 1.5 to 7.7 m/s. However, given the test conditions the uncertainty of the source at low wind speeds has been incorporated raising the specification by 0.1 m/s to 0.6 at 1.5 m/s and by <0.1 m/s for higher wind speeds. (See Table 2)

[3] The results for wind speed range 3.7 to 7.7 m/s were considered inconclusive because the expanded uncertainty overlaps the specification limit.

[4] Specification for ES A2659 is 1 m/s for the range 0 to 10 m/s. However, given the test conditions the uncertainty of the source at low wind speeds has been incorporated raising the specification by 0.8 m/s to 1.8 at 0 m/s and by <0.1 m/s for higher wind speeds. (see Table 2)

Table 2 Summary of Sources of Uncertainty

Contributions to Uncertainty	Resp. Shape[5]	Specification	Reference	Test Unit
		(m/s)	(m/s)	(m/s)
Water manometer reading and stability	Power	1.54 to 0.02		
Fit uncertainties in the calibration of *water manometer* to the Pitot tube pressure sensor.	Constant		0.0676	
Estimation of the *air density* of the tunnel	Linear		0.0001 to 0.002	
Determination and variation of the *air pressure* in the tunnel	Linear		0.0003 to 0.0063	
Determination and variation of the *air temperature* in the tunnel	Linear		0.0005 to 0.0125	
Estimation of the *vapour pressure* of the tunnel.	Linear		0.0009 to 0.0217	
Determination and variation of the *voltage* of the Pitot tube pressure sensor.	Linear		0.0001 to 0.0004	
Stability of the *flow* in the tunnel	Constant			0.0255
Measurement of the *frequency* output of the instrument under test.	Constant			0.0004
Stability of the *instrument* under test.				0.02 to 0.07
The conversion *algorithm* of the instrument under test from frequency to wind speed.	Linear			0.002 to 0.127
The *non-linearity* of the sensor, taken as the deviation of the measured values from a straight-line response. (WAA251)	Constant			0.03
The *non-linearity* of the sensor, taken as the deviation of the measured values from a straight-line response. (WAA151)				0.06

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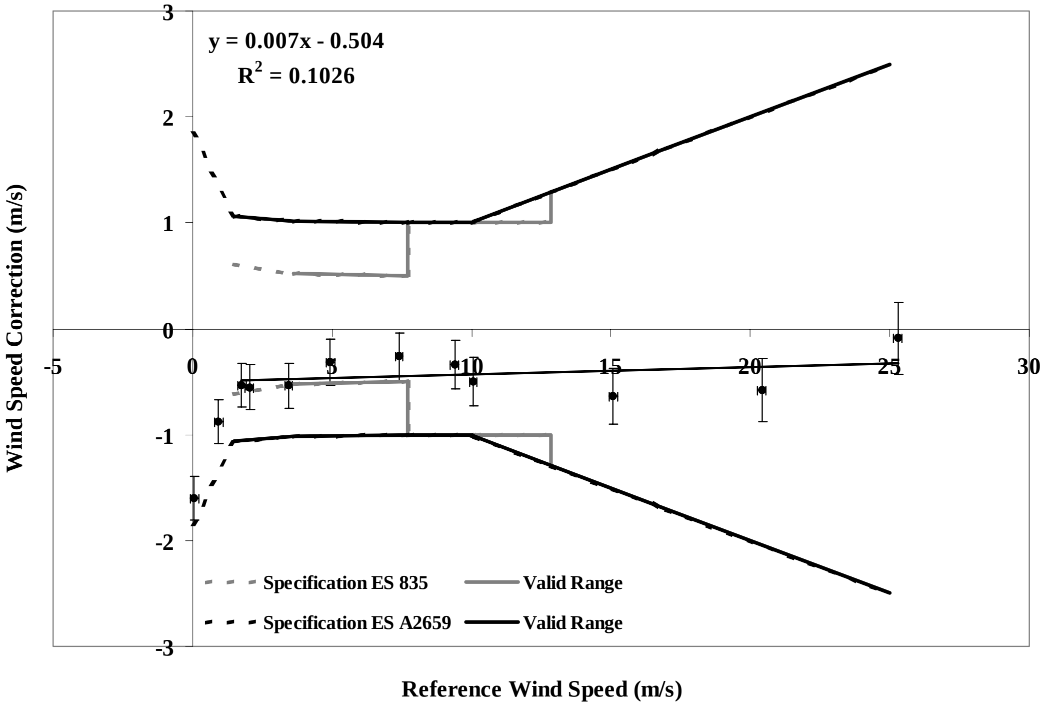
[5] The form of the contribution to uncertainties response to increasing wind speed

Figure 2. Wind tunnel tests of Vaisala Model WAA 151 (S/N S45504). The uncertainty bars, both x and y, on the data represents the expanded uncertainty for the measurand to a confidence level of 95%. See Appendix 2.2.



3.3 VAISALA WAA251 HEATED ANEMOMETER

Figure 3 shows the correction for the WAA251 heated anemometer as a function of wind speed. The calibration curve while approximately linear above 2 m/s has a significant gradient of 0.077 or 7.7% of reading resulting in the anemometer under-estimating the true wind speed by up to 1.5 m/s at 25 m/s. Below 5 m/s the anemometer over-estimates the wind speed by up to 1 m/s at 0 m/s. Approximately 0.44 m/s of this error attributable to the non-linearity and 0.53 m/s is attributable to the overrun or rundown characteristics of the anemometer at very low wind speeds, below 0.3 m/s. Specific bias results are given in Table 3.

The results for the WAA251 anemometer are within the specification for all wind speeds. However it is of concern that the response curve may have drifted in only six months and that the rundown time has dropped to < 8 ± 1 s, well outside specification. While no test of the WAA251 anemometer was carried out before installation; it would be expected that the anemometer should have shown an almost constant correction to the reference wind. This indicates a proportional difference in sensitivity of the WAA251 to wind speed and raises the suspicion that the model WAA251 has deteriorated during its short period in the field.

Figure 3. Wind tunnel tests of Vaisala Model WAA 251 (S/N 803408)
The uncertainty bars, both x and y, on the data represent the expanded uncertainty for the measurand to a confidence level of 95%. See Appendix 2.3.

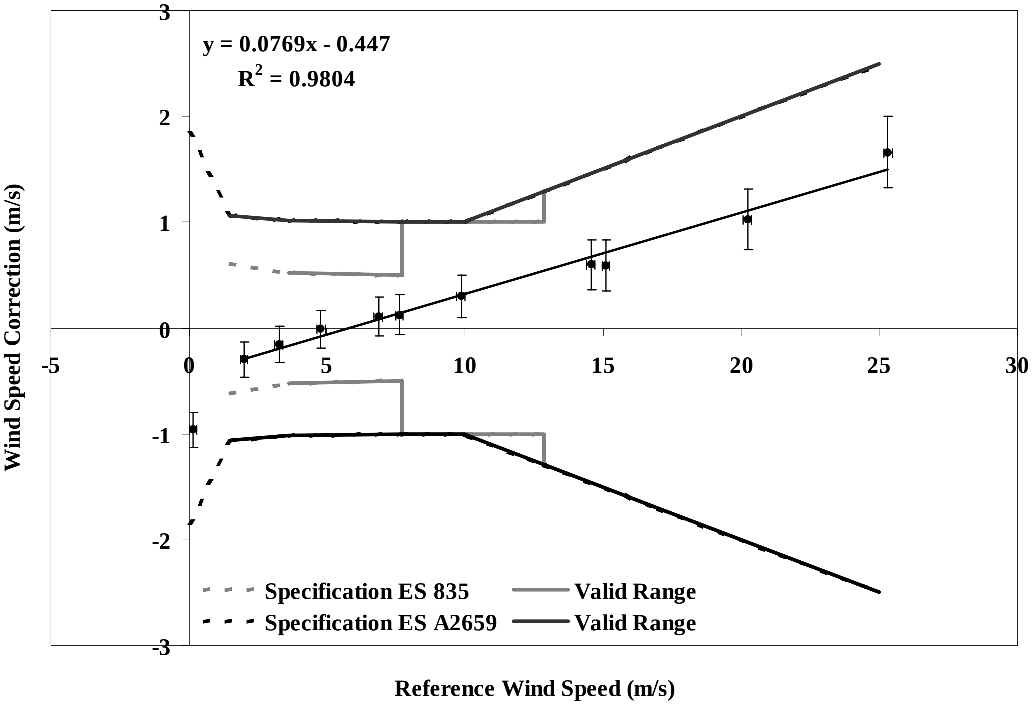


Table 3 Mean offset of the anemometer's measurement of wind speed in m/s.

Reference Wind Speed	*WAA151 Linearity Offset*	*Overrun/ Rundown Offset*	*WAA251 Linearity Offset*	*Overrun/ Rundown Offset*
0.1	-0.504	-1.094	-0.436	-0.526
0.9	-0.497			
1.8	-0.492			
2.0	-0.490		-0.293	
3.3	-0.480		-0.197	
4.9	-0.469		-0.079	
7.1	-0.452		0.080	
7.6			0.139	
9.4	-0.439			
10.0	-0.434		0.310	
14.6			0.672	
15.1	-0.399		0.713	
20.3	-0.362		1.107	
25.3	-0.328		1.499	

4. DISCUSSION

The under reading by the WAA251 heated anemometer at higher wind speed is possibly due to wear in the bearing after 6 months use in the field or degradation of the bearing lubricant. This interpretation is supported by the results of the rundown time constant test that gave an average value of 7.5 s for 4 tests. This is significantly outside the specified range for the rundown time constant (see Table 1) and is consistent with worn bearings or other deterioration of the bearing assembly including brake down of lubricants.

According to Vaisala Australia [4] the lubricant used in the unit is Shell's AeroShell Fluid 12 and is rated to meet specification MIL-PRF-6085D. Shell rates the lubricant with a temperature range of between -60 and 120°C [5] however it carries the warning that being a synthetic oil there can be incompatibilities between the oil and some sealing materials and paints [5]. If the lubricant is degraded then there are a number of possible explanations of the cause of the degradation. One is that the fluid is subject to localised high heating to temperature above the 120°C specified. Another is that the effects of being used in a very thin film, Vaisala state 6 mg per bearing [4]. This can catalysis degradation of the fluid at lower temperatures than the specification quotes. An alternative explaination is an incompatibility between the lubricant and other materials used in the bearing such as any seals.

It is noted that if the reduced rundown time and the under-estimation of the wind speed is due to bearing wear, this will impact on both models of anemometer. However, if the sole cause is the lubricant then only the model WAA251 heated anemometer will be affected. This will need further investigation to clarify the problem.

5. CONCLUSIONS

Both the WAA151 and the WAA251 anemometers meet the specifications for uncertainty and threshold wind speed for specification ES A2659. Against specification ES 835 the WAA151 passed the specification for uncertainty at all other wind speeds, threshold wind speed, maximum change in correction to the wind speeds and change from negative to positive correction.

Against the commonly used specification ES A2659 the model WAA151 anemometer passed the rundown time test with a rundown time of 45 s. However, it failed against ES 835.

The heated model WAA251 anemometer failed both specifications with a rundown time of <8 s. This is of particular concern since it will impact significantly on the measurements of wind gusts. This apparent deterioration of the anemometer after only six months use in relatively low wind run conditions calls into question the usefulness of the WAA251 anemometer in an operational network. Further work is required to confirm the cause of the low rundown time.

Neither anemometer was tested for the distance constant.

6. RECOMMENDATIONS

It is recommended that the WAA151 be field tested for between 6 and 12 months and then re-examined.

The WAA251 failed to satisfy either specification. While the WAA151 and WAA251 are based on the same design parameters, there are fundamental differences in the two units, particularly the inclusion of heating elements and the lubricant used in the bearing of WAA251. Consequently it is recommended that the WAA251 not be used or be withdrawn from the Bureau’s network until the re-examination of the WAA151 is complete. If the latter is found suitable for network use, then the WAA251 should be reassessed.

Further, examination of the cup construction suggests the units could be less suitable for high wind regimes including tropical cyclone areas.

7. REFERENCES

1 Bureau of Meteorology, Specification ES 835 Anemometer Cup Contact Type ,1969.

2 American Standard Test Method ASTM D5096-96 (Standard Test Method for Determining the Performance of a Cup Anemometer or Propeller Anemometer)

3 Bureau of Meteorology ES A2659 Guidance Specification (Functional) for a General Purpose Automatic Weather Station (AWS) E. E. Jesson June 1989.

4 Personal communication from Robert Ireland March 2001

5 AreoShell Book Edition 18, May 2003, p 236.

APPENDIX 1 - Conversion Calculations for Reference Wind.

Before commencing testing, the calibration of the Pitot tube's pressure transducer was checked against the reference water manometer. The Pitot tube was simultaneously connected to the water manometer and the pressure transducer. The output of the pressure transducer was monitored by a Hewlett Packard digital voltmeter (HP3457A S/N 3114A14559) and recorded using a personnel computer.

The linear regression of the fit of the voltage (V) against pressure (P_p) in mmH_20 using the regression function in Excel2000 is given below where the figures in brackets are the standard errors for the data. It was noted during testing that the zero offset of the pressure transducer drifted with time and this was checked at the beginning of each test and included in the calculations. Subsequent tests of the slope of the pressure transducers output demonstrated that this did not change with time. Therefore the linear regression equation was valid for all experiments.

$P_p = 9.959857\ (0.0183) * (V-V_o) + 0.066594\ (0.0849)$

Where V is the output of the pressure sensor

V_o is the zero offset of the voltmeter due to sensor drift

The linear regression fit gave a correlation coefficient of 0.999 and a standard error for the fit 0.161 for 10 observations.

The pressure measurement was then converted to wind speed (W) in m/s using the following equation.

$W = \surd \{ 2 * \rho_{H2O}/\rho_{Air} * g * P_p/1000 \}$

where g is gravity and the test location (m/s^2),

ρ_{H2O} is the density of water (kg/m^2), and

ρ_{Air} the corrected density of air in the tunnel (kg/m^2).

The density of air ρ_{Air} was corrected for changes in temperature using the following equation [3].

$\rho_{Air} = 1.2929 * 273.15 / T_t * (P_{amb} / 1.33322) – 0.3783 * V_p$

where T_t is the air temperature in the tunnel in Kelvin, and

P_{amb} is the ambient pressure in the tunnel (hPa).

After some checks of the sensitivity of the density to changes in relative humidity it was established that the effect was insignificant and a constant vapour pressure V_p of 8.61, equivalent to approximately 50% RH was used.

APPENDIX 2

Uncertainty analysis of the reference wind speed and Vaisala anemometer.

Table A2.1 Reference wind speed uncertainty analysis

The following table is an analysis of the major contributors to the uncertainty in the reference wind speed. These include the uncertainty in the

- fit of the voltage output of the Pitot tube sensor to the water manometer.
- the determination of the air density correction to the wind speed,
- the ambient air pressure in the tunnel,
- air temperature in the tunnel,
- vapour pressure.
- the voltage measurement and
- the stability of the air flow in the tunnel as estimated from the variation in the determination of the wind speed by the reference.

Reference ***Wind Speed***	***Std Uncert.*** ***Fit to Algorithm***	***Std Uncert.*** ***Density***	***Std Uncert.*** ***Pressure***	***Std Uncert.*** ***Temp***	***Std Uncert.*** ***Vp***	***Std Uncert.*** ***Volts***	***Std Uncert.*** ***Tunnel Stability***	***Combined Uncert.*** ***Total***	***Expand. Uncert*** ***Total***
0.06	0.068	0.000	<0.001	0.001	0.001	0.000	0.025	0.072	0.159
0.93	0.068	0.000	<0.001	0.001	0.001	0.000	0.025	0.072	0.159
1.77	0.068	0.000	<0.001	0.001	0.002	0.000	0.025	0.072	0.159
2.04	0.068	0.000	0.001	0.001	0.002	0.000	0.025	0.072	0.159
3.45	0.068	0.000	0.001	0.002	0.003	0.000	0.025	0.072	0.159
4.94	0.068	0.000	0.001	0.002	0.004	0.000	0.025	0.072	0.159
7.41	0.068	0.001	0.002	0.004	0.006	0.000	0.025	0.073	0.160
9.39	0.068	0.001	0.002	0.005	0.008	0.000	0.025	0.073	0.160
10.06	0.068	0.001	0.003	0.005	0.009	0.000	0.025	0.073	0.161
15.09	0.068	0.001	0.004	0.007	0.013	0.000	0.025	0.074	0.163
20.41	0.068	0.002	0.005	0.010	0.018	0.000	0.025	0.075	0.165
25.29	0.068	0.002	0.006	0.013	0.022	0.000	0.025	0.077	0.169

Note: All values in the above table are quoted in m/s.

A coverage factor of $k = 2.19$ for $\nu_{eff} = 12$ was derived for determining the expanded uncertainty at 95% confidence.

Table A2.2 Vaisala WAA151 wind speed uncertainty analysis

There are five identified contributors to the uncertainty in the estimation of the wind speed using the Vaisala anemometers excluding the calibration of the anemometer itself. These are the uncertainty

- in the regression calculation supplied by Vaisala,
- the frequency measurement used to monitor the anemometer,
- and the instability or precision of the anemometer as determine from the variance of the correct to the reference wind speed,
- the instability of the flow in the tunnel and
- the nonlinearity of the anemometers response.

Reference	***Std Uncert.***	***Std Uncert.***	***Std Uncert.***	***Std Uncert.***	***Std Uncert.***	***Combined Uncert..***	***Expand. Uncert***	***Expand. Uncert***
Wind Speed	***Fit to Vaisala Algorithm***	***Frequency***	***Tunnel Stability***	***Instrument Stability***	***Non-Lin***	***Vaisala WAA151***	***Vaisala WAA151***	***Correction***
0.06	0.002	0.0004	0.025	0.035	0.062	0.075	0.158	0.209
0.93	0.005	0.0004	0.025	0.035	0.062	0.076	0.159	0.209
1.77	0.009	0.0004	0.025	0.035	0.062	0.076	0.160	0.210
2.04	0.010	0.0004	0.025	0.036	0.062	0.076	0.161	0.210
3.45	0.017	0.0004	0.025	0.036	0.062	0.078	0.164	0.212
4.94	0.025	0.0004	0.025	0.037	0.062	0.080	0.168	0.215
7.41	0.037	0.0004	0.025	0.038	0.062	0.085	0.178	0.221
9.39	0.047	0.0004	0.025	0.038	0.062	0.090	0.189	0.229
10.06	0.050	0.0004	0.025	0.039	0.062	0.092	0.193	0.232
15.09	0.075	0.0004	0.025	0.040	0.062	0.109	0.228	0.260
20.41	0.102	0.0004	0.025	0.042	0.062	0.129	0.271	0.299
25.29	0.126	0.0004	0.025	0.044	0.062	0.149	0.314	0.340

Note: All values in the above table are quoted in m/s.

The uncertainty components for the instrument under test provided a degrees of freedom of ν_{eff} = 22 and associated coverage factor k=2.09. This together with the uncertainty components of the reference wind gave an ν_{eff} = 29 for the correction values and associated coverage factor of 2.05. In calculating the expanded uncertainty for the measurand the uncertainty for the tunnel stability was only incorporated once.

Table A2.3 Vaisala WAA251 wind speed uncertainty analysis

Reference *Wind Speed*	*Std Uncert.* *Fit To Algorithm*	*Std Uncert.* *Freq*	*Std Uncert.* *Tunnel Stability*	*Std Uncert.* *Instrument Stability*	*Std Uncert.* *Non-Lin*	*Combined Uncert.* *Vaisala WAA251*	*Expand. Uncert* *Vaisala WAA251*	*Expand. Uncert* *Correction*
0.15	0.002	0.0004	0.025	0.017	0.025	0.040	0.083	0.167
2.00	0.010	0.0004	0.025	0.020	0.025	0.042	0.089	0.169
3.25	0.016	0.0004	0.025	0.023	0.025	0.046	0.096	0.171
4.78	0.024	0.0004	0.025	0.026	0.025	0.050	0.105	0.176
6.85	0.034	0.0004	0.025	0.030	0.025	0.058	0.121	0.184
7.62	0.038	0.0004	0.025	0.031	0.025	0.061	0.128	0.188
9.85	0.049	0.0004	0.025	0.035	0.025	0.071	0.148	0.200
14.56	0.073	0.0004	0.025	0.044	0.025	0.093	0.195	0.235
15.10	0.076	0.0004	0.025	0.045	0.025	0.096	0.201	0.240
20.22	0.101	0.0004	0.025	0.055	0.025	0.121	0.253	0.285
25.31	0.127	0.0004	0.025	0.065	0.025	0.147	0.308	0.337

Note: All values in the above table are quoted in m/s.

The uncertainty components for the instrument under test provided a degrees of freedom of $\nu_{eff} = 26$ and associated coverage factor k=2.07. This together with the uncertainty components of the reference wind gave an $\nu_{eff} = 23$ for the correction values and associated coverage factor of 2.08. In calculating the expanded uncertainty for the measurand the uncertainty for the tunnel stability was only incorporated once.