MAINTAINING TRACEABILITY AT REMOTE SITES WITH PROCESS METROLOGY

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Introduction

This paper describes a method, used at the Fluke Corporation, to establish and maintain traceability for certain high-end products. The method is called Process Metrology. It will be shown that this method not only establishes a traceable chain through the Standards Laboratory to NIST, but it also provides the basis for a quality control system required for credible, traceable calibration.

Process Metrology

Process Metrology, as practiced at Fluke, is a two-loop quality control system linking the Standards Laboratory (SL) with specific calibration systems on the factory floor. A functional block diagram is given in Figure 1. The transfer loop involving the Standards Lab establishes traceability for the test system (test console, interconnections and operator). The local check standard loop provides the means to continuously monitor the performance of the manufacturing test system.

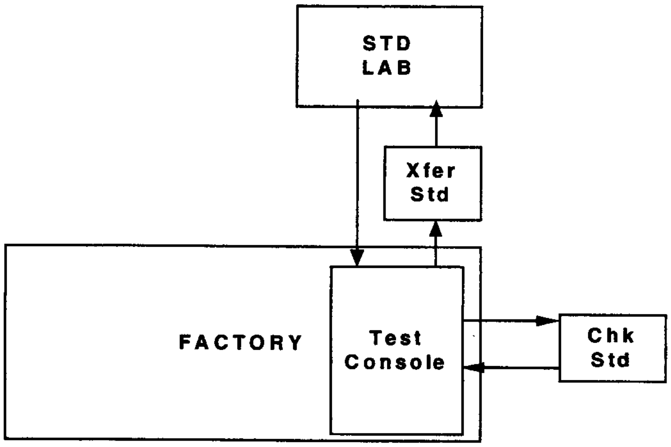


Fig. 1 Process Metrology Functional Diagram

Standards Lab Loop: An appropriate transfer standard is measured on the test console in the factory. It then is sent to the Standards Lab for measurement of the same electrical parameters. The difference between these two measurements is calculated and plotted. This represents the performance of the test console relative to the standards maintained by the Standards Lab. A regression model is used to filter the data, project future performance and to quantify uncertainty estimates. Limits for uncertainty are calculated with an error budget including the uncertainty of the Standards Lab measurements, the test limits of the product, and the uncertainty of the test console as calculated from the difference data. Operating criteria including in-tolerance operation, expected out-of-tolerance date, and system adjustment (calibration) information are derived from the processed difference data.

In addition to providing traceable calibration of the manufacturing test console, the standards lab loop serves as a quality control loop for the overall calibration system. Note that measurements on the transfer standard by the test console include the effects of operator, instrument-system interface, and the calibration process. A breakdown in any one of these components will be indicated by unusual, or out of tolerance performance of the difference data.

Local Check Standard Loop: In between the trips to the Standards Lab, the transfer standard is used as a check standard by the manufacturing test console. Since it is regularly measured by the Standards Lab, its performance will be well characterized. Daily, or before each production run, the transfer standard (now a check standard) is tested by the test console. If performance is within test limits for all parameters, the test console is proclaimed fit for use. Since little filtering is used in this loop, system errors will show immediately. This helps to prevent faulty calibration from sneaking into the system.

The Transfer Standard: Since the difference data will be filtered with a linear regression, there usually is no need for the short term stability of the transfer standard to be much better than the product to be calibrated. In fact, a sample of the product itself can usually function adequately as the transfer standard. This is especially convenient for supporting multifunction instruments such as precision calibrators and digital multimeters since the procurement and maintenance of multiple supporting standards is difficult and expensive.

Process Metrology Performance Equations

Accuracy of the production instruments (product), relative to NIST, includes three major error terms for each operating parameter. These include (1) the uncertainty of the Standards Lab with respect to NIST, (2) the error of the production test console with respect to the Standards Lab (Ediff), and (3) the error of the product with respect to the test console. Mathematically, this is expressed by the following equation:

$$E_{tot} = E_{SL} \oplus E_{diff} \oplus E_{product} \qquad (1)$$

where ⊕ indicates a statistical addition of terms

The total error must not exceed the specification limit L for each output parameter.

$$\left| E_{SL} \oplus E_{diff} \oplus E_{product} \right| \leq L_{spec} \qquad (2)$$

Equation (2) can be expressed in terms of the uncertainties and means of the distributions of each error term as follows:

$$\left| \mu_{diff} + \mu_{prod} \pm \sqrt{U_{SL}^2 + U_{diff}^2 + U_{prod}^2} \right| \leq L_{spec} \qquad (3)$$

where μ_{diff} is the mean of the difference data

μ_{prod} is the mean of the product data relative to the test console

U_{SL} is the uncertainty of the Standards Lab relative to NIST

U_{diff} is the uncertainty of the mean of the difference data

U_{prod} is the uncertainty of the product about its mean

L_{spec} is the product's spec limit

The product uncertainty can be either the allocated test uncertainty assigned in the overall error allocation, or the actual Confidence Interval of the product about its mean as measured by the production test console. In this analysis, the allocated test uncertainty will be used. This uncertainty is assumed to be normally distributed, with a zero mean, and with a 99% Confidence Limit set equal to the allocated test limit specification.

As mentioned earlier in this paper, the Difference Data will be modeled with a linear regression having a 99% uncertainty U_{diff}. Equation (3) can now be rewritten as

$$\left| a + bX \pm \sqrt{U_{SL}^2 + U_{diff}^2 + U_{prod}^2} \right| \leq L_{spec} \qquad (4)$$

where $a + bX$ is the linear regression representation for the mean of the difference data

Equation (4) is useful in its present form; however, we are primarily interested in the Difference Data and its limits. Usually, U_{prod} in equation (4) is much larger than either U_{SL} or U_{diff} ; therefore, it masks the effects of U_{diff}. It is desirable to manipulate equation (4) so as to clearly show the limits for the Difference Data. This can be done by applying the approximation $\sqrt{1+x} \approx 1 + x/2$ for $x << 1$. Equation (4) then becomes

$$\left| a + bX \pm \frac{0.5U_{diff}^2}{\sqrt{U_{prod}^2 + U_{SL}^2}} \right| \le L_{spec} - \sqrt{U_{prod}^2 + U_{SL}^2}$$

or equivalently

$$\left| a + bX \pm \frac{0.5U_{diff}^2}{\sqrt{U_{prod}^2 + U_{SL}^2}} \right| \le L_{diff} \qquad (5)$$

where $L_{diff} = L_{spec} - \sqrt{U_{prod}^2 + U_{SL}^2}$

The terms U_{prod}, U_{SL}, and L_{spec} in equation (5) are all constants. Regression terms, a and b are computed from the Difference Data using well known regression formulas. U_{diff}, the uncertainty of the regression based on the Difference Data, is computed from the following well known formula

$$U_{diff} = t\left(1 - \frac{\alpha}{2}, n-2\right) S_1 \sqrt{\frac{1}{n} + \frac{\left(x - \bar{x}\right)^2}{\sum\left(x_i - \bar{x}\right)^2}} \qquad (6)$$

where t is the students t,
S_1 is the standard deviation about the regression
$\bar{x}$ is the mean time for the Difference data
n is the number of terms in the regression data

Since $\sum\left(x_i - \bar{x}\right)^2 = (n-1) S_x^2$

where S_x is the sample standard deviation of the time (x) about its mean.

Equation (6) can be rewritten in the following convenient form

$$U_{diff} = t\left(1 - \frac{\alpha}{2}, n-2\right) S_1 \sqrt{\frac{1}{n} + \frac{\left(x - \bar{x}\right)^2}{(n-1) S_x^2}} \qquad (7)$$

The values of U_{diff} computed from equation (7) is used in equation (5) as a function of time (x). As long as the equation (5) is satisfied, the calibration system (Test Console) is adequate for calibrating the product at its claimed accuracy specifications.

Equation (7) as stated above, is the uncertainty of the regression representing the difference between measurements made on the transfer standard in the Standards Lab from those made on the same transfer standard by the production test console. It, together with the corresponding regression can be used to characterize the transfer standard for use as a check standard between cycles to the Standards Lab.

The corresponding control chart for the same data is identical to equation (7) except for a 1 under the radical as follows:

$$U_{data} = t\left(1-\frac{\alpha}{2}, n-2\right) S_1 \sqrt{1+\frac{1}{n}+\frac{\left(x-\overline{x}\right)^2}{(n-1) S_x^2}} \qquad (8)$$

Equation (8) is used to check the integrity of the data set. If t is chosen for a 0.99 Confidence Level, then only 1% of the data set should fall outside the bounds of equation (8). Therefore, this equation can be used to identify potentially faulty data.

Another useful parameter is the uncertainty of the Test Console relative to NIST. This can be computed from the above data with the following relationship:

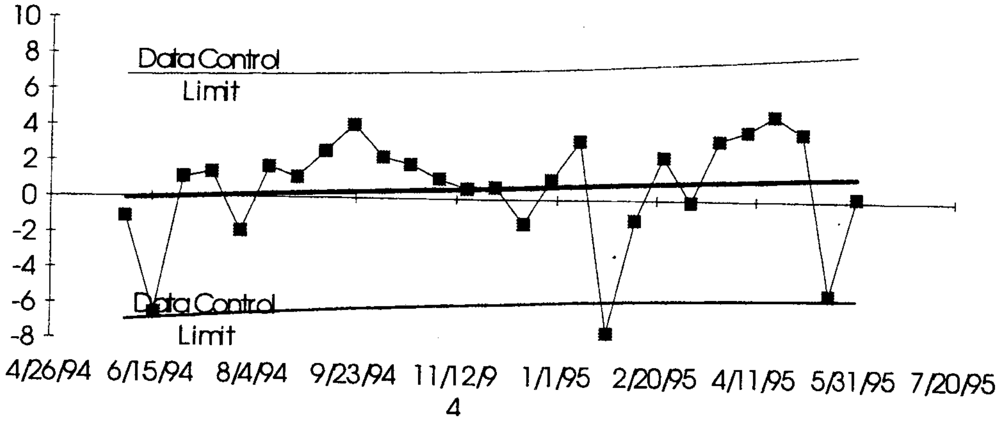
$$U_{calib} = |a+bX| + \sqrt{U_{diff}^2 + U_{SL}^2} \qquad (9)$$

Test uncertainty is required on Reports of Calibration according to ANSI/NCSL Z540-1.

<u>Examples</u>

A Fluke 5700A Multifunction Calibrator is used as a transfer standard to compare measurements made on the production test console with those made in the Standards Lab for more than 150 electrical parameters. Data for the difference between these two systems for 1 MOhm resistance is given in Appendix A. Figure 1 below is a plot of that data together with its regression and 99% Control Limits. Control limits are calculated with Equation (8). Any data falling substantially outside of the control limits is reviewed critically to determine whether or not it is legitimate. Occasional bad data and/or outliers should be removed or disregarded.

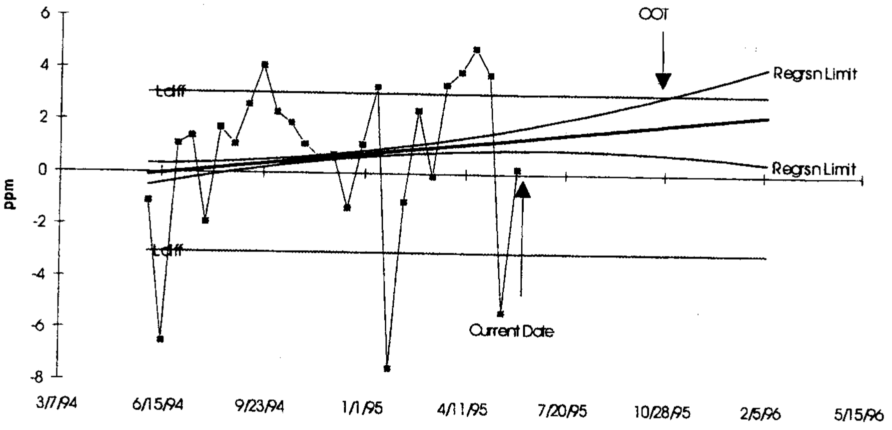
Fig. 1 Control Chart - 1 MOhm



After the data set has been approved, it is used by Equation (5) to compute calibration control boundaries for the Difference Data. The resulting regression with its regression limits and error limits are given in Figure 2. The region bounded by the Regression Limit lines is the left side of equation (5). The date that the Regression Limit lines first intersects Ldiff is the Out of Tolerance (OOT) date. Actually this OOT date is conservative since it assumes no additional data will be collected after the current date. If additional data is collected (the usual case) the OOT date can be estimated more accurately with a straight line extension of the Regression Limit beginning at the Current Date.

Note that the Regression Limit is not the classical Confidence Limit of the regression. It has been altered by the manipulations leading to equation (5) so as to allow focus on the Difference Data. The Regression Limits loci is useful strictly for identifying the OOT date, and for visualizing the contribution of the Test Console uncertainty relative to its allowable limits. The regression line itself, however, accurately reflects the average of the Difference Data. Therefore, the value of the regression at the current date is the

Fig. 2 Difference Data Control Boundaries (1 MOhm)

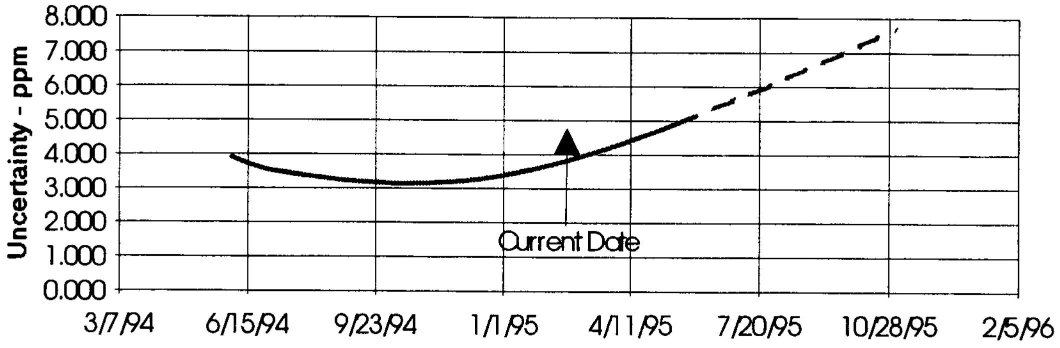


current error of the production test console relative to the Standards Lab. It can be used to calibrate the Test Console at that time.

The plots of Figure 2 show that this parameter (1 MOhm) is well controlled. The OOT date is nearly five months from the current date so a calibration will not be required for some time. Note too, that the noise of the system, as indicated by the spread of the two Regression Limit loci, is a reasonably small part of the total allowable error (Ldiff).

The corresponding total calibration uncertainty of the production test console, as given by equation (9), is plotted in Figure 3. Currently, it gives uncertainty of the production test console, relative to NIST, as 5.1 ppm. This information should be included on the Report of Calibration for this parameter (1 MOhm).

Fig. 3 Calibration Uncertainty, (1 MOhm)



System Reports
The data, as presented in Figure 1-3 above, could be printed for every parameter tested along with the Calibration Correction Table. This is unnecessary, however, since there may be a large number of parameters (>150) and usually only those parameters approaching the OOT dates are of interest. Furthermore, the data identifying the need for calibration can be presented more conveniently in tabular form.

Table 1 gives a typical system report in tabular form. It is usually limited to the ten or so parameters that are closest to being out of tolerance (OOT). It, along with the corresponding graphical displays, as in Figure 2, are generated by the system monthly for review. Other values can be printed at the operator's discretion. If calibration is necessary, the system automatically generates a table of calibration corrections for all system parameters. These are applied to the system semiautomatically after approval for recalibration is granted by the reviewing Process Metrology Council.

Table 1 Test Console Status Report

Item	Parameter	Days to O.O.T.	O.O.T.Date
1	19 ohms	47	July 17, 95
2	190 ohms	55	July 25, 95
3	1000 VDC	65	Aug 4, 95
4	100 VDC	71	Aug 10, 95
5	1.9 ohms	85	Aug 24, 95
6	0.02 VAC, 20kHz	90	Aug 29, 95
7	0.02 VAC, 100kHz	94	Sept 2, 95
8	0.5 VAC, 40 Hz	110	Sept 17, 95
9	0.19 A, 10 kHz	116	Sept 23, 95
10	1.9 A, 5 kHz	121	Sept 28, 95

Review Process

The Process Metrology Council (PMC), including the Corporate Metrology Manager and division Quality Assurance Managers, meets monthly to review the status of the various production test consoles. This group determines if and when to recalibrate the systems based on the projected OOT dates for system parameters. The Council authorizes the calibration, when required, and reviews its effectiveness. Although PMC meetings are a monthly event, the information is available on a common computing system so that members can check the state of the calibration of the various test consoles when they desire.

Comparison with Traditional Calibration

Traditional calibration requires regular recall of each of the Test Console's references for calibration at an appropriate laboratory. Process Metrology, on the other hand, transfers the calibration status of the system's references to the controlling calibration laboratory with a transfer standard, typically the product itself. Calibration is performed on-site, and often semiautomatically. Strengths of Process Metrology include (1) potentially better accuracy at the remote site, (2) lower system down time for calibration, and (3) quality control on the overall system including the system-operator interface.

On the other hand, Process Metrology requires the collection and processing of considerable data. This could be expensive unless it is supported by a suitable automated system. Frequent adjustment of the system (calibration) would be expensive, even with the information provided by Process Metrology, unless the test system includes software for performing automatic parameter adjustments (calibration) from calibration correction files. Finally, the system's transfer standard must have reasonable short term stability to avoid excessive transfer error between the standards lab and the production test console. This paper advocates using actual product to make this transfer since it contains all the relevant parameters. For high precision products, short term stability is usually significantly better than normal performance specifications. This may not be the case, however, for lower precision products.

Summary

Process Metrology, as described in this paper, provides a means to establish traceable, in-place calibration of production test consoles, on the factory floor or other remote sites. It includes a quality control function which monitors the performance of the overall system including the effects of the operator and the instrument-system interface. System calibration status is easily monitored with reports giving projected Out of Tolerance dates for the worst performing parameters. Calibration corrections are automatically computed by the system. System down time, and the need for reserve system standards, are minimized since calibration is accomplished on site.

Effective use of this process, however, requires an automated calibration system capable of performing the calculations described in this paper and with the ability for making system adjustments (calibrations) with correction files. This generally requires an investment in supporting software.

Whether or not Process Metrology is a cost effective means for establishing and maintaining traceability, with quality control, for a remote calibration system depends on the performance and through put demands on the system. In our case, Manufacturing Test management believes strongly in Process Metrology and insists that all new test systems employ this technology.

Appendix A - Data Supporting Figure 2

Lspec							
24 Hr Spc	Usl	Uprod	t(.99,n-2)	Ldiff			
1.60E+01	2.00E+00	12.8	2.79	3.045			
Xbar =	12/1/94						
Sx =	111.12						
		TEST CONSOLE OPERATING REGION					
	1 Meg						
Date	diff data						
(approx)	ppm	Regrsn	R+U'diff	R-U'diff	Ldiff	-Ldiff	Udiff
6/2/94	-1.1	-0.083	0.327	-0.493	3.045	-3.045	3.259
6/16/94	-6.5	-0.030	0.336	-0.395	3.045	-3.045	3.077
6/30/94	1.1	0.024	0.349	-0.300	3.045	-3.045	2.899
7/14/94	1.4	0.078	0.365	-0.209	3.045	-3.045	2.726
7/28/94	-1.9	0.132	0.385	-0.121	3.045	-3.045	2.560
8/11/94	1.7	0.186	0.409	-0.037	3.045	-3.045	2.401
8/25/94	1.1	0.240	0.436	0.044	3.045	-3.045	2.252
9/8/94	2.6	0.294	0.466	0.121	3.045	-3.045	2.115
9/22/94	4.1	0.348	0.501	0.195	3.045	-3.045	1.991
10/6/94	2.3	0.402	0.538	0.265	3.045	-3.045	1.883
10/20/94	1.9	0.455	0.580	0.331	3.045	-3.045	1.795
11/3/94	1.1	0.509	0.625	0.394	3.045	-3.045	1.730
11/17/94	0.6	0.563	0.673	0.453	3.045	-3.045	1.689
12/1/94	0.7	0.617	0.725	0.509	3.045	-3.045	1.675
12/15/94	-1.34	0.671	0.781	0.561	3.045	-3.045	1.689
12/29/94	1.1	0.725	0.840	0.609	3.045	-3.045	1.730
1/12/95	3.3	0.779	0.903	0.654	3.045	-3.045	1.795
1/26/95	-7.5	0.833	0.969	0.696	3.045	-3.045	1.883
2/9/95	-1.1	0.886	1.039	0.734	3.045	-3.045	1.991
2/23/95	2.4	0.940	1.113	0.768	3.045	-3.045	2.115
3/9/95	-0.1	0.994	1.190	0.798	3.045	-3.045	2.252
3/23/95	3.4	1.048	1.271	0.826	3.045	-3.045	2.401
4/6/95	3.9	1.102	1.355	0.849	3.045	-3.045	2.560
4/20/95	4.8	1.156	1.443	0.869	3.045	-3.045	2.726
5/4/95	3.8	1.210	1.534	0.885	3.045	-3.045	2.899
5/18/95	-5.3	1.264	1.629	0.898	3.045	-3.045	3.077
6/1/95	0.2	1.318	1.728	0.908	3.045	-3.045	3.259
6/15/95		1.371	1.830	0.913	3.045	-3.045	3.446
6/29/95		1.425	1.935	0.915	3.045	-3.045	3.635
7/13/95		1.479	2.044	0.914	3.045	-3.045	3.827
7/27/95		1.533	2.157	0.909	3.045	-3.045	4.022
8/10/95		1.587	2.274	0.900	3.045	-3.045	4.218
8/24/95		1.641	2.394	0.888	3.045	-3.045	4.416
9/7/95		1.695	2.517	0.872	3.045	-3.045	4.616
9/21/95		1.749	2.644	0.853	3.045	-3.045	4.817
10/5/95		1.802	2.775	0.830	3.045	-3.045	5.019
10/19/95		1.856	2.909	0.804	3.045	-3.045	5.223
11/2/95		1.910	3.047	0.774	3.045	-3.045	5.427
11/16/95		1.964	3.188	0.740	3.045	-3.045	5.632
11/30/95		2.018	3.333	0.703	3.045	-3.045	5.837
12/14/95		2.072	3.482	0.662	3.045	-3.045	6.044
12/28/95		2.126	3.634	0.618	3.045	-3.045	6.251
1/11/96		2.180	3.789	0.570	3.045	-3.045	6.458
1/25/96		2.234	3.949	0.519	3.045	-3.045	6.666
2/8/96		2.287	4.111	0.464	3.045	-3.045	6.874
2/22/96		2.341	4.278	0.405	3.045	-3.045	7.083
3/7/96		2.395	4.448	0.343	3.045	-3.045	7.292
3/21/96		2.449	4.621	0.277	3.045	-3.045	7.502
4/4/96		2.503	4.798	0.208	3.045	-3.045	7.712
4/18/96		2.557	4.979	0.135	3.045	-3.045	7.922
5/2/96		2.611	5.163	0.058	3.045	-3.045	8.132
5/16/96		2.665	5.351	-0.022	3.045	-3.045	8.343
5/30/96		2.718	5.542	-0.105	3.045	-3.045	8.553
6/13/96		2.772	5.737	-0.192	3.045	-3.045	8.764