PREDICTABILITY OF SOLID STATE ZENER REFERENCES

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Abstract - With the advent of ISO/IEC 17025 and the growth in laboratory accreditation, more complete, detailed uncertainty analyses are required. This often points out the need for improved accuracy starting from the top of the traceability chain of a calibration laboratory. This paper describes a program that has been in place for several years to provide better uncertainties for solid state 10V zener references. This program is an on-site calibration service that can model a reference's drift performance resulting in a very predictable projected value. An evaluation of the accuracy of the predictions is presented as well as a description of the tools used to make the predictions.

INTRODUCTION

Prior to the development of the solid-state zener reference standard (DCVS), standard cells were used by most laboratories to maintain the volt. Pampered, they are quiet and have very predictable drift characteristics. However, they are poor travelers making it very difficult to send them for calibration or to use them to deliver accurate voltages to a production line or remote site. Zener references were conceived as a means to easily transfer dc voltage anywhere that it was needed. For manufacturers of precision calibrators, the need was to deliver 10V accurate to about 1-1.5 parts in 10^6. Soon, many laboratories wanted to be able to maintain their own zener references so calibration uncertainties were improved to about a part in 10^7. With multiple standards, some history and the use of regression models, 0.3 parts in 10^6 can be maintained with annual calibrations [1]. With further characterization and care, zener references can be used for intercomparisons between Josephson Arrays with transfer uncertainties of about a part in 10^8 [2].

Though zeners travel much better than standard cells, the demand for increasingly better uncertainties also increased the reluctance of some owners to allow them to do so. Many of them use an on-site calibration service that uses a well-characterized zener reference with demonstrated ability to travel well. A proficiency test is performed, then the calibration using a procedure from the calibration service provider. This process was accredited in 1995 by NVLAP and in 1998 by DKD, the German accreditation body. After calibration, users employ a number of methods to re-assign the value throughout the calibration interval. Some use the calibrated value throughout the interval and increase the uncertainty by the drift specification. This works well if the more accurate workload can be scheduled early in the calibration period. If the uncertainty demands aren't as great, a simpler approach is to increase the uncertainty for the maximum drift immediately and use the same uncertainty as well as assigned value throughout the interval. A more sophisticated approach is to use a drift model for the reference and change the assigned value and uncertainty during the calibration interval. To execute this strategy, one must have some previous calibration history for the unit, knowledge of the behavior of similar devices, a mathematical model to apply, the ability to perform the drift and uncertainty calculations and create a table of assigned values and uncertainties to be used throughout the calibration interval. As the manufacturer, we were in the best position to look at large populations of the references to develop the models and evaluate the results. In 1996, we started supplying projections based on linear and non-linear drift models upon the third calibration event. In 1998, a study was performed [3] to evaluate the reliability of those projections. This paper repeats the study for a much larger population, separates the results for 732A and 732B references and provides drift data for the populations.

LINEAR AND NON-LINEAR DRIFT MODELS

A linear regression model for the zener standard is calculated using historical calibration data. The output voltage of the standard is estimated by the following equation:

$$V = ax + b \pm K \sqrt{S_{reg}^2 \left(\frac{1}{n} + \frac{(x - \overline{x})^2}{n S_x^2} \right) + u_{cal}^2 + u_{TC}^2 + u_p^2 + u_s^2}$$

ax+b represents the assigned value for the voltage, V, for any time, x, using a and b, the slope and offset terms for the regression. The remaining terms describe the uncertainty in the assigned value. Under the radical, the uncertainty of the regression based on its calibration history is combined with uncertainties due to calibration, temperature, pressure and seasonal effects based on populations of similar references. The combined uncertainty is expanded by the coverage factor, K. Non-linear drift is modeled by making a transformation of the time axis: x'=log (x – d) and then using x' instead of x in the equation above. A detailed description of the model and uncertainties was presented at NCSL in 1996 [1].

Figures 1 and 2 show the linear and non-linear models applied to the same calibration data. The linear model results in an uncertainty at the end of a one-year calibration interval of about 1 part in 10^6. By transforming the time axis prior to applying the linear regression tools, the uncertainty can be halved. For this example, the offset used in the transformation was 11/13/93. Our experience has shown that the transformed time axis works best for about 60% of the projections for either the 732A or the 732B.

EVALUATION OF THE PROJECTIONS

The quality of the projections is evaluated by comparing the measured value at the end of the calibration interval to the value that was projected at the beginning of the interval. Since the uncertainty of the prediction varies somewhat, these prediction errors are normalized by dividing them by the prediction uncertainty. Projections are made for a year following the calibration. Often, the next calibration occurs somewhat beyond the 1-year projection. In this case, the projection and uncertainty could be calculated further. However, we chose to calculate the projection error as the difference between the 1-year projection and the calibrated value. This may have caused the out-of-confidence (OOC) rates to be slightly overstated.

The 1998 Study

In 1998, 53 calibrations were studied with respect to their previous projections [3]. Two of the calibrations were found to fall outside of the confidence interval for an OOC rate of 3.8%. The data are plotted as a function of the calibration interval in Fig. 3 and by number of calibrations in Fig. 4. The study concluded that the goal of maintaining a confidence level of 95% for the one-year projections was met. It concluded that the uncertainty for the projections based on few calibrations may be slightly understated but somewhat overstated as the number of prior calibrations becomes greater.

732A Projection reliability

For the current study, Fig. 5 shows that 12 of the 268 predictions made for the 732A were found to be outside the prediction interval for an OOC rate of 4.5%. Of the 239 customer-owned units, 96% were calibrated at the customer's location. As in the 1998 study, the uncertainty for the projections were found to be a bit understated for small numbers of calibrations but decrease with more calibrations. Fig. 6 shows the standard deviation of the normalized prediction errors. It can also be seen that the prediction errors are fairly Gaussian with little (9%) bias so the 95% confidence level is about two sigma.

732B Projection reliability

For the current study, Fig. 7 shows that four of the 105 predictions made for the 732B were found to be outside the prediction interval for an OOC rate of 3.8%. Of the 73 customer-owned units, 96% were calibrated at the customer's location. The uncertainty for the projections for the 732B show better than 95% of the measured values at the end of the calibration period were found to be within the confidence interval for all the projections. This study again found that the confidence is lower for a small number of calibrations (Fig. 8). However, for the 732B, the standard deviations began to increase again for a high number of calibrations. This brings up the issue as to when early data should be excluded for the projections. Again, the prediction errors are fairly Gaussian with almost no bias (1%).

DRIFT RATES

732A Drift Rates

While analyzing the prediction reliability, we took the opportunity to examine the data for drift rate. Annualized drift rates were calculated from the shifts seen between adjacent calibrations. To keep short intervals from producing misleading drift rates, only calibration intervals of at least 70 days were considered. Data were also excluded when an adjustment was made to the output. 720 calibration pairs remained for analysis. Seasonal effects may make the slopes reported for the shorter intervals slightly higher than would be seen over a year period. Fig. 9 shows the 732A drift rates are normally distributed with a mean of $0.47 \cdot 10^{-6}$ / yr and a standard deviation of $0.5 \cdot 10^{-6}$ / yr.

732B Drift Rates

The drift rates for the 732B are shown in Fig. 10 for 335 calibration pairs. Here a bimodal distribution is evident with some units having a positive drift rate and a distinct separate group having mostly negative drift rates. The data were plotted in a number of ways to attempt to explain this distribution. Fig. 11 shows the 732B drift rates in serial number order. Here it is evident the higher serial numbers are associated with the negative drifts. Some of the lower serial numbers bear prototype or hardmodel serial numbers so may not fit "production sequence" and exhibit the negative drift rates as well. Some research showed that the positive drifts were associated with the Motorola references used in the 732A and early 732B units. The negative drifts were associated with Linear Technology references.

Fig. 12 shows a plot of the errors for the 31 predictions made for the higher serial number units having Linear Technology references. One unit was found to deviate from the predicted value more than the prediction interval for an OOC rate of 3.2%. The figure again shows the predictions getting better with more calibrations.

CONCLUSION

This study repeated the 1998 study with 7 times as many units. The results again validated the ability to project the zener reference values to a greater than 95% confidence for calibrations performed at the customer site and remaining at the customer site during the calibration interval. Though many factors are outside the control of the calibrating laboratory, this study shows there is adequate surveillance to maintain at least a 95% confidence in the projections. In addition, the drift data for over a thousand calibration pairs was presented. The drift characteristics of the Motorola and Linear Technology references are shown.

REFERENCES

[1] Kletke, Raymond, "Maintaining 10 Vdc at 0.3 ppm or Better in your Laboratory", NCSL Conference and Symposium, 1995

[2] Deaver, David, Hamilton, Clark, Jaeger, Klaus, Miller, William, Pardo, Leonard, Plowman, Dennis, "The 1999 North American 10V Jospephson Array Interlaboratory Comparison", NCSL Conference and Symposium, 2000

[3]   Kletke, Raymond, "Predicting 10 Vdc Reference Standard Output Voltage", NCSL Conference and Symposium, 1995

Fig. 1 Linear Drift Model

Fig. 2 Non-linear Drift Model for Same Device as in Fig 1
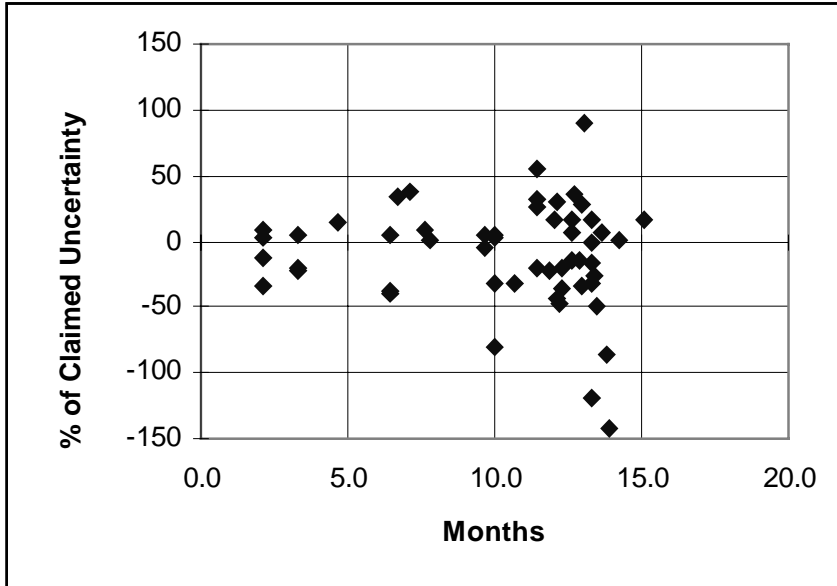
Fig. 3 Prediction Error vs. Calibration Interval, 1998 Study
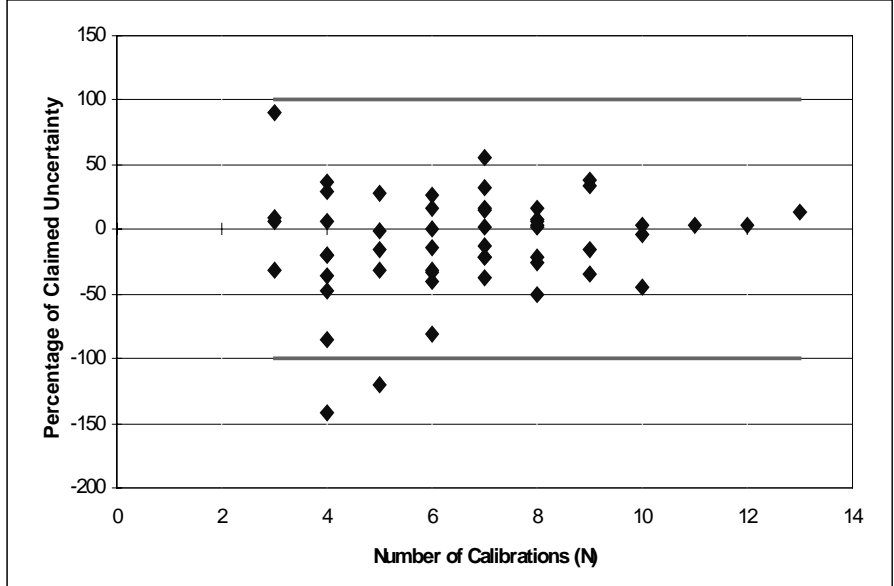
Fig. 4 Prediction Error vs. Number of Calibrations, 1998 Study
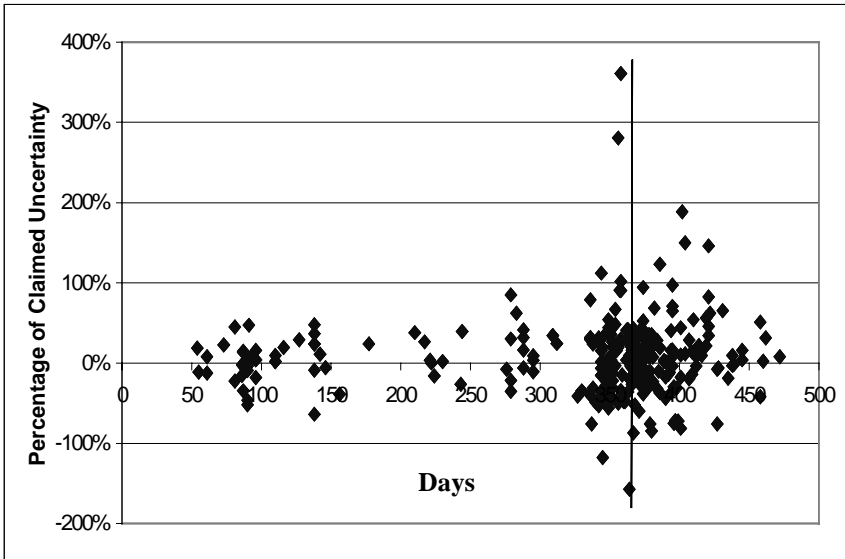
Fig. 5 732A Prediction Errors
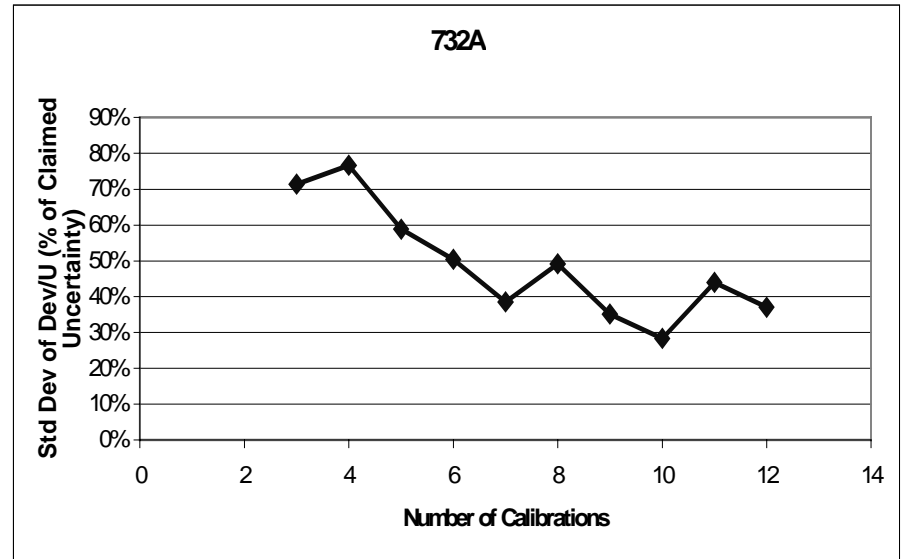
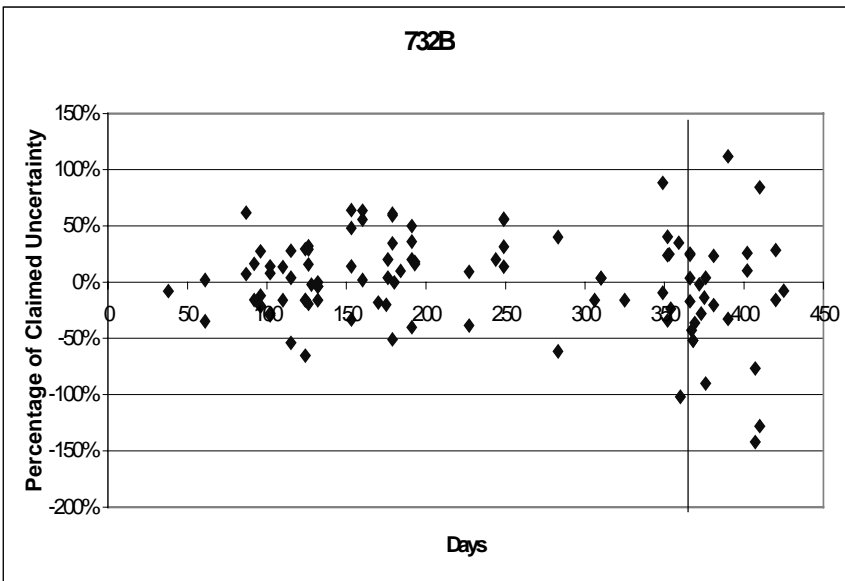Fig. 6 Std Dev of 732A Prediction Deviations vs. Prediction Uncertainty

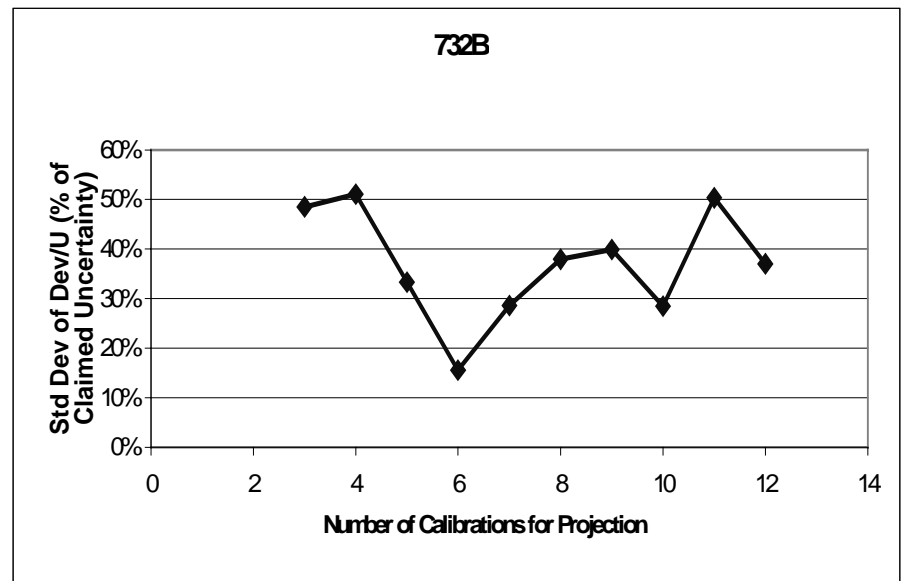Fig. 7 732B Prediction Errors vs. Calibration Interval

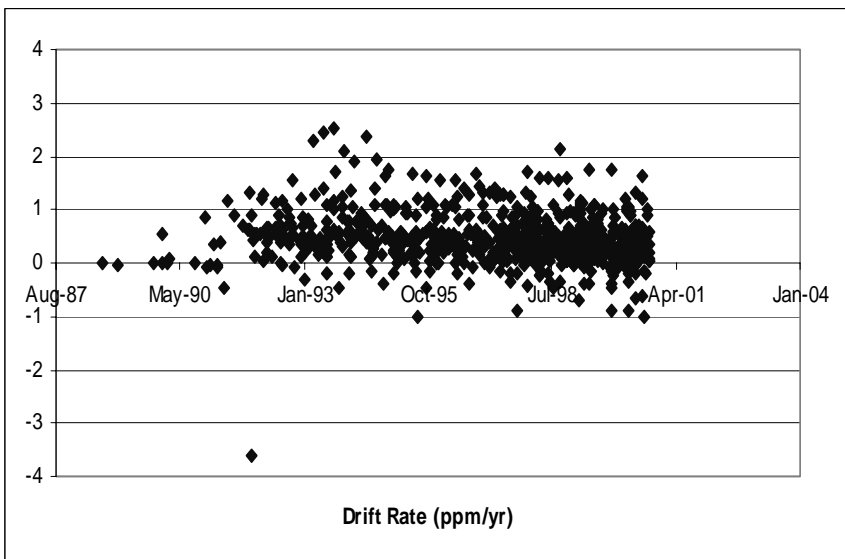Fig. 8 Std Dev of 732B Prediction Error vs. Prediction Uncertainty
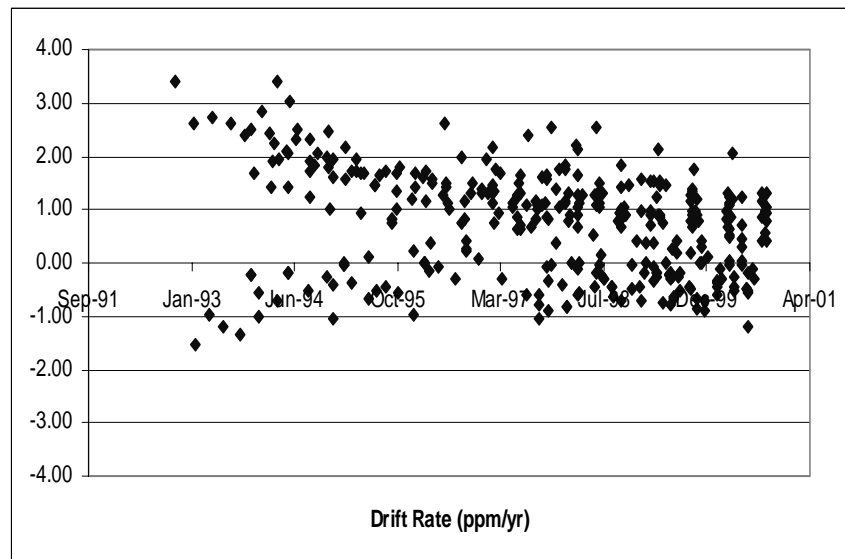
Fig. 9 732A Drift Rate (parts in 10^6 / year)

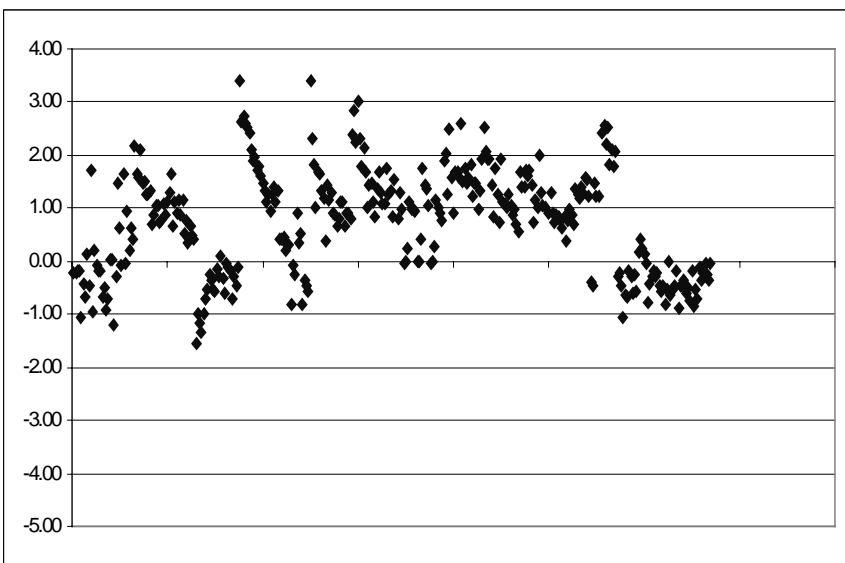**Fig. 10 732B Drift Rate (parts in 10^6 / year)**

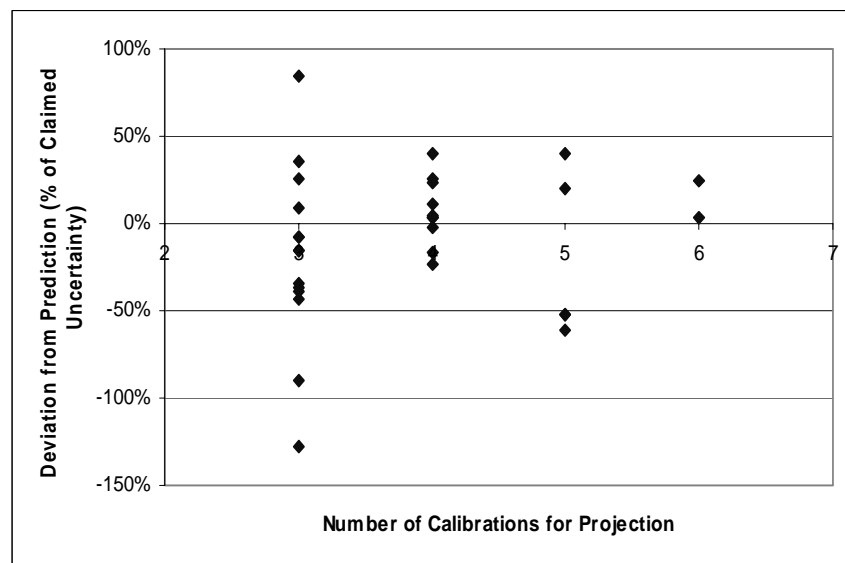**Fig. 11 732B Drift Rate (parts in 10^6 / year) in Serial Number Order**

Fig. 12 732B Prediction Error for Linear Technology (high s/n)