Instrument Test Report 659

Evaluation of the Output Variability of Rotronics MP101A Humidity Probes

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Authorisation

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Aims

1. Establish procedures for evaluating the Standard Error of humidity probes.
2. To establish the Estimated Standard Error for the Rotronics Model MP101A humidity probe.
3. To test the hypothesis that out of specification Rotronics probes display greater variability in output than ex-factory probes under similar conditions.
4. Develop output stability criteria for judging the fitness for use of Rotronics probes.

Introduction

The question arises as to whether the condition of humidity probes can be ascertained with reference to their data stream alone. Figure 1 and 2 display data for two probes ex-factory and one ex-field (black). Clearly there are differences in the response times of the probes (Fig.1) and the signal/noise ratios (Fig.2).

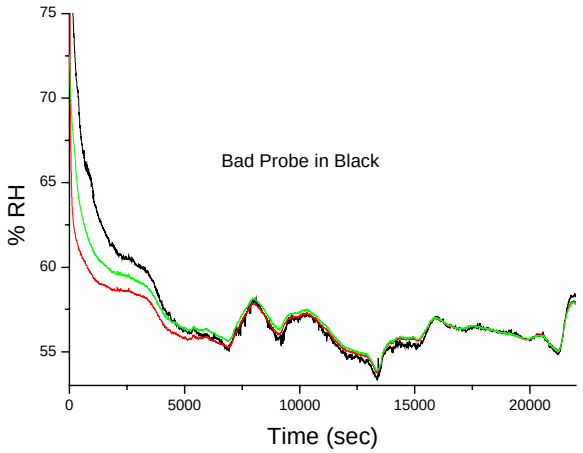


Figure 1. Plot of output of an ex-field Rotronics probe (black plot) and 2 ex-factory probes.

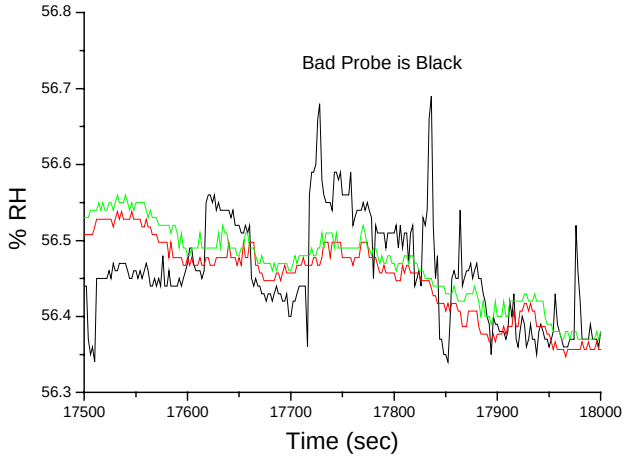


Figure 2. Expanded area of Figure 1 showing signal to noise.

The variability of the probes output can only judged with respect to some measure. That might be the measurement returned by another instrument, such as the Eastern General M2 Hygrometer, or a line of best fit for the probe data for example. If for example the variability is assessed with respect to another instrument then the total variance is given as;

$$Variance_{Total} = \sqrt{(\bar{x} - \bar{y})^2 + Var}$$

where $\bar{x}$ and $\bar{y}$ are the mean of the probes samples and the mean of the other instrument respectively. This term therefore refers to any bias or offset error between the probe and the other instrument. The second term *Var* is the random variability of the probe. The purpose of these experiments was to establish an estimate of the quantity *Var* which hereafter is referred to as the variance of the Rotronics probe. This value is required in order that its contribution to the overall uncertainty of verified probes can be estimated, and to provide a baseline in order that the variation of data streams from failing probes may be judged in future experiments.

Experimental

Rotronics MP101A probes ex-factory and verified at RIC Melbourne were placed centrally in a Heraus Votsch 4030 environmental chamber and their output captured via a data logger. The output Relative Humidity (RH) from each probe was logged every 2 seconds. The chamber was nominally in a steady state as defined in TN-RH-03 [1] at high humidity (approx. 82 % RH) or low humidity (approx. 30 % RH). These data were analyzed to investigate the Estimated Standard Error. These experiments were repeated for 5 Rotronics probes returned from the field.

Results and Analysis

Usual Variance of Ex-Factory Probes

The plots of RH versus time for each probe (1 – 4) appear in Figure 3. From Figure 3 it can be seen that the probes track each other, however, there are consistent differences between the probes, that is, scaling or offset errors.
A lag plot of Yi versus Yi-1 is shown in Figure x. It can be seen that the scatter of points is only weakly correlated suggesting that the noise seen is random.

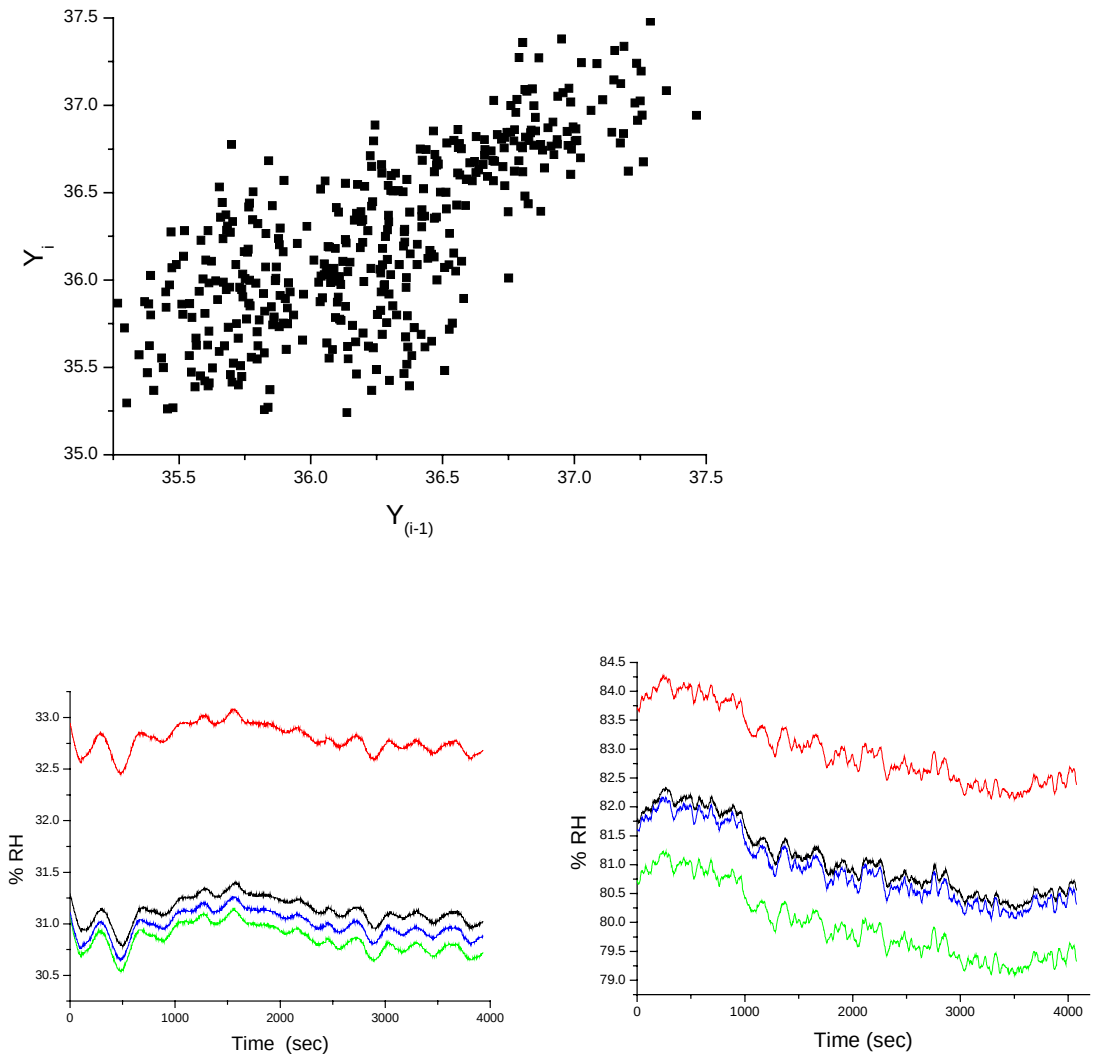


Figure 3. Plot of the output of each Rotronics Probe versus Time for Low and High RH.

The following two methodologies are presented for processing the output of the probes.

Scaling Factors

Firstly, the mean for the probes *j* is calculated for each time step *i*, for

$$\overline{x_i} = \frac{1}{n}\sum_{j=1}^{n} RH_{ji}$$

for all *i*, where RH_{ji} is the *i*th sample from the *j*th probe and *n* is the number of probes.

Then the mean value of $\overline{x_i}$ is then calculated,

$$\overline{X} = \frac{1}{m}\sum_{1}^{m} \overline{x_i}$$

for all *i* where *m* is the number of samples collected for each probe. Let $\overline{Y_j}$ be mean value for the *j*th probe i.e.;

$$\overline{Y_j} = \frac{1}{m}\sum_{1}^{m} RH_i$$

for all *i*.

The scaler F_j of the probe *j* is then calculated to be;

$$F_j = \frac{\overline{X}}{\overline{Y_j}}$$

The corrected RH (z_i) for each probe is found by multiplying the probe data by F_j such that;.

$$z_{ji} = F_j * RH_{ji} \cong \overline{x_i}$$

The actual values calculated for these data sets are shown in Table 1.

Table 1. Calculated Scalers for Probe Data

RH	F_1	F_2	F_3	F_4
Low	1.001226	1.000523	0.999188	0.999064
High	0.999166	1.000106	0.999464	1.001264

This scaling process has been applied to the data shown in Figure 3 and the results appear in Figure 4, which shows significant variation in the probe data however it was assumed that most of this variation was due to fluctuations of chamber humidity. The scaling values calculated were close to 1.0 however it can be seen (Table 1) that they were not the same at high and low humidity. Nor were they necessarily in the same direction.

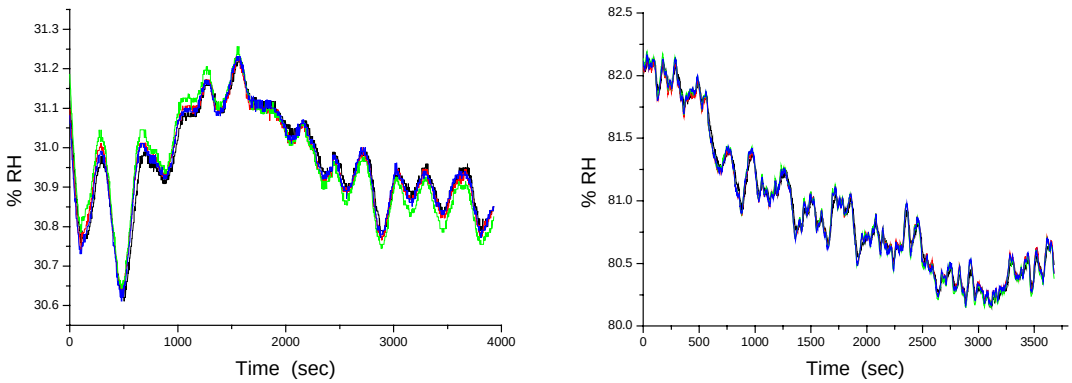


Figure 4. Plot of outputs shown in Figure 3 after Offset Adjustment.

The chamber variations are removed by calculating the difference d_{ji} between the data values z_{ji} and the mean of the probes $\overline{x_i}$ for each i;

$$d_{ji} = z_{ji} - \overline{x_i}$$

This data are plotted in Figure 5. This figure illustrates the better signal/noise ratio of these probes at lower RH.

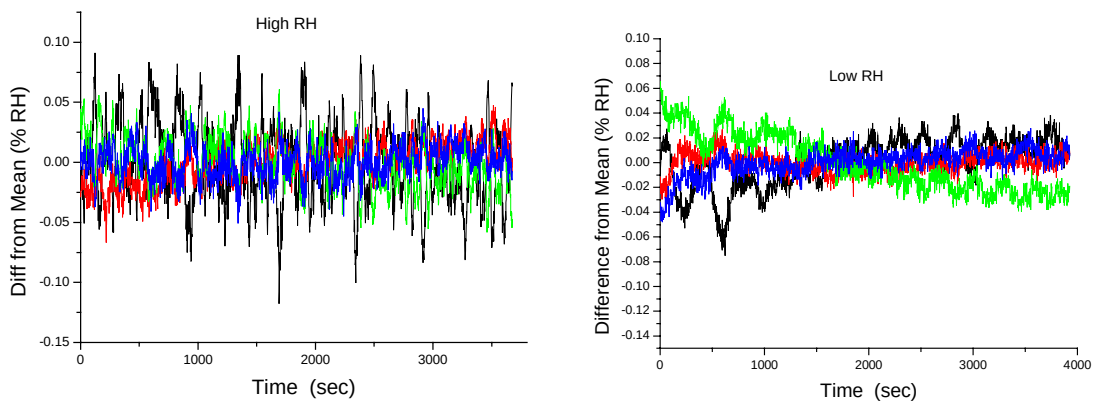


Figure 5. Plot of differences between the probe reading and the mean of the four probes.

Figure 6 combines the data from all probes and plots both the cumulative frequency and frequency of the d_{ji} values plotted in Figure 5. Summary of results are shown in Table 2. The y axis of the cumulative counts plots is scaled as probability rather than a linear axis and therefore data which were normally distributed would plot as a straight line.

Offset Calculation

An alternative method for removing the offset is to add a correction to each data set. If the additive offset for probe j is G_j then;

$$G_j = \overline{X} - \overline{Y}_j \text{ hence}$$

$$z'_{ji} = G_j + RH_{ji} \qquad z'_{ji} \neq z_{ji}$$

This was trialed and the results appear in Table 2 and Figure 7.

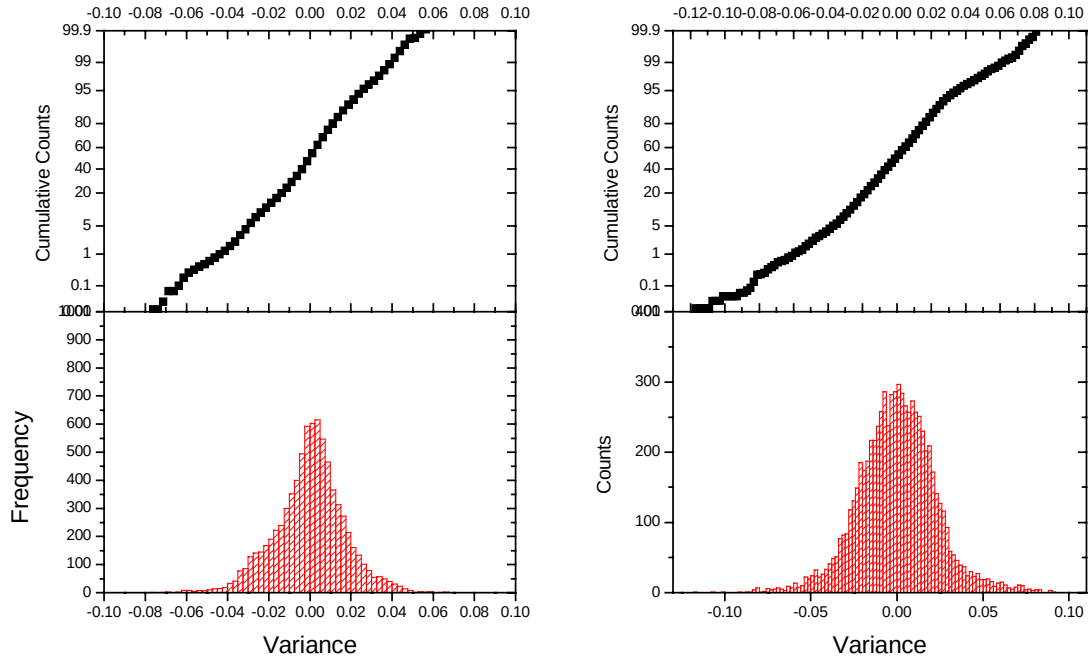


Figure 6.Cumulative counts and number of counts per bin for difference values at both low and high RH using a scaler.

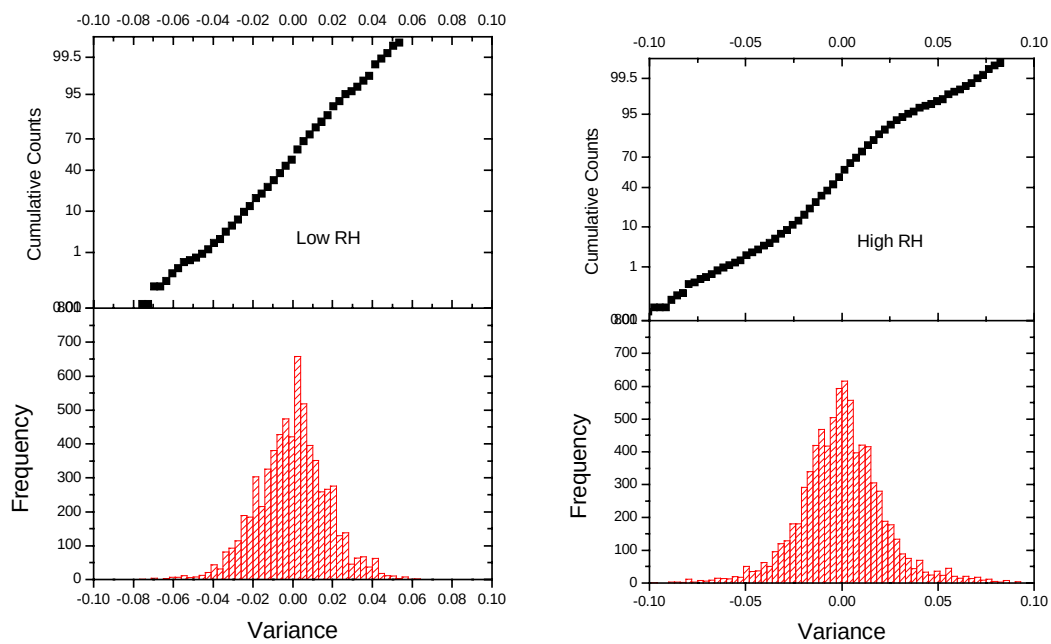


Figure 7.Cumulative counts and number of counts per bin for difference values at both low and high RH using an offset.

Figure 7 combines the data from all probes and plots both the cumulative frequency and frequency of the d_{ji} values when an additive correction was applied. It can be seen that the distributions for both RH ranges was approximately normal with means close to zero. The statistical analysis of the combined data for the four probes was calculated and is summarized in Table 2. In this case since the number of samples used to calculate the sample standard deviation *s* was very much greater than 30 the standard deviation of the samples was taken to be equal to the population standard deviation σ. These values are considered to be valid estimates of the variance of ex-factory probes.

Table 2. Parameters for the Probability Density Functions shown in Figure 4.

Correction Used	RH	Variance % RH	No. Samples
Scaler	High (82%)	2.7×10^{-4}	7355
	Low (30%)	5.2×10^{-4}	7860
Offset	High (82%)	3.0×10^{-4}	7355
	Low (30%)	4.8×10^{-4}	7860

The Estimated Standard Error of the mean, $\bar{\chi}$, is $\sigma_{\bar{x}}$ defined as;

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

where *n* is the number of samples and σ is the standard deviation of the population. $\sigma_{\bar{x}}$ was found to be approximately 3.1×10^{-6} % RH at low RH and 6.0×10^{-6} % RH at high RH.

Acceptance Criteria Based on Variance

It is clear from the data presented in the results section that the variance of the probes was not constant and that it was probably linearly dependant on the relative humidity measured. The results suggested that any criteria for examining the variance of a probe at low RH would be too restrictive at high RH. Therefore the variance obtained for high RH should be used to determine the acceptance level of probe variance. The distribution of variance can be represented by a standard version of the *chi-square distribution* for small numbers of samples [2]. Hence a confidence level for the probe variance is equal to;

$$\frac{(n-1)\sigma^2}{\chi^2_{\alpha/2}} \le s^2 \le \frac{(n-1)s^2\sigma^2}{\chi^2_{1-\alpha/2}}$$

where *n* is the number of samples, *s* is the variance of the probe under test, and α is the degrees of freedom which specifies the upper tail area of the chi-squared distribution (χ^2). The frequency distribution of the variance for both high and low RH is shown in Figure 8. The standard deviations were calculated for blocks of 30 sequential samples, that is over a one minute period.

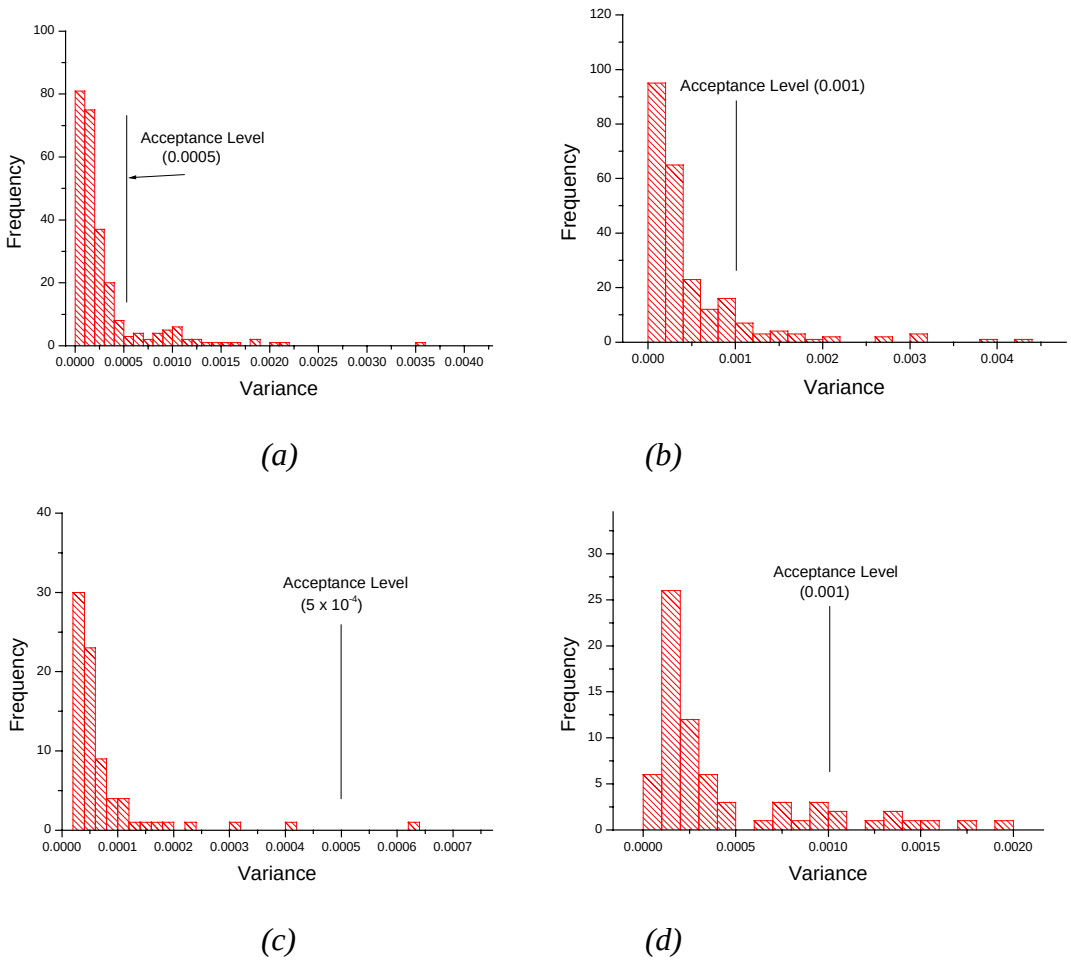


Figure 8. Frequency distributions of the variance of 30 sample blocks for both the low(a) and high (b) RH.black vertical line is the acceptance levels at low and high RH. Frequency distributions of the variance of 100 sample blocks for both the low(c) and high (d) RH. ***Note differing x-axis scales.***

It can be seen that the distributions are approximately chi-squared. The vertical lines show the upper 95 % confidence limit implied by the population variance if 30 or more samples are taken. They are equal to 1 x 10^{-3} at high RH and 5 x 10^{-4} at low RH.

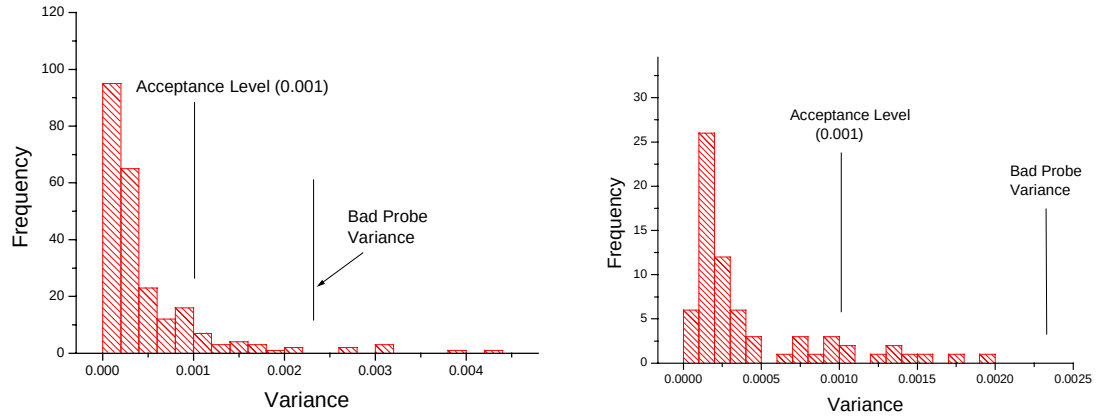
Examination of Out-of-Spec Probes

Can a defective or out-of-spec probe be identified as such solely on the variability of its output? To examine this question two cases were studied. In the first series of trials and analysis one out-of-spec probe was placed in the chamber with 2 accepted and verified ex-factory probes. In the second series of trials all the probes used were out of spec. Both these situations are seen as limiting cases.

Case I – Apparent Electronic Failure

The failed probe data shown in Figures 1 & 2 was the outputs of an out-of-spec probe (ex-field), black plot, and 2 ex-factory verified probes. Examination of the Figure 2

shows sharp discontinuities and level changes in the output of the ex-field probe that suggest intermittent electronic failure. This probe was calculated to have a variance of 0.0224 at high RH when the methodology suggested earlier was applied. Figure 9 shows this value plotted on the population variance distribution. This methodology has correctly identified the variability of the output of the probe as being outside expected values.



(a) *(b)*

Figure 9. Variance for the ex-field probe at high RH plotted over the population variance distribution for 30 samples (a) and 100 samples (b).

Case II – Apparent Contaminated Sensor

A group of four failed probes (ex-field) were sampled for some time and the same data processing was applied. The plot of the differences from the four-probe mean is shown in Figure 10.

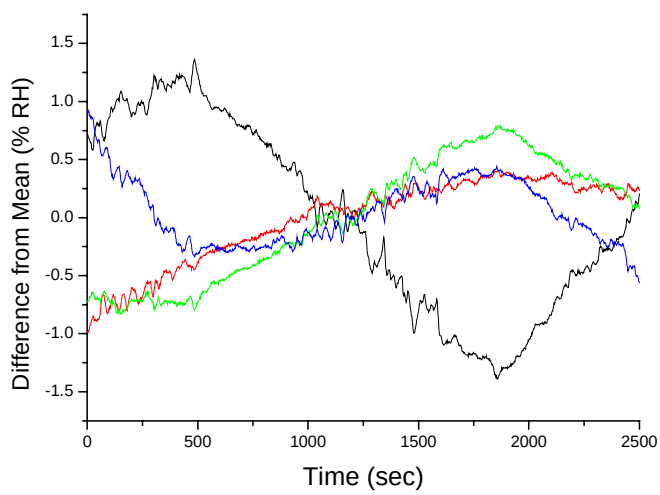


Figure 10. Plot of the difference from the collective mean of four failed probes (ex-field) at high RH

Figure 10 should be compared to similar plots of well-behaved probes such as Figure 5. Clearly there are large systematic differences between the probes leading to an elevated variance. The frequency plot of the variance of the probes (30 sample blocks) is shown in

Figure 11 and should be compared to Figure 8. The output plotted in Figure 10 would be expected if the sensor was failing or the probe was poorly adjusted. The methodology suggested would have removed large offsets, but it would fail to remove large offsets that were phase shifted. This type of response might be expected where the sensor had a degraded response due to contamination or degradation of the sensor polymer for example.

It is apparent that the distribution of variance, whilst being similar in shape to that of ex-factory probes, differs in spread by two orders of magnitude. The proposed acceptance level for variance is shown as a black vertical line.

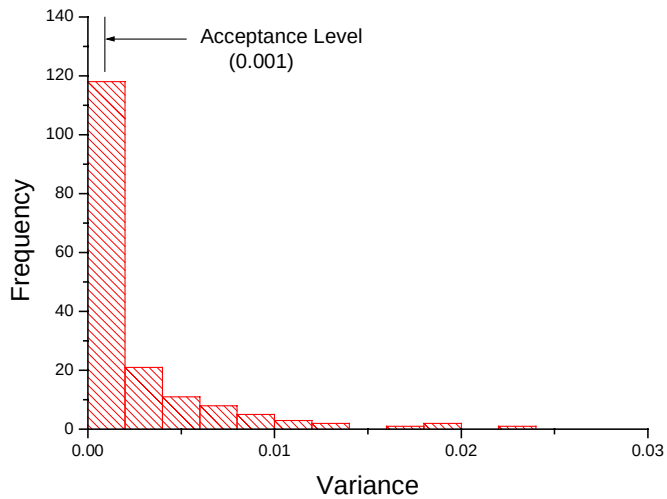


Figure 11. Frequency plot of variance of the 4 ex-field probes at high RH (30 sample blocks)Proposed acceptance level shown.

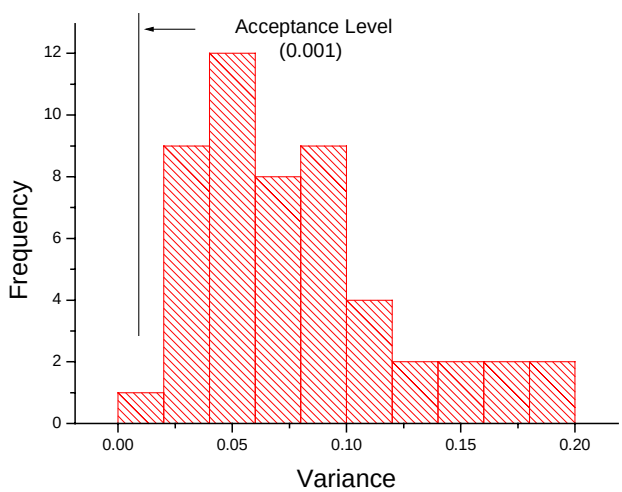


Figure 12. Frequency plot of variance of the 4 ex-field probes at high RH (100 sample blocks) Proposed acceptance level shown.

Figure 12 re-plots the data for the ex-field probes using variances calculated for 100 samples and should be compared to the data obtained for ex-factory probes (Figure 8). Again the acceptance level proposed is plotted as a vertical black line. From this plot

it can be calculated that approximately 2.2 probes per 100 would be accepted if variance is calculated using 100 samples. It can be seen that any arbitrary probe could be rejected using the proposed acceptance level of variance of 0.001 calculated for 100 sample points even if all the probes in the batch were “bad”. Table 3 summarizes the data obtained. The first 3 rows are the average variances found for 4 verified probes for various sample sizes. Row 4 is the average variance for the four ex-field probes measured whilst the remaining rows show the individual values which made up this average.

Table 3. Probe Variances Comparison

Probe Type	No. Samples	Mean Variance of Probe(s)
4 good	10	3.7×10^{-5}
4 good	100	1.6×10^{-4}
4 good	2000	2.7×10^{-4}
4 Fails	1344	2.4×10^{-1}
P1 Fail	1344	1.0×10^{-1}
P2 Fail	1344	2.4×10^{-1}
P3 Fail	1344	1.3×10^{-1}
P4 Fail	1344	6.3×10^{-1}

Clearly all out of-spec-probes would have failed the proposed criterion based on variance alone.

Conclusions

The procedure outlined in the results section involved the use of a scaler *F* to normalize the RH of each probe. The alternative approach of using an offset from the mean was also evaluated and the results also appear in Table 2 and Figure 5. From this table it appears that there is no inherent reason for adopting one method over the other, as judged by either the variance or the mean.

The uncertainty in the output of a verified Rotronics probe at any arbitrary humidity is composed of three main contributions, the uncertainty due to the reference measurement from the dew point hygrometer, a systematic or offset error due to inaccuracies in potentiometer adjustment, and the standard error of the probe. From this work it can be seen that the contribution of random errors by the probe to the overall uncertainty was approximately 0.017 % RH (95 % confidence) at low RH and approximately 0.023 % RH (95 % confidence) at high RH. Since the uncertainty in the hygrometer reading is of the order of 1 % RH and the offset errors of the probes are of the order of 2 % RH, the standard error of good probes may be neglected when calculating overall uncertainty.

The maximum acceptable level for variance in the probe output from the mean of the other probes within the chamber should be set at 5×10^{-4} at low RH and 1×10^{-3} at high RH and calculated for 100 samples or greater. It is estimated this criterion alone would lead to 2 bad probes per 100 being accepted, however a criterion with respect to offset error is also required or out-of-spec probes will be accepted.

[1] Technical Note: RH-TN-03v1, *Report on Humidity Testing Procedures*. J.Gorman Bureau of Meteorology Regional Instrument Centre, 2001
[2] L.L. Lapin, *Probability and Statistics for Modern Engineering 2ed.*, Duxbury Press 1980,p.325