PROJECTING ZENER DC REFERENCE PERFORMANCE BETWEEN CALIBRATIONS

Clark A. Hamilton
VMetrix, LLC
7712 Spring Drive, Boulder, CO 80303

Larry W. Tarr
Electrical Standards Laboratory
U.S. Army Primary Standards Laboratory
Redstone Arsenal, AL 35898

ABSTRACT

Two simple empirical models are proposed to predict Zener reference standard output voltage and uncertainty based on just 1 or 2 calibration points. The models are derived from a study of 140 Zener standards. The results yield a substantial reduction in uncertainty relative to the manufacturer's specification and illustrate the dominant influence of seasonal effects on projection uncertainty.

I. INTRODUCTION

Many standards laboratories rely on Zener reference standards for dc voltage and achieve traceability through periodic calibrations by a national metrology institute (NMI) or a Josephson standard. Typically, such calibrations give only a value and uncertainty at the time of test. This paper addresses the problem of predicting the value and uncertainty over the interval between calibrations [1]. The approach is to examine a large representative sample of measurement data, and then to construct an empirical model that describes the data without making any assumptions about its statistics. For any given standard, the model uses the available calibration data to predict a value and the representative sample of data to predict two time dependent uncertainties such that the predicted values fall within the uncertainty limits with a probability of 95% and 99% for all of the sample data and at all points within the calibration interval.

The models are tested with long measurement histories for a large sample of Zener reference standards. These histories come from Josephson standard measurements so that the uncertainty of the measurement is insignificant compared with the noise of the Zener standard. Fortunately, many such long data histories are available from the laboratories operating Josephson standards. Data sets are extracted from these histories to test and quantify a proposed model. A test data set consists of one or more measurements separated by the calibration interval (calibration points) followed by 10-30 measurements (validation points) during the next calibration interval. For example, a test data set might include calibration points on 3 January 1999, 10 January 2000, and then validation points every week until January 2001. Note that a continuous history on one Zener standard over several years can provide many test data sets because the test data set can be selected from the history starting at many different points within the history. The model is tested by making a time dependent plot of the prediction error for all test data sets. Empirical uncertainty functions are then constructed to achieve 95% and 99% compliance. The goal is to develop models that make an appropriate trade-off between simplicity and accuracy. The Zener reference standards used for the study are all the 10 V tap of Fluke model 732A or 732B dc reference standards.

II. THE SINGLE CALIBRATION, CONSTANT OUTPUT MODEL

Consider the simplest model, that is, V_Z is constant over the calibration interval and equal to a calibration value at the start of the interval. Manufacturer's specifications typically apply to this case. Test data sets consist of one year of measurement data drawn from a succession of up to 20 monthly starting points within each of the available histories of 140 different standards. The prediction error is the difference between the first point in each data set (the calibration) and each of the succeeding points. Figure 1 plots the prediction error over a one year calibration interval for 19 711 points in 1174 data sets. Empirical uncertainties that include 95% and 99% of the available data are

$$U_{95} = 2.0 + 0.0383\,t \qquad (1)$$

$$U_{99} = 3.0 + 0.0575\,t \qquad (2)$$

where U is the uncertainty in μV and t is the time in days from the calibration at $t = 0$.

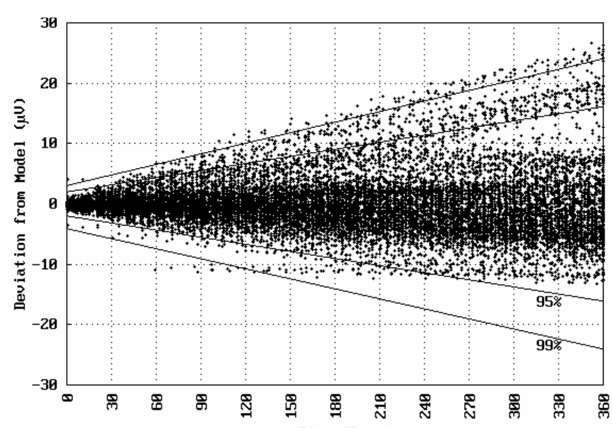

Fig.1 Prediction Error of the constant output model with 95% and 99% uncertainty lines.

In many cases, a time dependent uncertainty might be considered cumbersome in which case the uncertainty at the end of the 1 year interval could be used, that is, $U_{95} = \pm 16\ \mu V$ and $U_{99} = \pm 24\ \mu V$.

III. Linear Drift Model

The linear drift model for Zener reference voltage over the calibration interval is $V_Z = V_o + mt$ where V_o and m are given by a straight line passing through the most recent 2 calibration points. The drift rate m can be determined independently of seasonal variation if the calibration interval is always close to 1 year. In this case, the seasonal component is about the same for every calibration point and does not influence the calculated drift rate m. Figure 2 plots the prediction error for each of 681 test data sets for a 1 year calibration interval. Equations (3) and (4) are empirical approximations for the 95% and 99% uncertainties of the linear drift model.

$$U_{95} = 2.0 + 0.03\,t \qquad 0 \le t \le 100$$

$$U_{95} = 5 \qquad 100 \le t \le 365 \qquad (3)$$

$$U_{99} = 3.5 + 0.035\,t \qquad 0 \le t \le 100$$

$$U_{99} = 7 \qquad 100 \le t \le 365\,. \qquad (4)$$

Although the one year calibration interval is optimal, practical considerations may result in calibration intervals substantially different than 1 year. Figure 3 shows how the 99% uncertainty varies with calibration interval. For calibration intervals of less than 3 months, the drift rate cannot be reliably determined and the constant output model is superior to the linear drift model.

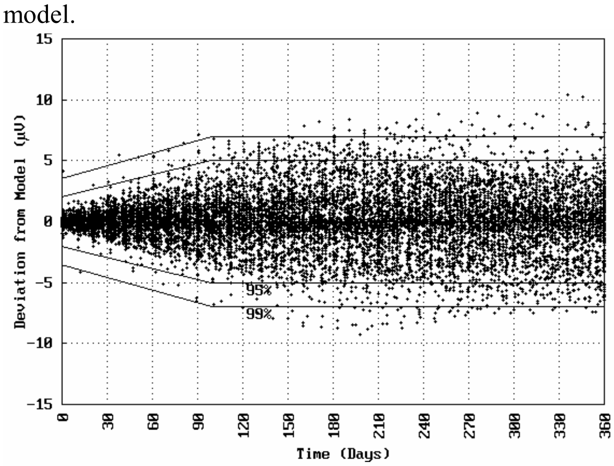

Fig. 2 Prediction error of the linear drift model with 95% and 99% uncertainty lines. Note that the Y axis range is half of that in Fig.1.

The constant value model is most appropriate for new or repaired units. After a second calibration at an interval of 6 months, the linear drift model can be used and Figure 3 shows that U_{99} can be reduced to13 µV. U_{99} is less than 9 µV for all calibration intervals greater than 9 months. U_{99} may be preferable over U_{95} because, although U_{95} correctly describes the entire data base, it may not adequately describe a specific unit with a large drift or seasonal dependence.

The calibration points of Figs 1-2 are single measurements, whereas it is common practice in most calibrating laboratories to assign a value based on the mean of many measurements taken over a week or more. To determine the utility of using multiple measurements to establish a calibration value, the algorithm that generated Fig. 2 is modified to base the calibration points on the mean value of 2 weeks of measurements. For the linear drift model with a 1 year calibration interval, the resulting prediction uncertainty shows an improvement from $U_{99} = 7\ \mu V$ to $U_{99} = 6.8\ \mu V$. Thus, after a few measurements to confirm that a standard under calibration is well behaved and free of travel induced transients, further measurements do not result in any significant reduction in the prediction uncertainty.

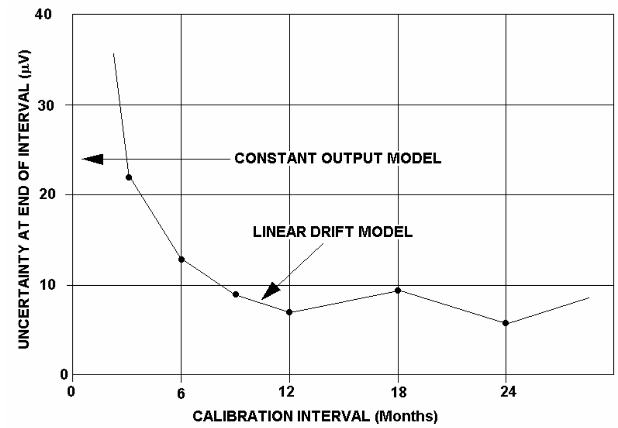

Fig. 3 Prediction uncertainty (99%) in µV of the linear drift model for a 10 V Zener reference as a function of the calibration interval.

IV. Seasonal Variation

Pressure, temperature, and humidity have all been shown to influence Zener reference standards [2-5]. The dominant factor in prediction uncertainty of the linear drift model is the seasonal dependence of the data. This seasonal dependence is probably a result of a slow response (20-40 day time constant) to environmental humidity as described in [2, 5] and further supported by the unique lack of seasonal dependence in the data of the one contributing lab (Sandia National Laboratories) that has tight humidity control. Figure 4 shows a 5-year history that is dominated by seasonal variation. The peak of the annual cycle occurs very close to March 1 for 5 consecutive years. The uncertainty of Eq. 3 and Eq. 4 is dominated by just a few standards with large seasonal variation. The uncertainty estimation for a given standard can usually be improved by quantifying its deviation from linear time drift. This can be done by making a number of measurements $M \ge 4$ over a period of 1 year. These measurements are used to compute a recursion fit line and then to compute the standard deviation σ_L to the fit line. σ_L is given by

$$\sigma_L = \sqrt{\frac{\sum X_i^2}{M-2}} \qquad (5)$$

where the X_i are the residuals to the fit line. The measurement times must be reasonably distributed over the year. The number of measurements M can be as small as 4. For small values of M, σ_L tends to be overestimated by up to 50%. σ_L was calculated for the 57 standards for which there were at least 20 reasonably distributed measurements over a 12 month interval. The results are summarized in the bar chart of Fig. 5 which plots the distribution of the 57 Zener reference standards as a function of annual scatter σ_L from a recursion fit line. For values of $\sigma_L > 0.5$ µV , seasonal dependence is the dominant factor. It is clear from Fig. 5 that seasonal dependence is the typical behavior of these Zener standards and not just an occasional anomaly.

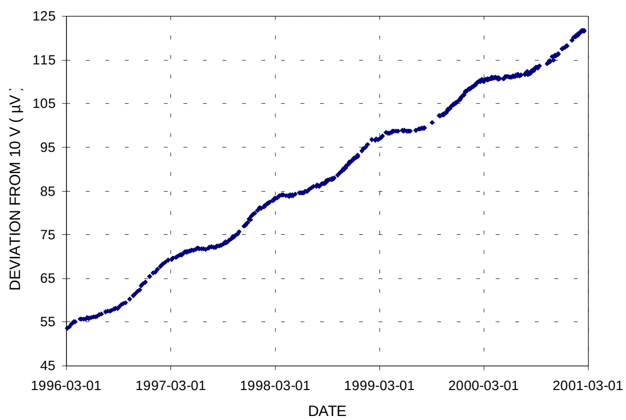

Fig. 4 A typical 5 year history including 387 measurements of a Zener reference standard.

The calculation of Fig. 2 was repeated for the population of standards represented by each bar in Fig. 5. The numbers at the top of each bar represent the 99% uncertainty of the linear drift model for the standards in that bar. For example, choosing 12 monthly points between 1997-03-01 and 1998-03-01 from the data of Fig. 4 yields a value $\sigma_L = 0.98$ µV. This falls into the second bar of Fig. 5 and we can therefore assign an uncertainty of $U_{99} = 6$ µV for the linear drift model over the interval 1998-03-01 to 1999-03-01.

V. Conclusion

Using data on 140 Zener reference standards, we analyzed two empirical models that predict the value and uncertainty of these standards during the interval between calibrations. The constant voltage model, based on a single calibration point, offers a small improvement over the manufacturer's specification. The linear drift model, based on two calibration points separated by at least 9 months, allows a substantial reduction in uncertainty. The uncertainty limits of the linear drift model are dominated by the seasonal humidity dependence that occurs in most of the standards in the study. The dominance of the seasonal humidity effect suggests adherence to a one year calibration interval and special vigilance in cases where the environmental conditions in the calibrating laboratory may be significantly different than in the client laboratory.

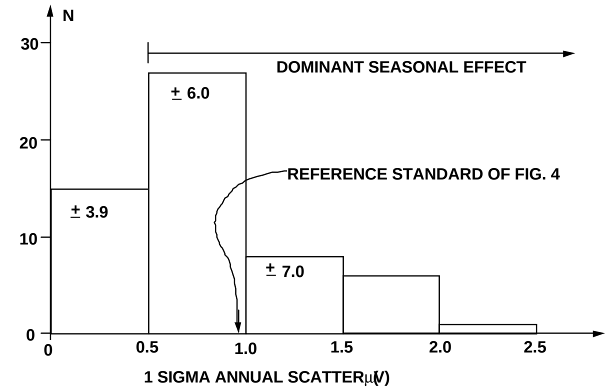

Fig. 5 A bar chart of the number of standards as a function of their 1 sigma scatter from linear drift over a 1 year interval.

Elimination of the seasonal dependence is perhaps the most important and readily achievable goal for reduction in the uncertainty of Zener reference standards. These results do not include components of uncertainty related to travel and uncertainty from possible differences in the elevation and environment between the calibrating laboratory and the client laboratory. These components need to be evaluated and combined with the results presented here.

Acknowledgement

The Army Primary Standards Laboratory at Redstone Arsenal, the National Institute of Standards and Technology, Sandia National Laboratory, and Hypres, Inc. contributed the data that made this study possible.

References

[1] David Deaver, "Predictability of Solid State Zener References," presented at the Measurement Science Conference, Anaheim, CA, 2001.

[2] L.X. Liu, T.Y. Sim, V.K.S. Tan, H.A. Chua, K.H. Lam, "Mathematical model to approximate the response of a Zener cell output under varying environmental conditions." *Metrologia*, vol. 37, pp. 213-218, 2000.

[3] W.B. Miller and L.P. Pardo, "Pressure Coefficient Measurements for Fluke 732B Zener Voltage Reference Standards," in *Proc. NCSL International Symposium,* 2000 (CD ROM).

[4] T. J. Witt, "Measurements of the temperature dependence of the output voltages of some Zener diode based voltage standards," *IEE Proc.-Sci. Technology*., vol. 145, no. 4, pp 1-5, July 1998.

[5] Y.H.Tang and J.E. Sims, "Evaluation of Standards for a 10 V MAP Service at NIST," in *Proc. NCSL International Symposium,* 2000 (CD ROM).