

# Establishing traceability for a high-performance ac/dc transfer standard

## Application Note

### Abstract

Introduction of new, high-accuracy alternating voltage DMMs and calibrators in the past few years has presented the electronics test equipment industry with the challenge of supporting their accuracy. A group at Fluke was tasked with developing an ac/dc transfer standard having uncertainties of about  $\pm 10$  ppm at moderate levels and frequencies, an accuracy that results in a ratio of product specification to National Institute of Standards and Technology (NIST) uncertainty of about 2:1. A major challenge was to develop and communicate a credible calibration system to support this product. Rigorous application of statistical principles to successive intercomparisons of nearly identical artifacts had already been proven capable of maintaining a Direct Voltage Standard within a few parts in 100 million of the 10 volt standard maintained at NIST, a ratio of about 1.2:1. This note describes the system developed to support traceable calibration of this new ac/dc transfer standard through application of these proven statistical techniques.

### Introduction

Fluke's 8508A Digital Multimeter (DMM), among others, has improved accuracy of routine measurement of alternating voltage to the point that calibrators are hard pressed to keep up. One new DMM can be *adjusted* using only a 10 volt dc standard and two resistors, but still must be *verified* by comparison to independent standards in order to confirm that the internal metrology is actually working as it was designed to work. The 8508A is calibrated (adjusted) in the conventional way, by bringing up a known, higher accuracy standard of alternating voltage.

Calibrator manufacturers have responded to the challenge by introducing new, ever more accurate instruments including Fluke's 5720A and competing products. The 5720A uses "Artifact Calibration" to support the accuracy of dc functions and resistance, and depends upon the stability of an internal ac/dc transfer standard for its ac accuracy. The accuracy of the internal ac/dc standard must be independently verified at least every two years for the calibrator to perform to specifications.

MIL-STD-45662A mandates a 4:1 Test Uncertainty Ratio (TUR) between the calibrator and the instrument calibrated unless another ratio can be justified. Currently manufactured calibrators have accuracies that are already less than four times the uncertainty routinely provided by NIST at some levels and frequencies. It is obvious that another approach will be required to support these calibrators. NIST has addressed this problem by

offering extra-cost improved uncertainties (as small as  $\pm 5$  ppm at some levels and frequencies). Fluke has developed the 792A AC/DC Transfer Standard to provide a traceable standard that meets the requirements of the 5720A and other existing calibrators. Design goals for the standard require an uncertainty at time of use of approximately  $\pm 10$  ppm at moderate levels and frequencies, a TUR of 2:1 from NIST's best accuracy.

Supporting a TUR as low as 2:1 cannot be accomplished by the usual procedure of shipping a standard to NIST for calibration, then using it for a year at the uncertainty NIST assigns to it. A much more complex approach is required, one that utilizes the principles of measurement process control. This paper describes the calibration system that was developed to support the accuracy of Fluke's 792A AC/DC Transfer Standard.

### Approach

#### Precedents

Statistical methods for computing and controlling the accuracy of calibrations were developed by the National Bureau of Standards (NBS) and others more than 20 years ago, and have gradually begun to be adopted in industry. Application of these statistical methods makes it unnecessary to maintain arbitrary TURs since the uncertainty in any transfer can be computed with confidence. One of the more useful statistical approaches utilizes linear regression (linear curve fitting) to predict the drift rate of a standard, to compute a value for the standard which is "better"

than the result of any one calibration, and to predict a value at points (times) different from the calibration points. (References [1] and [2] have good descriptions of the statistics of linear regression. Reference [3] is an especially clear presentation of the application of statistics to measurements.)

Rolf Schumacher [4] has shown that the value computed from linear regression on a set of data is less uncertain than any individual calibration result, even when that result was provided by a NIST calibration. Deming (as quoted by Schrenkenbach [5]) reached a similar conclusion, based on his understanding that variability exists in every process, and that overadjusting to respond to variability in a process can actually double the resultant variability. The common practice of using the latest NIST value as the proper value until another calibration is performed can actually degrade the accuracy of a given calibration system.

Fluke has extensive experience with application of statistical methods to calibration of instruments in designing and implementing its corporate 10 volt voltage standard [6], and its Direct Voltage Maintenance Program (DVMP) [7]. The uncertainties that can be achieved with well-behaved standards and repeated transfers to a stable and well-maintained standard at NIST are almost incredibly small. For example, the drift rate of Fluke's corporate voltage standard is now known to within about  $\pm 0.02$  ppm per year, and its absolute value relative to NIST's 10 volts is known to within about  $\pm 0.05$  ppm.

These uncertainties are the result of an unusually high number of transfers to NIST, and more importantly, to the existence of an unusually well-designed and maintained system for the calibration of 10 volts at NIST. The situation will be less ideal for the ac/dc standard, but nonetheless, the approach is valid, and has been chosen as the best one for maintaining accuracy of ac/dc difference at Fluke.

### The calibration support system

Because of the very small TURs involved, the 792A is provided with a correction table instead of being constructed to provide a specified absolute accuracy at time of use. That is, the accuracy is provided through correction tables, not through hardware, as is done for many standards. Therefore, part of the production process consists of calibrating the 792A and generating the correction table. As a result of this requirement, traceability must be provided for the product as shipped. A flow chart for traceability from NIST to the Fluke Primary Standards Laboratory, then to production test, and finally to the product is presented in Figure 1.

Two 792A AC/DC Transfer Standards are established in the Fluke Primary Standards Laboratory to form the Fluke Corporate Reference Standard for ac/dc difference. The reference standard is calibrated by connecting a NIST calibrated 792A to the test port and "test" 792As will be calibrated by connecting them to the same port. A constant bias in the comparison of the (internal) reference standards will not cause an error so long as nearly identical devices are being compared. The reference standard is thus little more than an apparatus for storing and transferring values obtained from NIST via the first transfer standard. A transfer standard, also a 792A, is compared to the reference standard frequently, and for an extended time period. These comparisons establish the offset between the reference standards and the transfer standard, as well as any difference in drift rates that may exist. This transfer standard transfers NIST values to the reference standards.

Figure 2 is a block diagram of the comparison system. The 792As, utilizing the Fluke RMS Sensor, provide a full-scale output of approximately two volts dc, which is measured by a Fluke 8500 series digital multimeter.

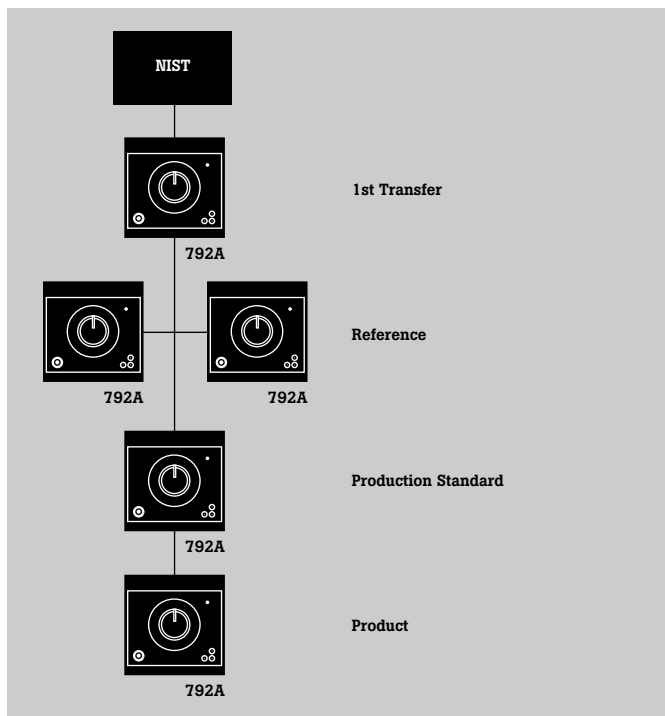


Figure 1. Flow chart for traceability from NIST to product.

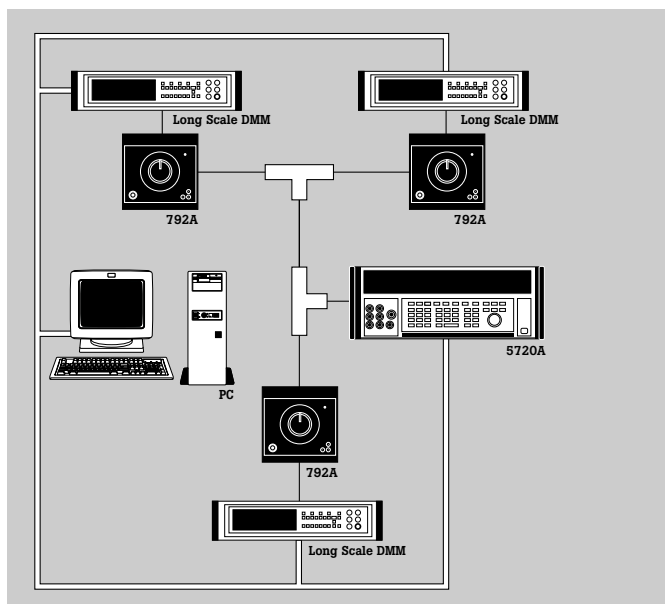


Figure 2. Block diagram of the 792A comparison system.

Since the reference standard consists of two 792As, and the "standard" ac/dc difference is the mean of the two, it is appropriate to compare "test" instruments to both standards at once. This is accomplished by connecting the "test" instrument to the test port, the open end of type N tee #1. The reference plane for the comparison apparatus is the center of that tee.

Both dc and alternating voltage are supplied to the input port of type N tee #1 from a 5700A/5725A combination. The responses of the three 792As are measured by means of the 8500-series DVMs, which are read over the IEEE bus by a PC. The PC also sets levels and frequencies for the calibrator, computes ac/dc differences, and stores results in a file as well as prints a hard copy record. Except for the turning of the 792A range switches, the operation is completely automated. Typical standard deviations for repeat comparisons at moderate levels and frequencies is approximately 0.25 ppm, increasing at higher and lower levels and frequencies.

After the comparisons are completed, one of the transfer standards is shipped to NIST for calibration, a process that requires about 10 weeks, since the highest available accuracy is needed. At the end of the 10 weeks, the standard is returned to Fluke, and additional comparisons to the reference standard are performed to detect any changes in its offset that might have occurred while the transfer standard was away from the laboratory. At this early stage, any such changes are attributed to the transfer standard drifting relative to the reference standard. It is possible to calibrate the reference standard in the presence of such drifts, because the relative drift rate has been determined, and the time of the NIST calibration is known.

Upon completion of this second set of comparisons, we have completed the first calibration of the reference standard, a process that requires some 16 weeks to accomplish. Figure 3 illustrates the transfer from NIST to the reference standard. The comparisons at Fluke establish transfer standard drift rate and offset relative to the reference standard. When the comparisons to the reference have been completed, the transfer standard is returned to NIST for a second calibration, and the process is repeated until the uncertainty in the reference standard's drift rate and offset from NIST standards have been reduced to acceptable levels.

The production standard is calibrated by comparing it directly to the reference standard. Two production standards are maintained, one active and one spare. The spare is maintained in the Fluke Standards Lab, where it is regularly compared to the reference standard. It is exchanged for the active production standard each 30 days, or at a shorter interval in the event of failure of the active standard.

## Mathematical considerations

Ultimately, the need is for bounding the difference between the ac/dc difference assigned to a product manufactured at Fluke and the ac/dc difference that would be assigned at NIST, that is, for assigning an uncertainty to a production instrument as it is shipped from the factory. (To avoid repeating "ac/dc difference" and "difference in the ac/dc difference" in the following, the word "value" will be used instead.)

In the following, it is assumed that everywhere in the traceability chain, except for the calibration at NIST, information about the value of a transfer standard is transferred by means of direct comparisons of nearly identical items. To the extent that this is true, it is possible to transfer values without bias, bias being defined as a consistent tendency for the measuring system to produce a value that is different from the "true value" of the difference between the two instruments.

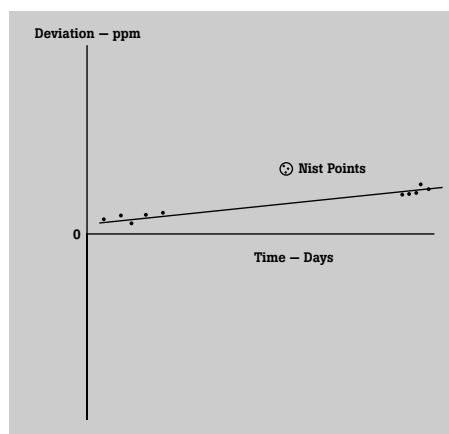


Figure 3. A "typical" transfer from NIST.

Given unbiased comparisons, with the further assumptions that differences between two instruments actually yield a straight line representing value versus time, and that measured points are random, independent, and normally distributed about the line, it is appropriate to apply statistical methods developed for analysis of linear regression. Under these assumptions, a *confidence interval* for the line for a particular time,  $T$ , is given by

$$Y = A + BT \pm t_s \sqrt{\frac{1}{n} + \frac{(T - T_{\text{bar}})^2}{(n-1)s_t^2}}$$

where  $A$  is the intercept and  $B$  the slope of the line,  $n$  is the number of points used in the regression,  $s$  is the sample standard deviation,  $t$  is student's  $t$  for  $n-2$  degrees of freedom and confidence level  $(1-\text{Alpha})$  (Fluke uses 99%),  $s_t^2$  is the variance in  $T$ , and  $T_{\text{bar}}$  is average time over which the data are taken. The meaning of a confidence interval is as follows: If a large number of determinations of  $A$  and  $B$  are made each utilizing  $n$  independent samples from the same population, approximately  $(1-\text{Alpha})$  of them are expected to fall within the computed confidence interval.

A *prediction interval* for a particular time,  $T$ , is given by

$$Y = A + BT \pm t_s \sqrt{\frac{1}{n} + \frac{(T - T_{\text{bar}})^2}{(n-1)s_t^2} + \frac{1}{n}}$$

For the average of  $n_2$  measurements, a modified prediction interval is

$$Y_{\text{bar}} = A + BT \pm ts \sqrt{1/n_2 + 1/n + (T - T_{\text{bar}})^2 / ((n-1)s^2)}$$

where  $n$  here refers to the total number of points used in the regression. Given the regression over  $n$  data points, with the assumptions listed above, a future value of  $Y$  (or  $Y_{\text{bar}}$ ) can be expected to fall within the prediction interval a fraction  $(1-\text{Alpha})$  of the time.

These equations apply only at a particular time,  $T$ , and the results at different times cannot be combined by the usual statistical methods because they are not independent. Individual values have the standard deviation,  $s$ , in common. For those cases where the *whole line* is under consideration, which includes this case, student's  $t$  in the equations should be replaced by  $\text{Sqr}(2F)$  where  $F$  is the  $F$ -function for  $(2, n-2)$  degrees of freedom and the desired confidence level.

## Sample uncertainty calculation

The test is initiated by comparing the transfer instrument to the reference standard maintained in the Fluke Primary Standards Laboratory. This instrument is then shipped to NIST, where it is calibrated, then returned to Fluke after about 70 days. Upon its return, it is again compared to the reference standard to determine whether there have been significant shifts in the difference between transfer and reference instruments. If such shifts are present, they will be assumed to be due to linear drift in transfer instrument, the reference units, or both. For these comparisons the equation is

$$V_r - V_{t1} = A_1 + B_1 T \pm t_{s_1} \sqrt{1/n_1 + (T - T_{\text{bar}})^2 / ((n_1-1)s_1^2)}$$

where  $V_r$  is the value assigned to the reference unit,  $V_{t1}$  is the value assigned to the first transfer standard,  $t_1$  and  $s_1$  are student's  $t$  and standard deviation,  $n_1$  is the number of points over

which the regression is performed, and  $T_{\text{bar}}$  is the average time. For convenience later, write this as

$$V_r - V_{t1} = A_1 + B_1 T \pm U_1$$

The transfer instrument is calibrated at NIST at average time  $T_{nr}$  with result

$$V_{t1} - V_n = A_n \pm U_n$$

where  $V_n$  is the value as maintained by NIST and  $U_n$  is the NIST uncertainty. NIST does not separate its smallest uncertainties into random and systematic components, so for this analysis, the NIST uncertainty is considered to be systematic, and will be added to the random components of uncertainty. If time,  $T_{nr}$ , is reported, then the reference standard may be calibrated using this transfer standard, even when the two are drifting relative to one another, since the difference versus time is known from the first equation.

With the results obtained so far, the reference standard can be calibrated and an approximate uncertainty calculated.

$$(V_r - V_{t1}) + (V_{t1} - V_n) = V_r - V_n \\ V_r - V_n = A_1 + B_1 T + A_n \pm (U_1 + U_n)$$

The reference standard calibration is only an interim calibration, pending more data from NIST, since any possible drift in the reference has not been identified. At least one more NIST calibration is required to give any information about drift in the reference, and at least five will be required to provide a reasonable level of confidence in drift rate of the standard.

With the reference standard calibrated, the production standard can now be calibrated. In this case, assume that there have been daily comparisons to the reference standard for the past 30 days. The equation is

$$V_{t2} - V_r = A_2 + B_2 T \pm t_{s_2} \sqrt{1/n_2 + (T - T_{\text{bar}})^2 / ((n_2-1)s_2^2)} \\ V_{t2} - V_r = A_2 + B_2 T \pm U_2$$

Expressing this result in terms of the NIST value

$$(V_{t2} - V_r) + (V_r - V_n) = V_{t2} - V_n \\ V_{t2} - V_n = A_1 + A_2 + A_n + (B_1 + B_2)T \pm U \\ U = \text{Sqr}(U_1^2 + U_2^2) + U_n$$

This uncertainty is approximate because it is not strictly proper to combine uncertainties in this way, even when dealing with normal distributions and equal confidence levels. However, it is possible to show that such a combination of uncertainties will always overestimate the uncertainty for normal distributions having equal confidence levels. For the purposes of this discussion, the approximation is sufficiently accurate. A rigorous treatment is available [8] and will be used in the actual error analysis.

With the production test instrument calibrated, it is possible to calibrate product. Here a single measurement is made, and

$$V_p - V_{t2} = A_3 \pm U_3$$

where  $U_3 = 3s$  and  $s$  is a pooled standard deviation obtained from repeat measurements on several production instruments. Expressing in terms of NIST values

$$V_p - V_n = A_1 + A_2 + A_3 + A_n + (B_1 + B_2)T \pm U_p \\ U_p = \text{Sqr}(U_1^2 + U_2^2 + U_3^2) + U_n$$

Through this long string of transfers, a product has been calibrated traceable to NIST. What is the resultant uncertainty,  $U_p$ ? More information is needed. Assume:

$$s_1 = s_2 = s_3 = 0.5 \text{ ppm} \\ n_1 = 10 \quad t_1 = 3.355 \quad T_{1\text{bar}} = 40.5 \\ T = 80 \\ n_2 = 30 \quad t_2 = 2.763 \quad T_{2\text{bar}} = 65 \\ T = 80 \\ n_3 = 1 \quad t_3 = 3 \quad U_n = 5.0 \text{ ppm}$$

Using the equations developed above, the uncertainties at time of cal, here assumed to be 80 days after first measurements of the difference between transfer instrument #1 and the reference, are

$$U_1 = 0.77 \text{ ppm} \quad U_3 = 1.50 \text{ ppm} \\ U_2 = 0.50 \text{ ppm} \quad U_n = 5.00 \text{ ppm} \\ U_p = 6.8 \text{ ppm}$$

Thirty days after cal (110 days after first measurement) the uncertainties will be, assuming no additional calibrations

$$U_1 = 1.13 \text{ ppm} \quad U_3 = 1.50 \text{ ppm} \\ U_2 = 1.32 \text{ ppm} \quad U_n = 5.00 \text{ ppm} \\ U_p = 7.3 \text{ ppm}$$

Evidently, given the standard deviations and uncertainties listed here, the 792A can be calibrated in production with sufficient accuracy to support a specification of  $\pm 10$  ppm, even using this fairly conservative method of combining errors. If the BIPM recommendations for combining uncertainties were to be followed, and the NIST uncertainty were to be taken as a 3s estimate, all the 1s estimates of uncertainty would be combined in quadrature, then multiplied by 3, yielding  $U_p = 5.3$  and  $6.4$  ppm for the two cases considered.

What has been demonstrated here is just a small part of the total task of supporting the calibration of the 792A in production, since only one level and frequency have been considered. In actuality, 13 voltage levels are calibrated at up to 14 frequencies, resulting in a total of 126 calibration points. Each point must be evaluated for total uncertainty just as was the single point in the example. Obviously, this will not be a manual calibration, and data must be collected, processed, and to a large extent, interpreted by computer.

Customers for the 792A will be spared the cost and effort of developing a sophisticated system to support their instruments, since they will be able to have them calibrated directly by NIST, or by another provider of calibration services, such as the Fluke Technical Centers.

## Conclusion

This paper has described the approach adopted for establishing traceability of the Fluke 792A AC/DC Transfer Standard as shipped from production. The test uncertainty ratio between product spec at time of use and uncertainty provided at NIST will be about 2:1, and there are four transfers between NIST and product. As a result, the test uncertainty ratio for any given transfer must approach 1.1:1. The system adopted utilizes statistical treatment of data to achieve the required low transfer uncertainties. An example of the uncertainty analysis shows that for the most critical ranges – those where NIST provides  $\pm 5$  ppm and product spec is about  $\pm 10$  ppm, the achievable test uncertainty ratios are adequate for the purpose.

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