An Evaluation of Artifact Calibration in the Fluke 5700A Multifunction Calibrator

Application Note

Artifact Calibration, as implemented in the Fluke 5700A Multifunction Calibrator, was a revolutionary concept when it was introduced in 1988. Today, with many thousands of instruments deployed throughout the world, questions often arise about how well Artifact Calibration stands up over time in real world applications:

- Does Artifact Calibration really work?
- Is the 5700A stable enough to support its specifications for periods up to one year between Artifact Calibrations?
- Is the two year full verification really needed?
- Can I really expect a 5700A calibrated in the factory to meet its specifications?

This application note answers these questions.

The data base

As Found and *As Left* Data

The Fluke Northwest Technical Center is equipped to repair and calibrate the 5700A. Upon arrival, As Found data is taken for operational instruments. For this study, data on approximately 260 instruments was available. The number is approximate because some instruments were returned for repair and may not have operated properly in all functions. Factory test data from new instruments was also used.

As Found data was processed in Microsoft Excel™ spreadsheets, using the statistical and graphing functions. As noted above, not all data was useable, and in some cases, outlying data points more than four standard deviations from the mean were discarded. As a result, the *As Found* data set analyzed consists of those points within four standard deviations of the mean.

Before they are returned to their owners, instruments are calibrated using Artifact Calibration, then externally verified where *As Left* data is collected.

Production test data

Data obtained in the final production test of 5700As is uploaded to a computer and is used to control the production process. Production test stations are maintained under rigorous control through the use of check standards (for process control) and through Process Metrology (to assure processes are maintained properly centered). A key requirement of the quality system is the $C_{pk} > 1.33$ (four sigma process) which must be maintained for each parameter.

This data is useful for resolving some questions about the error contributions of the service center measuring system.

Interpreting the data

This is complicated by the need to separate instrument performance from measuring system performance. Complete analysis of instrument performance requires complete knowledge of the contributions of the measuring system. Therefore, it was necessary to accurately assign offsets and variability to the measuring system or to the 5700A. In most cases, the combination of *As Found* and *As Left* data provides enough information to separate those error parameters with good confidence.

Does Artifact Calibration really work?

How it works—the idea behind it all

Artifact Calibration incorporates all the metrology functions usually performed by a standards or calibration laboratory into the instrument. Thus, the 5700A contains internal reference standards, an internal ratio device and a sensitive null detectorUnder the control of its internal software, the 5700A performs the metrology procedures necessary to determine offsets from nominal of its outputs, and to make internal corrections to drive the offsets essentially to zero. Artifact Calibration provides superior accuracy because the calibration environment and procedures are fixed by the design of the instrument, and thus are not subject to the range of conditions and capabilities found in the community of calibration laboratories.

Performing Artifact Calibration returns the direct voltage (dV), direct current (dc) and resistance functions to essentially the same accuracy the

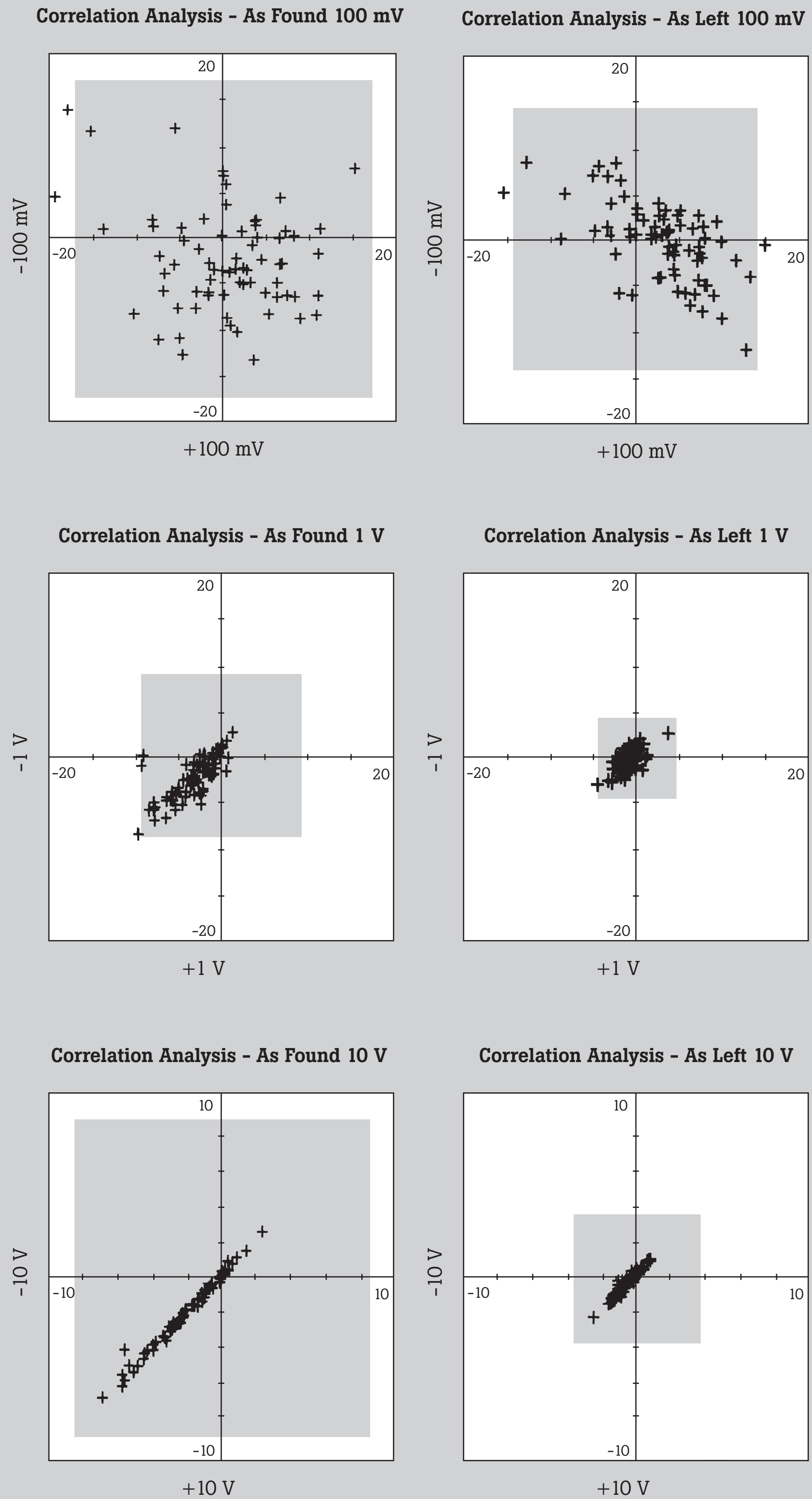

Figure 1. Scale values are ppm. Shaded boxes show one year specification, *As Found*, and 24 hour specification, *As Left*.

instrument had when it was first manufactured. This is accomplished by adjusting internal references by comparison to external standards, verifying ratio accuracy, performing measurements and making the adjustments needed to bring the outputs to nominal. Alternating current (ac) and alternating voltage (aV) outputs are returned to nominal referenced to an internal ac/dc difference standard, which is not adjusted during the process. Artifact calibration of aV and ac differ from the other functions only in that the internal reference is not measured or adjusted. Long term accuracy of those parameters depends upon long term stability of the internal ac/dc difference standard. As noted later (Figures 4 and 5) the long term stability of the external ac/dc difference standard would support verification intervals of *several* years in length.

Artifact Calibration is performed at intervals determined by the specifications to be maintained. For example, Artifact Calibration must be performed each 90 days to maintain the 5700A's 90 day specifications. The 5700A also provides a Cal Check function that may be used to monitor outputs relative to the internal standards. This feature provides users with a means for implementing a measurement quality program as required by paragraph 9.6 of ANSI/NCSL Z540-1 which requires "in-service checks between calibrations and verifications."

How well it works—the results

How well Artifact Calibration works is best shown by comparing *As Found* and *As Left* data for the direct voltage ranges. There we have equal voltages of opposite sign that are adjusted essentially identically by the Artifact Calibration process. Figures 1 and 2 are scatter plots of *As Found* and *As Left* measurement results on 72 instruments in our sample judged not to have been repaired.

The measured differences from nominal for dV are such that errors that affect both positive and negative output the same way (that is, internal and external standard error and ratio error) are positively correlated. The first are gain errors and will result in a straight line running at an angle from left to right at about 45°. The second are zero errors and results in a line running at an angle from left to right at about -45°. Random noise shows up as a more or less circular distribution of points.

The boxes indicate specification limits—one year for *As Found*, and 24 hour for *As Left*. Keep in mind these plots include not only the errors in the 5700A, but also errors contributed by the measuring system. All plots show measured difference from nominal in parts per million (ppm).

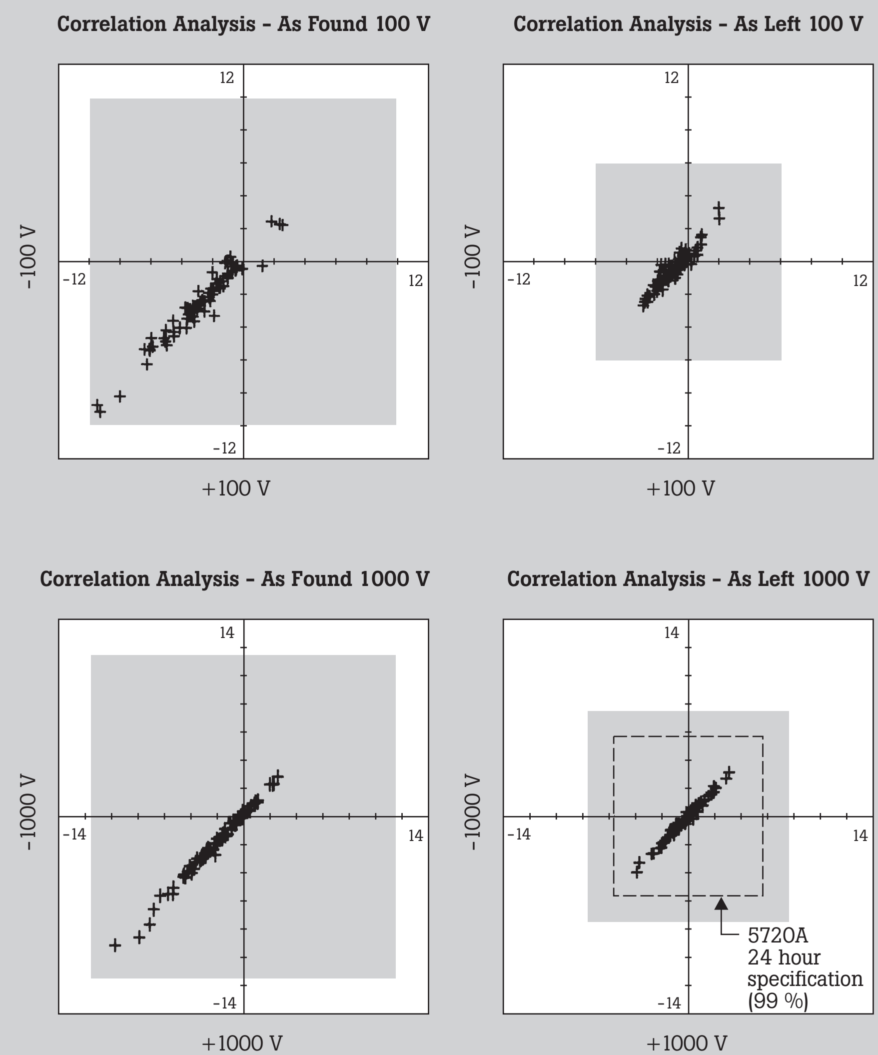

Figure 2. Scale values are ppm. Shaded boxes show one year specification, *As Found*, and 24 hour specification, *As Left*.

These plots show three things:

- Only a few points are outside specification *As Found*. Do these result from errors in the measuring system?
- All outputs are adjusted to well within 24 hour specifications.
- There is significant positive correlation in all but the 100 mV plots (Figure 1). In the *As Found* plots, these result from drift in internal standards, and to some extent, from less than ideal adjustment in the Artifact Calibration process. Positive correlation in the *As Left* plots result from less than ideal adjustment by Artifact Calibration.

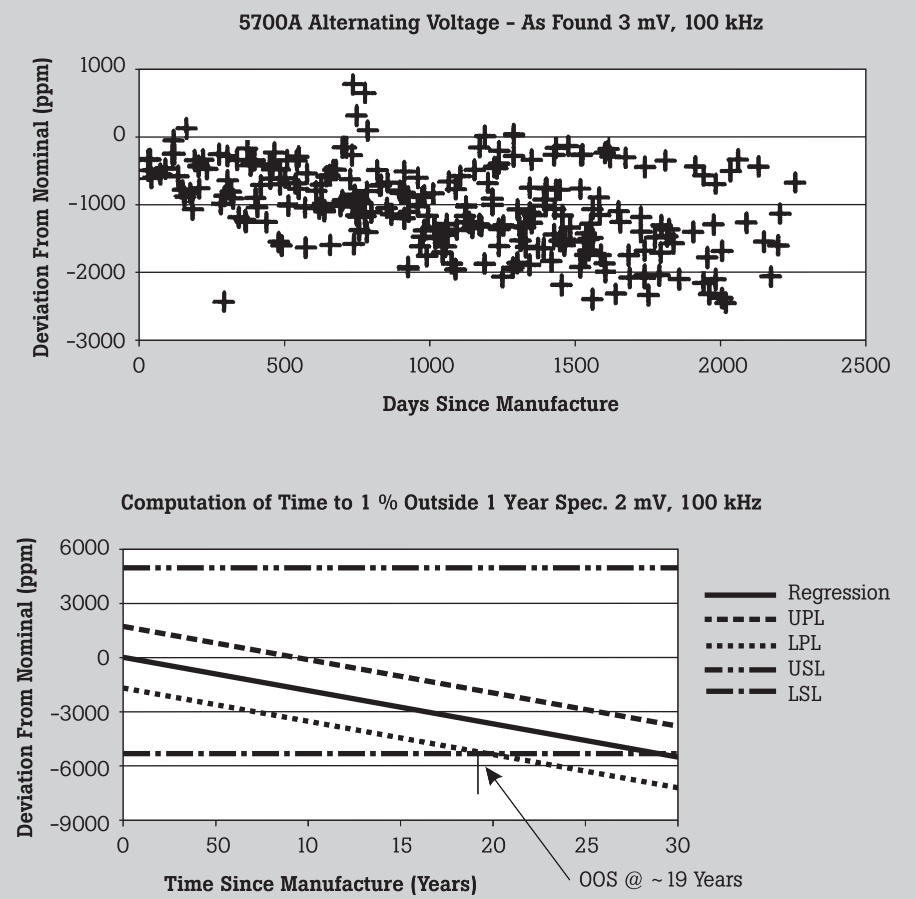

Figure 3. How time to 1 % Out of Specification is calculated.

5700A Stability

Many of the instruments in the data sample were measured several times during an approximately five year span, and presumably were Artifact Calibrated at one year or shorter intervals. Plotting *As Found* Data versus time since manufacture will reveal any long term drifts either in the instrument or the measuring system. That being true, it becomes possible to assess worst case limits for time stability of the 5700A.

The approach is shown in Figure 3. The upper portion of the figure shows the raw data for 2 mV, 100 kHz. (This parameter was chosen because it is one of the few having significant drift.) The graph in the lower portion shows how time to the 1 %-Out-Of-Specification point is determined. This is the point at which the regression line ± 2.58 σ intercepts the upper or lower specification limit, σ being the standard deviation of points about the regression line through the data. Thus, the time to 1 %-Out-Of-Specification is influenced by the drift and noise in the instrument, and in the measuring system. Offsets from nominal are ignored in this stability analysis, but of course will always impact actual performance.

Figures 4 though 8 are bar charts presenting the results of this analysis. They represent points measured in the full verification procedure. There are too many aV points to present in a single graph, so only the important specification breakpoints are presented.

The charts indicate that with a few exceptions the stability of the 5700As, maintained as recommended, is sufficient to support much tighter specifications. Of course, stability is only one contributor to instrument accuracy—uncertainty of standards and variability and errors in the adjustment process also contribute. In Figure 7, excessive variability makes it impossible to calculate stability for ± 100 mV and ± 1 V.

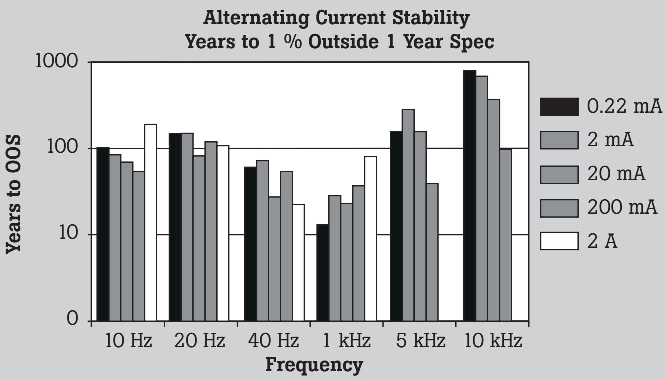

Figure 4. Alternating current stability in years to 1 % out of tolerance.

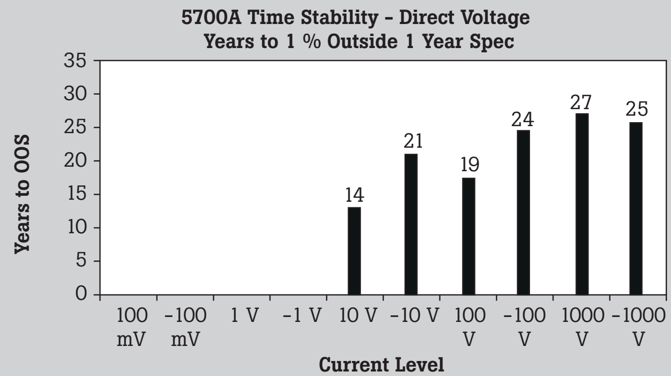

Figure 7. Direct voltage stability in years to 1 % out of tolerance.

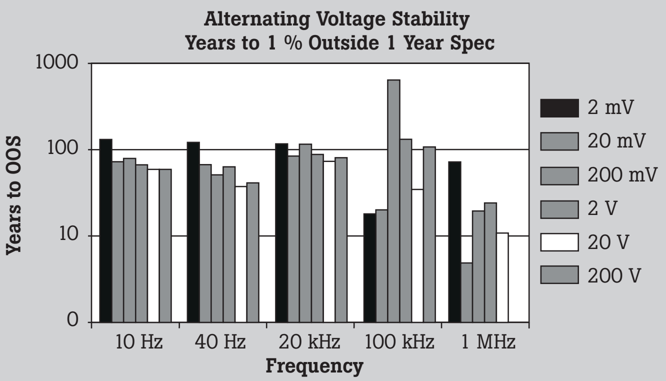

Figure 5. Alternating voltage stability in years to 1 % out of tolerance.

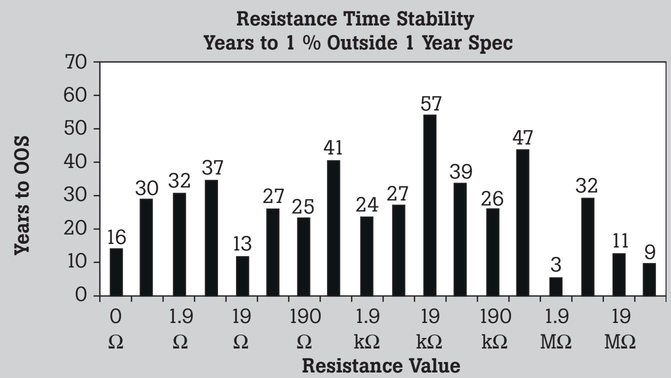

Figure 8. Resistance stability in years to 1 % out of tolerance.

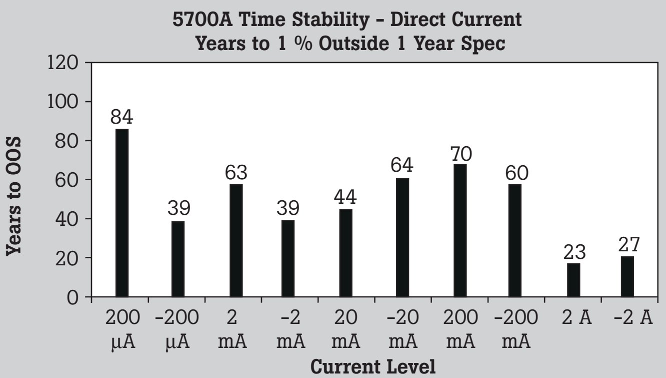

Figure 6. Direct current stability in years to 1 % out of tolerance.

Is the two year verification really needed?

Figure 9 shows why the answer to the question must be "yes". The plot shows significant drift and increased variability with increasing time since manufacture. The increase in variability results from different drift rates in different instruments. That this should occur is not surprising, since Artifact Calibration does not adjust the internal ac/dc difference standards, the reference for all alternating current and voltages. However, stability is more than sufficient to support the instrument's specifications.

Will a 5700A calibrated by the factory meet its specifications?

This is a two part question involving the performance of the 5700A and the ability of the factory to properly adjust instruments in the production process. The factory's ability to adjust instruments is closely monitored by the Fluke Standards Laboratory. 5700A process metrology was implemented to assure the accuracy of production measurements. That process is described in Baldock's *"Artifact Calibration, Theory and Application"* (see bibliography) and will not be addressed further here.

The best way to answer the first part of the question is to look at *As Found* data for a large number of instruments, all of which were initially

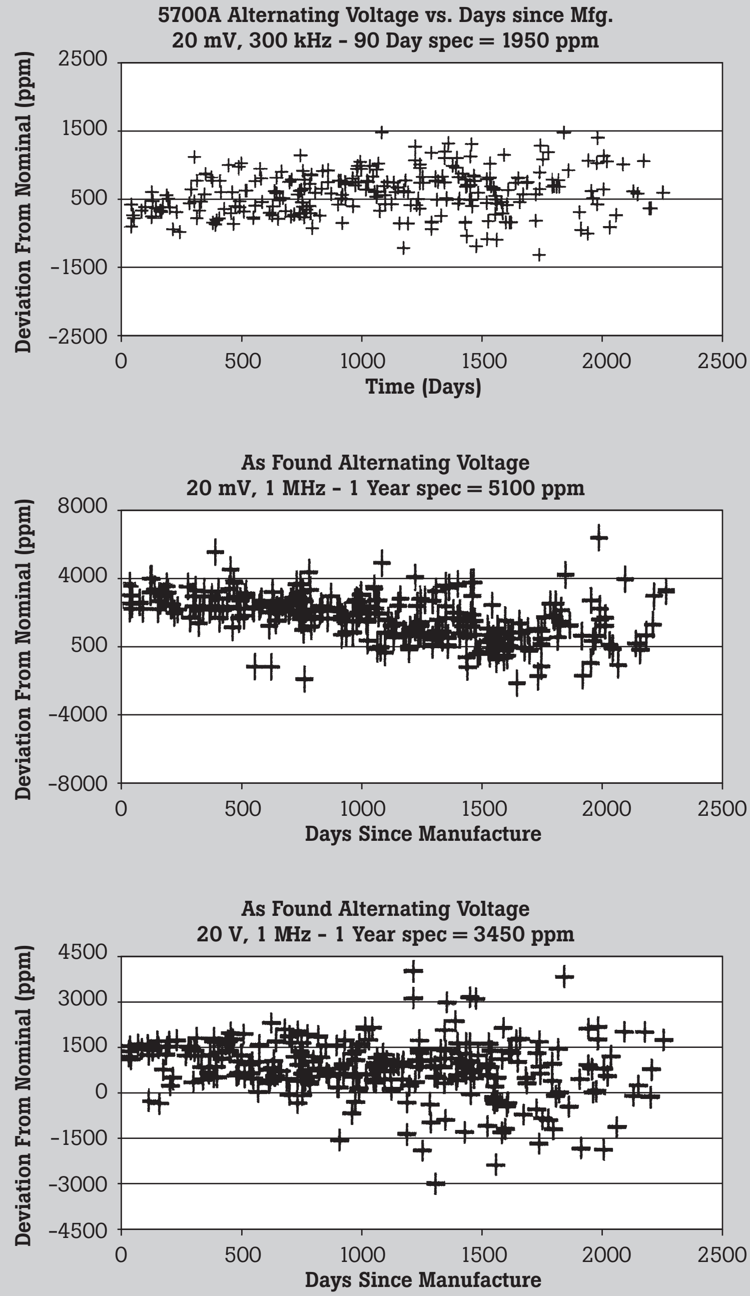

Figure 9. Long term drift and dispersion in alternating voltage outputs.

calibrated by the Fluke production facility. Figures 10 through 14 present *As Found* data for 260 5700As serviced by Fluke. Presented are the averages and 99 % confidence limits for each parameter measured in the recommended full verification.

Keeping in mind that this data includes any errors contributed by the measuring system, it is apparent that there is very high probability that an instrument will meet all its accuracy specifications, thus meeting one of the objectives of its designers—there should be a ⊕ 99 % probability that each parameter meets its specifications throughout the interval between Artifact Calibrations.

Figure 14 indicates smaller than 99 % probability at 100 mV and 1 Vdc. A further analysis was performed to eliminate

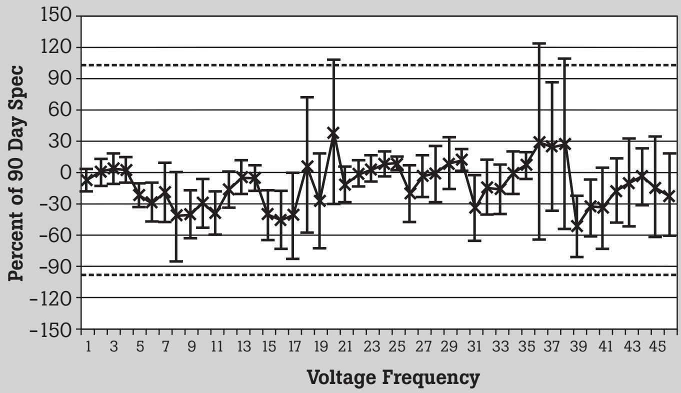

Figure 10. Deviations from nominal and 99 % limits, all verified voltages and frequencies.

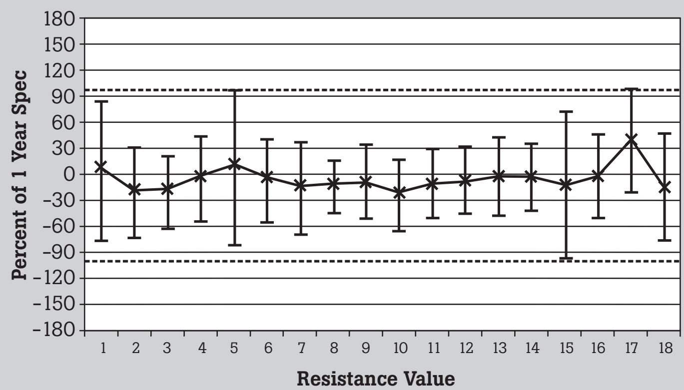

Figure 13. Deviations from nominal and 99 % limits, all resistance values.

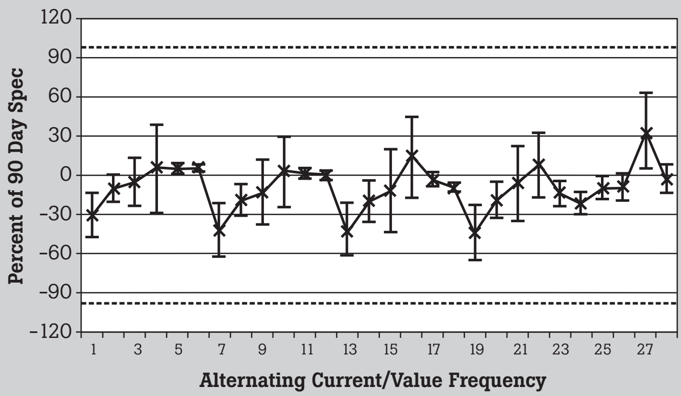

Figure 11. Deviations from nominal and 99 % limits, all verified currents and frequencies.

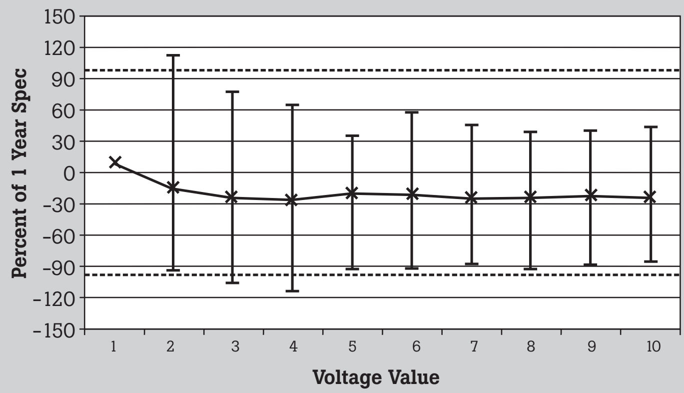

Figure 14. Deviations from nominal and 99 % limits, all verified direct voltages.

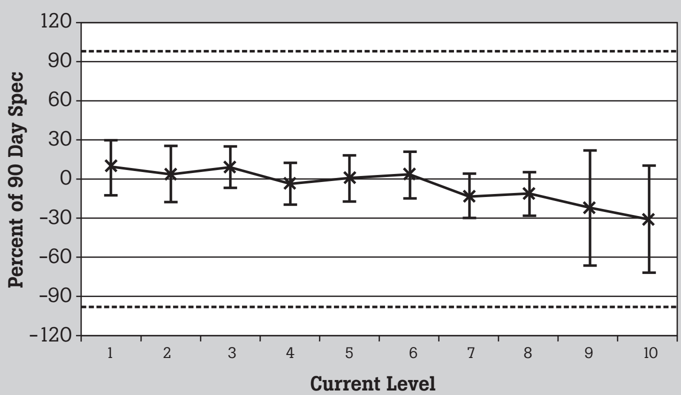

Figure 12. Deviations from nominal and 99 % limits, all verified direct current levels.

the measuring system contributions. The results of the analysis are presented in Table 1. The results indicate > 99 % probability that a 5700A will meet its one year direct voltage accuracy specifications, except at 1V, where the probability is 98.4 %. Refer to *"An Assessment of Artifact Calibration Effectiveness for a Multifunction Calibrator"* for a more complete discussion of this analysis and its conclusions.

Conclusion

Clearly, the answer to each of the four questions posed at the beginning of this paper is yes.

- Artifact Calibration indeed works as designed. Most if not all points were found well within specification at calibration. All outputs were adjusted to well within the 24 hour specification afterward.
- Two year verification is recommended. Instrument variability increases with time from manufacture. Verification identifies those few instruments that do drift while meeting specifications.
- With the exception of 1 Vdc, there is a greater than 99 % probability that all 5700As will meet their accuracy specifications. At 1 Vdc, the probability is a slightly smaller 98.4 %.

Voltage	1 year Spec ± ppm	24 Hour Spec ± ppm	As Found		CSS As Left			Time Trend?	Production			5700A Offset	5700A Std Dev	Sigma Multiple	Minimum % Found in Spec
			Mean	Std Dev	Mean	Std Dev	C_{pk} (24 Hrs)		Mean	Std Dev	C_{pk} (24 Hrs)				
0.1	17	14.5	1.8	7.2	3.0	5.4	**0.7**	No	-0.6	2.1	**2.2**	-0.7	5.1	3.2	99.8
-0.1	17	14.5	-2.1	6.8	0.4	4.6	**1.0**	No	-1.2	2.9	**1.6**	-1.3	5.7	2.8	99.4
1	9.2	7.2	-2.1	3.6	-0.6	1.2	**1.8**	No	-1.4	0.6	**3.1**	-0.2	3.5	2.6	99.1
-1	9.2	7.2	-2.3	3.5	-0.5	1.1	**2.0**	No	0.0	0.9	**2.7**	-1.8	3.5	2.1	98.4
10	8.4	5.4	-1.2	2.1	-0.3	0.6	**2.7**	No	-0.9	0.5	**3.2**	0.0	2.0	4.1	100.0
-10	8.4	5.4	-1.5	2.5	-0.2	0.6	**2.7**	No	-0.6	0.4	**3.7**	-0.6	2.4	3.2	99.9
100	10	7	-2.1	2.8	-0.9	1.3	**1.6**	No	1.0	0.6	**3.4**	-2.2	2.6	3.0	99.9
-100	10	7	-1.9	2.8	-0.6	1.2	**1.7**	No	-0.6	0.6	**3.8**	-0.7	2.5	3.6	100.0
-1000	11.6	8.6	-1.7	2.8	-0.3	1.6	**2.2**	No	-2.1	1.0	**3.7**	0.8	2.5	3.9	100.0
1000	11.6	8.6	-1.9	2.8	-0.5	1.6	**2.2**	No	-3.1	1.0	**3.3**	1.7	2.5	3.8	100.0

Note: CSS results have opposite sign from others.

Table 1. Summary of direct voltage analysis.

Artifact Calibration and the development of the 5720A Multifunction Calibrator

The design goal of the 5720A Calibrator was to specify the lowest possible output uncertainties while preserving the ease-of-use and simplified support qualities that made the 5700A so popular.

The first task was to determine what changes would be necessary to make the instrument and manufacturing processes to support the improved uncertainties. The study outlined here, along with other factory test data, supported those requirements.

The first improvement was in Artifact Calibration. Lower uncertainties would require outputs to be adjusted even more closely to the ideal levels. The reason for this can be seen in the scatter plots in Figures 1 and 2. As the *As Left* plots show, Artifact Calibration adjusts the 5700A back to a small percentage of its 24 hour specification. However, as you can see here, the 24 hour specification of the 5720A, described by the smaller box in Figure 2, *As Left Data, 1000 V*, requires even more precise adjustment to nominal. A large part of the 5720A development effort concentrated on improving the mean values returned by Artifact Calibration for all parameters.

The second challenge was to lower the uncertainty of the factory test system, particularly for those output values affected by thermal emfs. More rigorous testing procedures and enhancements to the Process Metrology system used to maintain the 5720A factory test equipment permitted a dramatic improvement in both the mean values of measurements as well as the noise level.

In addition to dramatically reduced uncertainty specifications, the 5720A permits the user to select either 99 % or 95 % confidence levels for the uncertainties reported by the calibrator when the "Spec" key is pressed. Also added were remote emulation of the 5200A AC Calibrator, a screen saver mode, lower dcV noise and a zero reminder.

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