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.

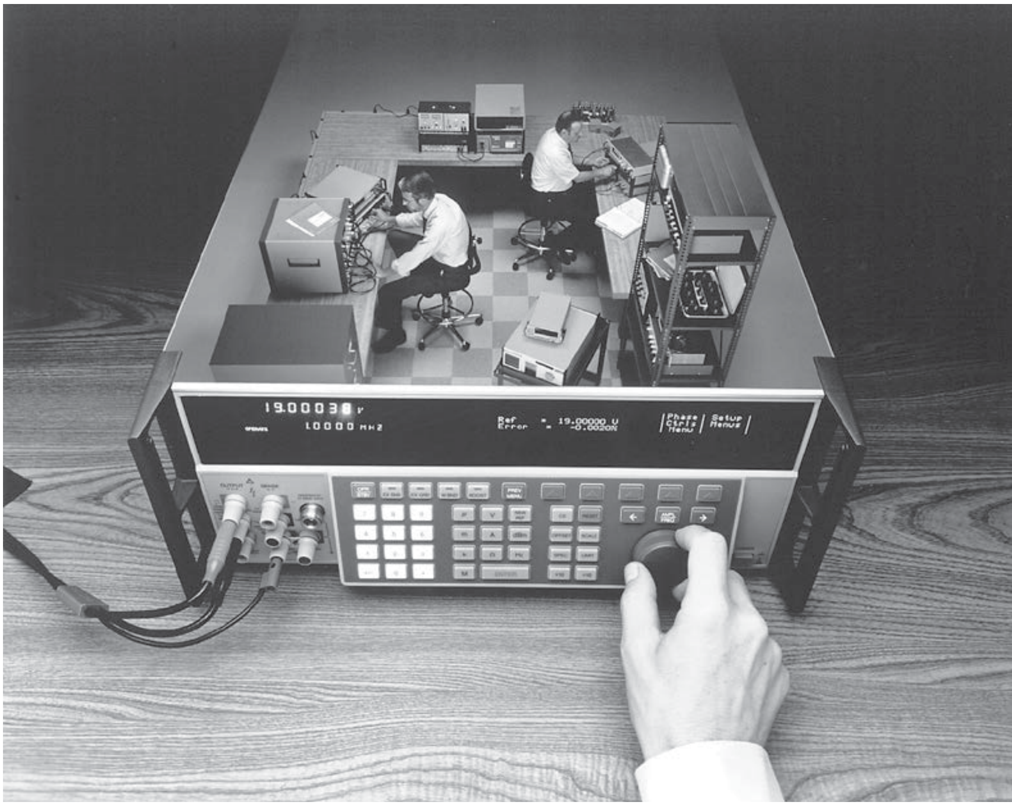


Figure 1. A Calibration Lab in an Instrument.

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 10 V 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 5730A 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 5730A is a higher performance variant of the 5700A.

Inside the 5730A 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 5730A is 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 proprietary 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

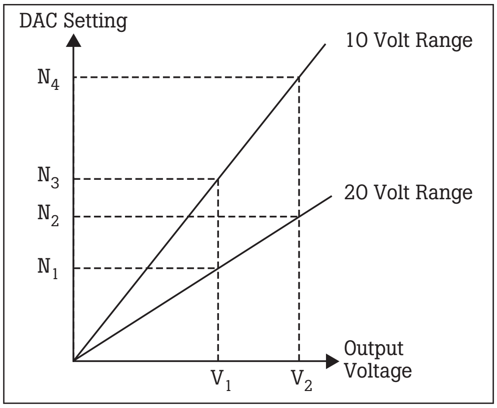


Figure 2. Digital-to-analog converter verification.

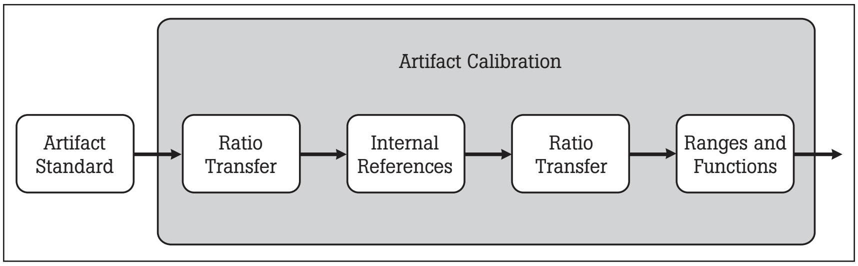


Figure 3. The traceability chain for the 5730A.

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

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 Calibration 732B DC Transfer Standard maintain the 5730A's accuracy and stability. These references are calibrated by comparing them to the external 10 V artifact standard. This comparison takes place internally, using the DAC and null detector to assign correction values.

Two Fluke Calibration solid-state thermal rms converters form the alternating voltage measurement reference for the 5730A.[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 Calibration 792A or 5790A.

Such external ac/dc transfer verifications are recommended to be done once every two years, as is common for such thermal transfer devices.

The transfer of resistance references to the 5730A is similar in concept to the transfer of direct voltage described earlier. Two resistors, having values of 1 Ω and 10 k Ω, 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 Calibration 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 Calibration 5730A 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 7.

The chart shows data collected on 100 instruments produced over a 60-day period. It is typical of data collected on well over many thousands of 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 user 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.

The 5730A 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 5730A) 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.

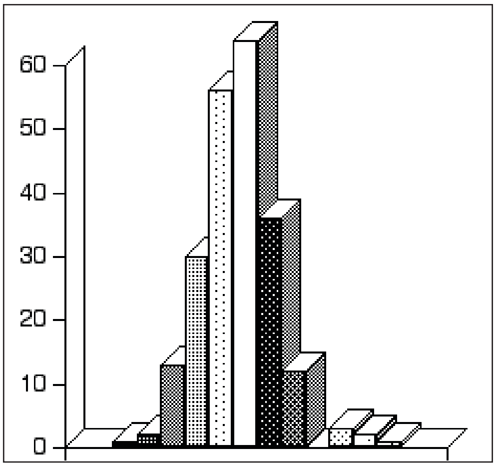


Figure 4. Measured results on Artifact Calibrated Instrument.

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

Using statistical techniques[6] it is possible to analyze the data collected during Artifact Calibration and internal Calibration Checks. With a computer, data can be imported, processed, displayed and used to assess the performance of the instrument.

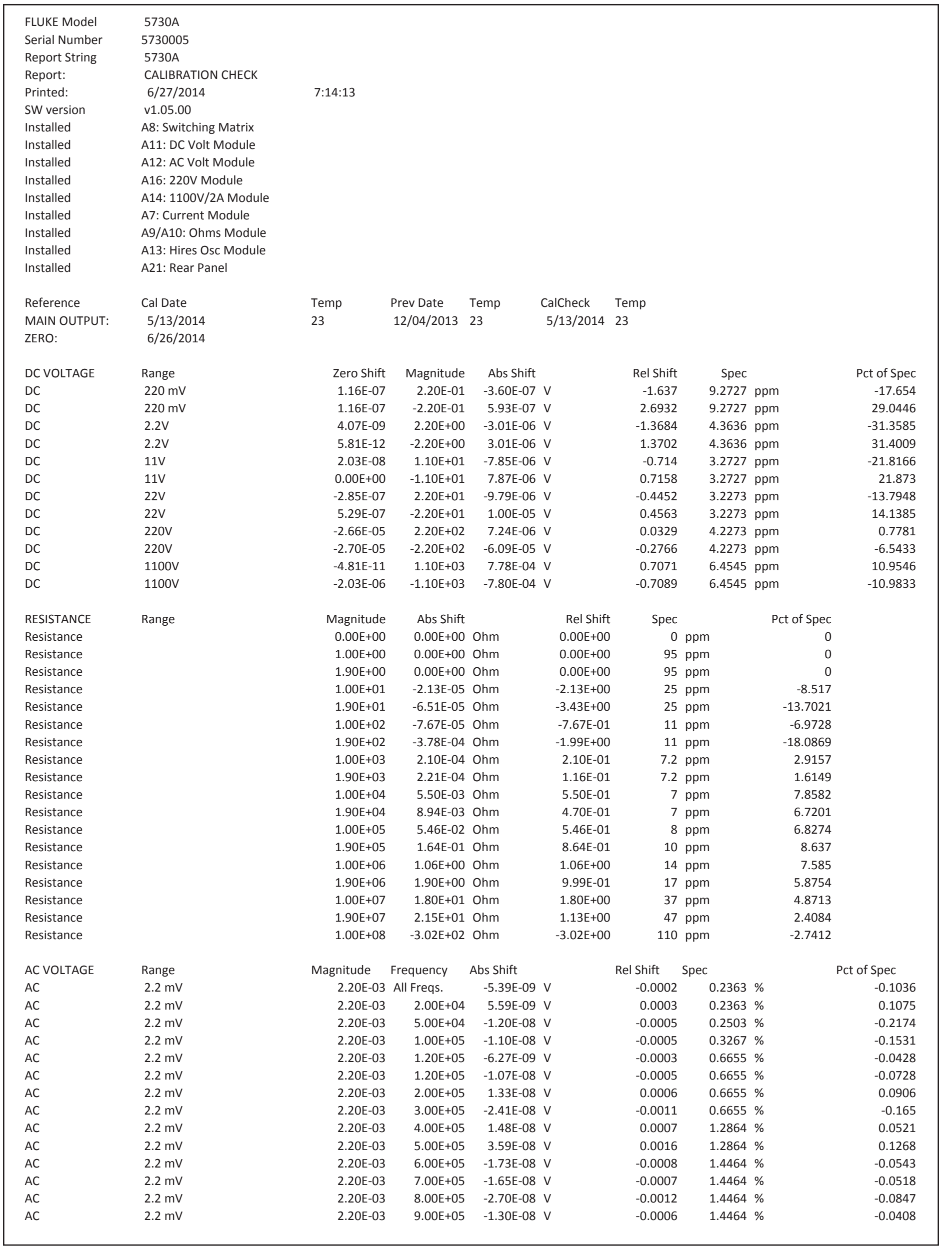
Constant performance

Figure 5 shows data collected using the Calibration Check function of a particular 5730A, where the output parameters are measured relative to its internal references. This Cal Check data is available in a comma separated variable data format (CSV) through the USB port on the calibrator or through inquiry from a computer via a remote interface.

The data file shows:

1. Identification and configuration information of the specific 5730A being checked.
2. Dates for the most recent calibrations and zeroing events on the 5730A calibrator.
3. All the individual data points measured in the cal check process.
4. Analysis of the measured shifts in this data since the time of the previous calibration shown in measured absolute shift values and shifts relative to the applicable instrument specification.

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.



FLUKE Model	5730A	
Serial Number	5730005	
Report String	5730A	
Report:	CALIBRATION CHECK	
Printed:	6/27/2014	7:14:13
SW version	v1.05.00	
Installed	A8: Switching Matrix	
Installed	A11: DC Volt Module	
Installed	A12: AC Volt Module	
Installed	A16: 220V Module	
Installed	A14: 1100V/2A Module	
Installed	A7: Current Module	
Installed	A9/A10: Ohms Module	
Installed	A13: Hires Osc Module	
Installed	A21: Rear Panel	

Reference	Cal Date	Temp	Prev Date	Temp	CalCheck	Temp
MAIN OUTPUT:	5/13/2014	23	12/04/2013	23	5/13/2014	23
ZERO:	6/26/2014					

DC VOLTAGE	Range	Zero Shift	Magnitude	Abs Shift		Rel Shift	Spec		Pct of Spec
DC	220 mV	1.16E-07	2.20E-01	-3.60E-07	V	-1.637	9.2727	ppm	-17.654
DC	220 mV	1.16E-07	-2.20E-01	5.93E-07	V	2.6932	9.2727	ppm	29.0446
DC	2.2V	4.07E-09	2.20E+00	-3.01E-06	V	-1.3684	4.3636	ppm	-31.3585
DC	2.2V	5.81E-12	-2.20E+00	3.01E-06	V	1.3702	4.3636	ppm	31.4009
DC	11V	2.03E-08	1.10E+01	-7.85E-06	V	-0.714	3.2727	ppm	-21.8166
DC	11V	0.00E+00	-1.10E+01	7.87E-06	V	0.7158	3.2727	ppm	21.873
DC	22V	-2.85E-07	2.20E+01	-9.79E-06	V	-0.4452	3.2273	ppm	-13.7948
DC	22V	5.29E-07	-2.20E+01	1.00E-05	V	0.4563	3.2273	ppm	14.1385
DC	220V	-2.66E-05	2.20E+02	7.24E-06	V	0.0329	4.2273	ppm	0.7781
DC	220V	-2.70E-05	-2.20E+02	-6.09E-05	V	-0.2766	4.2273	ppm	-6.5433
DC	1100V	-4.81E-11	1.10E+03	7.78E-04	V	0.7071	6.4545	ppm	10.9546
DC	1100V	-2.03E-06	-1.10E+03	-7.80E-04	V	-0.7089	6.4545	ppm	-10.9833

RESISTANCE	Range	Magnitude	Abs Shift		Rel Shift	Spec		Pct of Spec
Resistance		0.00E+00	0.00E+00	Ohm	0.00E+00	0	ppm	0
Resistance		1.00E+00	0.00E+00	Ohm	0.00E+00	95	ppm	0
Resistance		1.90E+00	0.00E+00	Ohm	0.00E+00	95	ppm	0
Resistance		1.00E+01	-2.13E-05	Ohm	-2.13E+00	25	ppm	-8.517
Resistance		1.90E+01	-6.51E-05	Ohm	-3.43E+00	25	ppm	-13.7021
Resistance		1.00E+02	-7.67E-05	Ohm	-7.67E-01	11	ppm	-6.9728
Resistance		1.90E+02	-3.78E-04	Ohm	-1.99E+00	11	ppm	-18.0869
Resistance		1.00E+03	2.10E-04	Ohm	2.10E-01	7.2	ppm	2.9157
Resistance		1.90E+03	2.21E-04	Ohm	1.16E-01	7.2	ppm	1.6149
Resistance		1.00E+04	5.50E-03	Ohm	5.50E-01	7	ppm	7.8582
Resistance		1.90E+04	8.94E-03	Ohm	4.70E-01	7	ppm	6.7201
Resistance		1.00E+05	5.46E-02	Ohm	5.46E-01	8	ppm	6.8274
Resistance		1.90E+05	1.64E-01	Ohm	8.64E-01	10	ppm	8.637
Resistance		1.00E+06	1.06E+00	Ohm	1.06E+00	14	ppm	7.585
Resistance		1.90E+06	1.90E+00	Ohm	9.99E-01	17	ppm	5.8754
Resistance		1.00E+07	1.80E+01	Ohm	1.80E+00	37	ppm	4.8713
Resistance		1.90E+07	2.15E+01	Ohm	1.13E+00	47	ppm	2.4084
Resistance		1.00E+08	-3.02E+02	Ohm	-3.02E+00	110	ppm	-2.7412

AC VOLTAGE	Range	Magnitude	Frequency	Abs Shift		Rel Shift	Spec		Pct of Spec
AC	2.2 mV	2.20E-03	All Freqs.	-5.39E-09	V	-0.0002	0.2363	%	-0.1036
AC	2.2 mV	2.20E-03	2.00E+04	5.59E-09	V	0.0003	0.2363	%	0.1075
AC	2.2 mV	2.20E-03	5.00E+04	-1.20E-08	V	-0.0005	0.2503	%	-0.2174
AC	2.2 mV	2.20E-03	1.00E+05	-1.10E-08	V	-0.0005	0.3267	%	-0.1531
AC	2.2 mV	2.20E-03	1.20E+05	-6.27E-09	V	-0.0003	0.6655	%	-0.0428
AC	2.2 mV	2.20E-03	1.20E+05	-1.07E-08	V	-0.0005	0.6655	%	-0.0728
AC	2.2 mV	2.20E-03	2.00E+05	1.33E-08	V	0.0006	0.6655	%	0.0906
AC	2.2 mV	2.20E-03	3.00E+05	-2.41E-08	V	-0.0011	0.6655	%	-0.165
AC	2.2 mV	2.20E-03	4.00E+05	1.48E-08	V	0.0007	1.2864	%	0.0521
AC	2.2 mV	2.20E-03	5.00E+05	3.59E-08	V	0.0016	1.2864	%	0.1268
AC	2.2 mV	2.20E-03	6.00E+05	-1.73E-08	V	-0.0008	1.4464	%	-0.0543
AC	2.2 mV	2.20E-03	7.00E+05	-1.65E-08	V	-0.0007	1.4464	%	-0.0518
AC	2.2 mV	2.20E-03	8.00E+05	-2.70E-08	V	-0.0012	1.4464	%	-0.0847
AC	2.2 mV	2.20E-03	9.00E+05	-1.30E-08	V	-0.0006	1.4464	%	-0.0408

Figure 5. Data collected using the Calibration Check function of a 5730A, where the output parameters are measured relative to its internal references.

Verification system and analysis program

Each and every 5730A is Artifact Calibrated, monitored for stability using the Calibration Check function and then finally verified using the custom-built automatic test equipment. The parametric capabilities of such 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.

System metrology

Traditionally, calibration of an automated calibration system is achieved by one of two means. Either each piece of equipment is removed from the system periodically and returned to the calibration lab, or, periodically, calibration equipment is brought up to the automated calibration system and the individual pieces of equipment calibrated in place. The disadvantage of these two support procedures is first that the system 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 5730A 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 6 shows Process Metrology.

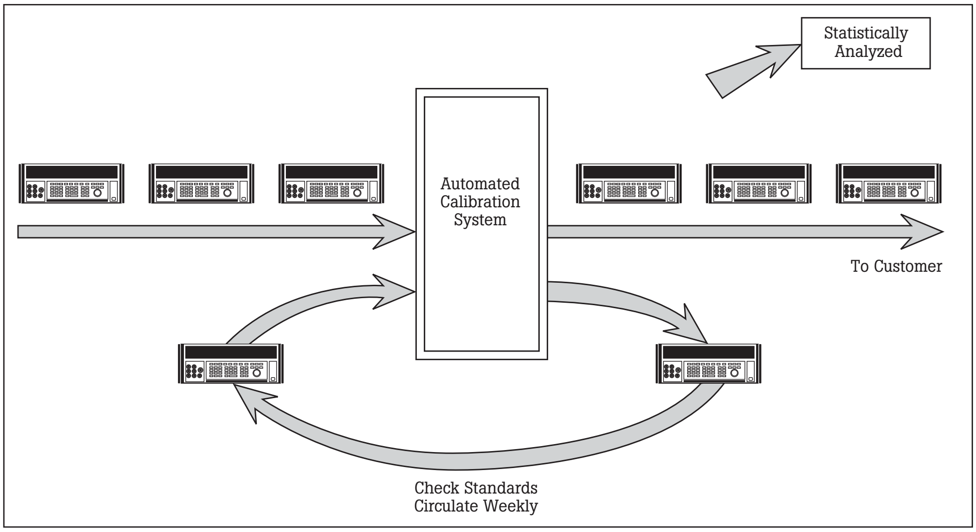


Figure 6. Process Metrology Flow.

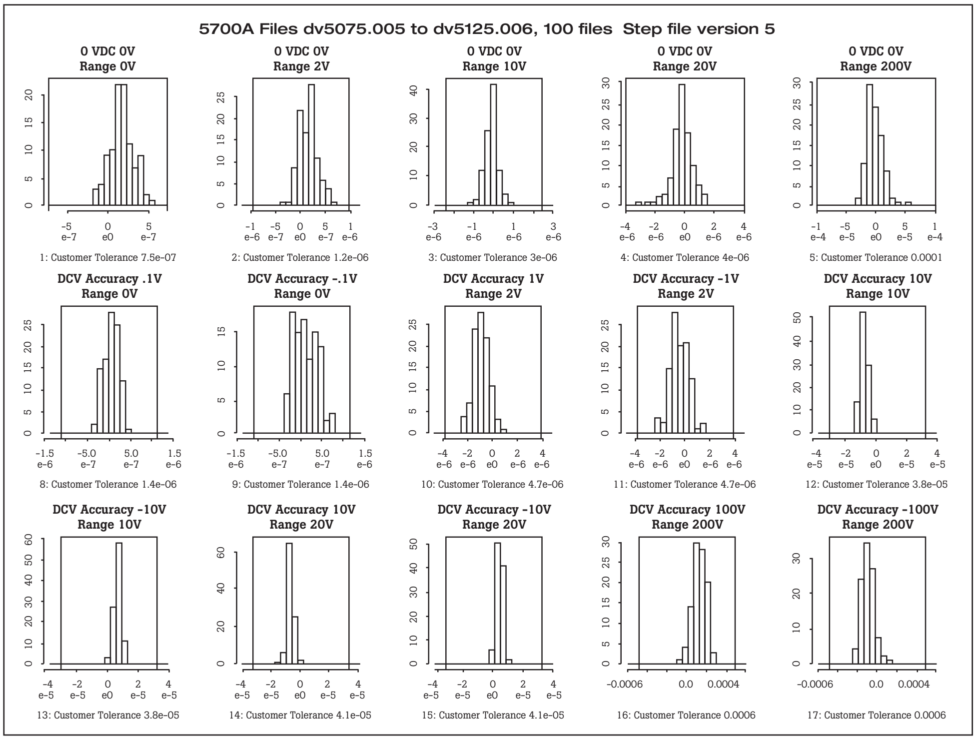


Figure 7. Measured production test results on a Fluke Calibration 5700 Series.

Process Metrology involves cycling check standards (5730As) through the automated calibration system on a weekly basis. These check standards are always the same 5730As. 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.

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.

References

1. Eccleston, Faulkner, Johnston, Prue and Theimann, Calibrator Brings Record Accuracy Even to Production and Repair, *Electronics*, September 8, 1982.

2. Baldock, Instrument Internal Calibration Reduces Cost of Ownership and Improves Performance, Measurement Science Conference, 1987.

3. Haynes, Achieving an Ultra Stable Reference for Modern Standard and Calibration Instrumentation, Measurement Science Conference, 1987.

4. Goyal and Brodie, Recent Advances in Precision AC Measurements, *IEEE Trans. Instrument. Meas.*, vol IM-33, pp. 164-167, 1984.

5. Haynes, An Automatic Test System for a Multifunction Calibrator, Measurement Science Conference, 1989.

6. Capell, From 4:1 to SPC, National Conference of Standards Laboratories, 1988.

7. Ehrenfield and Littaur, *Introduction to Statistical Methods*, 1964, McGraw-Hill, New York.

8. Becker, Chambers and Wilks, *The New S Language*, 1988, Wadsworth and Brooks/Cole.

9. Western Electric Co., Inc, *Statistical Quality Control Handbook*, 1956, Mack Printing Co., Easton.

10. Huntley, Murray, An Application of Process Metrology to the Automatic Calibration of Instruments, Measurement Science Conference, 1987.

Fluke Calibration.
Precision, performance, confidence.™

Electrical
RF
Temperature
Pressure
Flow
Software

Fluke Calibration
PO Box 9090, Everett, WA 98206 U.S.A.

Fluke Europe B.V.
PO Box 1186, 5602 BD
Eindhoven, The Netherlands

For more information call:
In the U.S.A. (877) 355-3225 or
Fax (425) 446-5116
In Europe/M-East/Africa +31 (0) 40 2675 200 or
Fax +31 (0) 40 2675 222
In Canada (800)-36-FLUKE or
Fax (905) 890-6866
From other countries +1 (425) 446-5500 or
Fax +1 (425) 446-5116
Web access: http://www.flukecal.com

Printed in U.S.A. 8/2014 1260355e_en
Pub-ID 10797-eng