Calibration and Traceability of a Fully Automatic AC Measurement Standard

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ABSTRACT

A recently introduced AC Measurement Standard (Figure 1) was designed primarily to support calibration of the latest Multifunction Calibrators. In order to have acceptable test uncertainty ratios, it is necessary for this standard to have long term specifications of the order of 25 ppm absolute uncertainty.

This paper describes the calibration system designed for use in its production and maintenance. It is based upon a Solid State Thermal Transfer Standard, the Fluke 792A and other support equipment. The system calibrates the AC Measurement Standard at 75 points and then verifies over 200 points between dc and 1 MHz and between 700 µV and 1000V. Similarly, it calibrates and verifies the 30 MHz option. Subsequent calibrations can be performed with far fewer points. The paper describes how calibration and verification can be performed at the manufacturer's factory, at independent service centers, and at the customer's facility.

Figure 1. Fluke 5790A AC Measurement Standard

INTRODUCTION

Each improved working instrument generally requires improvements in the unbroken traceability chain to a recognized National Laboratory. Advances in ac measuring instruments create the need for calibrators with tighter specifications, which must themselves be calibrated. Some of the newer calibrators contain internal reference standards which simplify the adjustment and verification process.[1] However, for users who desire to have verification with independent instrumentation or for users whose calibrators do not contain internal reference standards, a new class of instruments known as AC Measurement Standards are simplifying some of the more tedious portions of this calibration and verification process.

The calibration of these AC Measurement Standards needs to be accomplished in a production environment with speed, accuracy, and a minimum of labor. This necessitates an automated test system. The error budget does not allow the required precision to be maintained with traditional 3:1 or 4:1 test uncertainty ratios to a National Standard but must be accomplished by a statistical treatment of the uncertainties to a the National Laboratory.

PROJECT MANAGEMENT

Traditionally, calibration system design for an instrument such as the new AC Measurement Standard (UUT) has begun when its definition and specifications have become firm so the requirements of the calibration system can be clearly defined. In a product with development phases described as Breadboard Phase, Prototype Phase, Design Phase, Pre-production Phase, and First Production, the development of the method of calibration has generally started near the end of Design Phase. The development of the calibration system for the new AC Measurement Standard, however, began simultaneously with the development of the product itself. This afforded a number of significant advantages including:

1. Problems in the calibration system could be identified sooner.
2. Traceability through the company Standards Lab and to the National Laboratory could be started earlier since it often takes considerable time to establish tighter uncertainties through these labs.
3. The calibration system could be used in the development of the product itself.
4. Performance goals could be set for the phases of the product development schedule.
5. Calibration could be included in overall error analysis used for determining instrument specifications.
6. Internal hardware and software of the product being developed could be modified during development to simplify the calibration or reduce the uncertainties of the calibration. This becomes quite difficult to do in the latter phases of the product development.

CALIBRATION

The main inputs (Input 1 and Input 2) of the AC Measurement Standard (UUT) are specified for ac-dc difference accuracy from 70 mV to 1000V and for absolute ac accuracy from 0.7 mV to 1000V. Internally, each range has a dc gain constant and an ac multiplier for each of the calibration frequencies in that range. The internal architecture of the AC Measurement Standard is described in considerably more detail in [2].

DC CALIBRATION

The calibration of the dc constants is performed with the calibration test station configured as shown in Figure 2. DC of each polarity is applied at one level for each range. Ten UUT readings are taken, averaged and a dc gain constant and a dc offset constant are calculated for the range. A Multifunction Calibrator is used as the dc source. Its dc specifications are enhanced by a characterization process using a 10V DC Standard and a Reference Divider. SPC methods are used to determine the period between the characterizations.

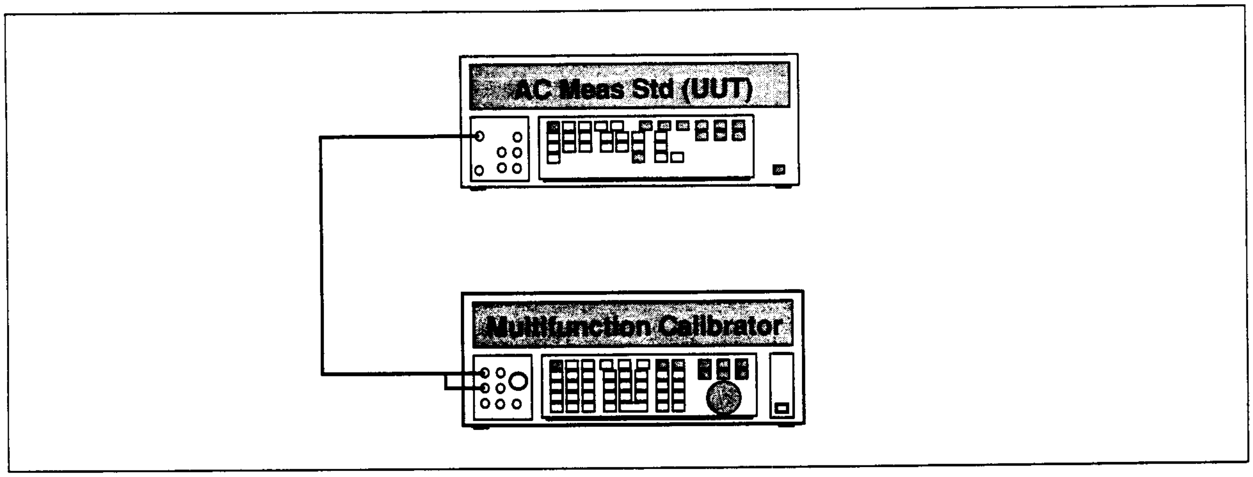


Figure 2. DC Calibration Configuration

AC CALIBRATION

Conceptually, the calibration of the ac multiplier for each frequency is straightforward. During calibration, the UUT prompts the user on the front panel or through the remote interface with the nominal voltage and frequency of each required calibration point. The user, or calibration system, applies the signal and then enters the exact value of the applied voltage into the UUT. Knowing the exact value accurately, however, is not so straightforward. The calibration system, configured for ac, is shown in Figure 3. The Transfer Standard [3] is the reference for ac-dc difference [4] and the UUT, previously calibrated for dc, is used to measure the level of the applied dc. The UUT has been designed to be able to take readings and present them on the display and to the remote interfaces during the portions of the calibration sequence when the UUT is prompting for the voltage and frequency of the next calibration point. ac and dual polarity dc are applied at each calibration point to determine the ac-dc difference and the absolute ac voltage.

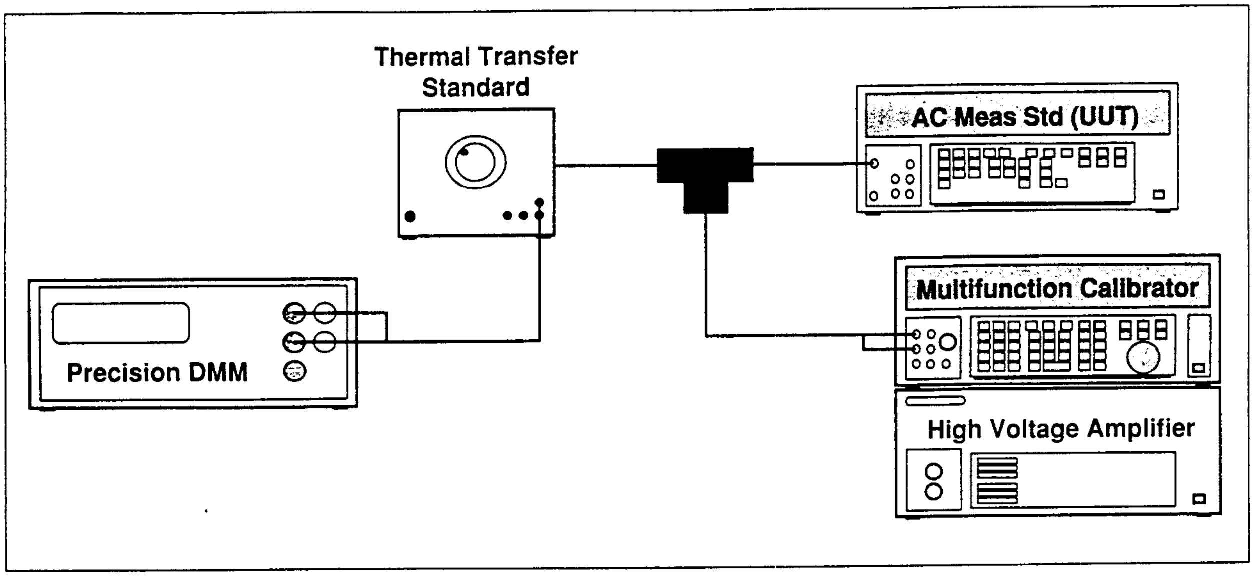


Figure 3. AC Calibration Configuration

Though the characterized Multifunction Calibrator is capable of providing accurate dc signals, there can be significant resistive loss between the output of the source and the reference point of the Tee between the Transfer Standard and the UUT due to the input impedance of the Transfer Standard which can be as low as 400 ohms. Accurate dc could be applied to the reference point if an additional sense connection were to be made between the source and the reference point of the Tee. This has some disadvantages, however; primarily the additional capacitive load that must be driven for ac measurements if it isn't removed for ac signals and the problem that external sensing is not available for all voltage levels. Instead, it was decided to use the dc readings of the UUT since it is calibrated for dc just prior to ac calibration. The sequence shown in Figure 4 is used for manually calibrating the AC Measurement Standard (UUT):

Step	Applied Signal	Xfer Std Reading	UUT Reading
1	+dc	dc_r^+	dc_u^+
2	–dc	dc_r^-	dc_u^-
3	ac	ac	

Figure 4. Manual AC Calibration Sequence

The readings from the Transfer Standard are used to calculate the ac-dc difference of the incoming signal. By using a Transfer Standard that is inherently linear, the ac signal does not have to be perfectly nulled to the same value as the average of the dc readings speeding the calibration considerably.

$$\text{Source AC-DC} = \left[\frac{dc_r - ac}{dc_r}\right] \bullet 10^6 - \text{X Corr} \quad \text{(ppm)}$$

$$\text{where:} \quad dc_r = \frac{|dc_r^+| + |dc_r^-|}{2}$$

and X Corr is the assigned ac-dc difference of the Transfer Standard for that voltage and frequency.

The dc readings from the UUT can then be used to calculate the applied ac voltage.

$$\begin{aligned} \text{Vac} &= dc_u \left(1 - \text{Source AC-DC} / 10^6\right) \\ &= dc_u \left(\frac{ac_r}{dc_r} + \frac{\text{X Corr}}{10^6}\right) \end{aligned}$$

$$\text{where:} \quad dc_u = \frac{|dc_u^+| + |dc_u^-|}{2}$$

Once the ac voltage is calculated, it is keyed into the UUT and the calibration is initiated for that point. Note that three sets of readings are required for each point.

The Automated Calibration Station takes readings in a slightly different sequence as shown in Figure 5.

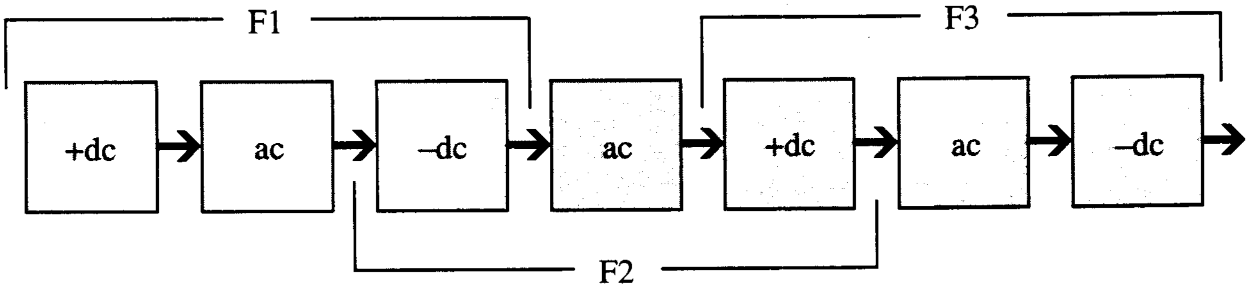
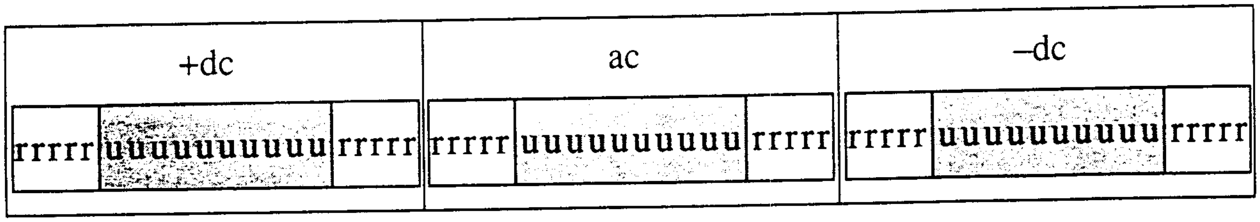


Figure 5. Automated AC System Calibration Sequence

This interleaved sequence has the advantage of having nearly a third fewer readings for full ac-dc transfers. It has the disadvantage of not being able to calculate the ac voltage while the ac voltage is applied; the next set of dc readings must be taken first. However, since the development of the Calibration System and the UUT was taking place simultaneously, this difficulty was overcome by allowing the UUT to be calibrated while the ac was applied, and then after the next dc measurements were taken, the instrument is told the exact value of the ac which was applied during the calibration. This does not change the value of the applied ac, it only allows the calculation of its value to be delayed. Developing the instrument and its calibration system simultaneously also resulted in the ability of the UUT to continue to make ac and dc measurements during calibration.

Each ac or dc reading is actually an average of ten UUT or Transfer Standard readings taken in the sequence shown in Figure 6.



where: rrrrr represents a Transfer Standard reading (Reference) and

uuuuuuuuuu represents an AC Measurement Standard reading (UUT).

Figure 6. Averaging Method for Automated AC Calibration

Though we are averaging quite a few readings, the symmetry of this technique provides a first order compensation for thermal drift. Note that for each set of readings, the Reference readings and the UUT readings are centered about the same point in time. In addition, the dc readings are centered in time at the same point in time as the center of the ac readings. [5]

MILLIVOLTS CALIBRATION

For the three lowest ranges (22 mV, 7 mV, and 2.2 mV), a bootstrap technique is used for calibration as shown in Figure 7.

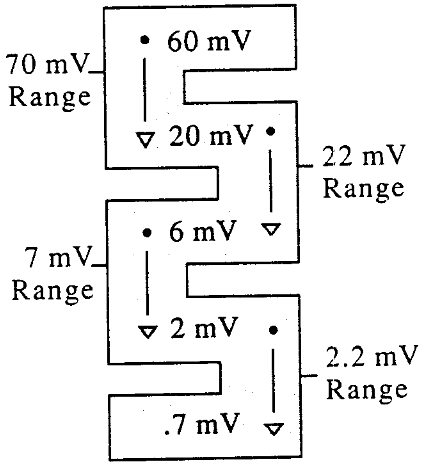


Figure 7. Bootstrap Calibration Levels

The 70 mV range is calibrated at 60 mV at six frequencies from 10 Hz to 1 MHz using the method previously described, with the Transfer Standard as the reference. To calibrate the 22 mV range, 20 mV at each frequency is applied to the UUT. Readings are taken on the 70 mV range and the measured values are used to calibrate the 22 mV range. Then measurements are made at 6 mV on the 22 mV range to calibrate the 7 mV range. Similarly, 2 mV is measured on the 7 mV range to calibrate the 2.2 mV range.

PERIODIC CALIBRATION

Seventy ac points are initially required to calibrate the UUT. Internally, corrections are interpolated between the linear, square law, and a polynomial fit. Subsequently, unless a major repair is made, it is necessary to calibrate only 14 points to compensate for shifts in the UUT during the calibration interval.

WIDEBAND CALIBRATION

Calibration of the wideband option is performed by measuring the absolute gains of the wideband circuitry at 1 kHz, then its flatness with respect to 1 kHz. The wideband calibration will be described in a subsequent paper.

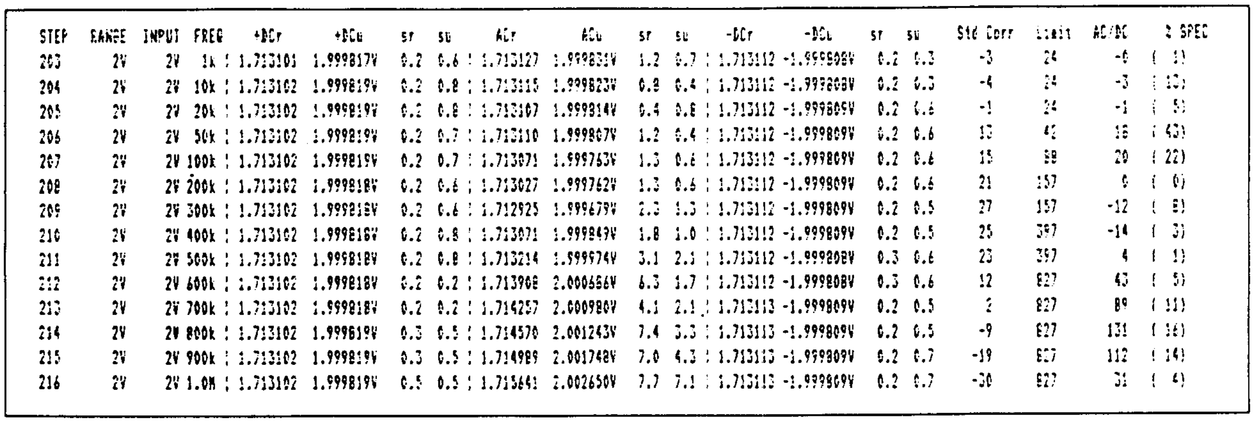
AC VERIFICATION

The automated calibration station is used to verify the results of the calibration. During development of the AC Measurement Standard, more points were verified than will be checked during production to establish confidence in the calibration process. 464 points were verified early in Design Phase for each of the nine instruments. Later, Design Phase instruments and Pre-production instruments were verified at 392 points. Production verification is currently at 237 points.

Verification of the ac-dc difference specifications is performed by measuring the ac-dc difference of the source with both the Transfer Standard and the UUT as described in Figures 4 through 6. In this case, ac readings are taken by the UUT instead of performing a calibration. The ac-dc error is the difference between the two ac-dc difference readings.

$$\begin{aligned}\text{AC-DC Error} &= \text{Meas AC-DC}_u - \text{Meas AC-DC}_r \\ &= \left(\left[\frac{dc_u - ac_u}{dc_u} \right] - \left[\frac{dc_r - ac_r}{dc_r} \right] \right) \cdot 10^6 + \text{X Corr} \quad \text{(ppm)}\end{aligned}$$

During a verification, a printer at the Automated Calibration Station records the averaged readings of the Transfer Standard (r) and the UUT (u) for each test point. The sample standard deviation is calculated for each of the readings and is used to characterize the performance of the station and, if they are uncharacteristically high, to identify suspect readings. A small portion of the printout is shown in Figure 8. Note that each +dc and –dc reading is used for two steps, as we are using the interleaved sequence of readings for verification as well. A reading that exceeds the test limit is flagged to the right of the % SPEC column for easy identification as a failure.



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STEP RANGE INPUT FREQ   +DCr     +DCu      sr  su    ACr      ACu      sr  su    -DCr     -DCu      sr  su  Std Corr Limit AC/DC  % SPEC
203    2V    2V   1k ¦ 1.713101 1.999817V 0.2 0.6 ¦ 1.713127 1.999831V 1.2 0.7 ¦ 1.713112 -1.999808V 0.2 0.3    -3     24    -6   (  1)
204    2V    2V  10k ¦ 1.713102 1.999819V 0.2 0.8 ¦ 1.713115 1.999823V 0.8 0.4 ¦ 1.713112 -1.999808V 0.2 0.3    -4     24    -3   ( 10)
205    2V    2V  20k ¦ 1.713102 1.999819V 0.2 0.8 ¦ 1.713107 1.999814V 0.4 0.8 ¦ 1.713112 -1.999809V 0.2 0.6    -1     24    -1   (  5)
206    2V    2V  50k ¦ 1.713102 1.999819V 0.2 0.7 ¦ 1.713110 1.999807V 1.2 0.4 ¦ 1.713112 -1.999809V 0.2 0.6    13     42    16   ( 43)
207    2V    2V 100k ¦ 1.713102 1.999819V 0.2 0.7 ¦ 1.713071 1.999763V 1.3 0.6 ¦ 1.713112 -1.999809V 0.2 0.6    15     58    20   ( 22)
208    2V    2V 200k ¦ 1.713102 1.999818V 0.2 0.6 ¦ 1.713027 1.999762V 1.3 0.6 ¦ 1.713112 -1.999809V 0.2 0.6    21    157     0   (  0)
209    2V    2V 300k ¦ 1.713102 1.999818V 0.2 0.6 ¦ 1.712925 1.999679V 2.3 1.3 ¦ 1.713112 -1.999809V 0.2 0.5    27    157   -12   (  8)
210    2V    2V 400k ¦ 1.713102 1.999816V 0.2 0.8 ¦ 1.713071 1.999849V 1.8 1.0 ¦ 1.713112 -1.999809V 0.2 0.5    25    397   -14   (  3)
211    2V    2V 500k ¦ 1.713102 1.999818V 0.2 0.8 ¦ 1.713214 1.999974V 3.1 2.1 ¦ 1.713112 -1.999808V 0.3 0.6    23    397     4   (  1)
212    2V    2V 600k ¦ 1.713102 1.999818V 0.2 0.2 ¦ 1.713908 2.000666V 6.3 1.7 ¦ 1.713112 -1.999808V 0.3 0.6    12    827    43   (  5)
213    2V    2V 700k ¦ 1.713102 1.999818V 0.2 0.2 ¦ 1.714257 2.000980V 4.1 2.1 ¦ 1.713113 -1.999809V 0.2 0.5     2    827    89   ( 11)
214    2V    2V 800k ¦ 1.713102 1.999819V 0.3 0.5 ¦ 1.714570 2.001243V 7.4 3.3 ¦ 1.713113 -1.999809V 0.2 0.5    -9    827   131   ( 16)
215    2V    2V 900k ¦ 1.713102 1.999819V 0.3 0.5 ¦ 1.714989 2.001748V 7.0 4.3 ¦ 1.713113 -1.999809V 0.2 0.7   -19    827   112   ( 14)
216    2V    2V 1.0M ¦ 1.713102 1.999819V 0.5 0.5 ¦ 1.715641 2.002650V 7.7 7.1 ¦ 1.713113 -1.999809V 0.2 0.7   -30    827    31   (  4)
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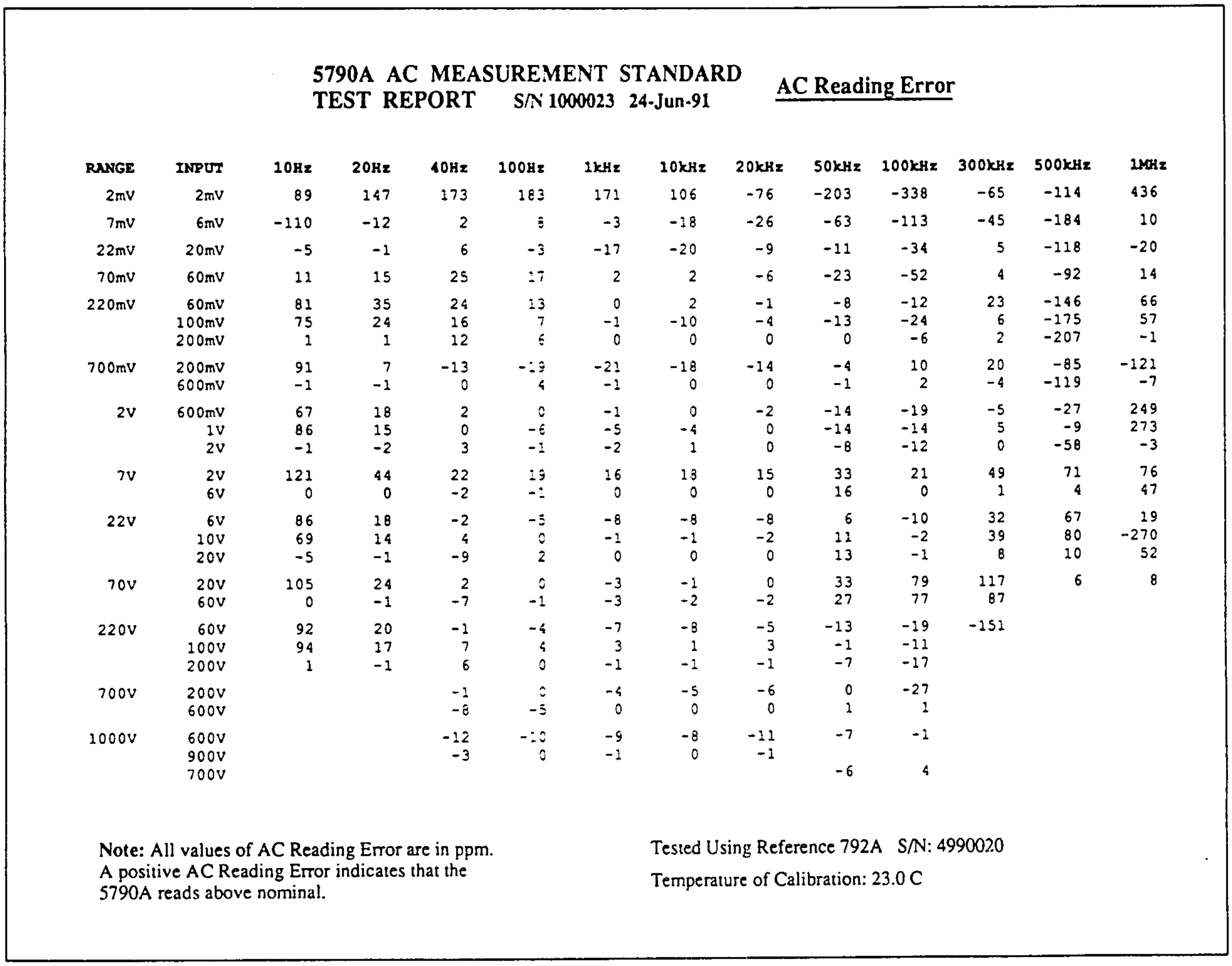
Figure 8. A Portion of the AC Verification Printout

The results of verification are summarized in a calibration report (Figures 9a and 9b), which is shipped with the customer's instrument. It contains a chart for absolute ac errors and a chart for ac-dc errors.



5790A AC MEASUREMENT STANDARD
TEST REPORT S/N 1000023 24-Jun-91

AC Reading Error

RANGE	INPUT	10Hz	20Hz	40Hz	100Hz	1kHz	10kHz	20kHz	50kHz	100kHz	300kHz	500kHz	1MHz
2mV	2mV	89	147	173	183	171	106	-76	-203	-338	-65	-114	436
7mV	6mV	-110	-12	2	5	-3	-18	-26	-63	-113	-45	-184	10
22mV	20mV	-5	-1	6	-3	-17	-20	-9	-11	-34	5	-118	-20
70mV	60mV	11	15	25	17	2	2	-6	-23	-52	4	-92	14
220mV	60mV	81	35	24	13	0	2	-1	-8	-12	23	-146	66
	100mV	75	24	16	7	-1	-10	-4	-13	-24	6	-175	57
	200mV	1	1	12	6	0	0	0	0	-6	2	-207	-1
700mV	200mV	91	7	-13	-19	-21	-18	-14	-4	10	20	-85	-121
	600mV	-1	-1	0	4	-1	0	0	-1	2	-4	-119	-7
2V	600mV	67	18	2	0	-1	0	-2	-14	-19	-5	-27	249
	1V	86	15	0	-6	-5	-4	0	-14	-14	5	-9	273
	2V	-1	-2	3	-1	-2	1	0	-8	-12	0	-58	-3
7V	2V	121	44	22	19	16	18	15	33	21	49	71	76
	6V	0	0	-2	-1	0	0	0	16	0	1	4	47
22V	6V	86	18	-2	-5	-8	-8	-8	6	-10	32	67	19
	10V	69	14	4	0	-1	-1	-2	11	-2	39	80	-270
	20V	-5	-1	-9	2	0	0	0	13	-1	8	10	52
70V	20V	105	24	2	0	-3	-1	0	33	79	117	6	8
	60V	0	-1	-7	-1	-3	-2	-2	27	77	87		
220V	60V	92	20	-1	-4	-7	-8	-5	-13	-19	-151		
	100V	94	17	7	4	3	1	3	-1	-11			
	200V	1	-1	6	0	-1	-1	-1	-7	-17			
700V	200V			-1	0	-4	-5	-6	0	-27			
	600V			-8	-5	0	0	0	1	1			
1000V	600V			-12	-10	-9	-8	-11	-7	-1			
	900V			-3	0	-1	0	-1					
	700V								-6	4			

Note: All values of AC Reading Error are in ppm.
A positive AC Reading Error indicates that the
5790A reads above nominal.

Tested Using Reference 792A S/N: 4990020

Temperature of Calibration: 23.0 C

Figure 9a. AC Reading Error Calibration Report

5790A AC MEASUREMENT STANDARD
TEST REPORT S/N 1000023 24-Jun-91

AC-DC Difference

RANGE	INPUT	10Hz	20Hz	40Hz	100Hz	1kHz	10kHz	20kHz	50kHz	100kHz	300kHz	500kHz	1MHz
220mV	60mV	-73	-26	-16	-5	8	6	9	17	21	-15	154	-58
	100mV	-73	-21	-13	-5	3	12	7	16	27	-3	178	-54
	200mV	-1	-2	-12	-7	-1	-1	0	0	5	-2	206	1
700mV	200mV	-98	-14	6	12	14	11	7	-2	-17	-27	78	114
	600mV	1	1	0	-4	1	0	0	1	-2	4	119	7
2V	600mV	-65	-16	0	2	3	3	4	16	22	8	30	-247
	1V	-85	-14	0	6	5	4	0	14	14	-5	9	-273
	2V	0	1	-3	1	1	-1	0	7	12	0	58	3
7V	2V	-99	-22	0	2	6	4	6	-11	1	-27	-49	-54
	6V	0	0	1	0	0	0	0	-16	0	-2	-4	-48
22V	6V	-86	-18	2	5	8	9	8	-6	10	-32	-67	-19
	10V	-66	-10	0	3	4	4	6	-8	6	-36	-76	273
	20V	5	1	9	-1	0	0	0	-12	1	-7	-10	-51
70V	20V	-102	-20	0	2	6	5	4	-29	-76	-114	-2	-5
	60V	-2	-1	5	-1	1	0	0	-30	-80	-90		
220V	60V	-92	-20	1	4	8	8	5	14	19	152		
	100V	-94	-16	-7	-4	-3	-1	-3	1	11			
	200V	-2	0	-7	-1	0	0	0	6	16			
700V	200V			9	8	12	13	14	8	35			
	600V			8	4	0	0	0	-1	-1			
1000V	600V			13	11	10	9	12	7	1			
	900V			5	2	3	2	3					
	700V								8	-3			

Note: All values of ac-dc difference are in ppm.
A positive ac-dc difference indicates that more alternating
than direct voltage is required to produce the same reading.

Figure 9b. AC-DC Difference Calibration Report

ERROR ANALYSIS

In the error analysis, an attempt was made to identify as many of the error sources as possible and to separate them into random and systematic components. Some sources can contribute both systematic random errors. Once identified, the contribution from the various sources were reduced, if possible, and quantified for inclusion in the error analysis. Particular attention was paid to the elimination of as many of the systematic sources as possible.

RANDOM ERROR SOURCES

- Source Noise
- UUT Measurement Noise
- Transfer Standard Noise
- Standards Lab Transfers
- Temperature Variations
- Injected External Noise
- DC Source Error
- Short Term Drift and Low Frequency Noise

SYSTEMATIC ERROR SOURCES

- Standing Waves
- Ground Currents
- Injected External Noise
- Standards Lab Transfers
- Linearity – Transfer Standard
- Linearity – AC Measurement Standard

SYSTEMATIC ERROR SOURCES

STANDING WAVES: If calibration and verification are not taking place at the same reference point at which the instrument is specified. an error, quite significant at the higher frequencies, is introduced due to standing waves. The AC Measurement Standard has a considerably higher termination impedance than the source or the internal cable connecting the input to the measurement circuitry. Since the cables are considerably shorter than the wavelengths of the input frequency, the standing wave errors will be proportional to the square of the frequency and one of the significant terms will be proportional to the square of the cable length as well. This will cause the instrument to read high.

GROUND CURRENTS: The effect of ground currents were reduced in several ways:

1. Establishing a single earth ground reference point at the source.
2. Grounding the chassis of the test equipment and the UUT to the earth ground reference point.
3. Keeping the source cable short to reduce the common mode voltages.

EXTERNAL NOISE SOURCES: Because the AC Measurement Standards has RMS responding sensors with considerable bandwidth, external sources of noise can produce systematic as well as random errors. In particular, we found that some our low level measurements could be affected if we had some types of video display terminals too close to the calibration system. or if the system controller was not grounded to the common earth ground point.

SYSTEMATIC TRANSFER ERRORS FROM THE STANDARDS LAB: Because we are treating calibration as a statistically controlled process (SPC), points that show a mean significantly removed from desired come under scrutiny, even if they are well within specifications. As a result, we have been able to trace some of systematic error back into the Standards Lab.

LINEARITY – TRANSFER STANDARD: The ac-dc difference of the Transfer Standard has level-dependent error component. This error can be minimized by keeping the nominal voltages close to the traceable points of the Transfer Standard.

LINEARITY – UUT: The linearity of the UUT is also a factor. Linearity errors are minimized by nulling the reference DAC to the input signal fairly closely so the linearity of the measurements are dependent primarily on the DAC and not the linearity of the amplifiers or the solid state rms sensor. Careful attention was paid to the linearity of the lower ranges, as their linearity can be a major contributor to the errors of the bootstrap calibration used on those ranges.

RANDOM ERROR SOURCES

SOURCE NOISE: Source noise contributions were measured during development by filtering and attenuation. As a result, two techniques are being used to reduce the source noise:

1. Use of EXT GRD and an external strap from LO to the ground reference point to reduce the common mode signals generated by ac current returing to the source.
2. Internal transfers of the Multifunction Calibrator, used to enhance its accuracy, are turned off for ac since the accuracy of the AC Measurement Standard is dependent upon the accuracy of the Transfer Standard and not upon the accuracy of the ac source. This reduces the source noise by eliminating the small updates made to the output of the Calibrator as a result of these internal transfers.

AC MEASUREMENT STANDARD (UUT) INJECTED NOISE: The AC Measurement Standard has slight differences in input capacitance for the lower ranges when the internal measurement circuitry is switched between the external input and the internal reference. Though the difference is small and the deviations produced are well within the instrument specifications, they do contribute to the uncertainty of the Transfer Standard measurements. The effect is most noticeable at low levels and high frequency, where the source has a 50Ω output impedance. This does not cause any difficulty with the UUT measurements because it always loads the source with the same capacitance while it is looking at the input. To reduce the noise, Transfer Standard measurements are made with the UUT in External Trigger. In External Trigger, the UUT measurement circuitry is connected to the input so the Transfer Standard measurements will be taken with the same loading as the UUT measurements. Measurement noise for the UUT itself has been reduced through careful design of the instrument internally and by averaging readings, generally ten.

TRANSFER STANDARD NOISE MEASUREMENT: Transfer Standard noise has been reduced by using External Trigger for the UUT, paying careful attention to grounding, and by averaging readings, generally ten.

STANDARDS LAB TRANSFERS: For the factory calibration system, AC-DC Transfer Standards are calibrated monthly to reduce their uncertainty. Monitoring of these Transfer Standard units used for calibration and factory data on new Transfer Standards has allowed their specifications to be tightened in a number of areas. The factory units are held within considerably tighter limits though the error analysis for the AC Measurement Standard uses the published customer specifications for the Transfer Standard.

TEMPERATURE: Since the tightest specifications for the UUT are for a ±5°C temperature window, factory calibrations are made as close to the center point of 23°C to allow the user as much of the ±5°C window as possible. Factory calibrations are performed in a temperature stabilized room with ±1°C control.

EXTERNAL NOISE SOURCES: External noise sources can be a source of random noise as well as systematic noise. Electrical noise sources such as video display terminals are kept some distance, about 4 feet from the UUT. The location of the Automated Calibration Station is separated from the assembly areas and well away from the fabrication shops.

DC SOURCE ERRORS: The dc uncertainty of the Multifunction Calibrator can be reduced by characterizing the dc periodically using a 10V Reference Standard and a Reference Divider. SPC techniques are used to determine the frequency of the characterization.

SHORT TERM DRIFT AND LOW FREQUENCY NOISE: Short term drift and low frequency noise that are linear, or with a period long enough that their contribution during the measurement cycle can be considered linear, are reduced by interleaving Transfer Standard measurements with UUT measurements.

We have succeeded in identifying most sources of systematic error and reducing their effects. For the error analysis, the remaining error sources are considered to be random and independent, which allows their variances (calculated or measured to the same confidence level) to be added. The error analysis and measurements during the Pre-production run of instruments indicate that we should be able to maintain our goal of ±3 sigma limits to 80% of the customer specification for the production process.

RESULTS

The Automated Calibration Station has been used to characterize the Prototype, Design and Pre-production instruments. A modified system was used to conduct environmental testing for each of these phases. A number of design improvements were made as a result of the data collected during the environmental testing. During development, a scatter chart was developed to give a quick visual indication of the results. It is a plot of the ac-dc measurement error as a percentage of specification above 70 mV, and absolute ac error as a percentage of specification below 70 mV. Figure 10 is a scatter chart for a Design Phase instrument which is used for demonstrations and stability testing. It has been shipped to a number of locations throughout the US. The scatter plot shown is for a verification which was taken 4 months after its last calibration.

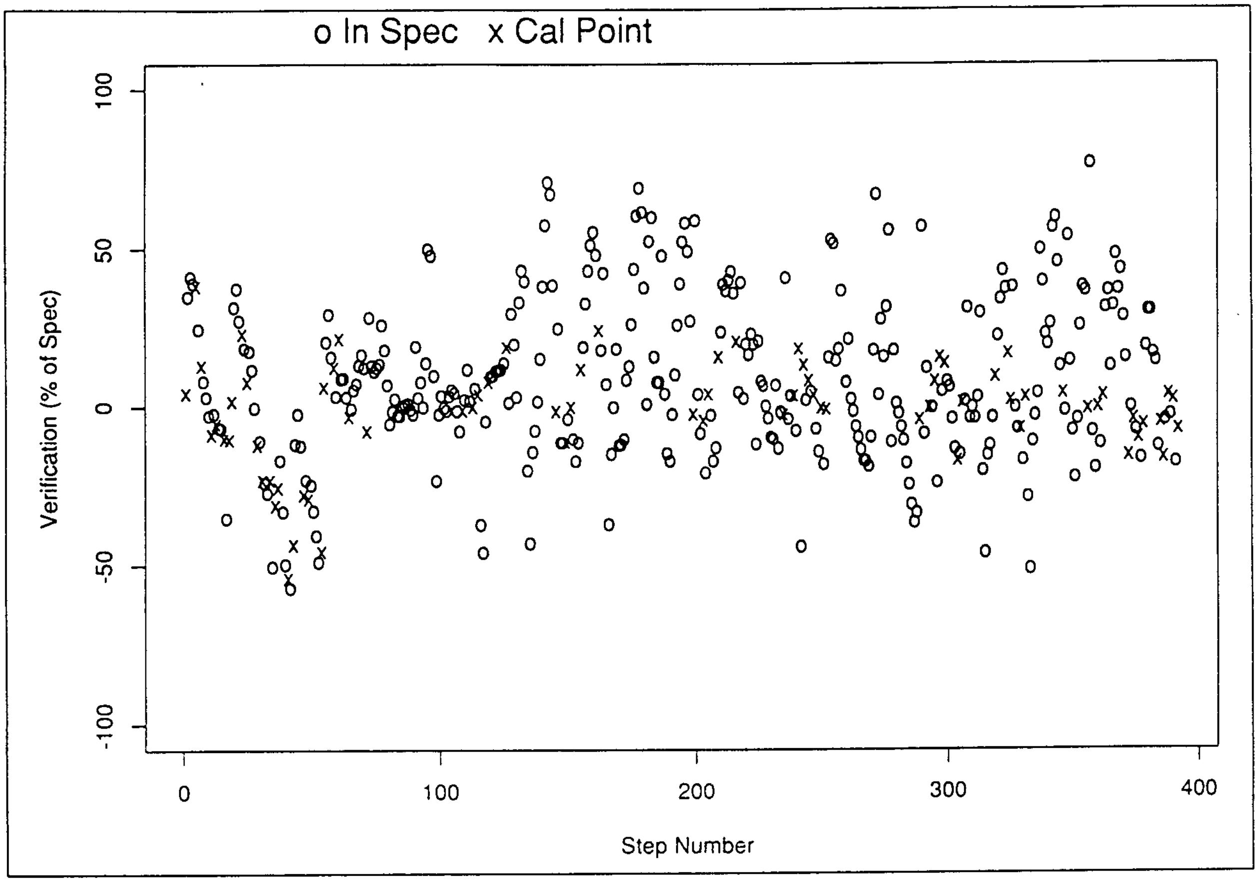


Figure 10. Scatter Plot of Design Phase Stability Instrument

Figure 11 is a scatter plot for a representative Pre-production instrument. The four points that stand out below the bulk of the points are found on many of the other instruments. The two on the left are being improved by increasing the delay slightly before measurements are taken after switching the internal measurement circuitry between the internal reference and the input. The two on the right are also found on a number of instruments and are being improved by a slightly different fit algorithm between 20 kHz and 100 kHz on the 7V and 22V ranges.

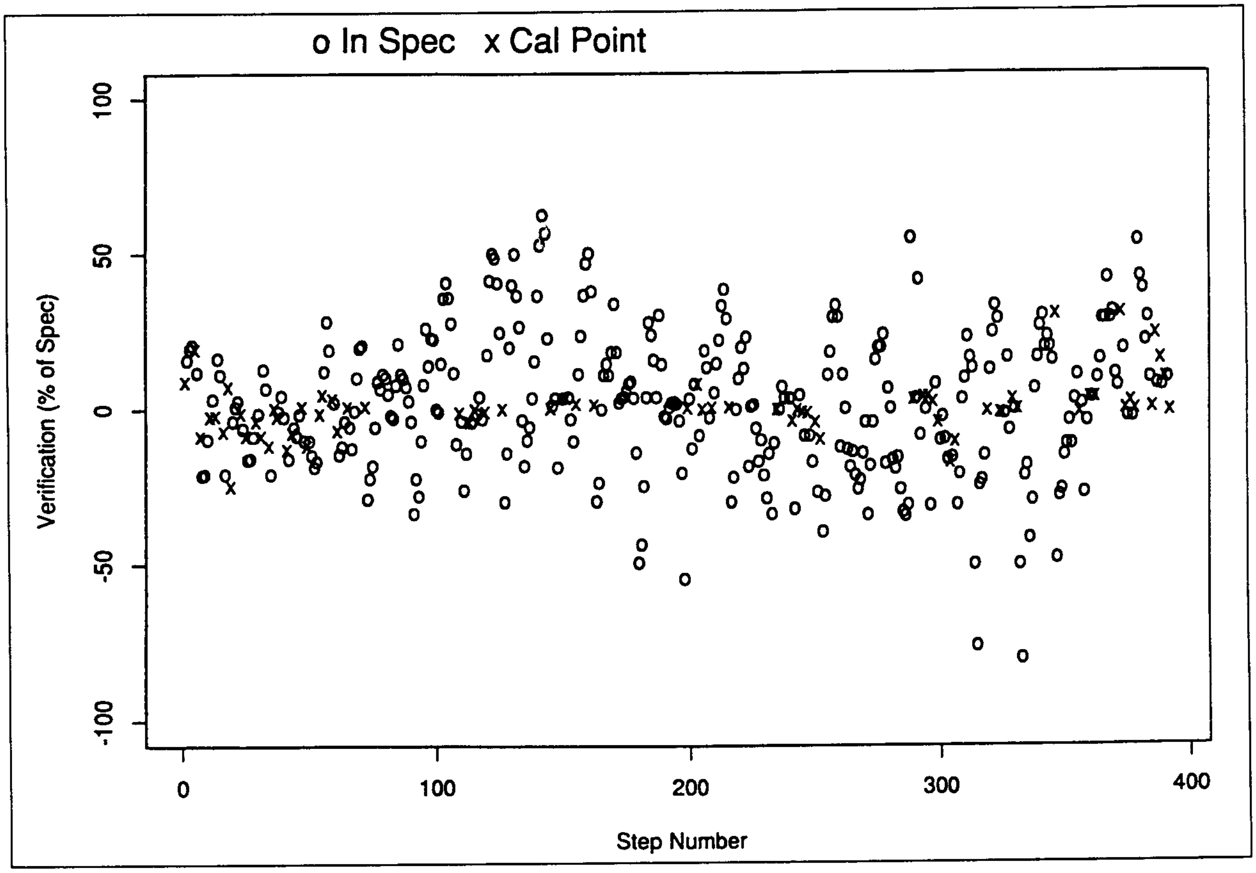


Figure 11. Pre-production Instrument Scatter Plot

Figure 12 is a scatter plot for eight representative Pre-production instruments showing minimum and maximum readings for each of the 392 verification points. Some have had the modifications required to improve the points at the lower portion of the plot which are a little large as a percentage of specification and some have not, which accounts for the large difference between the minimum and maximum for those points.

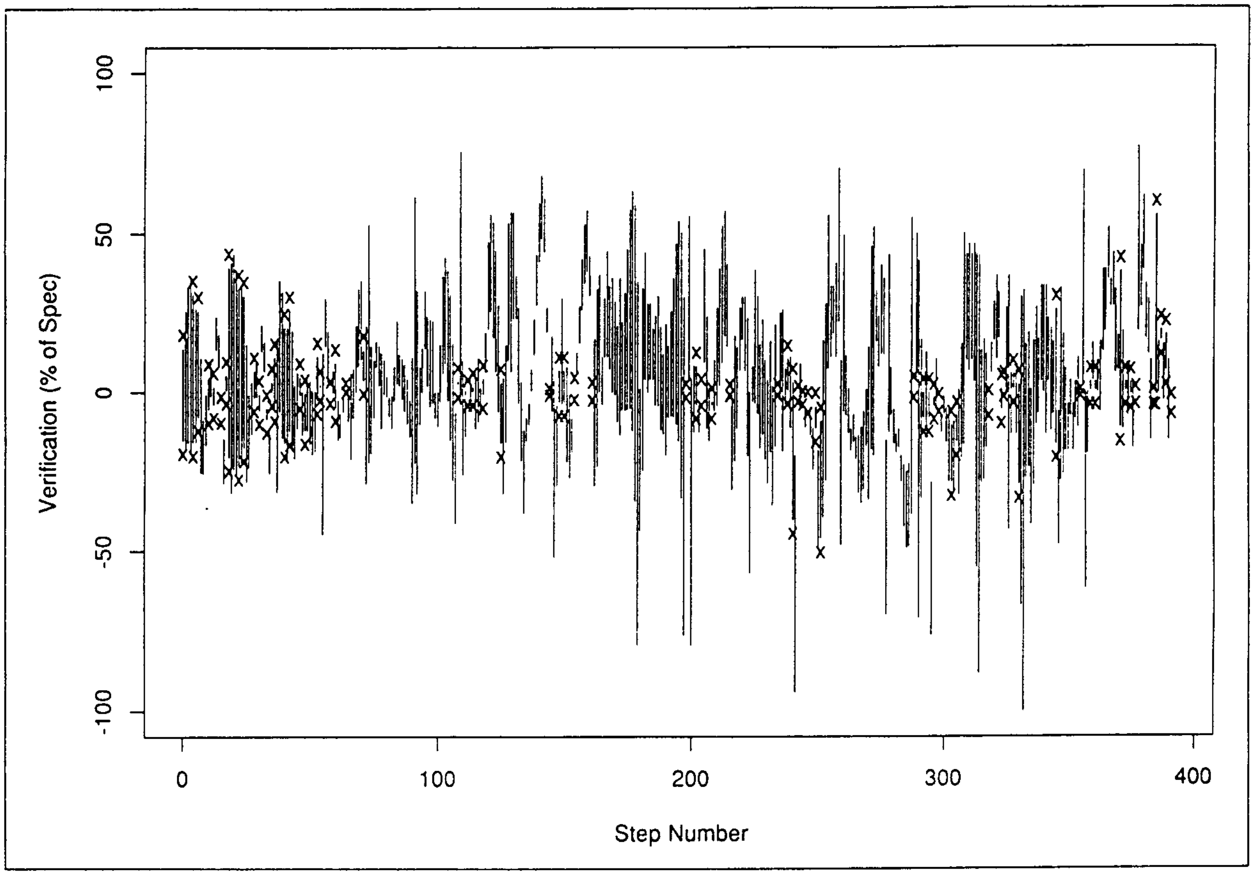


Figure 12. Min/Max Scatter Plot for Eight Pre-production Instruments

By starting the development of the Automatic Calibration Station simultaneously with the development of the new AC Measurement Standard, and by treating calibration and verification as a process with quantifiable means and standard deviations, we have been able to greatly reduce calibration uncertainties. Developing the instrument and its calibration system in parallel has allowed us to eliminate many of the systematic errors in the calibration process.

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