Update on the Performance of the WVSS-II Hygrometers Fitted to the FAAM BAe 146.

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1. Introduction

Previous reports on the performance or the WVSS-IIs fitted to the FAAM BAe 146 aircraft (e.g. Vance et al., 2015) used data from one particular configuration of these instruments and, most notably, showed that the WVSS-II fitted to the flush inlet ("air sampler") reported significantly higher humidities, in dry conditions, than the one fed from the modified Rosemount inlet. Although it was possible that the observed difference was due to other effects, it was supposed that the discrepancy arose from the inlets, as this appeared to be the most significant difference, and because over reading of flush inlet-fed WVSS-IIs, in comparison to other hygrometers, had been noted by other groups (A. Hoff and S. Carlberg, personal communications, 2011). This attribution was, however, an assumption whose investigation was precluded by the fixed configuration in which the data were recorded. The work reported herein, seeks to investigate the source of this apparent wet bias.

2. Instrumentation and Data Selection

The airborne instruments used in this study are as described in Vance et al., 2015, with the exception that which WVSS-II was connected to each inlet was varied, and each WVSS-II was flown with and without its sample cell heater running. This was done with the intention of separating out the effects of these three variables: inlet, heater, and instrument. As it is clearly impossible to fly the same instrument in two different configurations, simultaneously, it is necessary to make use of a third instrument as a transfer standard. For this purpose, the General Eastern chilled mirror hygrometer (GE) was used, as it was the only other instrument to have been present and operational on all flights. The use of the GE in this capacity does, however, put considerable limitations on this study because of its relatively slow response, poor performance in very dry conditions, occasional oscillations following a rapid change in humidity, and, when its mirror temperature is between 0 and -40 ^{o}C, the increased uncertainty in its output arising from the possibility that it could be reporting either a dew point or a frost point.

The data selection in this study is similar, in principle, to that used in previous work but is necessarily different as a result of the absence of the Buck CR2 from many of the flights used. Two criteria were used to select data: firstly, the rate of change of the humidity in both instruments had to be below a certain threshold, so that rapidly changing conditions, in which measurement is more challenging, are rejected; secondly, the differential rate of change between the two WVSS-IIs had to be below a certain value, so that data are rejected when it seems likely that one of the instruments is, by some definition, malfunctioning. This second criterion is, however, ignored if the rate of change of one WVSS-II is very low, because the situation may exist where one instrument has reached its lower limit, but the other is continuing to respond to atmospheric conditions. As there is interest in the performance of WVSS-IIs near their dry limits, it is important to not reject these data. The precise value of these thresholds was arrived at by inspection and set so as to reject around 90% of the data. All flights were inspected, individually, to remove any where gross errors were apparent in the humidity data. Unlike previously, no offset corrections between instruments were carried out.

Previously the two WVSS-IIs have been referred to by the inlet to which they were connected ('wvssF' or 'wvssR') but in this study, due to the changing configurations, that form of identification is no longer helpful; here we shall refer to the WVSS-IIs strictly by their serial numbers. To link with previous reports:

- 378 is the original wvssF which failed in the latter part of the previous study;
- 388 is the original wvssR;
- 4229 is instrument which replaced 378 in the latter part of that study - the 'new' wvssF.

In addition to these, 4252 shall also be mentioned, although there are currently no airborne data from this instrument. The configurations flown are given in table 1. It will be noticed that configuration 1 is split into two parts: this has been done as there appears to have been a change in the relative performance of the GE and WVSS-IIs, which prevents comparison across this time (figure 1). During October 2013 the aircraft underwent extensive maintenance (C-check), requiring the removal of most instruments; the main data recording system was also replaced at this time. Figure 1 shows the difference between data from the GE and both WVSS-IIs (388 and 4229), as a function of the WVSS-II absolute humidity (d_v), recorded in the two parts of the configuration 1 period (before and after October 2013); the four data sets are overlaid with binned medians. Conversion of humidity data to absolute humidity makes use of the temperature measurement from the deiced sensor, and the aircraft's reduced vertical separation minima (RVSM) pressure. The cause of this change in the difference between the GE and WVSS-IIs is not currently known, nor it considered, here; it is simply noted that the GE cannot be used to compare instruments across this time.

The reader should also note that in October 2018, a comparison (described in section 4) was carried out against FAAM's MBW 973-L calibrated chilled mirror hygrometer (MBW Calibration, 2018), and all data from 388, presented here, have been corrected according to the results of this.

config.	dates	flight no.	flush	Rosemount
0	Feb 2011 - Mar 2013	b573 -b756	378, heated	388, unheated
1a	April 2013 - Sept 2013	b772- b809	4229, heated	388, unheated
1b	Nov 2013 - May 2014	b810 - b850	4229, heated	388, unheated
2	May 2014 - Nov 2014	b851 - b872	388, unheated	4229, heated
3	Nov 2014 - Jan 2018	b873 - c071	388, heated	4229, unheated
4	Jan 2018 - Apr 2018	c074 - c093	4229, unheated	388, heated
5	Apr 2018 - May 2018	c094 - c102	388, unheated	4229, heated
6	May 2018 - July 2018	c103 - c110	388, unheated	4229, unheated
7	July 2018 - Oct 2018	c111 - c121	4229, unheated	388, unheated

Table 1. Configurations of WVSS-IIs, showing serial numbers on each inlet, with its sample cell heater state, and dates flown.

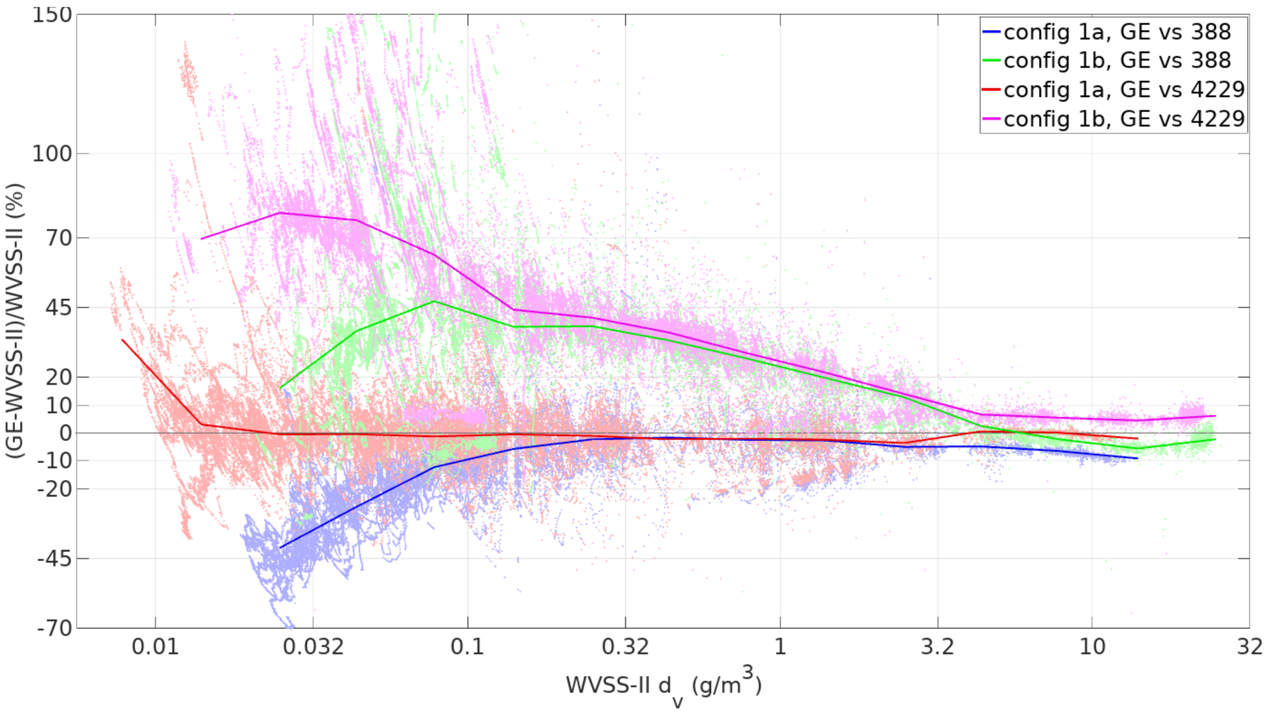

Figure 1. Comparison of GE to WVSS-II absolute humidity before and after October 2013.

3. Inlets, Heaters, Serial Numbers

It was hoped that by varying the configuration it would be possible, unambiguously, to locate the source of the wet bias seen previously. In order to achieve this, data were selected in pairs of groups from the sixteen available (eight configurations, two inlets) described in table 1, so that only the parameter of interest varied. In the following sections, table 1 is partially reproduced with each of these pairs highlighted in different colours. For each of these groups, binned medians are calculated for WVSS-II minus GE, as a percentage of GE absolute humidity. The difference of these medians is then plotted in the colour of the pair of groups being compared. This exercise is carried out, separately, to investigate differences arising from the inlets, the heating of the sample cell, and those inherent to the particular instruments. Where there are more than one possible pair of groups, all are plotted so that, for example, the inlet comparison plot has six green lines, arising from the six possible differences between the three configurations with 388, unheated, on the flush inlet, and the two with 388, unheated, on the Rosemount inlet. In addition, it is possible to choose pairs of groups where none of the parameters under investigation change. Although it is to be hoped that these differences would be identically zero, this is clearly never going to be the case, and these 'control' comparisons provide an indication of possible uncertainty in other 'test' intercomparisons.

3.1 Control Comparisons

Figure 2 shows eight control comparisons covering the six configurations. There appears to be no significant bias in this case, as expected, but the spread of values is significant, being similar to that seen when comparing by cell heater state (section 3.3).

config.	flush	Rosemount
0	0378, heated	0388, unheated
1a	4229, heated	0388, unheated
1b	4229, heated	0388, unheated
2	0388, unheated	4229, heated
3	0388, heated	4229, unheated
4	4229, unheated	0388, heated
5	0388, unheated	4229, heated
6	0388, unheated	4229, unheated
7	4229, unheated	0388, unheated

Table 2. Data groups used as controls.

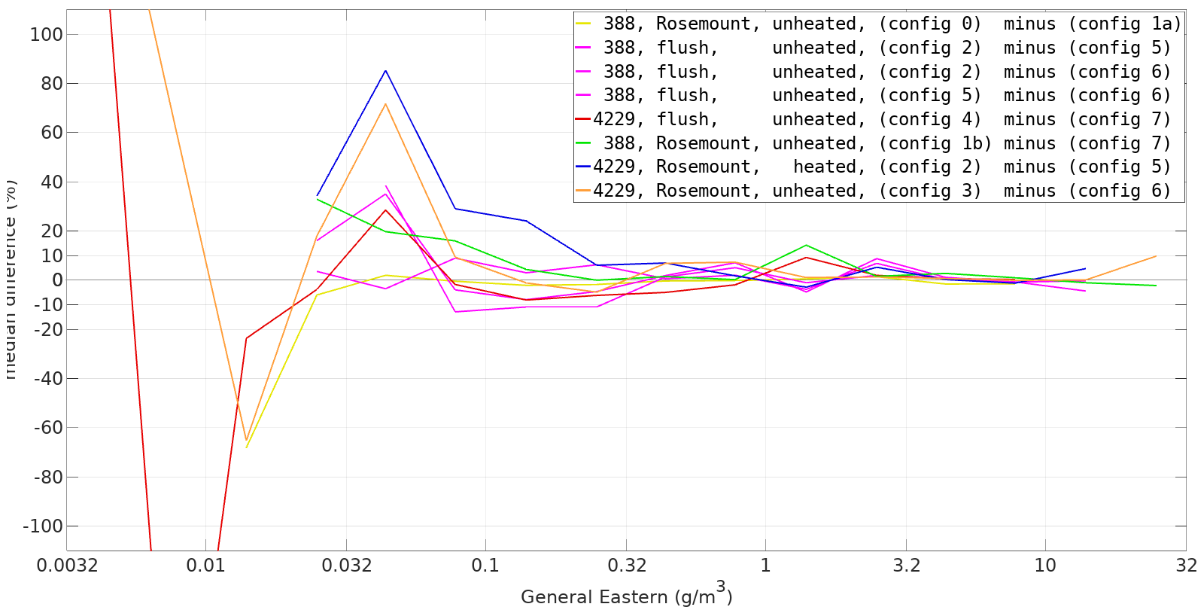

Figure 2. Differences between different groups of similar configurations, showing no obvious bias, but substantial spread.

3.2. Comparison by Inlet

Figure 3 shows eleven comparisons covering the five configurations, all differences being flush inlet minus Rosemount. There is no clear difference in the humidity range covered, although this range is limited by the performance of the GE, and considerable spread is seen, especially under drier conditions.

config.	flush	Rosemount
0	0378, heated	0388, unheated
1a	4229, heated	0388, unheated
1b	4229, heated	0388, unheated
2	0388, unheated	4229, heated
3	0388, heated	4229, unheated
4	4229, unheated	0388, heated
5	0388, unheated	4229, heated
6	0388, unheated	4229, unheated
7	4229, unheated	0388, unheated

Table 3. Data groups used to investigate inlet-generetated differences.

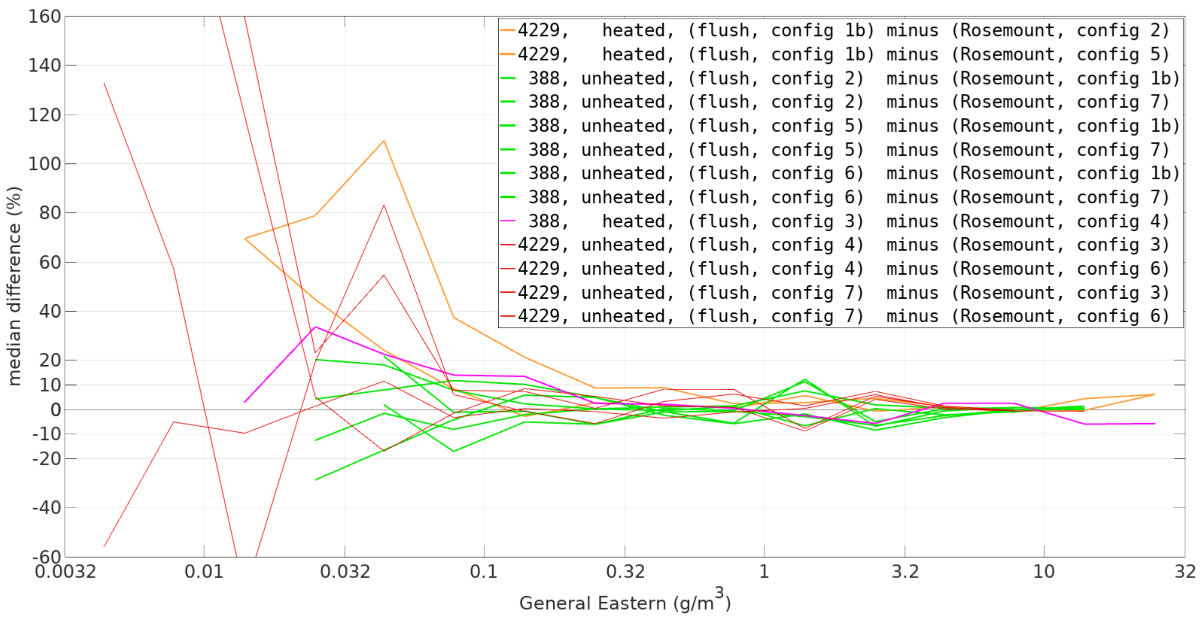

Figure 3. Differences of medians (flush minus Rosemount) showing no clear difference resulting from inlet type.

3.3. Comparison by Heater State

Figure 4 shows eleven comparisons covering the four configurations, all being plotted as heated minus unheated. As with the comparison by inlet, there is no clear bias in these data, and the spread between them is similar.

config.	flush	Rosemount
0 1a	0378, heated 4229, heated	0388, unheated 0388, unheated
1b 2 3 4 5 6 7	4229, heated 0388, unheated 0388, heated 4229, unheated 0388, unheated 0388, unheated 4229, unheated	0388, unheated 4229, heated 4229, unheated 0388, heated 4229, heated 4229, unheated 0388, unheated

Table 4. Data groups used to investigate heater-generetated differences.

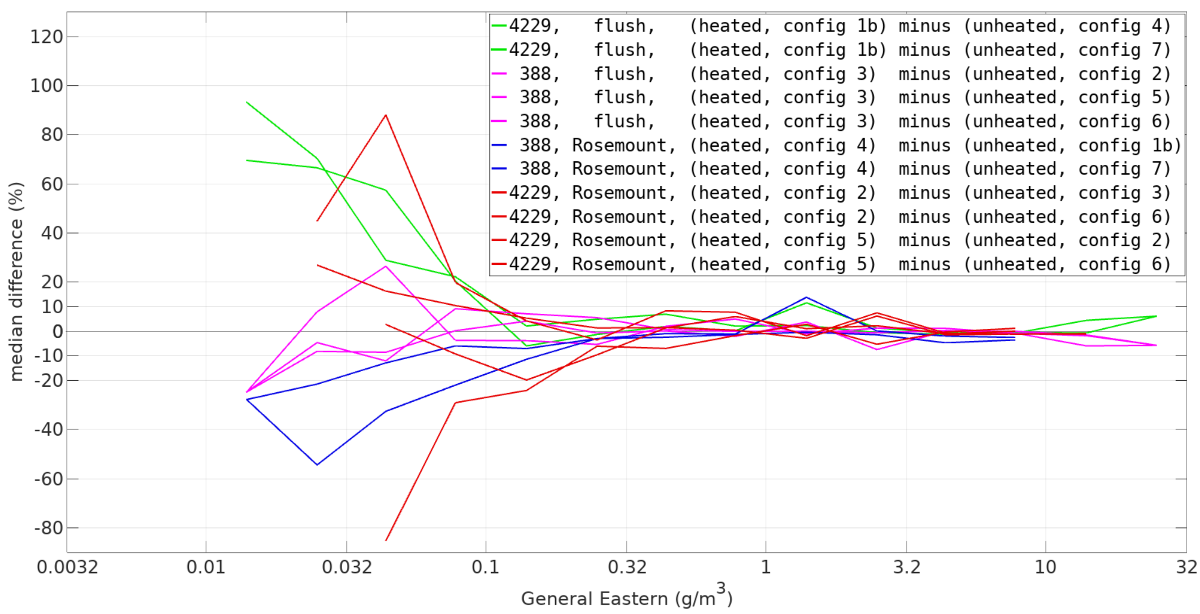

Figure 4. Differences of medians (heated minus unheated) showing no clear difference resulting from cell heater status.

3.4. Comparison by Serial Numbers

Figure 5 shows eight comparisons covering the seven configurations, all being plotted as 'old' minus 'new'; these are, with only one exception 388 minus 4229. In this case, there does appear to be some bias with 388 reporting lower values than 4229 but, again, the spread of the differences is significant and this cannot be regarded as conclusive.

config.	flush	Rosemount
0	0378, heated	0388, unheated
1a	4229, heated	0388, unheated
1b	4229, heated	0388, unheated
2	0388, unheated	4229, heated
3	0388, heated	4229, unheated
4	4229, unheated	0388, heated
5	0388, unheated	4229, heated
6	0388, unheated	4229, unheated
7	4229, unheated	0388, unheated

Table 5. Data groups used to investigate differences between instruments.

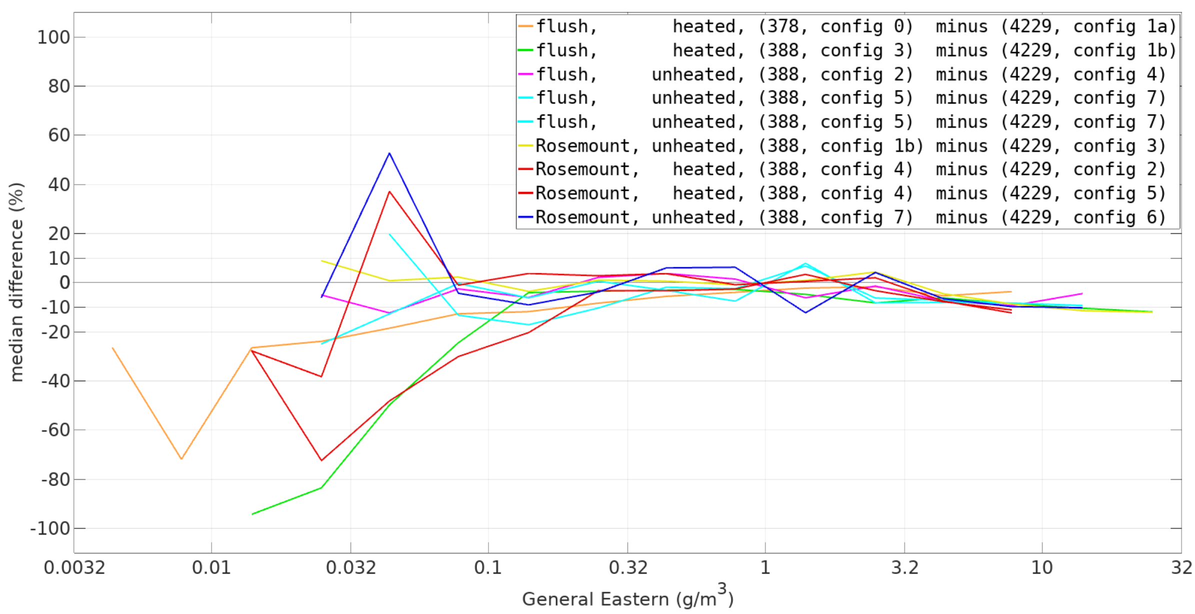

Figure 5. Differences of medians (old minus new) showing some suggestion that 4229 may report slightly higher values than 388.

4. Laboratory Measurements

In October 2018, three WVSS-IIs were compared against FAAM's calibrated MBW chilled mirror hygrometer. One WVSS-II and the MBW were fed in parallel from a Michell PSD2 pressure swing drier and Michell DG2 dew point generator (Michell Instruments, 2018a, 2018b), via stainless steel tubing; the flow rate from the humidity generator was thought insufficient to feed more than two hygrometers at a time. The WVSS-II and MBW were compared at a number of frost points. Such a comparison was carried out with each of the three WVSS-IIs (388, 4229 and 4252). Although the MBW could readily achieve mirror temperatures of -80 °C, it was discovered early on that it would not stabilise at mirror temperatures greater than 0 °C, and so no comparison could be carried out at high humidities. Although this exercise was very limited, and needs to be repeated, it did produce useable calibration data for 388 and 4252, presented in figure 6, overlaid upon the accuracy defined in the specification of the WVSS-II (SpectraSensors, 2018). It can be see that both instruments, but especially 388, under read significantly in very dry conditions, and it would seem likely, despite the calibration of 378 being uncertain, that this would have contributed to the apparent wet bias seen previously. Figure 7 shows a comparison of 378 vs 388,

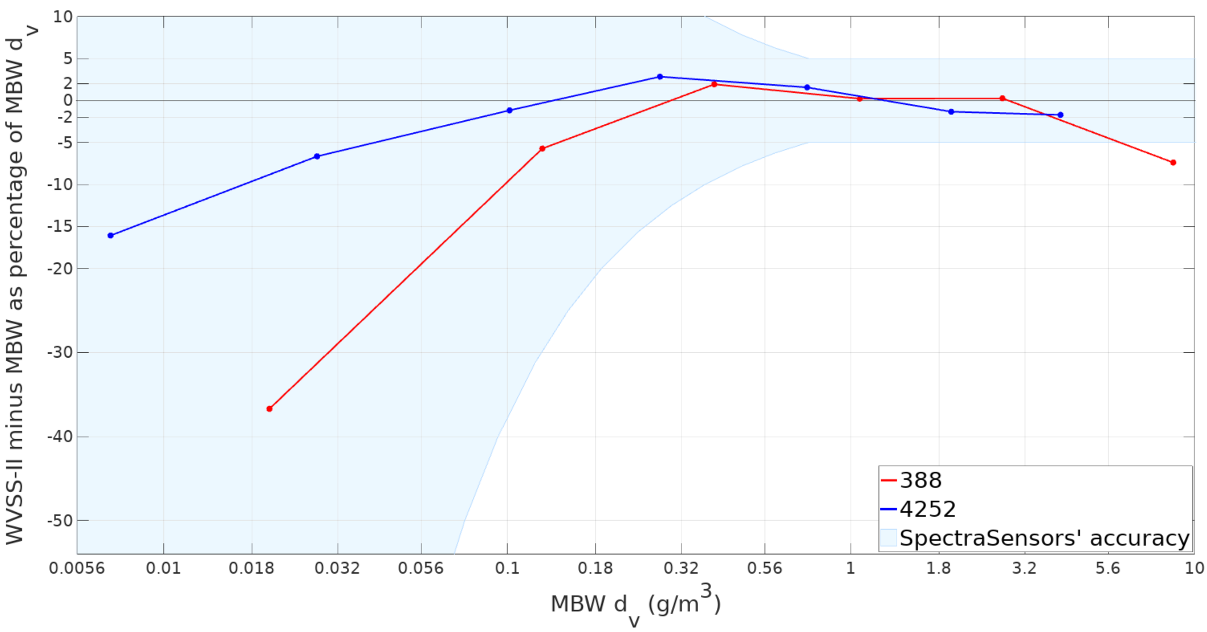

Figure 6. Comparisons of 388 and 4229 to the FAAM MBW hygrometer, with curves indicating the accuracy stated by SpectraSensors for the WVSS-II.

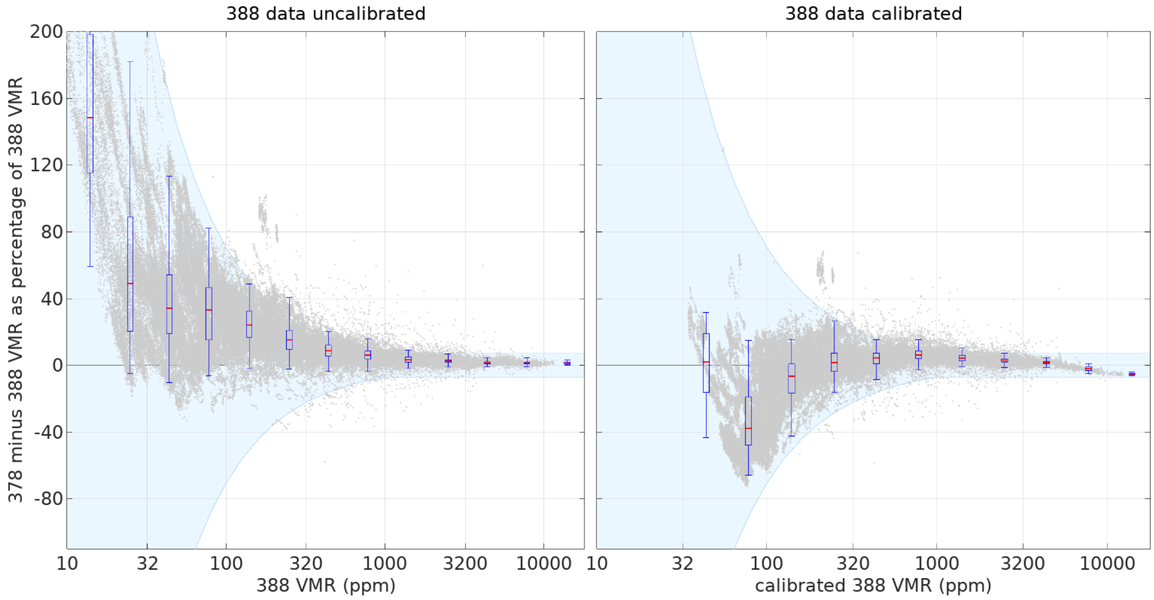

Figure 7. Comparisons of 378 vs 388 volume mixing ratios; the pale blue shaded area denotes SpectraSensor' accuracy x $\sqrt{2}$. The left axes compare the raw data from both instruments, while the plot on the right has been produced with the 388 data adjusted according to the October 2018 calibration.

before and after calibration of 388; the difference is quite striking, however, it can be seen that both before and after the calibration, the binned quartiles of the differences, shown with blue boxes (whiskers give 2nd and 98th percentiles), lie within $\sqrt{2}$ x SpectraSensors' stated accuracy. Attempts to calibrate 4229, however, were unsuccessful. It was also noticed that, when attempting to measure dry air, the humidities reported by 4229 varied in a cyclical manner, between frost points of -55 and -40 °C (almost an order of magnitude, in absolute humidity). The period of the initial cycle was about ten minutes, but the period increased the longer that 4229 was allowed to run, such that after running overnight, the period was almost three hours (figure 8). The spikes occurring approximately every one minute were caused by a problem with the pressure swing drier which was subsequently corrected. As a result, no useful calibration of 4229 was obtained. It is worth noting that, even at the shorter end, it could be difficult to detect this type of behaviour if it occurs in the air, as it occurs much more slowly than many of the changes encountered in flight, but there are grounds to believe that it has contributed to some 'odd' behaviour' seen in flight data, and it also calls into question the validity of the data from 4229, used here, and previously.

5. Discussion

Comparison of flight data has been largely unproductive and inconclusive. Although it is believed that this method could provide the necessary data, it would require a hygrometer sufficiently capable and reliable to use as a transfer standard, and this was lacking in the period covered. The GE, which had to be used as a transfer standard, performs poorly in drier conditions and is incapable of reaching the low humidities necessary to asses the performance of WVSS-IIs in very dry conditions. Comparing by inlet type and cell heater state suggest that there is no substantial difference but, due to the large spread in these differences, and the limited humidity range over which the comparison could be carried out, on account of the GE's limited performance, these results must be regarded as inconclusive, and in need of further investigation. Similarly, when different WVSS-IIs are compared although there is some evidence that 4229 may report higher values than 388, the bias is small compared to the spread of data and, again, this should be regarded with caution.

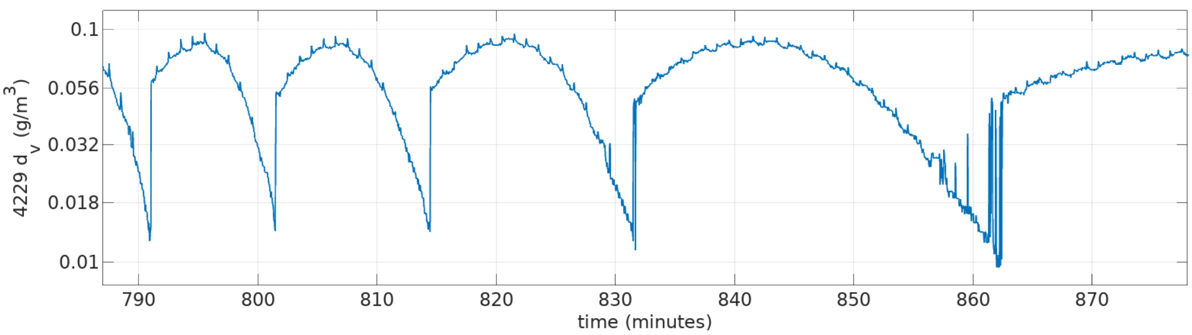

Figure 8. Oscillations observed in 4229 humidity during laboratory work, October 2018.

The limited laboratory work has been more enlightening. Comparisons with the FAAM MBW were limited both by the time available and the inability of the MBW to stabilise above 0 °C but useable measurements were made with 388 and 4252. From the perspective of atmospheric research, the deviation of the 388 and 4252 from the MBW is a serious issue, which needs to be addressed, but it should also be stated that, in terms of SpectraSensors' specification for the WVSS-II, 4252 is well within this at all values measured, and 388 only exceeds the specification at the wettest value.

Although calibration of 4229 was not possible, this exercise made clear a serious issue with the instrument, which was considerably less obvious in the airborne data. Again, although it would appear that 4229 is currently unusable as a research instrument, at humidities above 0.5 g/m^3, it was within SpectraSensor's specifications, but as there is considerable doubt about the repeatability of these measurements, they are not presented, here.

From this work there are grounds to believe that the wet bias seen previous was most likely due to differences in the performance of 378 and 388, and was not due to inlet design. During the period before October 2013, when 4229 had replaced 378, very dry conditions were very seldom sampled, and so no useful data exist in the region of the supposed wet bias that might have challenged the supposition of inlets being the cause of the difference.

The key finding of this work is that, in order for WVSS-IIs to be used as research instruments on the FAAM aircraft it is crucial that they are properly calibrated, as they can exhibit considerable errors at lower humidities; the MBW comparisons described herein should be considered only as preliminary, and should be repeated. Work should also be carried out to characterise the pressure and temperature sensors within the sample cell, and to quantify permeation through the heated inlet hose. It would also seem prudent that calibrations be carried out on a regular basis until long term stability is confirmed.

6. Acknowledgements

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