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Repeatability of the Monash Wind Tunnel

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1. AIM

To examine the repeatability of anemometer calibrations performed at the wind tunnel at the Monash University facility of Engineering at Clayton (MONASH) and their relationship to the previous calibrations performed at the wind tunnel at the CSIRO Atmospheric Research at Aspendale (CAR).

2. BACKGROUND

Networks and Measurements Section sponsored the Regional Instrument Centre (RIC) to evaluate calibration and verification methods for wind speed in the observation network. The RIC produced a technical report TN 2002-009 [1] on the theoretical uncertainty of using a pitot tube reference and instrument test report ITR2002_662 [2] on the consistency of calibrations of Sy706 anemometers performed at two Melbourne wind tunnels. The instrument test report concluded that further work on the reproducibility of the MONASH wind tunnel would be required before a recommendation can be made as to what wind tunnel would be suitable for Bureau anemometer verification work. The findings are the subject of this report.

3. TEST PROCEDURE

The evaluation of the MONASH wind tunnel using pitot tube as the reference was in accordance with TN 2002-009 [1], and the calibration data for the pitot tube against the analogue pressure transducer is summarised in Appendix I. The test procedure and evaluation were based on that used in ITR 2002-662 [2] for the MONASH wind tunnel. The data were collected on 12 and 13 June 2002.

The details of the equipment used at the MONASH facility are as follows:

- Synchrotac 706 (Sy706) anemometers (5): Serial Numbers 81286, 81268, 81279, 81287, 81283.
- TSI Hot-wire anemometer: Serial Number 01040518.
- The MONASH pitot static tube. The pitot tube had been moved since the last test was performed in December 2001. It was placed back into position by sight using ITR2002_662 [2] as the reference.
- An analogue pressure transducer amplifier system and a differential water manometer.
- Fluke digital multimeter 8842A: Serial Number 4609294.
- TSI Hot-wire anemometer: Serial Number 01040518.
- Rosemount Slimline RTD Serial Number 0541.
- Datataker 500: Serial Number 16532.
- Paroscientific 1107-102 barometer: Serial Number 56315.
- HP53131A Universal Counter: Serial Number 3736A23981.
- Tektronix digital CRO: Serial Number B020157.

4. RESULTS

The Bureau uses a single linear relationship between wind speed and instrument output for the Sy706 anemometers, the first order polynomial is in the form

$$S = A_x \Omega + B_x \qquad (1)$$

where S is the wind speed (ms^{-1} or knots) Ω is the frequency output of the anemometer (Hz), A_x is the inferred slope (ms^{-1}/Hz) and B_x is the inferred wind speed for zero output.

The MONASH data obtained in June 2002 was processed to provide data pairs of mean output and mean 'Tunnel Wind' speed. The 'Tunnel Wind' speed estimates were obtained from application of the Bernoulli equation [1]. These statistics were then used to derive sensitivity coefficients (slope and intercept, A_{June_Monash}, B_{June_Monash} respectively) via least squares analysis of equation (1), and the results are presented in Table 1. Tabulated in Appendix II are the mean anemometer output, 'Tunnel Wind', number of samples for each mean and the 95% expanded uncertainty for the 'Tunnel Wind' speeds.

The differences between the derived slopes from MONASH performed in June 2002 and the calibrations performed in December 2001 data sets are shown in Table 2. The differences between the derived slopes from MONASH performed in June 2002 and the calibrations at CAR data sets are shown in Table 3.

Table 1. Least square analysis results for the Monash calibrations of June 2002.

Anemometer	**No. of Speeds**	**Intercept (ms^{-1})**	**Std. Error Intercept**	**Slope (ms^{-1}/Hz)**	**Std. Error Slope**	**Std. Error Fit**
81268	17	0.2393	0.0316	0.5409	0.0008	0.0605
81279	16	0.2328	0.0337	0.5397	0.0008	0.0642
81283	16	0.1114	0.0401	0.5446	0.0009	0.0691
81286	16	0.1484	0.0467	0.5454	0.0012	0.0895
81287	16	0.2350	0.0382	0.5434	0.0009	0.0743
Average		***0.1869***		***0.5428***		

Table 2. Least square analysis slopes for Dec 2001 and June 2002 MONASH calibrations.

Anemometer	**MONASH Dec 01 Slope (ms^{-1}/Hz)**	**MONASH June 02 Slope (ms^{-1}/Hz)**	**%Difference MONASH June 02 – MONASH Dec 01**
81268	0.5499	0.5409	-1.64
81279	0.5518	0.5397	-2.19
81283	0.5545	0.5446	-1.78
81286	0.5523	0.5454	-1.25
81287	0.5527	0.5434	-1.68
Average	***0.5522***	***0.5428***	***-1.71***

Table 3. Comparison of the linear least squares analysis slopes for the CAR calibrations expressed as a percentage of the MONASH June 02 calibration.

Anemometer	**Car Sept 01 Slope (ms^{-1}/Hz)**	**Car Mar 02 Slope (ms^{-1}/Hz)**	**%Difference MONASH June 02 – CAR Sept 01**	**%Difference MONASH June 02 – CAR Mar 02**
81268	0.5440	0.5716	-0.57	-5.37
81279	0.5460	0.5695	-1.15	-5.23
81283	0.5423	0.5678	0.44	-4.07
81286	0.5471	0.5683	-0.31	-4.03
81287	0.5441	0.5689	-0.13	-4.48
Average	***0.5447***	***0.5692***	***-0.35***	***-4.64***

Figure 1 shows the linear regression to the data collected at MONASH for Synchrotac 81287 and both sets of calibration data collected by CAR. At each reference wind speed the U_{95} in measurement is displayed as a set of error bars.

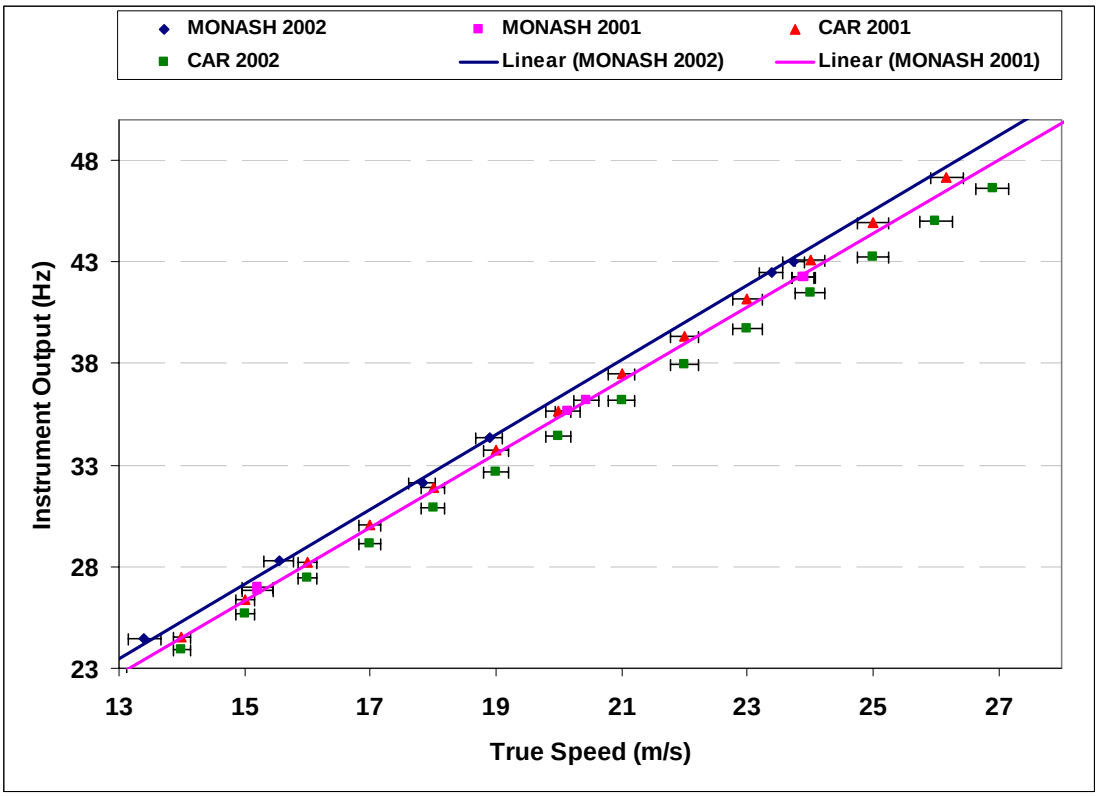


Figure 1. Linear regression for Synchrotac 81287 performed at Monash, with U_{95} included compared against both calibration checks performed by CAR.

5. DISCUSSION

The MONASH June 2002 results are on average 1.7% less than those obtained at MONASH in December 2001. This equates to an average difference in the derived wind speed of approximately 0.8 ms^{-1} (at an approximate wind speed of 35 ms^{-1}). The analysis shows that differences in the two MONASH wind tunnel calibrations were just outside their combined 95% uncertainties derived from [1].

One of the possible contributors to the difference between the two MONASH calibrations could be the small difference in position of the pitot tube within the MONASH wind tunnel. The pitot tube had been moved since the last test was performed in December 2001; the pitot tube was placed back into the last operating position by sight only using ITR2002_662 [2] as a reference for position.

The relative position of the pitot tube must be incorporated in any future uncertainty analysis when working at the MONASH wind tunnel.

Figure 1 shows that the September 2001 CAR calibration resides between the MONASH calibrations and is within each of their combined 95% uncertainties and that the difference between the MONASH calibrations and CAR March 2001 calibration is of the order of 5%. The March 2002 CAR calibration is significantly different from all other calibrations performed on the anemometers.

As shown in Appendix I the relationship between the signal from the differential pressure transducer and the manual reading of the water manometer height had varied from the previous calibration performed in December 2001. If it is assumed that the change in calibration is a potential offset, unaccounted in the uncertainty analysis [1],

a further contribution to the uncertainty needs to be included to the pitot tube derived estimate of height, h.

6. CONCLUSION

The differences in sensitivities (represented by least squares slope) of the Syn706 anemometers tested using the MONASH wind tunnel were of the order of 2% for both periods. Therefore the calibrations performed at MONASH were not quite repeatable since the U_{95} of the two calibrations performed at MONASH did not overlap. This small difference between U_{95} overlap suggests that future MONASH calibrations should accommodate some more sources of uncertainty if one assumes the instruments have a stable sensitivity.

The overall relationship between the MONASH and CAR calibrations showed that there was a high degree of agreement between the two MONASH calibrations and the CAR September 2001 calibration. There was however significant offset between the calibrations performed at CAR in March 2002 and the calibrations performed at MONASH and those during September 2001 at CAR.

The difference between the two sets of MONASH slope calibrations for the 5 Syn706 anemometers is a maximum of 2.2%. The 95% uncertainty of the calibration process at MONASH, referenced to the MONASH wind tunnel, appears to be <2%. This implies that the method used at MONASH could be used to examine the consistency of wind measurement across the observing network. However, determination of true wind speed will have to await better definition of a reference standard.

7. REFERENCES

[1] Forgan B.W. (2002) The Uncertainty in the wind speed on the application Bernoulli's Equation for the Bureaus wind system. Bureau of Meteorology, Tech. Note 2002_009, pp 13.

[2] Berechree, M.I. (2002). Wind Tunnel Evaluation Test Report. Bureau of Meteorology, Inst. Test. Rept. 2002_662, pp 44.

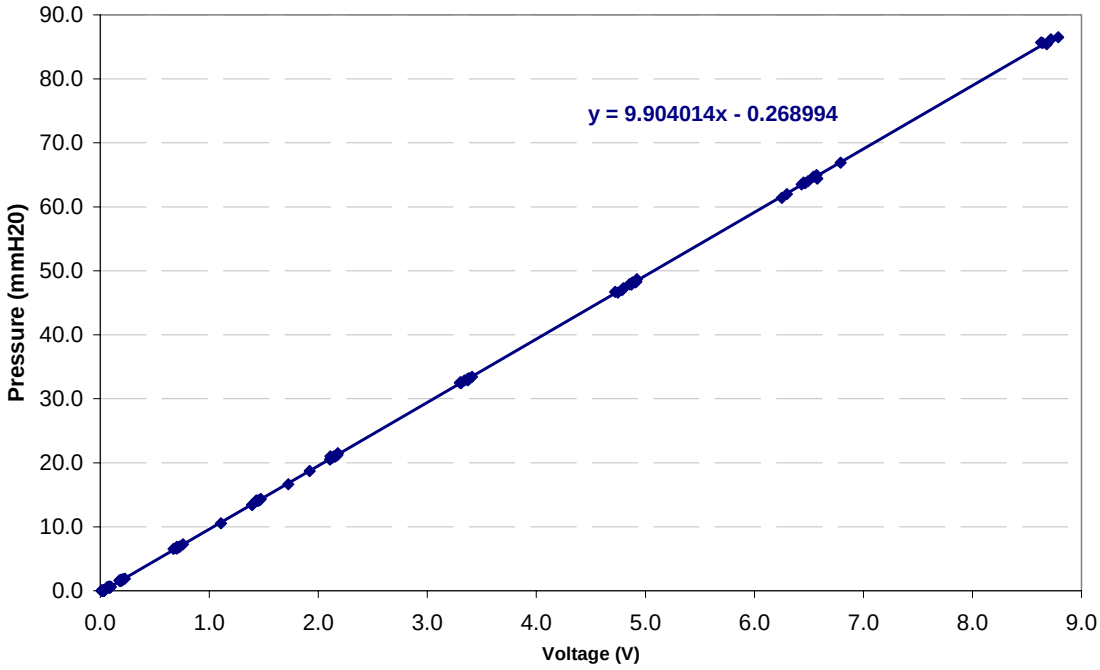
Appendix I. Conversion Calculations for Reference Wind

The procedure for calibrating the pitot static tubes pressure transducer as a representation of the reference water manometer followed that used in ITR2002_662 [2].

A linear regression of the fit of the voltage (V) from the pressure transducer against the mmH_2O displacement (P_p) from the water manometer is given below where the figures in the brackets are the standard errors for the data:

$$P_p = 9.9040(0.0057) * \text{Voltage} - 0.2689(0.0204)$$

with a coefficient of determination of 0.99997 and an overall standard error of the fit of 0.143.



FigureI-1. Linear regression of the fit of the voltage from the pressure transducer against the displacement reading from the water manometer.

The difference in calibration of the pitot tube between the June 2002 and December 2001 was approximately +0.15% using a least square analysis for slope. This would equate to a difference in the calculated wind speed of 0.08 ms^{-1}. The change in the combined 95% uncertainty, as based on [1], and are shown in table I-1.

Table 1. Analysis of the effect of 0.15% change in the slope between height estimates and voltage of pitot tube on the combined U_{95} uncertainties for Syn706 Serial Number 81283.

Speed (m/s)	%Difference (U95)
5.37	0.14
10.49	0.14
15.23	0.13
18.76	0.12
23.47	0.10
28.40	0.08
32.83	0.06
38.09	0.04

Appendix II. Wind Tunnel data

Tables II-1 through to II-5 lists the statistics for each Syn706 anemometers output, and derived MONASH wind speeds used for the least squares regression analysis. Major contributors to the uncertainty at each mean wind speed were as follows:

- fit of the pressure transducer (V) verse the water manometer (mmH_20).
- the air density within the wind tunnel.
- the uncertainty in measurement for the digital multimeters.

Table II-1. Statistics for S/N 81286

Number of Samples	Average Instrument Output (Hz)	Standard Deviation Instrument Output (Hz)	Speed (m/s)	Standard Deviation (m/s)	U95 m/s	U95 %
32	5.1322	0.0618	2.94	0.0538	0.646	11.38
8	9.3714	0.0516	5.23	0.0298	0.518	7.30
37	19.9803	0.1032	10.97	0.0376	0.308	2.56
45	28.0351	0.1193	15.32	0.0307	0.236	1.46
50	34.4018	0.1737	18.89	0.0335	0.202	1.03
53	42.9208	0.1563	23.58	0.0431	0.179	0.74
43	52.0098	0.1681	28.49	0.0421	0.171	0.59
33	59.6500	0.2720	32.87	0.0498	0.173	0.52
59	69.8100	0.2819	38.23	0.0437	0.181	0.47
50	60.5550	0.2194	33.07	0.0442	0.173	0.51
36	51.9542	0.1791	28.51	0.0392	0.171	0.59
32	42.8875	0.1500	23.57	0.0312	0.180	0.74
46	33.8802	0.1785	18.66	0.0435	0.204	1.06
31	27.5752	0.1363	15.09	0.0317	0.239	1.50
32	19.5431	0.0985	10.75	0.0233	0.314	2.66
9	8.9637	0.0607	5.14	0.0409	0.524	7.47
21	4.8744	0.0491	2.95	0.0312	0.656	11.74

Table II-2. Statistics for S/N 81279

Number of Samples	Average Instrument Output (Hz)	Standard Deviation Instrument Output (Hz)	Speed (m/s)	Standard Deviation (m/s)	U95 m/s	U95 %
14	4.8987	0.0345	2.95	0.0613	0.655	11.72
18	9.3468	0.0437	5.28	0.0353	0.515	7.24
59	19.7217	0.1130	10.81	0.0448	0.313	2.64
57	28.3646	0.1100	15.48	0.0254	0.234	1.44
71	34.4358	0.1342	18.83	0.0313	0.203	1.04
56	43.0989	0.2716	23.62	0.0249	0.179	0.74
71	51.5566	0.2054	28.04	0.0256	0.171	0.60
68	60.3607	0.2748	32.75	0.0459	0.172	0.52
68	70.1072	0.2408	38.07	0.0372	0.181	0.47
56	59.5727	0.2360	32.31	0.0293	0.172	0.52
69	52.2480	0.2678	28.45	0.0308	0.171	0.59
63	43.4568	0.2338	23.82	0.0383	0.179	0.73
49	30.8131	0.1375	16.87	0.0304	0.220	1.25
66	27.6564	0.1215	15.10	0.0350	0.239	1.51
55	19.5093	0.1089	10.73	0.0476	0.315	2.68
33	9.9757	0.0539	5.63	0.0345	0.498	6.75
33	5.6314	0.0490	3.31	0.0508	0.634	10.95

Table II-3. Statistics for S/N 81283

Number of Samples	Average Instrument Output (Hz)	Standard Deviation Instrument Output (Hz)	Speed (m/s)	Standard Deviation (m/s)	U95 m/s	U95 %
21	9.5817	0.0819	5.36	0.0305	0.510	7.08
64	19.0663	0.0895	10.50	0.0359	0.320	2.76
86	27.9929	0.1263	15.32	0.0434	0.236	1.46
78	34.1646	0.1561	18.76	0.0251	0.204	1.05
86	42.7828	0.2632	23.53	0.0347	0.180	0.74
94	52.0279	0.2055	28.44	0.0421	0.171	0.59
105	60.8315	0.2290	32.88	0.0432	0.173	0.52
87	69.6946	0.2662	38.07	0.0378	0.181	0.47
82	60.7774	0.2809	33.12	0.0405	0.173	0.51
66	51.5244	0.2074	28.22	0.0331	0.171	0.60
72	42.9828	0.1908	23.65	0.0375	0.179	0.74
72	34.2250	0.1214	18.75	0.0353	0.204	1.05
60	28.1217	0.1120	15.46	0.0355	0.235	1.45
49	19.2882	0.0902	10.58	0.0484	0.319	2.74
27	9.2464	0.0604	5.08	0.0396	0.526	7.53
20	5.2996	0.0849	2.78	0.0602	0.664	12.01

Table II-4. Statistics for S/N 81268

Number of Samples	Average Instrument Output (Hz)	Standard Deviation Instrument Output (Hz)	Speed (m/s)	Standard Deviation (m/s)	U95 m/s	U95 %
33	5.5248	0.0452	3.37	0.0523	0.665	12.05
9	9.4866	0.0718	5.43	0.0389	0.525	7.51
61	19.5043	0.0937	10.79	0.0235	0.317	2.72
97	28.1023	0.1264	15.42	0.0318	0.237	1.47
82	34.3489	0.1466	18.84	0.0421	0.204	1.05
90	42.7776	0.2108	23.50	0.0306	0.180	0.75
104	51.8911	0.2339	28.35	0.0340	0.171	0.60
114	60.6252	0.2510	32.98	0.0426	0.173	0.52
101	69.9893	0.2497	38.12	0.0511	0.181	0.47
103	60.7684	0.2373	33.00	0.0347	0.172	0.52
95	51.6561	0.2373	28.20	0.0380	0.172	0.60
76	42.8976	0.1982	23.52	0.0341	0.180	0.75
98	35.0656	0.1378	19.20	0.0468	0.202	1.03
80	28.3376	0.1075	15.53	0.0284	0.236	1.46
54	19.1693	0.0969	10.56	0.0289	0.324	2.83
39	9.1448	0.0483	5.20	0.0477	0.543	8.04
23	5.1823	0.0754	2.98	0.0635	0.684	12.76

Table II-5. Statistics for S/N 81287.

Number of Samples	Average Instrument Output (Hz)	Standard Deviation Instrument Output (Hz)	Speed (m/s)	Standard Deviation (m/s)	U95 m/s	U95 %
26	4.5625	0.0525	2.79	0.0527	0.665	12.05
12	8.8335	0.0692	5.07	0.0403	0.524	7.49
40	19.1338	0.1007	10.57	0.0199	0.319	2.74
45	28.2891	0.1291	15.55	0.0259	0.234	1.43
53	34.3432	0.1990	18.89	0.0291	0.203	1.03
51	42.5073	0.1902	23.38	0.0386	0.180	0.75
47	52.2149	0.2028	28.59	0.0355	0.171	0.59
61	61.4149	0.2162	33.54	0.0355	0.173	0.51
43	69.6174	0.3116	38.13	0.0498	0.181	0.47
52	59.2025	0.2329	32.37	0.0324	0.172	0.52
49	52.0424	0.2055	28.51	0.0306	0.171	0.59
41	43.0254	0.2147	23.74	0.0471	0.179	0.74
34	32.1512	0.1156	17.83	0.0321	0.211	1.14
46	24.4820	0.0979	13.40	0.0257	0.263	1.84
39	19.3351	0.1074	10.70	0.0281	0.316	2.69
12	9.4438	0.0528	5.38	0.0075	0.511	7.11
17	5.1739	0.0506	3.11	0.0447	0.646	11.38