FLUKE®

Artifact Calibration
Theory and Application

Application Note

Introduction

Electronic instruments generally contain both a large number and a wide variety of components. The circuit configuration and the values of the components determine the characteristics of the instrument. Unfortunately, because nothing is absolutely stable, the value of any component varies with time, and because of this, instruments require periodic calibration to assure continued compliance with specifications. Until the advent of the microprocessor, periodic calibration generally required the physical adjustment of components within the instrument. This was done to bring the instrument into compliance with external standards. Complex instruments might contain dozens of internal physical adjustment points such as potentiometers and variable capacitors. The adjustment process could take many hours to complete.

This approach to calibration requires traceable stimulus and measurement at each of these points. The systems used have been both manually operated and complex. Such systems may include various reference components or stimulus values, as well as bridges and other instruments. The support of these complex and lengthy calibrations required a large and costly array of equipment, processes and manpower.

Figure 1. A Calibration Lab in an Instrument

In the mid-1970s, instrumentation broke new ground by using the microprocessor, not only to enhance capabilities and operation, but also to simplify the calibration process. For example, the Fluke 8500A (a high-accuracy multimeter) was designed to store and use software correction factors to compensate for gain and zero errors on each range of the instrument. This process of storing constants (based on comparison to external standards) has been utilized extensively in the calibration of instruments. Today, internal software corrections have eliminated the need to remove instrument covers to make physical adjustments in almost all types of instrumentation. However, for instruments that do not support Artifact Calibration (defined below), it is still necessary to provide a large array of external stimulus or measurement capability for purposes of calibration.

Artifact Standards and Artifact Calibration

An artifact standard is a standard that maintains a small, concise set of derived values. An example of this is a 10V zener reference such as the Fluke 732B DC Transfer Standard. Typically, the artifact standard is in the category (and of the technology) commonly considered to be a transfer standard. This is in contrast to an intrinsic reference such as the Josephson Voltage Reference which generates values based on physical constants.

Artifact Calibration is the process of transferring the assigned value(s) of an artifact to a large array of multidimensional parameters. Typically the term Artifact Calibration is used to describe the process when it is implemented internally in an instrument. For example, consider the calibration of a dc source that has several ranges extending from millivolts to one kilovolt. To calibrate such an instrument, whether it uses internally stored constants or requires manual adjustment, you ordinarily need an external reference voltage such as a zener reference or standard cell; a null detector to make comparisons; a Kelvin-Varley ratio divider (which is usually self-calibrating), and a decade divider. For calibration, this array of equipment is connected in various configurations to provide the traceable source and measurement parameters.

Now consider the calibration of the dc source with the capability of Artifact Calibration. Then all that is necessary is to apply the artifact, in this case a dc reference. The dc source being calibrated would have to have the equivalent of the Kelvin-Varley divider, null detector and decade divider built in. And it would use those built-in devices to transfer the accuracy of the artifact to the many ranges of the instruments. In essence, an instrument capable of Artifact Calibration takes over the manual metrology functions of establishing ratios and making comparisons. This is done by placing circuitry, microprocessor control and software inside the instrument so that it can perform these same functions. The driving force behind this change has been the need to reduce the time and equipment costs associated with conventional manual or semi-manual calibration and to provide more uniform quality.

Technological advances in components and software are now allowing manufacturers to emulate what is humorously illustrated in Figure 1. Null detectors can be built on a chip. Ratio systems can be reduced to a single circuit board. Thin-film resistor networks can replace bulky wire-wound resistors.

Artifact Calibration and the Fluke 5700A Calibrator

The Fluke 5440A Precision DC Voltage Calibrator[1] was introduced in 1982 and was the first instrument to employ Artifact Calibration. This limited embodiment of Artifact Calibration uses an external 10V reference and decade divider as traceable standards. Comparisons are made using an external null detector, and through this process internal references and dividers are calibrated. The Fluke 5700A, introduced in 1988, expanded on the capability of the 5440A's Artifact Calibration techniques.[2] The expansion included the additional functions of alternating voltage, resistance and direct and alternating current. The 5720A is a higher performance variant of the 5700A.

Inside the 5700A and 5720A there is a null detector for making comparison measurements and divider for scaling between ranges. The inclusion of the measurement system in the instrument being calibrated eliminates the need for the operator to read the difference between the externally applied voltages and internally generated voltages and allows the instrument's software to control the nulling process. The null detector zero is calibrated and made traceable by periodic adjustment against an internal short.

Internally, the 5700A and 5720A are configured to emulate activities in a conventional metrology lab. A microprocessor controls all functions and monitors performance, routing signals between modules by way of a switch matrix. Like all modern instruments, no physical calibration adjustments are made. Instead, correction constants are stored in non-volatile memory. Numerous internal checks and diagnostic routines ensure that the instrument is always operating at optimum performance. A Fluke ultra linear pulse width modulated digital-to-analog converter (DAC) functions as a divider within each calibrator. This divider, like any ratio divider such as a Kelvin-Varley divider, functions on the basis of dimensionless ratio. That is, there are no absolute quantities involved. The repeatable linearity of a pulse width modulated DAC depends only on a highly reliable digital pulse train. To maintain high confidence, this linearity is checked and verified during Artifact Calibration. This is done by comparing two fixed voltages on different ranges of the DAC. Figure 2 illustrates this comparison. It should be noted that the precise values of the two voltages V1 and V2 are unimportant; it is only required that they be stable during the measurement process.

If the DAC is perfectly linear, then: $N4/N3 = N2/N1$

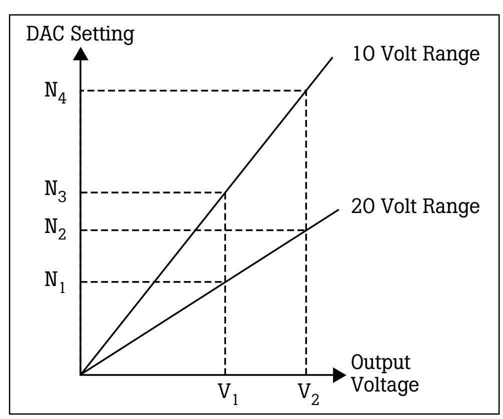

Figure 2. Digital-to-analog converter verification

An analog-to-digital converter (ADC) provides null detection capability. Using the ADC together with the DAC, comparisons are made and values assigned for the correction constants stored in memory.

Two reference amplifiers[3] similar to those used in the Fluke 732B DC Transfer Standard maintain the 5700A/5720A's accuracy and stability. These references are calibrated by comparing them to the external 10V artifact standard. This comparison takes place internally, using the DAC and null detector to assign correction values.

Two Fluke solid-state thermal rms converters form the alternating voltage measurement reference for both the 5700A and 5720A.[4] One thermal converter makes real time ac/dc comparison measurements to maintain the output voltage. A second is used only during Artifact Calibration to compare the external dc artifact to the internally generated ac voltages. To maintain confidence, a software routine directs intercomparison of the two converters to ensure that their characteristics track each other. The traceability of this internal ac/dc reference, used only during Artifact Calibration, is verified by periodic comparison to an external ac/dc transfer reference like the Fluke 792A or 5790A.

The transfer of resistance references to the 5700A and 5720A is similar in concept to the transfer of direct voltage described earlier. Two resistors, having values of 1Ω and 10 kΩ, form the working internal references for the calibrator. Their values are assigned using the DAC and null detector by comparing them to external resistance artifact standards like the Fluke Model 742A-1 and 742A-10K. The DAC and null detector system then establishes ratios of various other values within the calibrator, and stores them in non-volatile memory.

The Traceability Path

Traceability is often defined as "the ability to relate individual measurement results to national standards or nationally accepted measurement systems through an unbroken chain of comparisons ...." This requirement must be met with Artifact Calibration as rigorously as it is with all other calibration methods. This means that no adjustments can be made without comparison to traceable standards, and that all transfer of values must be done using reliable ratiometric techniques.

The Artifact Calibration block diagram shown in Figure 3 illustrates the unbroken traceability chain. The values of the external artifacts are transferred to the internal references by a built-in self-calibrating ratio device (like the self-calibrating Kelvin-Varley divider in the lab). The ratio device then transfers values from the references to the output parameters. The integrity of the system is enhanced by built-in self-check routines and through periodic verification by external comparison.

With Artifact Calibration, there are several important factors to consider during the design and manufacturing processes. They assure that manufacturing reliably produces instruments that truly and fully meet their calibration criteria.

These vital factors are:

1. The design must be correctly analyzed to identify sources of error. The possibility of a design oversight cannot be ignored. Rigorous testing and analysis must be performed during the instrument's development.
2. Manufacturing processes must ensure that components and construction meet design criteria. These processes must be monitored to ensure consistency of production.
3. Instrument operation must be fully verified in production to eliminate the possibility of unusual faults.[5] This verification must itself be fully traceable. The production process of the Fluke 5700A includes 237 verification points. Data from each of these verifications is collected and analyzed to ensure that the production process is in control. A representative chart is illustrated in Figure 4. A more comprehensive display of the data is shown in Figure 10.

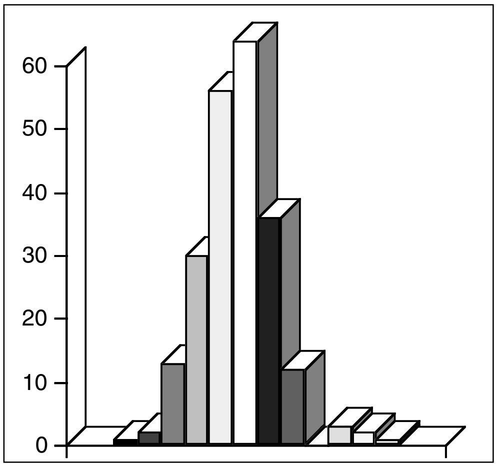

Figure 4. Measured results on Artifact Calibrated Instrument

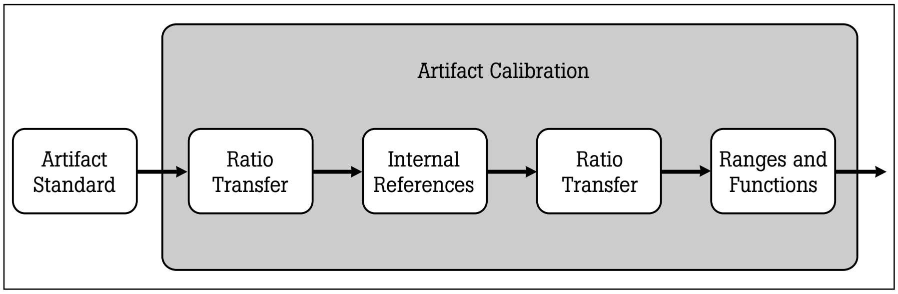

Figure 3. The traceability chain for the 5700A and 5720A

The chart shows data collected on 100 instruments produced over a 60-day period. It is typical of data collected on well over 1,000 instruments. This external verification confirms the integrity of the circuitry used to assign values based on Artifact Calibration. Consequently it is only necessary for the customer to reverify the function of the circuitry on a very infrequent basis. The performance of this group of instruments demonstrates that the Artifact Calibration process has properly adjusted the instruments. The measured results indicated in Figure 4 are similar to those that would have been obtained using traditional manual calibration methods. The results are shown to fall in a Gaussian (normal) distribution with the predominant value (mean) centered at nominal.

Fluke production criteria is set so that each verification point must show a 3-sigma normal distribution limited to 80% of the instrument's 24 hour specifications. This is equivalent to 3.75-sigma relative to 100% of the specification, or approximately 1 out of 10,000 will fall beyond the limits. Results have shown that the Artifact Calibration process exceeds these criteria for most verification points. In addition to the 3-sigma criteria, other statistical tests are performed on the data to ensure that the production process is in control.

4. The instrument must have diagnostic routines capable of verifying that its internal calibration system is functioning correctly. These routines should establish the same confidence in calibration as is expected with an operator performing manual calibration, using conventional techniques. This may be achieved (as is the case with the 5700A and 5720A) by maintaining a set of internal, environmentally controlled references. These are used to make periodic internal comparisons.

Data Collection

The driving force behind Artifact Calibration has been the need to reduce the operator time required to calibrate precision instruments, along with a reduction in the amount of support equipment required. A secondary benefit—one with potentially more impact on the metrology function—is the opportunity for data generation, collection and analysis.

In order to implement Artifact Calibration in an instrument, that instrument must include sophisticated analog hardware as well as a microprocessor and software. With internal references and internal comparison capability, the capacity is there to collect data at the time of Artifact Calibration. Perhaps more significantly, the capability is there to execute these routines between calibrations. This allows the measurement of drift and of performance changes relative to the internal references.

A traditional instrument that is reviewed only during calibration (say once every 6 months to one year) may go out of calibration without the knowledge of the user. Where critical tests rely on the instrument's accuracy, this lack of awareness may have extremely costly and potentially dangerous consequences.

The ability to run internal Calibration Checks between external calibrations allows the operator to monitor the performance between calibrations and helps to avoid these situations. If the instrument's internal references are well controlled and impervious to environmental changes, then these Calibration Checks can be performed with the instrument in its working environment. This instills confidence without the need to return the instrument to the calibration lab. Note that these Calibration Checks do not adjust the instrument's output, but merely evaluate the instrument's output against

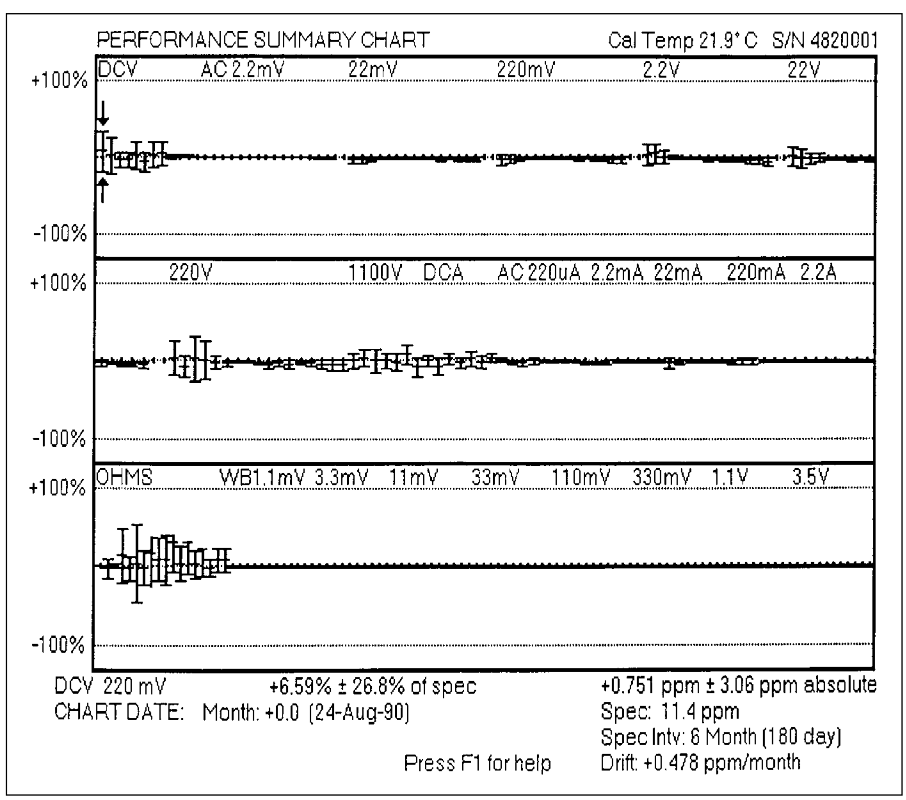

Figure 5. Artifact Calibration Data and Calibration Check Data

internal references. Comparison of the internal reference values to external traceable standards is necessary to make traceable internal adjustments.

Using statistical process control techniques[6] it is possible to analyze the data collected during Artifact Calibration and internal Calibration Checks. With a personal computer (PC) and the appropriate software, data can be imported, processed, displayed and used to assess the performance of the instrument. Figures 5 and 6 show screens from a software package that collects and analyses 5700A or 5720A internally generated calibration data.

Performance Summary Chart

From the single screen illustrated in Figure 5 it is possible to observe the current performance of the instrument being charted. Each instrument output value or range is shown as a vertical bar, the center of which is the measured value at that point and the length of which is the confidence in that measured value. The confidence band is based on the number of historical values collected for that point and their distribution.[7] The cursors (shown in the top left hand corner) can be moved to select which point is described by the text at the bottom of the screen. By pressing a function key the data about the selected point can be expanded as shown in Figure 6.

Constant Performance

Figure 6 shows data collected using the Calibration Check function of a particular 5700A, where the output parameters are measured relative to its internal references—illustrated by the ○. Also, the internal references are plotted relative to external artifact standards—illustrated by the blocked-in square ■. Each time an Artifact Calibration is performed the Calibration Check data is renormalized to that external calibration so that it always represents the most recent traceable comparison.

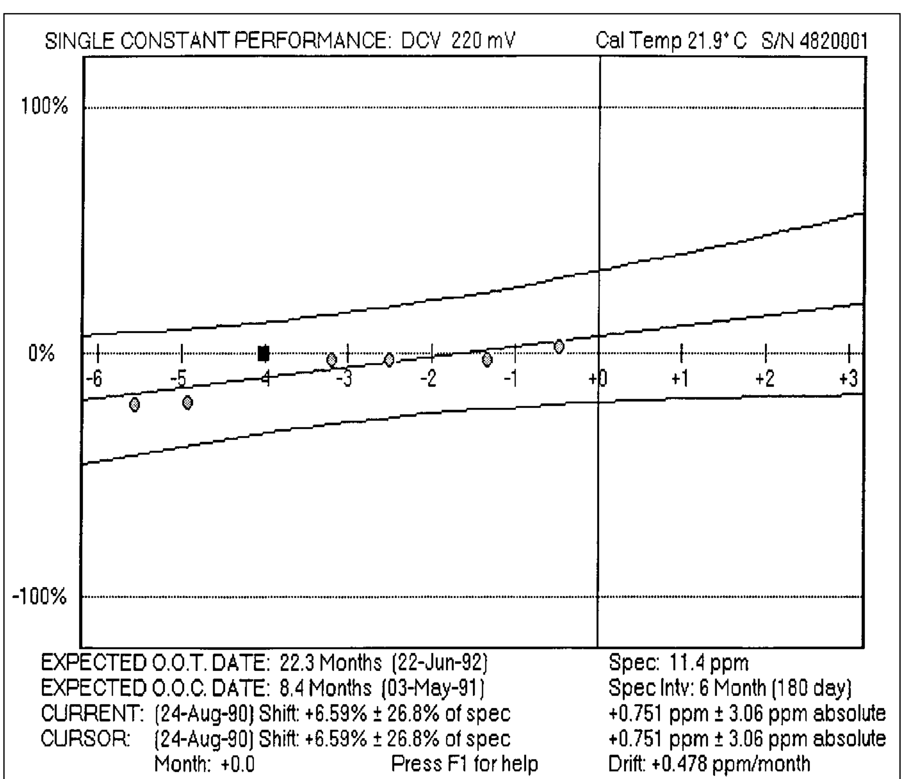

Figure 6. Artifact Calibration Data and Calibration Check Data Single

The display shows:

1. Data points collected.
2. Instrument performance relative to specification.
3. Predicted time at which the instrument will exceed the allowed specification (out of tolerance—O.O.T.)
4. Hyperbolic confidence limits around measured and predicted performance.
5. Predicted time that confidence limits will exceed the allowed specification (out of confidence—O.O.C.)

The single graph of Figure 6 shows the 220 mV dc range of 5700A serial number 4820001. Here it can be seen that an Artifact Calibration ■ was performed approximately four months ago, and since then four Calibration Checks ○ have been performed. The drift rate is estimated to be 0.478 ppm/month, with an expected out of tolerance to occur in 22.3 months—approximately four times the calibration interval. You will note that the out of confidence date is only 8.4 months away, which in this specific situation represents a 3-sigma confidence band. As more data is collected using Calibration Checks the out of confidence date will approach the out of tolerance date.

Using the data collected from an instrument it is possible to detect a potential problem with that instrument. This will eliminate the implications and cost of an instrument being out of specification during use. Also, if enough history has been collected, it is possible to extend the period between Artifact Calibrations and reduce future maintenance and calibration costs.

Verification System and Analysis Program

Each Fluke 5700A and 5720A is Artifact Calibrated, monitored for stability using the Calibration Check function and then finally verified using the custom-built automatic test equipment shown in Figure 7. The parametric capabilities of this test equipment are described in detail in An Automatic Test System for a Multifunction Calibrator, Measurement Science Conference, 1989.[5] Each calibrator is subjected to 237 verification tests. These tests cover all parameters including accuracy, load and line regulation, distortion, voltage and current compliance, and noise.

Data Collection and Analysis

The data from each of the 237 tests for each calibrator is downloaded from the local controllers to a central UNIX-based system and stored there by serial number. The data is analyzed using an "S Language" statistical package.[8]

The graphs in Figure 10 show the presentation format of the data for a population of instruments. The maximum error allowed on any individual parameter of a specific instrument is set to 80% of the 24-hour specification.

The statistical package is exercised once a week to ensure that the internal calibration process of the 5700A/5720A is in control. A set of tests is performed on the data. These are derived from Shewhart control charts.[9] The program divides the data for each test point in to three zones as shown in Figure 8.

Zone A is 2 standard deviations to 3 standard deviations.

Zone B is 1 standard deviation to 2 standard deviations.

Zone C is the mean ±1 standard deviations.

The following tests are applied to each point measured:

cpk:

3 sigma must be < test spec

3 sigma + mean must be < test spec

1: All points must be less than 3-sigma.
2: No more than 9 points in a row can be beyond zone C.
3: No more than 6 points in a row can show a steady increasing or decreasing trend.
4: No more than 14 points in a row can alternate up and down.
5: No more than 2 out of 3 points in a row can be on the same side of zone A
6: No more than 4 out of 5 points in a row can be on the same side of zone B or beyond.
7: No more than 15 points in a row can be in zone C and on the same side of the mean.
8: No more than 8 points in a row can alternate on either side of the mean if none is in zone C. Presently the preceding criteria are still being refined in a process that will likely continue as we discover more of the predictive nature of these tests. Currently the tests are being used to alert production personnel. They then use their judgment to determine the cause of the problem and implement corrective action.

System Metrology

Traditionally, calibration of ATE is achieved by one of two means. Either each piece of equipment is removed from the ATE periodically and returned to the calibration lab, or, periodically, calibration equipment is brought up to the ATE and the individual pieces of equipment calibrated in place. The disadvantage of these two support procedures is first that the ATE is out of service while being calibrated and second that calibration must occur regularly whether the equipment is really going out of specification or not.

The 5700A/5720A automated calibration system is supported by Process Metrology.[10] Process Metrology is a technique where you monitor the process for compliance with traceable standards rather than monitor the test equipment. If the process shows signs of going out of calibration it is then time to take action. As before, this could be to take the system off line and recalibrate the individual instruments. However, you will notice through this procedure that the equipment is only off line when it is found to be necessary rather than on a rigorous scheduled basis. In addition, if something shows signs of going wrong before a regularly scheduled calibration that will also be obvious, and you can avoid the use of potentially out of calibration equipment. By this means you may predict problems before they occur.

Figure 9 shows two separate loops to the Process Metrology chain. First, every 10th production instrument, after it has been through the automated calibration system, is sent to the Fluke Standards Lab. There each performance point that has

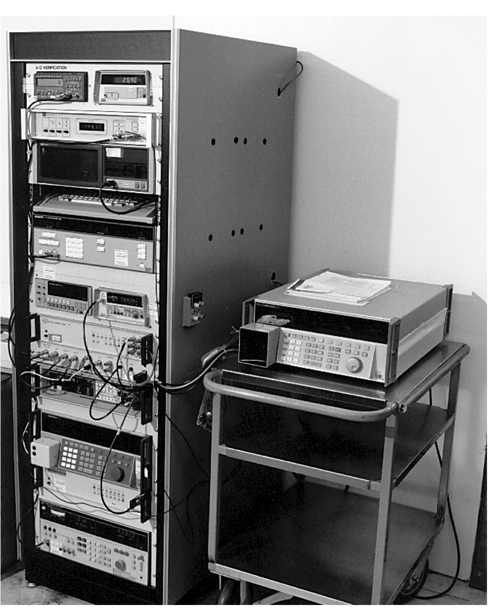

Figure 7. 5700A Automated Calibration System

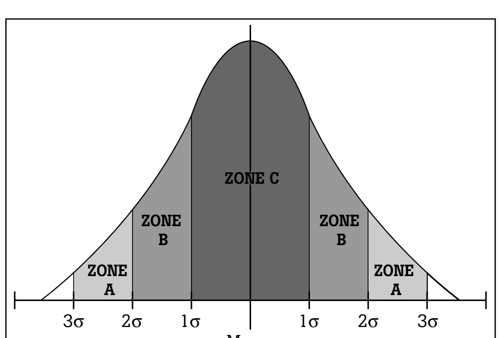

Figure 8. 5700A Verification Test Zones

been measured by the automated system is verified independently. The two sets of data are correlated and analyzed for discrepancies. Similar tests as those applied to the instrument data described above, are used to analyze this correlation information and to predict the need for adjustment or maintenance of the automated calibration system.

A second loop involves cycling two check standards (5700As) through the automated calibration system on a weekly basis. These check standards are always the same 5700As. Stability data on the check standards is plotted relative to the automated system. Any irregularities that occur in this data then suggest a change in the check standards or in the system and warn the operators to investigate further.

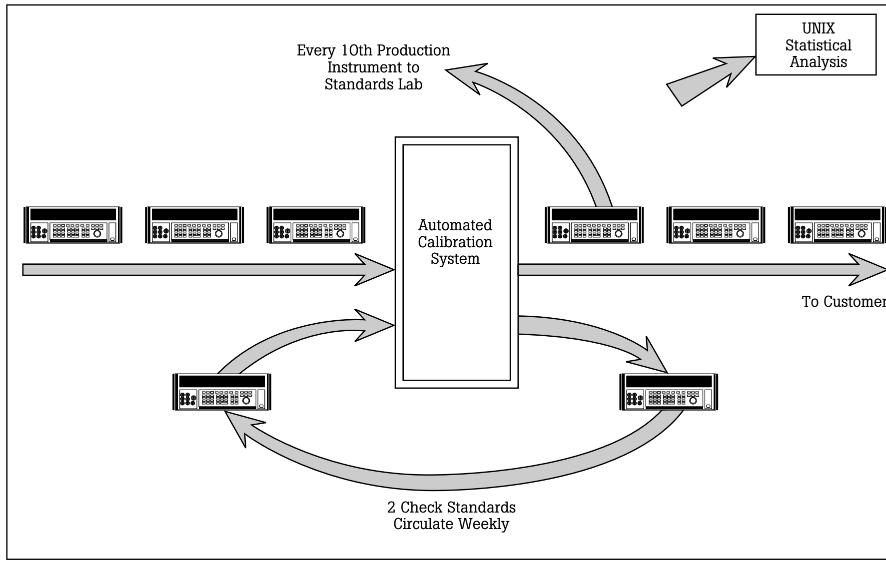

Figure 9. Process Metrology Flow

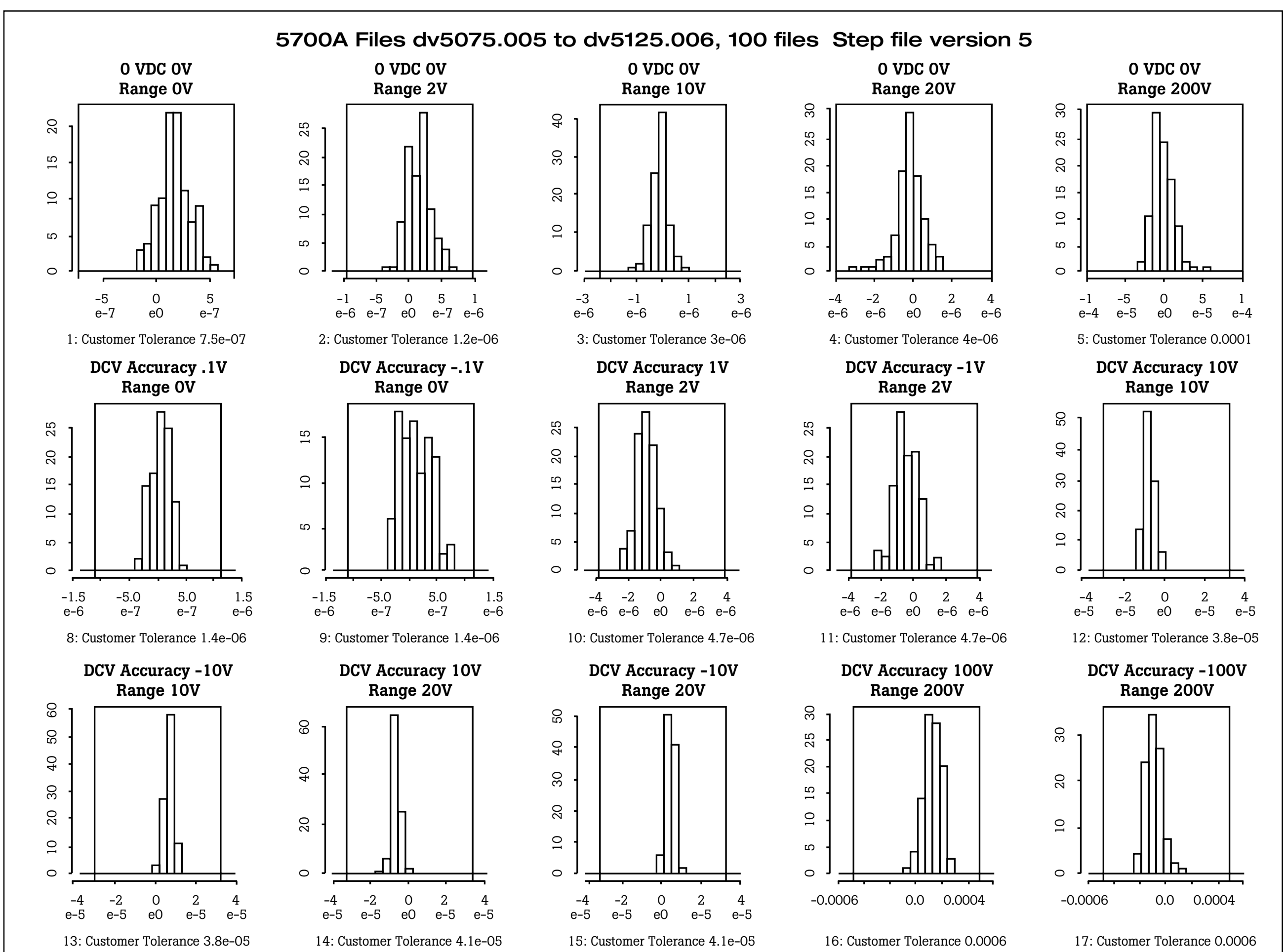

Figure 10. Measured production test results on a Fluke 5700A Calibrator

Summary

Artifact Calibration is the process of completely calibrating an instrument by comparison to a small number of artifact standards, and thereby assigning values to internally generated parameters. Traditionally such comparisons are performed external to the instrument, using a wide array of equipment to transfer the value of standards to various ranges and functions. With Artifact Calibration, comparisons are performed using built in ratio and measurement devices. This technique reduces the cost of maintaining the instrument's calibration. For calibration to be fully traceable the instrument must be designed correctly, manufactured correctly and adjusted correctly. This is as true of an Artifact Calibrated instrument as it is of a traditionally calibrated instrument. Data was presented that shows the performance of a large population of Artifact Calibrated instruments. The data confirms that the instruments meet all performance criteria within 3-sigma confidence limits. Inclusion of highly stable references in an instrument enables it to exercise its software routines to measure the performance of the instrument between comparisons to external Artifact Standards. This increases the operator's confidence that the instrument is in calibration. Using statistical software programs can also enhance the user's ability to predict the performance of the instrument.

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