**Presented**
**2005 August**
**2005 NCSL INTERNATIONAL**
**WORKSHOP AND SYMPOSIUM**
**Washington, D.C.**

# Evaluating the Contribution of Stability in the Measurement Uncertainty of Resonant Quartz Pressure Transfer Standards

Speaker/Author: Michael Bair
DH Instruments, Inc
4765 East Beautiful Lane
Phoenix, AZ 85044-5318
Phone: (602) 431-9100   Fax: (602) 431-9559
mbair@dhinstruments.com

## 1. Abstract

As the role of a transfer standard is to propagate measurements defined by another standard, the ability of a transfer standard to resist changes in output due to age or frequency of use is a significant aspect of its performance. This type of uncertainty is often called "stability" or "reproduceability".

Stability is a predicted systematic uncertainty. Errors from stability may be reduced through prediction of the direction and magnitude of the change and application of a mathematical correction based on this prediction. However, the uncertainty in this type of correction tends to be very high if it is not developed from experience with a specific artifact. Generally, the uncertainty contributed by stability error is controlled by regular comparison of the transfer standard with a reference and readjustment as necessary (recalibration). An instrument whose instability or drift follows no predictable pattern requires an extensive calibration process in which many points in the range are verified and a complex compensation model is used for readjustment. An instrument whose drift follows a predictable pattern may be able to be calibrated with a simpler compensation scheme.

This paper examines the stability of resonant quartz pressure transfer standards (referred to commercially as a quartz reference pressure transducer or Q-RPT™). The results are analyzed to determine the extent to which either full or partial compensation is justified to lower measurement uncertainty and/or extend calibration intervals.

## 2. Introduction

Theories may be developed to understand the causes of the drift of a Q-RPT to better predict its change over time. To examine these theories a detailed understanding of the design of the sensor would have to be considered. Though an effort to provide explanations as such may be justified by a manufacturer of these devices, this paper is only intended to consider stability using a metrological approach and does not critique the mechanical design of the sensors.

The metrological approach to this study is concentrated primarily on the stability characteristics of a large sample of Q-RPTs over one interval rather than the behavior of a small sample studied over a greater number of calibrations [1,2,3]. Examining a large sample is intended to capture the behavior of a significant population of Q-RPTs. A larger sample provides information more valuable as a product specification to help the metrologist predict an uncertainty component in pressure stability for a device that has not been tested for stability. This approach also considers the benefits of a one point offset correction at barometric pressure against a reference with a lower uncertainty than the Q-RPT in question.

## 3. Stability Of Q-RPTs

Experience with a population of over one thousand resonant quartz pressure transfer standards reveals no significant influence of frequency or intensity of use on stability in pressure calibration type applications. Excluding mistreatment or contamination, this experience shows that drift of a Q-RPT is primarily a function of time.

Analysis of the recalibration results of Q-RPTs shows the stability of a Q-RPT to be a combination of a constant value (offset) and a change in the slope over its range. Relative to the tolerances claimed for the transducers, significant changes in linearity are very rarely observed.
A single point calibration at zero pressure for gauge pressure Q-RPTs or at barometric pressure for absolute pressure Q-RPTs can correct for offset but not for slope changes.

To study the drift of Q-RPTs over time, 16 absolute pressure Q-RPTs of various ranges were recently selected at random for analysis. Barometric range transducers were excluded and are considered separately. The data was collected as follows:

- A number of Q-RPT recalibrations were randomly selected. Excluded were barometric range Q-RPTs (which are considered later). The ranges varied from 350kPa absolute (50 psia) to 10 MPa absolute (1500 psia).

- The amount of time elapsed between each Q-RPT's previous calibration and current calibration was determined.

- For each Q-RPT data set a simple linear regression was applied to determine the best fit slope and intercept. One slope and intercept were calculated on the as received data "as is". Another slope and intercept were calculated after applying an offset correction that was determined at barometric pressure by comparison with a piston gauge.

- A small number of calibrations were eliminated as outliers due to atypical Q-RPT conditions such as contamination or other problems requiring repair. The 16 samples were retained out of 19 originally selected.

- The change in slope and intercepts were normalized for a 12 month interval based on the length of the previous calibration interval.

- Values for the change in slope and intercept for the Q-RPTs with and without the offset correction were determined for the entire group by calculating 2.1 standard deviations (95% confidence) of each characteristic.

Table 1 provides results for the analysis described above. Listed for each Q-RPT are:

- The calibration interval, in days.
- The change in slope normalized for a 12 month period, in parts per million.
- The change in intercept normalized for a 12 month period in, parts per million of the span of the Q-RPT.
- The change in intercept based on an offset correction performed at atmospheric pressure in parts per million of the span of the Q-RPT.

A summary provides:

- Average and 2.1 standard deviations (95% confidence) of the 16 examples for a 12 month period for slope and uncorrected and corrected intercept.

| **Q-RPT** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
|---:|:-:|:-:|:-:|:-:|:-:|:-:|:-:|:-:|
| Calibration interval [days] | 169 | 346 | 385 | 385 | 395 | 373 | 409 | 409 |
| Change in slope/12 months [ppm] | 23.9 | 9.0 | 9.3 | 11.9 | 24.9 | -22.4 | -3.6 | 7.3 |
| Uncorrected change in intercept/12 months [ppm span] | 43.3 | -4.5 | 25.8 | -22.6 | 52.2 | -22.1 | -7.9 | -10.2 |
| Corrected change in intercept/12 months [ppm span] | -3.6 | -2.5 | 2.0 | -3.6 | 5.0 | -3.1 | -8.2 | -1.9 |
| | | | | | | | | |
| Q-RPT | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Calibration interval [days] | 334 | 410 | 424 | 385 | 413 | 413 | 472 | 472 |
| Change in slope/12 months [ppm] | -17.2 | 15.7 | -5.9 | -16.3 | 10.5 | 8.4 | 42.1 | -2.6 |
| Uncorrected change in intercept/12 months [ppm span] | -19.4 | 21.7 | -9.0 | 3.6 | 57.5 | -67.6 | -25.3 | -83.0 |
| Corrected change in intercept/12 months [ppm span] | 5.3 | -1.2 | -4.8 | -1.1 | -1.0 | 1.7 | 7.0 | -7.6 |

| **Combined Results** | **2.1 Standard deviations 95% Conf** | **Average** |
|---:|:-:|:-:|
| Change in slope/12 months [ppm] | 36 | 6 |
| Uncorrected change in intercept/12 months [ppm span] | 81 | -4 |
| Corrected change in intercept/12 months [ppm span] | 9 | -1 |

**Table 1.** Analysis of stability for various Q-RPT ranges.

It can be concluded from the results of Table 1 that the dominant component in stability is the change in offset. Correcting the offsets results in very small changes in the intercepts and the same change in slope that is observed for the uncorrected offsets. The slope drift error is of a lower magnitude and is not a constant over the range, it is proportional to the measured pressure making it an “of reading” type of error that is given in Table 1 in parts per million of reading.

It can also be concluded that the offset drift characteristic is proportional to the span of the Q-RPT. Therefore the lower the range, the lower, the drift in terms of pressure.

The averages of each value are also of interest. All of the Table 1 averages are close enough to zero to indicate there are no trends in the sign or magnitude of slope or intercept drift.

## 4. Stability Of Barometric Q-RPTs

The previous section demonstrates from absolute pressure Q-RPT calibration data that the main component of Q-RPT drift over time can be significantly reduced by using a single point comparison at barometric pressure to correct for offset drift. For gauge pressure Q-RPTs the behavior is the same as absolute Q-RPTs. However, in gauge measurement mode, barometric pressure is a perfect zero by definition so a reference to determine the offset against is always readily available. A separate pressure reference is not needed. When considering absolute pressure Q-RPTs, it is a misconception to think that an operator must create an absolute zero pressure by applying a vacuum. In fact this would be the most difficult way of correcting for an offset considering the effort it would take to create a dependable zero absolute pressure with the use of a vacuum system. Also, zero absolute pressure is outside the calibrated range of a Q-RPT. A much more convenient and dependable way of correcting for the offset is to compare to a reference at some pressure in the calibrated range. Barometric pressure is a convenient point as the comparison can be completed without making pressure connections between the Q-RPT and the reference and the pressure does not need to be controlled.

Ideally a primary reference such as a piston gauge operated in absolute mode would be used to correct for absolute pressure Q-RPT offsets because of the piston gauge's dependability and low measurement uncertainty in pressure. The most ideal pressure to perform an offset correction on a Q-RPT would be the mid point of span pressure value. This would have the effect of eliminating almost all drift due to changes in offset and minimize the drift in slope by as much as ½ of the actual drift. Figure 1 is a fictitious, but realistic example that demonstrates this correction.

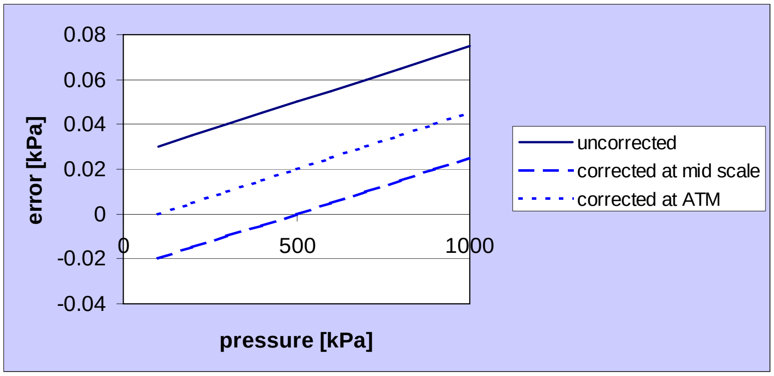

**Figure 1.** Demonstration of mid scale and atmospheric correction.

Once a Q-RPT is brought to a laboratory, connected to a piston gauge and compared at midscale, it would be practical to compare at pressures throughout the range to correct for any change in slope. With the additional points a full calibration is performed and the convenience of a one point check, possibly in-situ, has been lost. Though using a piston gauge for a one point check may be ideal from a statistical point of view, it is much less practical than having a portable barometer with sufficiently low uncertainty to correct another Q-RPT.

One can imagine a scenario in which a user has a number of Q-RPTs of different ranges and wants to limit the effect of drift in absolute measurement mode by correcting the offset, but does not have a piston gauge available as the reference, or cannot remove the Q-RPTs from a remote measurement system and return them to a laboratory where their piston gauge is operated. In this case, an operator might use the lowest absolute range Q-RPT at their disposal to provide an offset correction for the higher range Q-RPTs. If the corrections were well maintained, the uncertainty component due to stability for each of the Q-RPT would be the possible change in slope of each Q-RPT and the stability of the lowest absolute Q-RPT at atmospheric pressure. The most ideal Q-RPT to use as a reference is the 100 kPa (15 psia) barometric range because it is the lowest absolute pressure range available and therefore has the lowest predicted drift compared to the higher ranges.

In order to provide a meaningful estimate of uncertainty due to drift when correcting with a barometric Q-RPT, the stability of the barometric range must be evaluated. Table 2 provides recalibration data for 10 separate 100 kPa Q-RPTs. The analysis is similar to that of Table 1 but for this analysis the 100 kPa Q-RPTs need only be evaluated for stability at 100 kPa where they would be used to correct the offsets of other Q-RPTs. Since there is only one range there is no need to normalize the results to a percent of full scale and measured offsets are given in pressure.

When considering the results in Table 2, it should be remembered that the observed changes are at the full scale, 100 kPa (15 psia), of the Q-RPT. This means that the disagreements are due to changes in both offset and slope.

| **Q-RPT** | **1** | **2** | **3** | **4** | **5** |
|---:|:---:|:---:|:---:|:---:|:---:|
| test-ref at 100 [kPa] | -0.005 | 0.003 | 0.000 | 0.001 | 0.001 |
| cal interval [days] | 757 | 370 | 296 | 419 | 197 |
| change/year [kPa] | -0.00241 | 0.00296 | 0.00000 | 0.00087 | 0.00185 |
| | | | | | |
| Q-RPT | 6 | 7 | 8 | 9 | 10 |
| test-ref at 100 [kPa] | 0.001 | 0.002 | -0.004 | -0.003 | -0.002 |
| cal interval [days] | 371 | 401 | 374 | 392 | 376 |
| change/year [kPa] | 0.00098 | 0.00182 | -0.00410 | -0.00257 | -0.00194 |

2.2 standard deviations (95% confidence) = 0.0054 kPa/year
Average = -0.0006 kPa/year

**Table 2.** Analysis of 10 barometric Q-RPTs.

The results shown in Table 2 are similar to those in Table 1. The average of the drift approaches zero and is approximately the same percent of span discovered in Table 1 for various ranges.

The barometric ranges could also have their offsets corrected at atmosphere like other Q-RPTs. However this is a little less practical than the other ranges because this is the lowest range available, hence there is not a lower Q-RPT range to use as a reference. In the example above, a piston gauge in the calibration laboratory might be used to correct a barometric Q-RPT before it is used to correct the offset of a group of other Q-RPTs at barometric pressure.

## 5. Q-RPTs In Parallel

One way to reduce the probability of a change in offset is to utilize two Q-RPTs in parallel measurement mode. It was demonstrated in the data in Table 1 that the drift characteristic of two separate Q-RPTs are independent and random. This is true even if the drift of a single Q-RPT shows a trend.

When measuring a parameter with two instruments at the same time, the uncertainty of the average value of the two instruments is often less than the uncertainty of only one of the instruments. The amount of the reduction of the uncertainty depends upon the uncorrelated components of the uncertainty of each device [4]. Since drift is random from one Q-RPT to the next, this component of uncertainty, among other uncorrelated uncertainties, can be reduced by a factor of square root of 2.

The statistical rule above can easily be tested with the results of the ten barometric Q-RPT stability tests. The Q-RPTs in the upper part of Table 2 are averaged with the lower part of Table 2 as if they were measuring barometric pressure together. The results can then be analyzed in the same way as was done in Table 2. Table 3 shows the results of this analysis.

| Q-RPT (combined) | 1,6 | 2,7 | 3,8 | 4,9 | 5,10 |
|---|---|---|---|---|---|
| change/year [kPa] | -0.0007 | 0.0024 | -0.0020 | -0.0008 | -0.0000 |

2.2 standard deviation (95% confidence) = 0.0038 kPa/year
Average = -0.0006 kPa/year

**Table 3.** Analysis of various barometric Q-RPTs in parallel mode.

2.2 standard deviations yields results in Table 3 of 0.0038 kPa per year and is very close to the average in Table 2 of 0.0054 kPa divided by the square root of two (1.4). This clearly shows the change is uncorrelated and the uncertainty due to drift is justifiably reduced by the square root of 2 when two Q-RPTs are used in parallel.

## 6. Influence Of Stability In An Uncertainty Budget

It has been demonstrated in the previous sections that there is benefit to correcting the offset of a Q-RPT. To quantify this benefit a product uncertainty budget was created for a specific example of one range of Q-RPT to show the differences in the expanded uncertainty for the different situations described in this paper. A product uncertainty budget is intended to describe a typical uncertainty in measured pressure of any Q-RPT selected in that range. This is much different than a calibration uncertainty budget or a measurement uncertainty budget whose uncertainties are specific to a unique device and based on specific measurement data. If calculated properly, the result of a product uncertainty analysis should be larger than an conventional measurement uncertainty analysis for 95 out of 100 single devices.

Table 4 shows five uncertainty budgets that describe the uncertainty in pressure for a Q-RPT range. The five uncertainty budgets are:

- The uncertainty in pressure for a Q-RPT for 12 months without offset correction.
- The uncertainty in pressure for two Q-RPTs measuring in parallel without offset correction.
- The uncertainty in pressure for a Q-RPT for 12 months with an ideal offset correction (what might be experienced if a reference with a very low uncertainty was used to properly maintain stability offset, or if the Q-RPT is measuring gauge pressure).
- The uncertainty in pressure of a Q-RPT with offset corrected by a barometric Q-RPT.
- The uncertainty in pressure of two Q-RPTs in parallel with offset corrected by a barometric Q-RPT.

| **Variable or Parameter** | Uncorrected Q-RPT | Uncorrected Parallel Q-RPT | Ideal Corrected Q-RPT | Barometer Corrected Q-RPT | Barometer Corrected Parallel Q-RPT |
|---|---|---|---|---|---|
| **relative values** | % of reading | % of reading | % of reading | % of reading | % of reading |
| reference | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 |
| linearity | 0.0015 | 0.0011 | 0.0015 | 0.0015 | 0.0011 |
| hysteresis | 0.0015 | 0.0011 | 0.0015 | 0.0015 | 0.0011 |
| repeatability | 0.0015 | 0.0011 | 0.0015 | 0.0015 | 0.0011 |
| line pressure | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| temperature | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 |
| stability | 0.0023 | 0.0016 | 0.0023 | 0.0023 | 0.0016 |
| **COMBINED** | **0.004% of rdg + 0.0041% span** | **0.003% of rdg + 0.0029% span** | **0.004% of rdg + 0.0009% span** | **0.004% of rdg + 0.0010% span** | **0.003% of rdg + 0.0009% span** |
| **EXPANDED FOR (K=2)** | **0.008% of rdg + 0.0082% span** | **0.006% of rdg + 0.0058% span** | **0.008% of rdg + 0.0018% span** | **0.008% of rdg + 0.0020% span** | **0.006% of rdg + 0.0016% span** |
| **constant values** | % span | % span | % span | % span | % span |
| reference | 0.00003 | 0.00003 | 0.00003 | 0.00003 | 0.00003 |
| resolution | 0.00003 | 0.00003 | 0.00003 | 0.00003 | 0.00003 |
| precision | 0.0008 | 0.0006 | 0.0008 | 0.0008 | 0.0006 |
| line pressure | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| temperature | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0005 |
| barometer (dyn comp) | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **stability** | **0.0040** | **0.0028** | **0.0000** | **0.0004** | **0.0004** |

**Table 4.** Uncertainty budgets for a 700 kPa (100 psi) Q-RPT.

The uncertainty budgets in Table 4 are given in two separate tables. On top are the uncertainties that are considered to be relative and are given in percent of reading. The values below the combined and expanded results are considered to be constant and are given in percent of span. Since the offsets for the barometric Q-RPTs in Table 2 are given in units of pressure (Pa), a span of 700 kPa (100 psi) was chosen for this example so that the component for offset stability could be represented in percent of span.

Figure 2 is a graphical representation of the uncertainty budgets for this Q-RPT range. In the calculation for this chart the expanded relative uncertainty value is root sum squared with the expanded constant uncertainty value. This is justified because the main constant uncertainty – stability – is considered to be uncorrelated with the relative uncertainties. The uncertainty budget for the ideal corrected Q-RPT also represents the uncertainty budget for a gauge pressure 700 kPa range Q-RPT. The ideal corrected and barometer corrected are shown as one since they are almost identical.

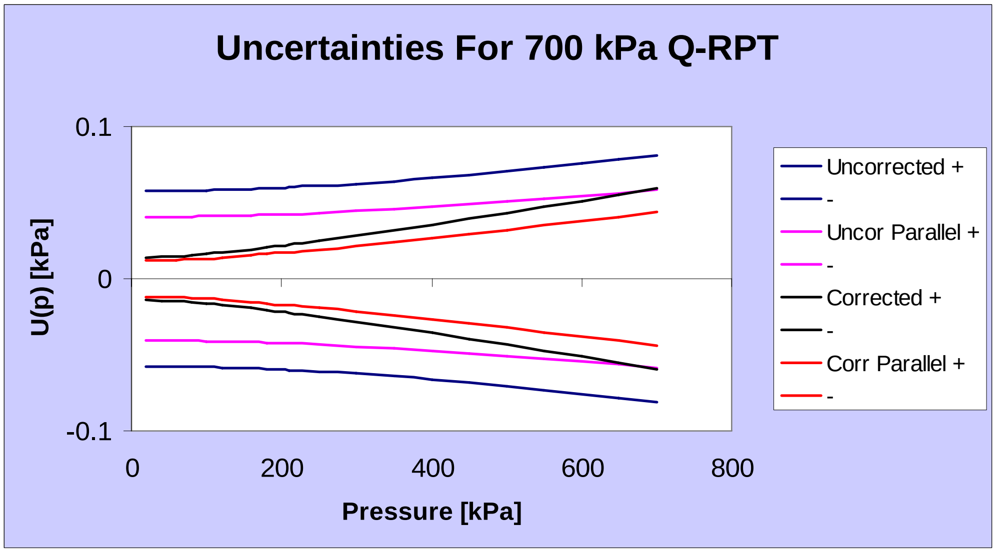

**Figure 2.** Graphical representation of Table 4.

Generally, performing the same analysis for all ranges, gives results very similar to what is shown in Figure 2 with the magnitudes of x and y axis being relative to the span of the Q-RPT.

## 7. Conclusion

This analyses presented in this paper are for groups of Q-RPTs. The same type of analysis can be performed for a single Q-RPT, but there is a major difference. As mentioned in the introduction and demonstrated in the paper, the effect of stability for a population Q-RPTs is random. However, for a single Q-RPT the stability is expected to be somewhat systematic, i.e. repeatable, from one calibration to the next, as long as the interval and conditions of use are the same. Therefore, once measured over a sufficient amount of time, the uncertainty due to stability of a Q-RPT may be predictable.

For most Q-RPTs, lower pressure measurement uncertainties are realized when the offset drift can be reduced or eliminated by a correction performed experimentally. The magnitude of the benefit of this procedure is dependent upon how often the comparison can be performed and of the uncertainty of the reference available. Q-RPTs that measure gauge pressure automatically correct for changes in offset when resting at zero gauge pressure.

When correcting for offset on an absolute Q-RPT, it is never compared at zero absolute pressure. The most ideal pressure to correct a Q-RPT is 50% of the Q-RPT's span where the drift in slope can also be minimized. However, this is not practical because if a lower range Q-RPT is being used as the reference, it is most likely a significantly lower range and cannot measure pressure high enough to reach 50% of the range of the Q-RPT being corrected. Therefore the most logical and convenient pressure to compare is atmospheric pressure. All absolute Q-RPTs can measure barometric pressure and there is no need to connect the two Q-RPTs together as they can be opened to atmosphere. To enhance the convenience of making this comparison, a function to perform this comparison at atmospheric pressure, called AutoZ, is included with DHIs. The determination and application of an offset correction can be fully automated when the Q-RPTs can be interfaced together with an RS-232 connection, or can be semi-automated when the reference cannot be interfaced with the Q-RPT being corrected. This is an important feature because it facilitates more frequent comparisons and lower uncertainties are realized.

Lower uncertainties are also realized when two Q-RPTs of the same range are used to measure the same pressure and averaged. However, the benefits are not limited to reducing the uncertainty in stability, all uncorrelated uncertainties are also reduced.

## 8. References

1. Paroscientific, 2004, http://www.paroscientific.com/recalibrationprog.htm "Conformance And Stability Tests Of High Pressure Portable Field Standard"

2. Dr. Theo P. Schaad, Paroscientific Inc., http://www.paroscientific.com/stabreport.htm "Stability Test Report Of 760-15a Portable Field Standard"

3. February 25, 2004, Dr. Theo Schaad, Principal Scientist, Paroscientific Inc., "Fifteen-Year Test Of Barometer Long-Term Stability"

4. ISO/TAG 4/WG3, June 1992, "Guide To The Expression Of Uncertainty In Measurement"