The Metrology Behind Wideband/RF Improvements to the Fluke Calibration 5790B AC Measurement Standard

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1. Abstract

For over 20 years, the Fluke 5790A has been the most precise AC voltage measurement standard in the industry. The evolution of through-hole components to surface mount components and the Restrictions of Hazardous Substances (RoHS) directives have driven the need to redesign the 5790A. In addition to the component changes, many improvements to the operation of the product were made. The United States Air Force requested that the wideband frequency measurement range to be extended to 50MHz, which would also enable the 5790B to calibrate the 50MHz 1 mW reference output that is common to many RF power meters. This paper provides a review of improvements to the 5790B (referred to as the product in this paper), challenges to the project related to the flatness calibration of the wideband output, information on the calibration methods as well as the validation of methods and metrological confirmation of the instrument itself.

2. Product Features

The differences in features between the redesigned Fluke Calibration 5790B and its predecessor the Fluke 5790A are summarized in Figure 1. Innovative firmware features allow direct current measurements through stored shunt data in memory. The addition of 50 MHz wideband feature also enables direct power measurements of common REF OUT output of power meters.

5790A	Features	5790B
YES	AC/DC Transfer Mode	YES
YES	Absolute Measurement Mode	YES
-	Specifications for Non-sinusoidal waveform measurements	YES
-	DC Voltage Specifications	YES
-	FW support for shunt values	YES
YES	Wideband option (30 MHz)	YES
-	Wideband option (50 MHz)	YES
-	Option for calibrating REF OUT of Power meters	YES

Figure 1. Summary of features for the redesigned 5790B

3. Wideband Input Calibration Steps

The calibration of the wideband output of the product consists of two steps:

- Wideband Gain Calibration
- Wideband Flatness Calibration

Both steps require the use of source that has been characterized to a fraction of its specifications. The term characterization in this process is used to describe the process of establishing a measurement quantity and statistically justified time interval for which the measurement quantity is stable and reproducible to predefined significant process limits. While the Wideband Gain Calibration remains unchanged since the initial publishing of the Fluke 5790A service manual, the Wideband Flatness Calibration presents its challenges and is discussed later in this paper. The wideband input flatness calibration has evolved over the years. The product is designed to work with a source that has an impedance of 50 Ω. It is desirable to have input impedance that is very close to a nominal 50 Ω when characterizing the source and the source output impedance close to nominal 50 Ω when calibrating the wideband input of the product. When the Fluke 5790A service manual was initially published the method depicted in Figure 2 was used. The source (Fluke 5720A with wideband option) is characterized for flatness with a Fluke A55-3V thermal voltage converter. This thermal voltage converter has input impedance of 600Ω and required a connection to a Tee and a 50 Ω load. The equivalent load impedance as seen by the characterized source is approximately 46Ω and to make matters worse, it is changing as a function of the test frequency due to impedance flatness imperfections in the thermal voltage converter (TVC) as well as the load.

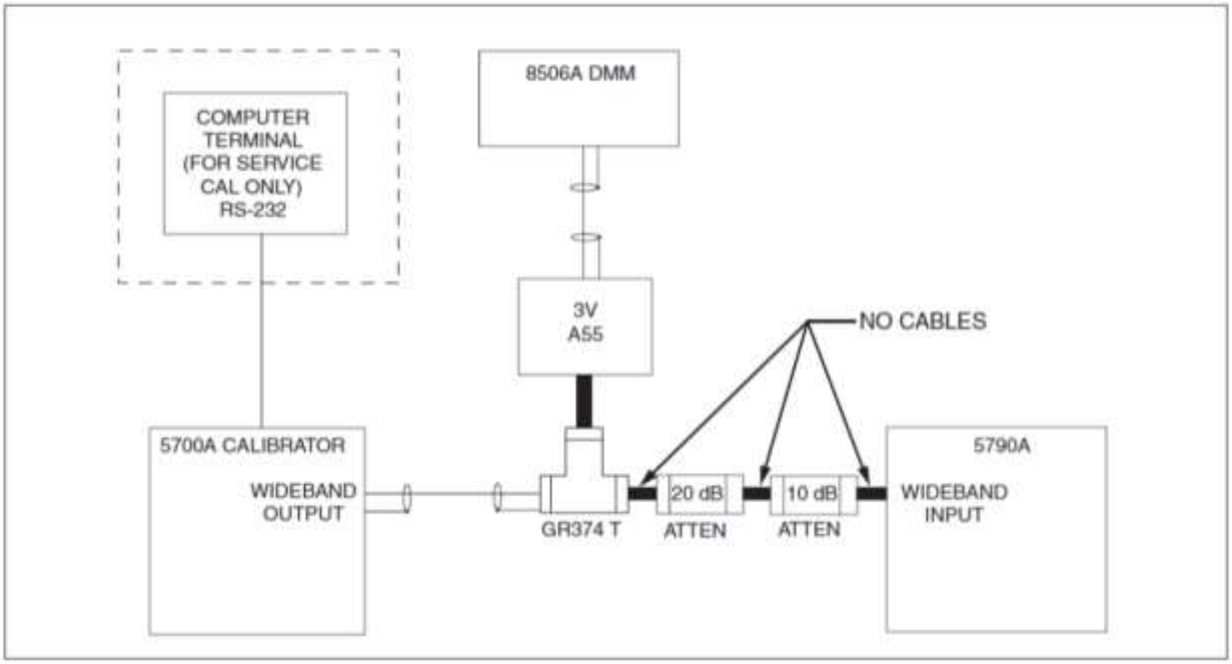

Figure 2. Diagram of source characterization for flatness from Fluke 5790A service manual.

New and improved method for source characterization was introduced during the 2006 National Conference of Standards Laboratories International (NCSLI) conference. In this method a 50 Ω thermal voltage converter with exceptional impedance flatness and impedance very close to 50 Ω is calibrated using a working standard Fluke A55-3V. The source is then characterized using the 50 Ω thermal voltage converter. A simplified diagram of this characterization from the 2006 NCSL paper is shown below in Figure 3. This method was elected for extending the capability to 50 MHz.

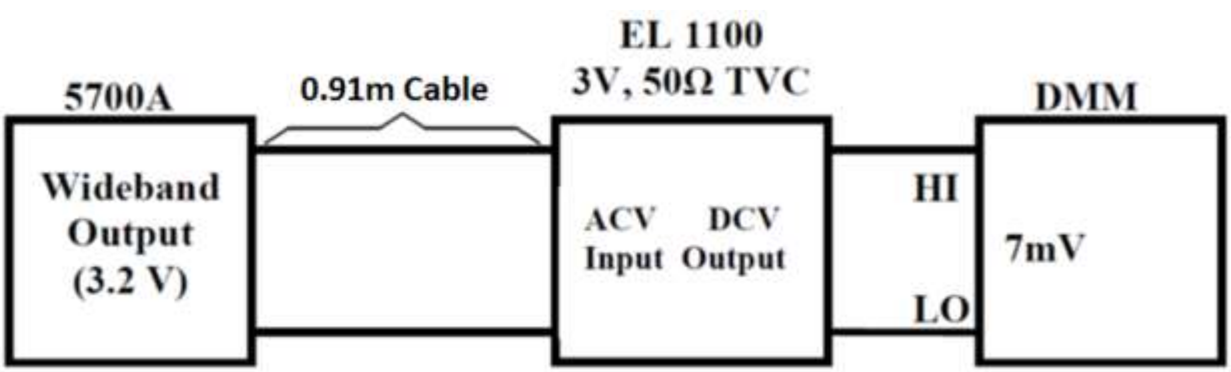

Figure 3. Diagram of source characterization using new method for impedance matching.

The steps of calibrating the flatness of Fluke 5790B wideband input are as follows:

- Calibration (extension of current process) from 30 MHz to 50 MHz of working standard Fluke A55-3V TVC.
- Calibration (extension of current process) from 30 MHz to 50 MHz of working standard Precision Measurement EL1100 TVC.
- Calibration (extension of current process) from 30 MHz to 50 MHz of working set JFW attenuators.
- Characterization of the source using the EL1100 TVC.
- Calibration of the product using the characterized source and attenuators.

4. Source Selection

The key to success in this process is the stability and reproducibility of the source. The first four steps use a TVC to level the signal of the source. It is critical that the reference frequency is exceptionally stable and reproducible. The process for calibrating a Fluke 5790A (30 MHz wideband option) uses a Fluke 5720A with a 30 MHz wideband option source. Unfortunately a 50 MHz option Fluke 5720A source was not available at the early stage of this project. It was essential to qualify a source with 50 Ω output impedance for the process to insure the stability of the source. A Fluke 9640A (Figure 4) was chosen due its output capability to source in the 10Hz to 50MHz band. Features that influenced the decision to employee Fluke 9640A in this project were:

- Frequency range 1 Hz to 4 GHz
- Device leveling at the leveling head
- Low SWR (<1.1 for $f \leq 500$ MHz)
- Output set resolution of 0.001dB

Figure 4. Fluke 9640A.

5. Measurement Techniques

In addition to source stability and reproducibility, attention to measurement techniques when using thermal voltage converters are critical in the process. Because thermal voltage converters are generally nonlinear devices, their output sensitivity has to be experimentally derived. In addition, leveling of the source signal at each test frequency is used to eliminate errors. Since the thermal voltage converter is prone to drift, a closing measurement with the reference frequency should always be performed, thus minimizing the influence of thermal converter drift. It is demanding to fulfil all of these techniques successfully without automation. Therefore, a modified MET/CAL version of calibration software was developed to control the Fluke 9640A and to extend testing to 50 MHz.

6. Establishing Validation Criteria

It is important to establish criteria for validation/metrological confirmation of the measurement results. It is an accepted practice to compare measurements to a validated method and/or another laboratory or National Metrology Institute (NMI) measurement process with similar uncertainty capability. In the case of the Fluke Calibration 5790B there are limited similar products in the market and/or laboratories making measurements to the level of uncertainty we require. Fluke has previous results of Interlaboratory Comparisons (ILC) of components of the process up to 30 MHz. This ILC have been performed with other United States based laboratory on attenuators flatness calibration. The following validation criteria was established for the extension of the measurement process to 50 MHz:

- 6.1. Each step is reproducible within the assigned expanded uncertainty.
- 6.2. The new automated software and source can generate results comparable to the results of the validated system up to 30 MHz.
- 6.3. The measurements above 30 MHz follow the logical curve/trend of the data up to 30 MHz.

7. Reproducibility of the New Source (Fluke 9640A)

Following our predefined criteria of "what good looks like" we analyzed the data graphically. Three consecutive runs were graphically evaluated as shown in Figure 5 (Flatness calibration of TVC) and Figure 6 (a magnified low frequency view of the same TVC as in Figure 5). The conclusion of the TVC results are:

- Poor reproducibility.
- Review of low frequency data (< 1 MHz) shows that multiple points have reproducibility errors outside or near the uncertainty bands (Figure 6).
- Abnormal response with large inflection points at high frequency.
- Although noisy, the data has the overall response typical for EL1100 population

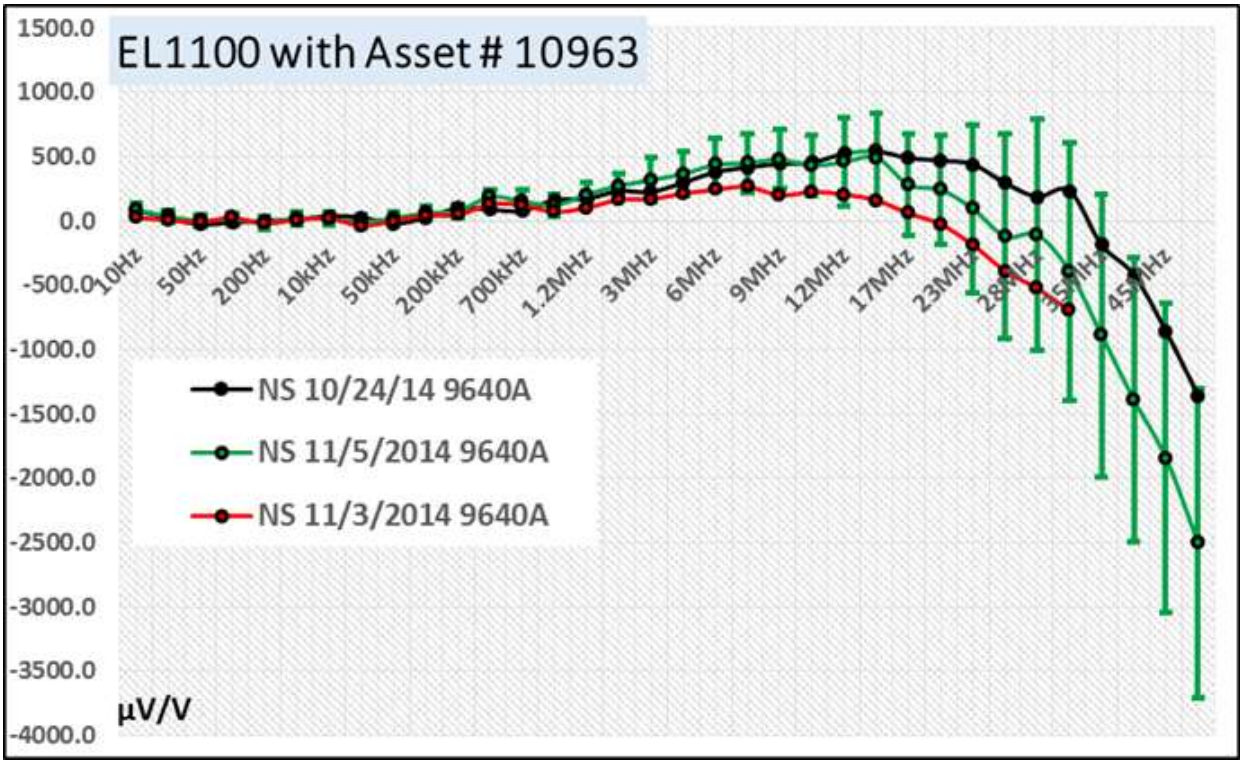

Figure 5. Graphs of three flatness calibrations of TVC.

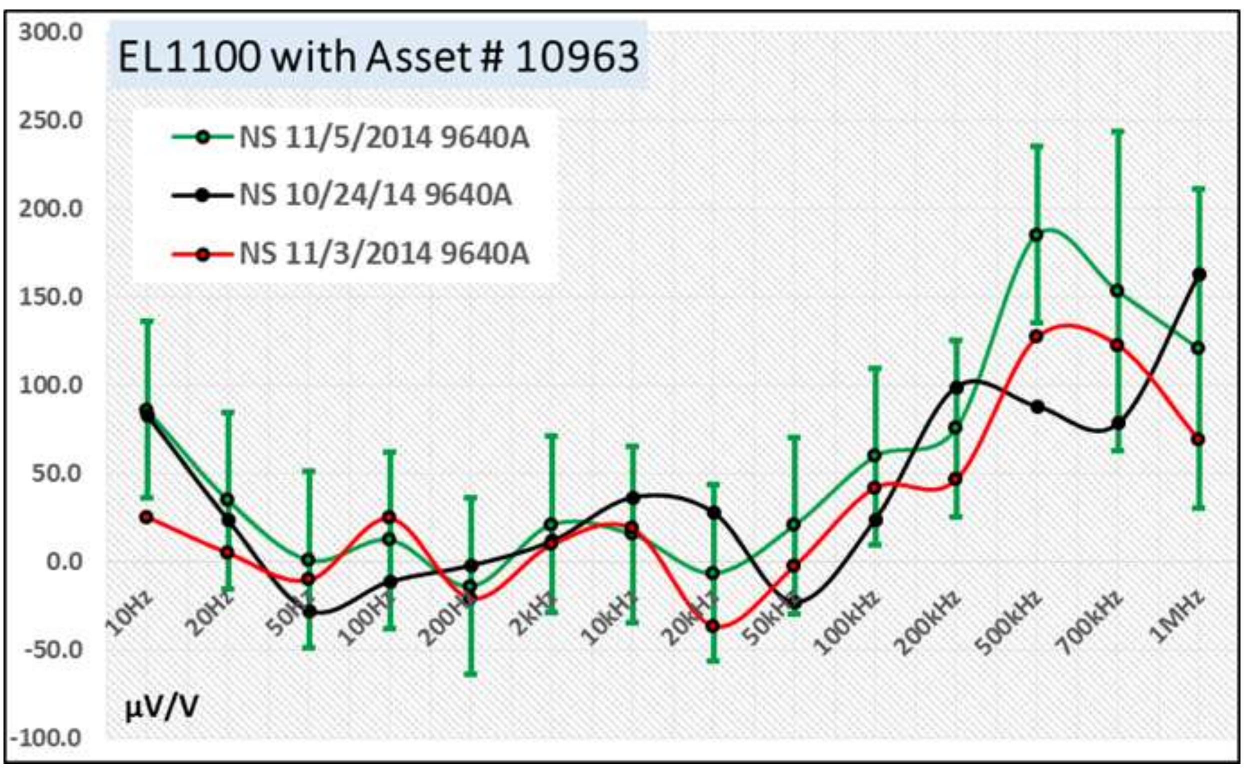

Figure 6. Magnified view of the low frequencies flatness calibrations of TVC.

Similar reproducibility results were observed for the JFW Attenuators Flatness Calibration reproducibility, where we observed abnormal flatness response with variations exceeding the uncertainty of the measurements as illustrated in Figure 7.

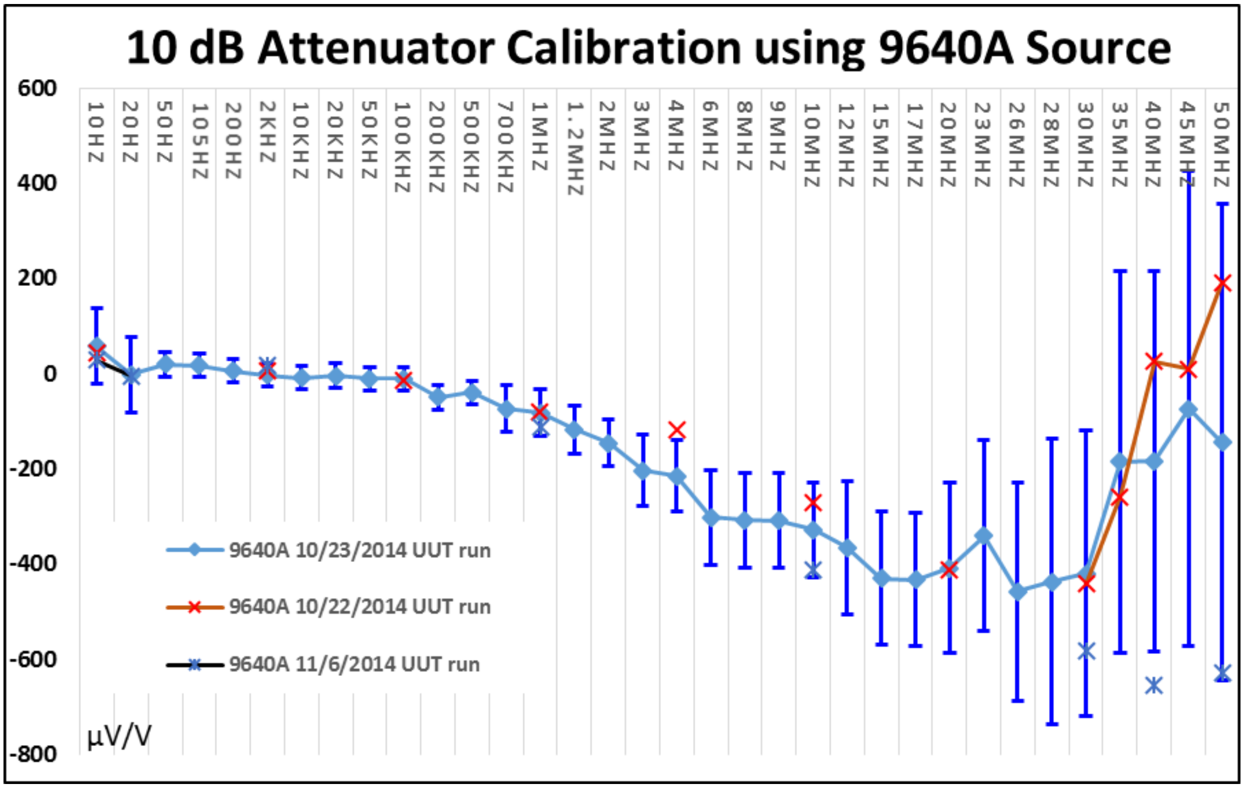

Figure 7. JFW Attenuators Flatness Calibration reproducibility using Fluke 9640A source.

8. Investigation of Poor Reproducibility when using Fluke 9640A

Based on the results of the repeat flatness calibrations of TVC, attenuators and previously defined criteria; the process did not meet requirements. The following reasons were identified and investigated:

8.1. The Source Is Not Sufficiently Stable.

Stability is defined as repeatability and reproducibility. Repeatability is the ability of the source to provide consistently reference amplitude signal for the duration of the measurement cycle. Reproducibility - to go back to the same level after the output has been changed in the following sequence: output at 1 kHz → output at test frequency → output at 1 kHz. To investigate source stability a new variation of the software was developed to use a known good source (Fluke 5720A with 30 MHz wideband option). Statistical evaluation of reproducibility of the source and AC voltmeter was assessed via statistics of the raw data during multiple runs. Using Fluke 5720A source, the statistics for the calibrator repeatability (Min/Max variation) at 1 kHz were as follows: Fluke 5790A: |14 μV/V|, Fluke A55-3V/Keithley 2182A: |290 μV/V|. Using 9640A source, the statistics for the calibrator repeatability (Min/Max variation) at 1 kHz were as follows: Fluke

5790A: |240 µV/V|, Fluke A55-3V/Keithley 2182A: |670 µV/V|. The results of above study are portrayed in Figures 8 and 9.

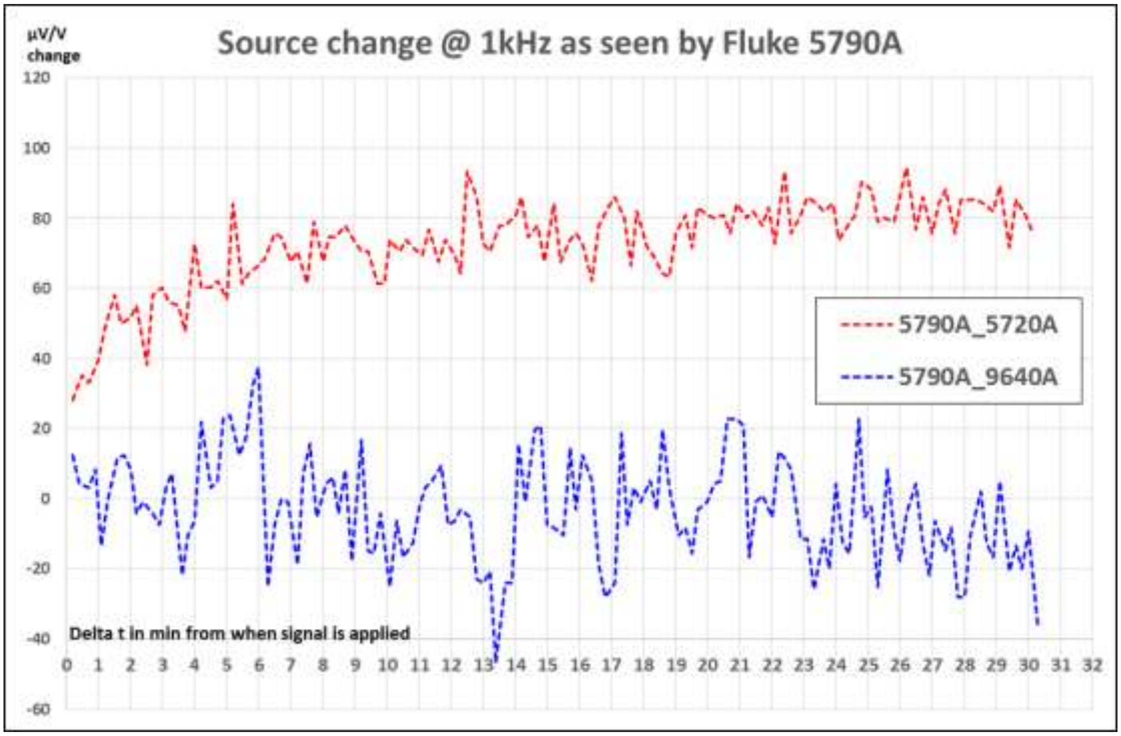

Figure 8. Source variation as seen by the AC Voltmeter.

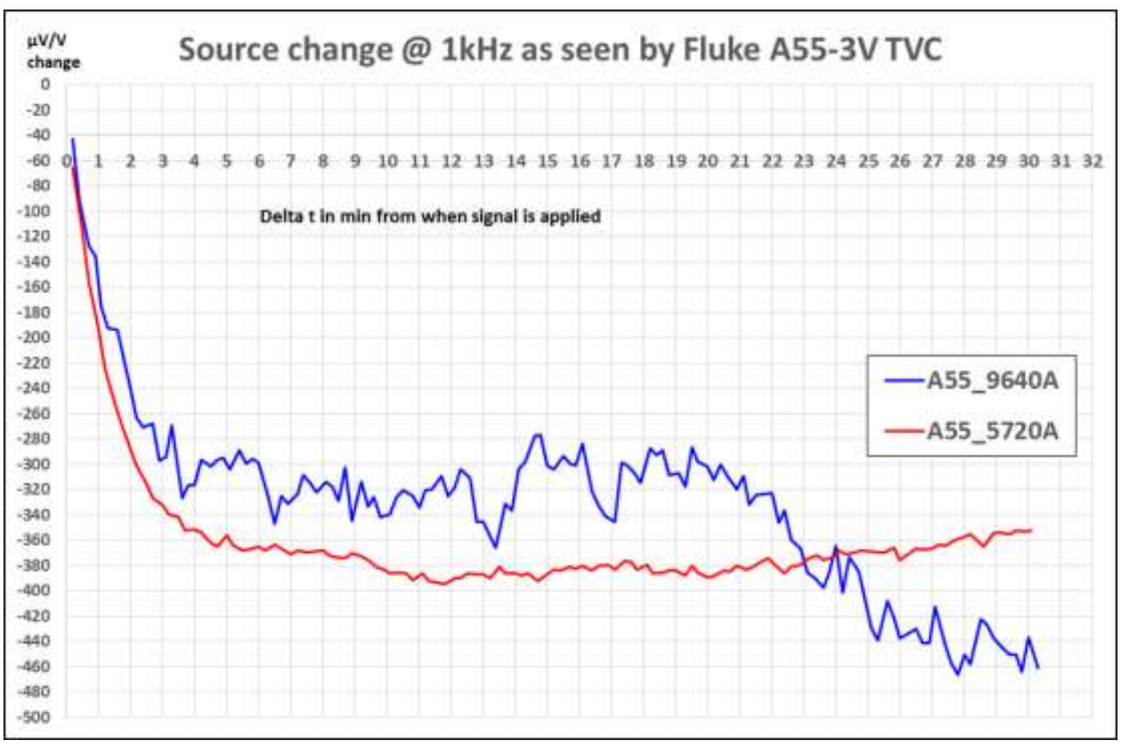

Figure 9. Source variation as seen by the TVC/Keithley 2182A.

Figure 10 adds more insight to the stability of the source at the critical for the process reference signal at 1 kHz. Historically, the 1 kHz was chosen as reference frequency because of the exceptional stability of the Fluke 5720A. The graph shows that the 9640A source 1 kHz is comparable to its 10 Hz stability.

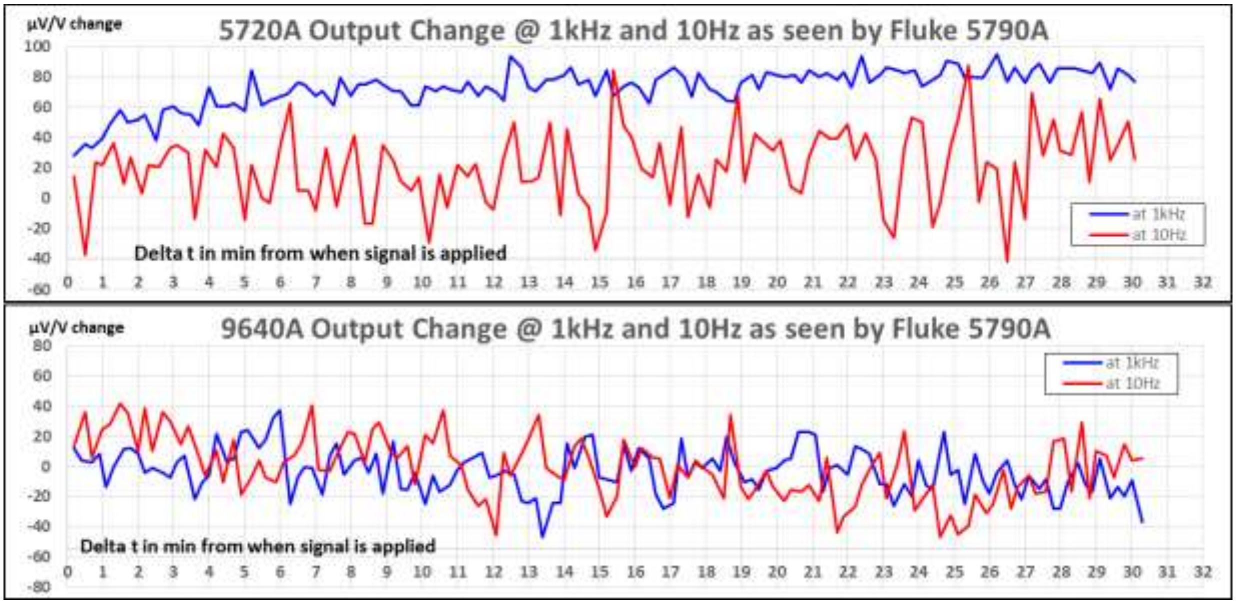

Figure 10. Graphical comparison of 10 Hz to 1 kHz on both sources.

The analysis of the new source reproducibility relative to the 30 MHz process source identified a gap in performance of the new source. Based on these results the following two possible reasons were suspect but not investigated and are only listed here as information.

8.2. The AC Voltmeter is not Stable

Two different meters were used in the development process. The first one was a Fluke 5790A with prototype 50 MHz wideband input module. The device appeared to work as normal 5790A, with the exception that the firmware was not modified to the new prototype hardware. The second one was a Fluke 5790B prototype device, which in its nature is an incomplete product. This was not further investigated after the findings about the source stability.

8.3. Software Induced

The software was radically changed to use a different command protocol for the Fluke 9640A vs. the Fluke 5720A. In addition, the software was updated to utilize new programming features in the MET/CAL software environment. This was not further investigated after the findings about the source stability.

In conclusion, the choice of the source, the 9640A is a really good RF signal generator, but not adequate for our process. It is performing satisfactory within its performance characteristics as concluded from the statistics of the measurements. Its absolute amplitude accuracy is specified as: 0.266% at 3 V @ 1 kHz. Our reproducibility study showed that it is performing at 0.024% ($^1/_{10}$ of specifications). The use of Fluke 9640A was abandoned and at this time a prototype Fluke 530A with 50 MHz option became available and was put in its place.

9. Measurement Results using Fluke 5730A 50 MHz Wideband Source.

Similar to the 30 MHz wideband, the prototype 5730A 50 MHz source had exceptional stability needed for the project extended capability. Additional sources of variation were uncovered and resolved such as:

- Input/output relays of prototype devices were not reproducible.
- AC Voltmeter initial firmware causing noisy measurements at low frequency (< 50 Hz).
- GR Tee reproducibility.

The reproducibility of EL 1100 TVC as well as its extended response beyond 30 MHz as expected met the previously set validation criteria, as shown in Figure 11.

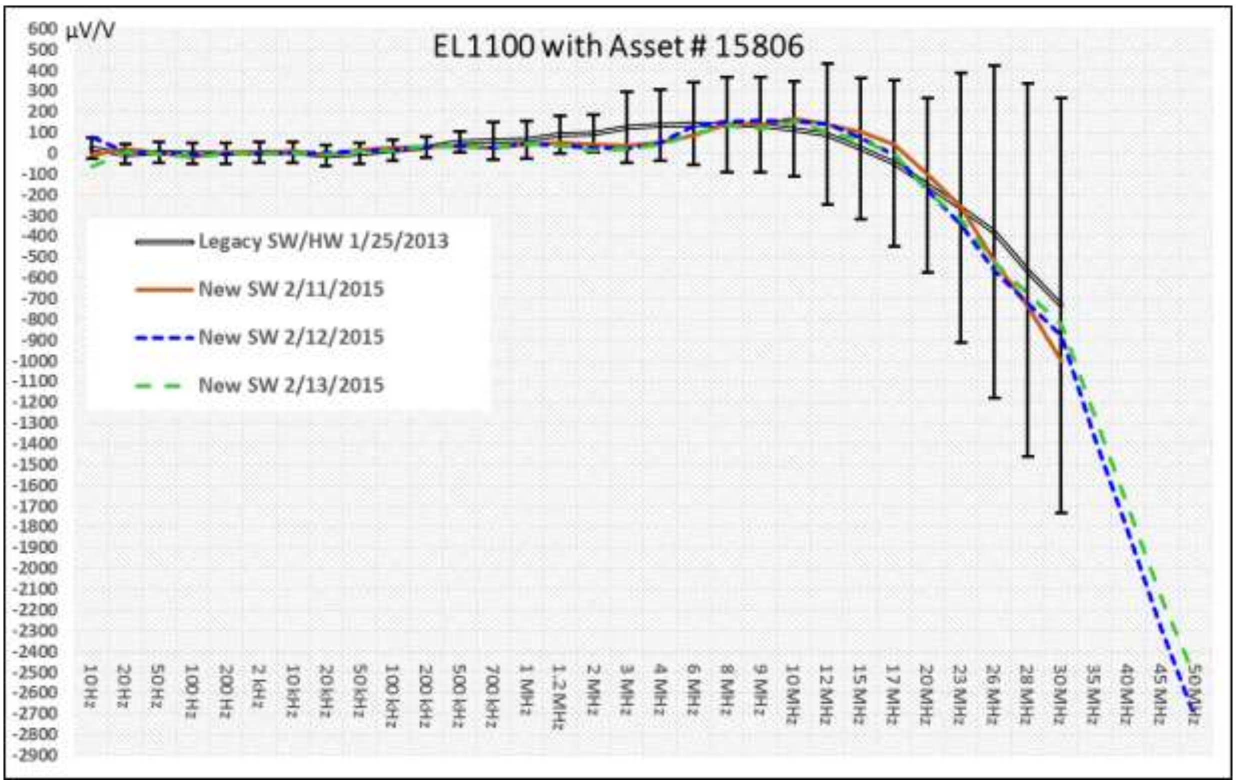

Figure 11. TVC measurement reproducibility when using Fluke 5730A wideband source.

Satisfactory results were observed in the attenuators flatness calibration process. Shown in Figure 12 are flatness calibration for JFW 10 dB attenuator including multiple calibrations to 50 MHz, as well as historical 30 MHz calibrations dating from 2010. The new system is reproducible and extended flatness response beyond 30 MHz is a logical projection of the flatness response – see Figure 12 for details.

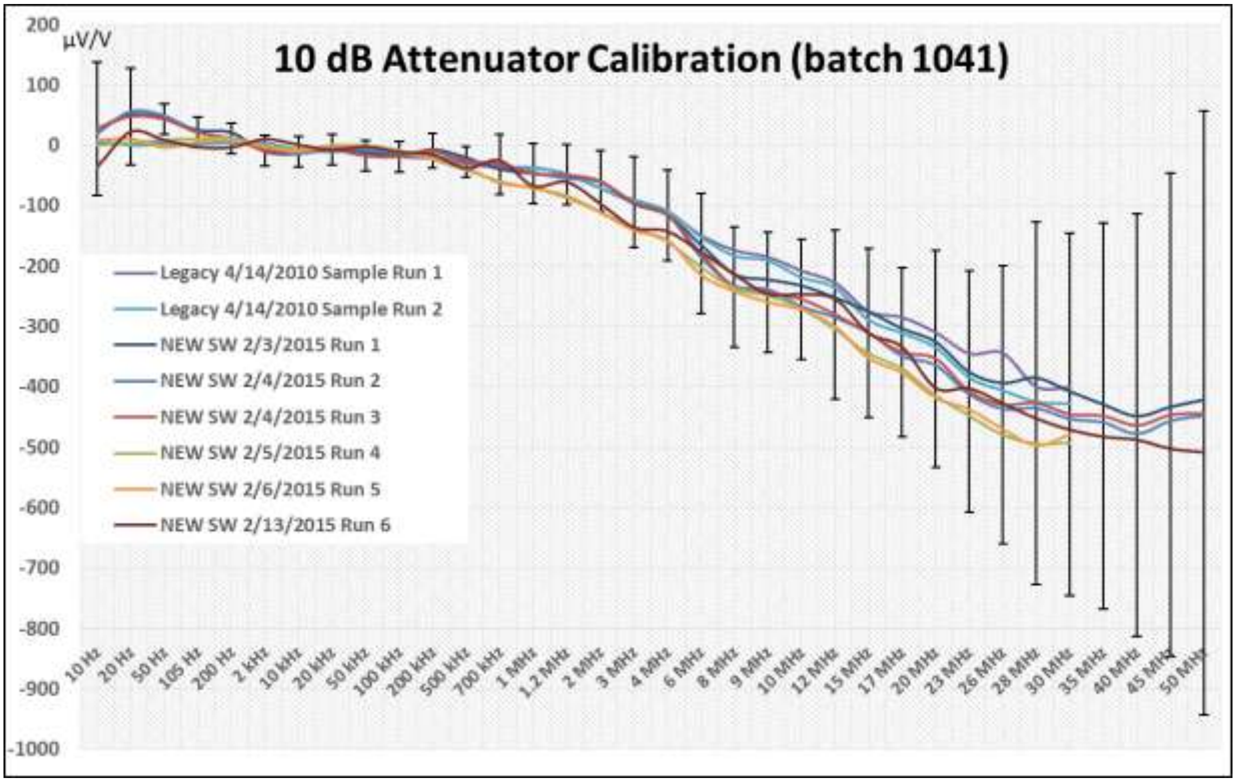

Figure 12. Flatness calibration reproducibility of JFW 10 dB attenuator.

10. REF OUT Capability

The addition of 50 MHz measurement capability for the product provided the framework for absolute power measurement as function of voltage. The defined customer requirements for this feature is to provide power accuracy specifications of 0.46% (0.23% voltage). This new requirement exceeded the projected flatness specification of 0.6%. The initial strategy for metrological traceability was to derive power from flatness at 223.607 mV (1mW). The assumption was that going from voltage to power domain was simple conversation of $P = \frac{V^2}{R}$, where R is assumed to by nominal of 50 Ω, given the fact that through all steps in the flatness system calibration we stay as close as possible to 50 Ω match. The validation strategy was to verify that calibrated Fluke Calibration 5790B can measure REF OUT of various power meters within its published specifications relative to absolute measurements of dedicated 0 dBm power reference system (Tegam 1830A with Keysight 478A Option H76). The strategy was carried as described above and the validation of results (Table 1) was evident for unsatisfactory results.

REF OUT->	***HP 436A***	***HP E4419A***
5790B measurement	***0.9861 mW***	***0.9885 mW***
TG/Sensor measurement	***0.9957 mW***	***0.9986 mW***
Product Error relative to TG/Sensor [%]	***-0.96%***	***-1.01%***

Table 1. Validation Fluke 5790B absolute power measurement results.

Analysis of the system revealed that the error is caused by impedance mismatch and specifically the product impedance change between 1 kHz and 50 MHz, where the flatness measurement is established. Measurements of the product and its dedicated 0 dBm cables revealed that they are far from perfect. Figure 13 shows impedance from 100 kHz to 50 MHz.

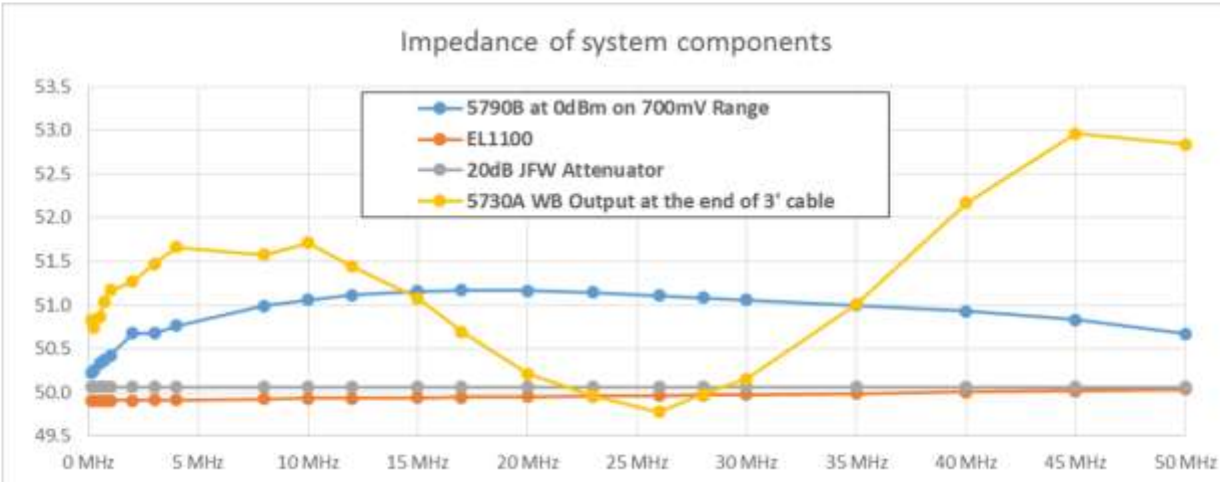

Figure 13. Impedance of the product and components of flatness calibration.

The failure of the Initial Strategy method instilled doubt in our flatness measurements and specifically in the EL1100 calibration (a three step process starting with 600 Ω TVC). A confirmation of our results for flatness calibration was needed. A 50 Ω TVC used in this process was sent to Physikalisch-Technische Bundesanstalt (PTB) for calibration. PTB was the only NMI that had this capability, uncertainty and could perform this calibration on short notice. Figure 14 illustrates the results of this informal proficiency test (PT) and confirmed our confidence in our calibration process with a very good agreement of the measurements.

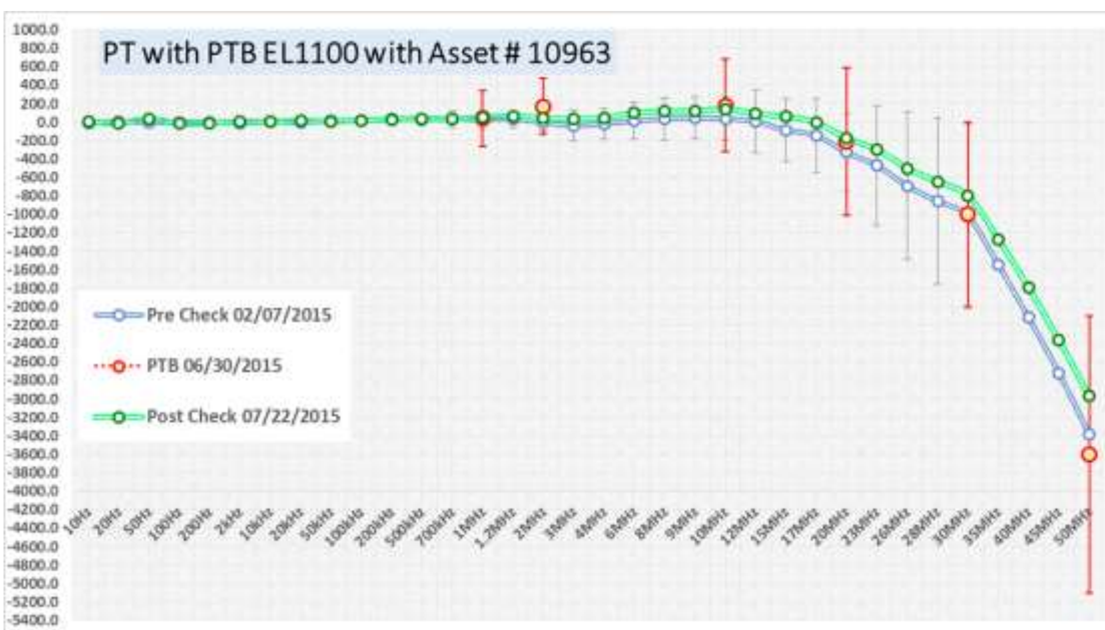

Figure 14. EL 1100 PT with PTB.

The initial strategy for absolute power traceability failed and was replaced with a more robust method. The new method is based on a 0dBm characterized source. The source is selected to have Z_O close to 50 Ω as to minimize impedance mismatch errors. The source is characterized using RF power measuring system (two systems were used during the project: Tegam 1830A/Keysight 478A H76 & Tegam 1830A/Tegam M1130A). As with any characterization the characterization interval is a function of the statistically evaluated stability. Our initially chosen source was Fluke 5730A with prototype 50 MHz wideband option with a 20 dB attenuator on the output. The attenuator was chosen based on its impedance properties and provided exceptional impedance match. Source was expected to be stable for 1 month and re-characterized monthly. The allocated stability of this source was expected to be within 0.1% between characterizations. Long term stability study was conducted over 45 days to determine validity of the chosen interval. The graphical evaluation of the stability shows a sudden shift of 0.17% - Figure 15. This shift was considered significant to the level of uncertainty required by the system. Based on the study there is no justification that the source can be used with monthly characterizations. There are other options to ensure the integrity of the source during calibration: Characterize before use with the coaxial RF power standard… or utilization of check standard to ensure stability. Analysis of data for the calibrator used in this study revealed that the source signal to the attenuator is adequately stable, but the connection reproducibility caused the sudden shift.

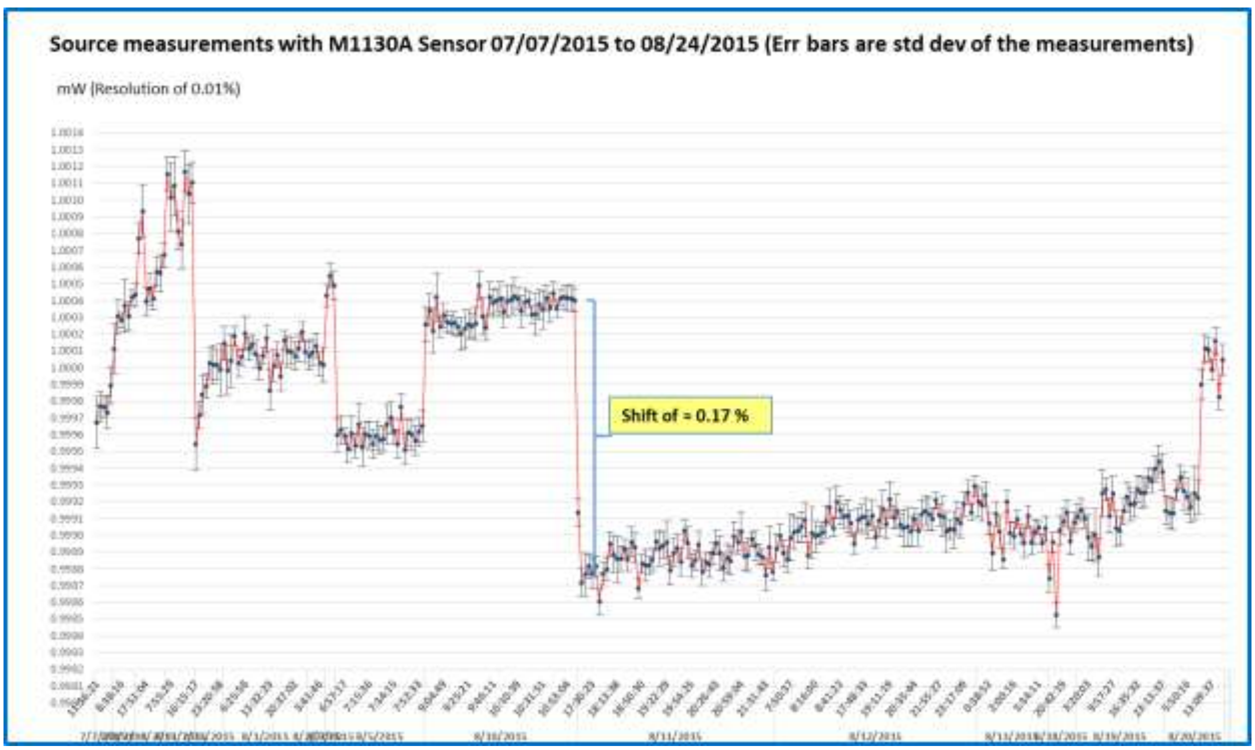

Figure 15. Stability study for a 0 dBm source (Fluke 5730A with 20 dB attenuator).

11. Additional Product Improvements

When the Fluke 5790A was first introduced only limited testing beyond a single amplitude in a range was performed. The addition of a 4 dB attenuator to the attenuator set enabled linearity test capability. A large population of 5790B devices were tested and the high correlation in the product empowered the firmware group to incorporate a common downscale linearity correction. The following two graphs show the state of the linearity prior and after the firmware corrections were added.

Figure 15. Flatness linearity of the product.

12. Summary and Conclusions

It is challenging to validate a process without a standard to compare to. Graphical evaluation of a process proved to be a valuable tool. Designing the software to allow access to individual samples in a repeatability loop can give you the level of detail needed to troubleshoot complex problems. Going from voltage domain to power domain was more challenging than anticipated.

The calibration of the EL 1100 TVC at PTB provided the needed confidence in the methods to extend calibration to 50 MHz. The collaboration between engineering and metrology during design of a product is essential to ensure that product meets specifications and provide statistical confidence in the specifications.

13. References

[1] Fluke 5790A – Service manual January 1992

[2] N. Faulkner and David Deaver, “Verifying the Wideband Input of an AC Measurement Standard”, NCSLI Workshop & Symposium, 2006.

Available on the Fluke Calibration web site:

http://us.flukecal.com/category/literature-type/articles-and-education