

# Accrediting Artifact Calibration of a Multi-Function Calibrator

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## Abstract

*A decade ago, two companies introduced electronic instruments incorporating Artifact Calibration, a technology by which an instrument calibrates itself using a small number of external standards, thereby significantly reducing the cost of calibration and simplifying their path of traceability.*

*Some national standards laboratories have been cautious about accepting Artifact Calibration, perhaps because most of the external verification traditionally done is replaced by characterizations performed inside the instrument beyond the control and oversight of the operator. However, the large reduction in cost of ownership that comes with Artifact Calibration is a strong motivation for broader acceptance, particularly for high accuracy instruments whose calibration would otherwise require time-consuming procedures and more expensive standards.*

*Toward this end, the national standards laboratories of the Netherlands (Nederlands Meetinstituut or NMI), Sweden (Sveriges Provnings-och Forskningsinstitut or SP), and Germany (Physikalisch-Technische Bundesanstalt or PTB) undertook an independent evaluation of Artifact Calibration as implemented in the Fluke 5700A with the goal of increasing acceptance of Artifact Calibration. This paper gives background for the project and briefly reports preliminary project results and conclusions. A more complete report will be published later in 1998, and among others will be presented at the October 1998 meeting of the DC/LF experts group of the European co-operation for Accreditation (EA).*

## Acknowledgments

I am in the enviable position of writing the first paper reporting on this project after having done little of the work, so I find it particularly essential to give my heartfelt thanks to: Gert Rietveld, Cock Oosterman, Cees van Mullem, and Joop Dessens of NMI; Håkan Nilsson, Pär Simonson, Jan Jacobson and Mikael Ohlsson of SP; Torsten Funck of PTB; Peter Schneider and Joost Korthout at Fluke Europe; and Warren Wong, Larry Eccleston, and Dave Deaver from Fluke USA.

## Introduction

From the prehistoric invention of tools, through the Industrial Revolution and the advent of the assembly line, through the invention of the electronic computer, to the present, more and more processes once performed by hand have been automated. Made possible by technological advances and made economically desirable by the rising cost of labor and of supporting ever more accurate specifications, the appearance of Artifact Calibration seems inevitable in retrospect. However, history and precedent are at the core of metrology and new methods must, in a sense, be calibrated themselves before they are fully integrated into the accepted system of calibration.

The introduction of digital/analog conversion and a microprocessor to electronic instruments opened the door for automation of some tasks and the transfer of other tasks from the analog to

the more repeatable digital domain. Numerical correction factors, also called cal(ibration) constants, provided high-resolution, drift-free adjustments to correct for variations between instruments and within a given instrument over time. Self-calibration procedures, such as autozeroing on voltmeters, allowed the instrument to adjust the cal constants based either on results entered by the operator from external measurements or on internal measurements done as part of the calibration. Artifact Calibration, an advanced form of self-calibration, was introduced in the Fluke 5440A DC Calibrator and is the basis of calibrating the 5700A Multi-Function Calibrator and the Hewlett Packard 3458A Multimeter.

Artifact Calibration drastically reduces the number of points manually calibrated. An automated procedure compares external fixed-value standards, or artifacts, to stable internal standards using an internal null detector and other hardware, then compares the rest of the instrument to the internal standards, adjusting the cal constants accordingly. Excellent discussions of Artifact Calibration may be found in [1], [6] and [7].

Artifact Calibration has several advantages. Self-calibration is performed with a consistency and exactness virtually impossible in a manual calibration procedure. It lowers the cost of ownership and simplifies the traceability chain of the instrument by requiring fewer external standards and calibration steps. This is particularly important for a multi-function instrument where the variety of standards required and the number of ranges to calibrate is considerable. Artifact Calibration also has some disadvantages. The internal switching and advanced self-measurement ability to make Artifact Calibration possible raises the cost of the instrument. It also requires that the method of Artifact Calibration be trusted to perform up to its manufacturer's claims.

The fact that Artifact Calibration has not been included on all subsequent instruments does not denigrate its effectiveness but simply indicates that the balance between costs and benefits must be weighed in each case. Indeed, if Artifact Calibration were inexpensive to incorporate it would likely be included in all instruments.

### **Barriers to Acceptance**

Trust in Artifact Calibration requires a "bottom line" approach to metrology. A traditional certificate of calibration indicates, for a specific value, the measured value, the uncertainty of the measurement, and when the measurement was made. For example, a 10V zener reference is measured by a standards laboratory to be 9.999987V with an uncertainty of +/- 0.5 PPM (parts per million). The uncertainty usually indicates a limit two standard deviations from the measured value; for a normally distributed error, the value should then be within the uncertainty of the calibrated value about 95% of the time.

If the instrument is to be adjusted, the first measurement is saved as an "As Found" result, the adjustment is made based on the first measurement either manually or automatically by the instrument, then a second measurement is made and saved as an "As Left" result. This provides proof of past and future compliance with specifications and a data point for predicting drift trends of the instrument.

The instrument uncertainty for subsequent use at that value may be computed from the calibrated value combined with noise and drift specifications given by the manufacturer and/or trend analysis of data gathered from the instrument. The result is a broader uncertainty around the calibrated value. For the above example, if noise and drift amounts to 1.0 PPM of additional uncertainty, then the zener reference has a value of 9.999987V +/- 1.5 PPM. For a variable source or a measurement device, the uncertainty of values between those calibrated is computed from nearby calibrated points using a formula supplied by the manufacturer.

Instead of directly providing a measured value and uncertainty, Artifact Calibration attests that the value is within the manufacturer-specified absolute uncertainty of the nominal, provided Artifact

Calibration was done recently enough and the artifacts used had the required uncertainty specifications. The uncertainty given includes all causes of error: artifact uncertainty, internal measurement uncertainty, drift, and noise. For the previous example, if the absolute uncertainty is 2.0 PPM, the value would be guaranteed to be 10.000000V +/- 2.0 PPM. To the end user, the result is the same: a value and an uncertainty which then may be used to calibrate instruments of lesser accuracy; the way the result was achieved is different.

Another barrier to broader acceptance of Artifact Calibration arises from questions regarding traceability, particularly the lack of independent scientific research confirming the manufacturer's traceability claims. To establish traceability, an unbroken chain of calibrations must be established from the instrument to a national standards laboratory or other nationally or internationally recognized institute. With Artifact Calibration, the traceability chain goes into an instrument from the artifacts and comes out the other side through the output terminals, but the intermediate links are not plainly visible. An adage of metrology is "seeing is believing": the chain of traceability should be clearly demonstrable. The documentation of the instrument may describe what takes place inside the instrument during Artifact Calibration and how the results are applied to the instrument, but without independent analysis and acquisition of empirical data, there are not enough points of reference to confirm traceability.

If one is not able to use Artifact Calibration, calibration must be done the traditional way. This has meant doing full verifications before and after every Artifact Calibration, thereby canceling any benefits to be derived from Artifact Calibration. The only truly satisfactory solution to this problem is to reduce the frequency of full verifications while still satisfying the requirements of the accrediting bodies involved.

To address this problem, the national standards laboratories of Sweden, Germany, and The Netherlands (Sveriges Provnings-och Forskning (SP), Nederlands Meetinstituut (NMI) and Physikalisch-Technische Bundesanstalt (PTB), respectively) embarked on a study of 5700A Artifact Calibration, arising from a project considered for proposal to the European Union's Standards, Measurements and Testing (SMT) program in 1995. The purpose of the study was to independently evaluate the traceability of Artifact Calibration in the 5700A, toward an eventual goal of more widespread acceptance and accreditation of the process.

### **Artifact Calibration in the 5700A**

To calibrate a 5700A, one needs three artifacts: a 10V dc standard; a 10 k $\Omega$  resistor; and a 1 $\Omega$  resistor. The 5700A compares its internal dv and resistance references against these standards in turn, then the internal references are used to calibrate everything else, using an internal null detector, an AC/DC transfer standard dedicated to calibration, a flexible switching architecture, and lots of microprocessor elbow grease. The AC/DC transfer standard is the same thermal transfer device used in the Fluke Z102, Z103, 792A and 5790A, henceforth called the "ac cal sensor;" a second AC/DC transfer device is used during normal operation. Calibrating current involves transferring previously calibrated voltage and resistance ranges, so no external current measurement is required for calibration. 5700A calibration is well described in [4].

A few parts of the 5700A are not adjusted by Artifact Calibration. Some are verified during Artifact Calibration such as the linearity of its highest accuracy DACs. Others must be indirectly verified during external verification: the frequency response of the ac cal sensor; the stability of parts of the instrument downstream of the calibration reference plane, such as the relays, printed circuit board traces, and internal connections to the output terminals. The manufacturer claims that these parts are stable enough not to require adjustment by Artifact Calibration. This is no different from stability assumptions made about the behavior of any instrument, Artifact Calibrated or not. The evidence so far strongly suggests that these assumptions are valid [8], [9]. However, the effect of the hypothetical drift of those parts of the 5700A not calibrated is illustrated in figure 1. Figure 1 assumes that the drift rates are linear. This might not be the case; in practice, the drift

rate is more likely to decrease over time as the sensor “seasons.” However, the linear model will do to illustrate the principle.

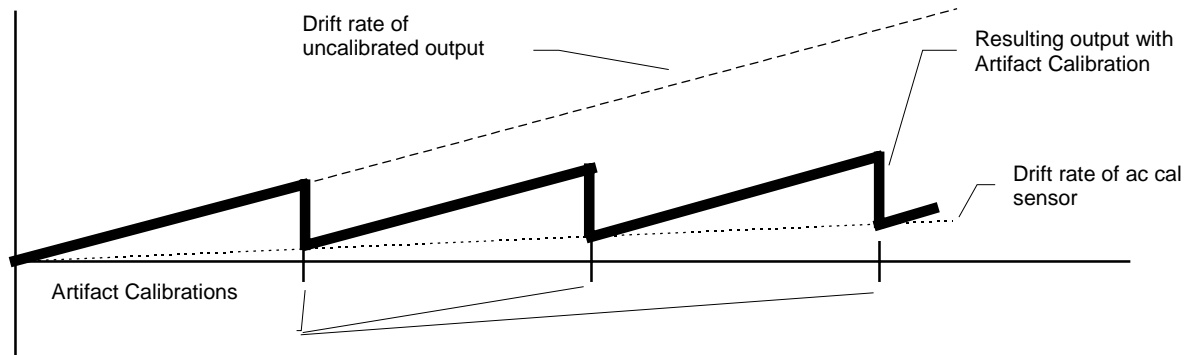


Figure 1. Illustration of effect of ac cal sensor drift

A full verification is done when the instrument is manufactured, and a full verification is recommended once every two years to confirm that drift of the non-Artifact Calibration part hasn't exceeded specifications. Otherwise, the manufacturer claims that if Artifact Calibration is done at least once every specified interval (24 hours, 90 days, 180 days, or 1 year, depending on the accuracy specifications the instrument owner wishes to use) and Zero Calibration is done at least once every 30 days, the 5700A will meet its absolute uncertainty specifications.

Printed calibration reports, both of the shifts introduced in the output by the latest Artifact Calibration (the "Cal Shifts" report) and of the calibration constant values before and after Artifact Calibration (the "Cal Consts" report) are available so that the adjustments done can be clearly seen. The Cal Shifts report is intended to show the effect of the Artifact Calibration adjustment (i.e. changing cal constants) on the output. It does so by computing the DAC settings using the new and old cal constants, then computing the resulting output shift. The Cal Consts report lists the values of all cal constants, old, new, and default.

The 5700A also provides a procedure called CalCheck, which does all of Artifact Calibration except for the comparisons to external artifacts. This characterizes the various ranges of the 5700A relative to the more stable internal references and ac cal sensor, indicating how stable the instrument is between calibrations.

All of the above apply to the original 5700A, the 5700A Series II and the 5720A. In addition, relative specifications are provided for both instruments in the event that the artifacts used have uncertainties different from those specified by the manufacturer.

As in any microprocessor-based instrument, during calibration adjustments are made in the form of modifying internal calibration constants (or correction factors). Unlike physical adjustments (such as turning a potentiometer), the physical hardware is not changed and therefore the drift rate and other hardware performance factors are not affected. The adjustment is more directly analogous to changing the entry in a correction table stored outside the instrument, given that the linearity of any DACs involved is much better than the uncertainty specifications.

## Earlier Studies

There are several approaches to assessing the trustworthiness and traceability of Artifact Calibration. A "black box" approach gathers data from Artifact Calibration of one or more instruments over time, confirming that it does its job without taking into account how it does it. A statistical variant of "black box" testing looks at the behavior of a population of instruments, providing results more applicable to a typical instrument. A "white box" (or "glass box") approach looks inside the instrument, analyzing the process itself to determine if its results should in theory be correct. An intermediate approach, called "opaque box," uses only the simplest assumptions about how the instrument works, for instance verifying that errors in the artifact values will produce corresponding errors in the instrument output.

In 1990, SP published the results of an opaque box study of the 5700A and 3458A [2]. They introduced intentional errors in the references and verified that the results tracked the errors. With a couple of minor concerns, the results indicated that Artifact Calibration works as hoped in the instruments studied.

In 1996, Les Huntley published a statistical analysis of calibration and verification data gathered on many 5700As by the Fluke service center and factory [3]. The analysis concludes that Artifact Calibration meets the manufacturer's claims (i.e. that it is conservatively specified) and includes analyses that address concerns about the stability of those parts of the 5700A not corrected by Artifact Calibration. Because the results are statistical, however, it doesn't necessarily mollify the concerns of an owner of a particular instrument, for whom acquiring and using historical data may be the ultimate solution. No one has demonstrated that Artifact Calibration has failed to work in a properly functioning 5700A. However, the question is where the burden of proof lies. From the point of view of an accrediting body, it lies with the user of the instrument.

## **This Study**

The 5700A has been described as a "cal lab in a box." The purpose of the European study is to audit the Artifact Calibration methods of the Fluke 5700A as if it were a calibration laboratory.

Three 5700A Series II calibrators provided by Fluke were used for the evaluation. Fluke also provided technical information as required for the analysis and formulation of tests; otherwise, the analysis and testing were done by SP, PTB, and NMI. More background for this study can be found in [1].

Before analysis and tests were performed, work on the instrument was partitioned into functional groups: direct voltage (dv); alternating voltage (av); direct and alternating current (dc and ac); resistance; and embedded firmware. The embedded firmware was assessed independently because the analysis requires a different skill set from rest of the evaluation, and because analyzing the quality of the embedded firmware as a whole was deemed useful to assessment of the quality of the complete instrument.

Black box testing is analogous to an interlaboratory comparison of a known standard. The black box testing consisted of running Artifact Calibration on the instruments provided, preceded and followed by full verifications to determine whether Artifact Calibration maintained the 24 hour specifications.

Opaque box testing is analogous to verifying that the instruments are set up and connected correctly in a laboratory. The opaque box tests were to run Artifact Calibration, intentionally introducing shifts in the external standards and comparing the resulting output shifts with expectations. Opaque box tests were run separately for each output function. Both "soft" and "hard" shifts were introduced, a "soft" shift being the entry of an erroneous value for the standard during Artifact Calibration (e.g. using a 10V standard and entering its value as 10.1V) and a "hard" shift being use of a different artifact value (e.g. using a 10.1V standard instead of 10V).

Glass box testing is analogous to assessing the correctness of the calibration procedures and the continuity of the traceability chain of a laboratory. The glass box tests were preceded by a thorough analysis of the embedded firmware, the hardware, and the calibration procedures of the instrument, thus providing a thorough look "through the glass." The analysis itself was a major part of the evaluation, indicating whether the instrument calibrated itself properly, using metrologically sound principles. The results of the analysis also indicated what tests would most completely and efficiently assess the performance of the actual instrument.

Among the glass box test methods used were: measuring certain internal points of the 5700A; introducing shifts to the internal calibration constants and measuring the effects of the shifts on the output, noting whether Artifact Calibration removes the shifts and correctly indicates the shifts in the Cal Shifts report; repeatability tests; and linearity tests.

The wideband option was not included in the study because it is calibrated by traditional methods.

## Results

This is a preliminary summary of the results, based on presentations made at a meeting of the participants in Eindhoven, The Netherlands, from January 19 to 21, 1998, and conclusions agreed upon by the participants at that meeting. Some final tests and further analysis remain to be done, but the final report is expected to be complete before the EA meeting in October 1998.

Black box tests confirmed that, after Artifact Calibration, all instruments met their 24 hour specifications. Opaque box tests, introducing "soft" and "hard" shifts to all artifacts, resulted in measured output shifts corresponding to predicted values within the 24 hour specifications. Also, the shifts given in the Cal Shifts report matched predicted values. Results from a repeatability test performed on all calibration constants by running Artifact Calibration fourteen times and analyzing the scatter of each constant, indicated that Artifact Calibration was consistent enough to produce results within specifications.

Direct voltage glass box tests included changing the 2.2V and 11V gain constants and checking the effect on the output and running multi-point linearity tests on the 11V, 220V, and 1100V ranges. The choice of ranges came from an analysis of the use of the hardware and the cal constants during instrument operation and calibration. The results were favorable.

Direct and alternating current glass box tests consisted of applying shifts to several gain and flatness correction cal constants and measuring the resulting output shifts at various ranges, amplitudes, and frequencies.

Glass box testing of resistance was relatively simple because the calibration constants simply represent the true values of the fixed resistors in the 5700A. Changing the calibration constant values simply changes the displayed values when resistors are selected.

Alternating voltage glass box testing included: measuring the difference between the point where  $av$  is internally calibrated and the output terminals; and introducing shifts to various gain, flatness, and convergence cal constants and measuring the resulting output shifts. The introduction of shifts to various constants produced the expected results with one minor question outstanding about the effect of "convergence" constants above 120 kHz. This will be resolved before the final report is released.

The second part of  $av$  glass box testing is significant because it illustrates a limitation of self-calibration: sometimes it cannot measure the value at the output terminals because of architectural limitations or safety considerations. Therefore, the difference between the point where the instrument can measure its output and the outside world needs to be examined. In the case of  $av$ , most significant is the effect of the standing wave ratio of the signal path from the

internal reference plane to the output terminals. The resulting voltage drop, VSWR, is a function of the output frequency and is corrected by a calibration constant which is set in the factory (or after instrument service) and is not touched by Artifact Calibration.

The analysis of the embedded firmware found no discrepancies between the stated algorithms used and their implementation and confirmed that metrological principles were correctly followed. Also, it was confirmed that the calibration constants are protected by a checksum and otherwise handled in such a way that the most common corruption of the constants (for instance, if power fails while nonvolatile memory is being updated) will not affect output accuracy and any corruption of the cal constants will be detected and clearly reported to the user. Because this third-party analysis of a calibration instrument's embedded firmware was a new experience for all parties involved, much was learned about how to do such an analysis in the future.

### **Preliminary Conclusions**

These conclusions are by necessity preliminary for the same reason the results are preliminary.

The testing and analysis has shown that direct voltage, direct current, and resistance are traceable and no external verification beyond the biannual full verification recommended by the manufacturer are required to keep the instrument in calibration.

The traceability for alternating voltage and current is not so clear because Artifact Calibration does not include the effects of the ac cal sensor or any drift in VSWR behavior. Although evidence in [3] indicates that these drifts are well within the uncertainty specifications for a population of instruments, it does not guarantee the same for an individual instrument in the view of the participants of this project. However, traceability may be established and maintained by gathering and saving historical data in the form of verification results and the calibration. As trends become clearer, the interval between verifications may increase until the manufacturer-recommended two year interval between full verifications is reached.

Because the Cal Shifts report gives shifts only at selected representative values, to be certain that the effect of Artifact Calibration on any value, not just those shown in the report, may be thoroughly calculated, it was recommended that both the Cal Consts report and the Cal Shifts report be saved after every Artifact Calibration.

The final report will give sample "recipes" for a significantly reduced set of full verifications of a new instrument depending on the calibration interval and corresponding set of uncertainty specifications selected by the user. The recipes to be included in the final report are suggestions only, because it is up to the accrediting body and the owner of the instrument to agree upon a schedule of Artifact Calibrations and full external verifications that, in their opinion, will produce a traceable result.

Someone who has owned a 5700A for some time and kept historical data should be able to justify switching to a two year full verification interval, contingent on the agreement with the overseeing calibration laboratory.

Only an As Left verification need be performed, because the correspondence shown between calibration constant changes and measured output shifts indicated that, as long as the Cal Shifts and Cal Consts reports are saved, As Found results may be reconstructed within specified uncertainty if necessary. The Cal Consts report would only be used if a problem occurs because analysis of the report is at present complex and difficult, and the mere retention of the report is sufficient to establish traceability.

A more general project, TOSCA (Traceability of Self-Calibrating Apparatus) has been submitted for European Community funding. The result will be a general method of independent evaluation

of self-calibrated instruments. Many of the TOSCA partners were also involved in the 5700A study described here. The need to evaluate self-calibration is increasing, as more self-calibrating instruments are introduced, including several for non-electronic quantities. Some weighing instruments now include internal mass references, for instance. There will certainly be more self-calibrating instruments, whether they calibrate from artifacts or by other means, and broader acceptance of their methods will benefit everyone.

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