Artifact Calibration

An evaluation of the Fluke 5700A Series II Calibrator

NMi
Van Swinden
Laboratorium B.V.
The Netherlands

Physikalisch
Technische
Bundesanstalt
Germany

SP Swedish National
Testing and
Research Institute
Sweden

Note

Although this is a searchable document, care must be taken when **copying** and **pasting**.

Due to the limitation of the OCR software the contents will appear correct but when copied and pasted into an external document the contents may be **incorrect**.

Artifact Calibration

An evaluation of the Fluke 5700A Series II Calibrator

Authors:

Gert Rietveld
Cees van Mullem
Cock Oosterman
Joop Dessens
Torsten Funck
Pär Simonson
Håkan Nilsson
Karl-Erik Rydler
Jan Jacobson
Mikeal Ohlsson

Eindhoven, The Netherlands, November 1999

Contents

Preface

This report describes the results of an evaluation of Artifact Calibration as implemented in the Fluke 5700A series II calibrator.

The main reason for Fluke to initiate this evaluation was the unsatisfactory situation that Artifact Calibration was not accepted by the European cooperation for Accreditation (EA) as a valid method for calibration. The intention of the internal Artifact Calibration feature of the Fluke 5700A calibrator is that it measures the complete scope of the calibrator using only a few external reference standards. It thus is a very efficient and cost effective way for the user to calibrate the instrument. However, since the whole calibration process occurs *inside* the instrument, no assessment of the calibration method can be done (as required by EA).

This report intends to fill this gap: it describes the results of a thorough evaluation performed as a combined effort of three independent European National Metrology Institutes, where the manufacturer Fluke provided extra information where necessary.

The study itself was unique in several aspects. The great range of capabilities of the Multi-Function Calibrator required the input of different disciplines in the project. In fact, the co-operation of metrologists, software specialists, and the technical experts of the manufacturer was one of the keys to the success of the project.
Furthermore, the actual way of evaluating the Artifact Calibration process first had to be developed since to the best of our knowledge no such metrological evaluation of a measurement instrument had been performed before. It finally was found that Artifact Calibration should be evaluated along the lines followed during an assessment of an accredited laboratory: if Artifact Calibration may be viewed as a calibration laboratory inside an instrument, then the evaluation is like opening the top lit of the instrument and stepping into this laboratory, assessing it as any 'normal' calibration laboratory.

This view determined the subsequent steps in the evaluation work, and thereby also the setup of this report.

The first two chapters give an introduction into the project and give some general information on the Fluke 5700A series II calibrator. Chapter 3 subsequently describes in a comprised form the set up in the 'calibration laboratory': what 'instruments' are used, and how they are used in realizing the normal functionality of the calibrator (forming the 'scope' of the assessment). A crucial part of the evaluation is described in Chapter 4, where the Artifact Calibration process is studied. Special attention was paid to the question whether Artifact Calibration realizes traceability to (inter)national reference standards over the complete range of capabilities of the calibrator.

Based on the theoretical work of chapters 3 and 4, a series of practical tests were performed that tested in increasing detail whether the Artifact Calibration was functioning correctly (black box, opaque box, and glass box tests respectively). The results of these tests are described in the chapters 5 to 7.

Chapter 8 and 9 finally summarize the conclusions and give recommendations on how to use Artifact Calibration in an accredited laboratory. Already in this preface we would like to mention the main conclusion, namely that Artifact Calibration can be used as a method for calibrating the Fluke 5700A series II calibrator, if it is combined with less frequent conventional calibrations. Artifact Calibration is found to be an important tool for improving and securing the quality in a calibration laboratory.

The authors would like to express their thanks to Fluke Europe and Fluke USA for the support during the project, especially to Joost Korthout, Peter Schneider, Dave Bartley, and Dave Deaver. Joost Korthout and Annie Ouborg of Fluke Europe managed to transform the extensive project report into the report presented here.

The evaluation team
November 1999

1 Introduction

1.1 Project Objective

The Fluke 5700A Multi Function Calibrator (MFC) is a precision instrument that can be used as reference source to calibrate a wide variety of electrical measurement instruments. The functions and ranges cover the functionality commonly used in handheld and bench multi-meters with a reading up to 8½ digits.

In the development of new equipment used in metrology, the 5700A Multi-Function Calibrator incorporates a new concept: Artifact Calibration (Artifact Cal). With this feature the manufacturer guarantees that - using just one voltage standard (10V), two resistance standards (1Ω and 10kΩ) and executing the internal Artifact Cal function - the instrument will be adjusted within its 24 hours specification.

To provide confidence in the calibrator performance between calibrations, the calibrator is equipped with a calibration check (CalCheck). The CalCheck process is similar to the Artifact Cal procedure, except the internal references are used as reference standards, and the calibrator is not adjusted. Furthermore, the instrument is also equipped with an extensive internal self-testing and diagnostics of the analog and digital functions and systems, respectively the so-called SelfTest and SelfDiagnostics functions.

As in the United Stated the Artifact Cal method is accepted, National Standard Laboratories (NSLs) and the accredited calibration laboratories within the European cooperation for Accreditation (EA) do not accept it as a traceable calibration method. Accredited laboratories in Europe may use Artifact Calibration to adjust the calibrator, but after this a full calibration is required by the accreditation organization. The main reason for this is the fact that the traceability is not clearly demonstrated in the Artifact Calibration (to the user it is a 'black box' process), and therefore can not be independently evaluated by the assessor.

The variation in acceptance leads to different methods of calibration of the Multi Function Calibrator, namely

1. A yearly full verification by the NSLs and the EA laboratories before and after adjustment
2. Frequently performing adjustments by making use of only the Artifact Cal feature and less verifications by other laboratories.

This results in a totally different quality, reliability and cost of ownership.

Therefore, on behalf of Fluke Europe B.V. (The Netherlands) a consortium of three independent National Metrology Institutes, NMi (Netherlands), PTB (Germany) and SP (Sweden) has evaluated the Artifact Cal feature. The evaluation is split up in three major parts, the metrological study of the functional blocks in the MFC, the practical investigations as result of this study and the formulation of the conclusions and recommendations to obtain an effective and reliable use of the Artifact Calibration.

The practical investigations are further split into three different approaches; Black Box, Opaque Box and Glass Box. Besides the evaluation of the hardware functions (DC voltage and linearity, AC voltage, Resistance and Current), also the evaluation of the firmware has been included in the project. It consists of software evaluation for the different hardware functions, the storage of the calibration constants and the general firmware requirements of an automatic system.

The aim of the project is to evaluate whether a Fluke 5700A series II Multi Function Calibrator is adjusted to within its 24 hours specification by making use of the Artifact Calibration procedure. In other words: the project aims to evaluate the traceability chain realized by Artifact Calibration, so that the users of the Fluke 5700A series II calibrator in accredited laboratories may utilize this feature.

1.2 Previous Work

The National Metrology Institute of Sweden (SP) carried out a previous study on the Fluke 5700A calibrator. This study is comparable with the black box and opaque box approach of this evaluation (reference 9).

Also, the manufacturer has performed many studies. One important study has been done by Les Huntley on the long-term stability of a set of 260 calibrators (see references 16, 17, and 20).

The consortium has used these studies during the evaluation to extend the black box approach and the measurements on AC Voltage.

1.3 Project Set-up

1.3.1 Evaluation Approach

Fluke has made three MFC units available to the project, one for each institute, These MFC's were exchanged between the institutes once. Hence each institute measured on two individual instruments. The institutes were provided with listings and protocols of the firmware and operator manuals as necessary background information for the evaluation.

The project partners, staff and respective responsibilities were:

- NMi Van Swinden Laboratorium B.V, The Netherlands

Project coordination	: Gert Rietveld, Cock Oosterman,
DC + AC Current	: Cees van Mullem, Joop Dessens
Resistance	: Gert Rietveld

- Physikalisch Technische Bundesanstalt, Germany

DC Voltage and linearity	: Torsten Funck

- Swedish National Testing and Research Institute, Sweden

AC Voltage	: Pär Simonson, Karl-Erik Rydler, Håkan Nilsson
Firmware	: Jan Jacobson, Mikeal Ohlsson

The major activity in the project is the verification of the 24 hours specifications of the Fluke 5700A series II Multifunction Calibrator by performing measurements with absolute traceability towards international measurement standards before and after the use of the Artifact Cal feature. To perform these measurements the executing laboratories have performed the measurements within the scope of international written standards EN 45001 and ISO Guide 25. Therefore the approach for this technical evaluation of Artifact Cal of the Fluke 5700A Calibrator is set up in three phases which simulates as complete as possible the evaluation of a laboratory.

1. The black box approach is performed as a normal Artifact Cal procedure. The results on the output terminals are compared with the specifications (24 hours, 95% confidence level) as prescribed in the manuals.

To compare with laboratory accreditation: This approach is comparable with the inter-laboratory comparison where the laboratory must perform measurements on a particular field and demonstrate that the results are within the laboratory accredited Best Measurement Capabilities. Only the output results are compared.

2. The opaque box approach is performed as a normal Artifact Cal procedure with this exception that the input values of the reference standards are given to the calibrator with an offset from the real values. After the Artifact Cal, the measured values at the output terminal have

to follow this offset, on the internal metrological principles, in a predictable way. With this extra information the calibration method used within the instrument is checked. The opaque box approach especially checks whether the traceability chain is as realized as expected.

To compare with laboratory accreditation: This method is comparable with the assessment of the measurement system in a laboratory. The actual set up is checked, with special attention to the traceabillity chains realised in the laboratory.

3. The glass box approach is performed with the knowledge of what the end result must be as predicted from the firmware and hardware functions. Software and hardware values brings in new correction values (manipulation) and must result in predictable deviations measured on the output on the terminals or on specific internal places on the printed circuit boards. The measured results will be compared with the predicted values (these values do not necessarily have to be the 24 hour specification). This performance gives a clear view on the internal procedures (only the tested ones). Also specific tests are done to confirm the detailed functionality and calibration method of the calibrator.

To compare with laboratory accreditation: This is method is comparable with the detailed assessment of the calibration procedures, containing the traceability, performed in a calibration laboratory.

These three evaluation approaches together should lead to an assessment of the Artifact Cal concept and to the conclusion the instrument meets or does not meet its specifications.
A total measurement program was set up where the above tests are included in the most effective way. For this reason, an investigation of the theoretical approach of Artifact Cal took place before the measurements started. This includes a firmware evaluation where the basic principles are split into functional blocks and where the relation to the hardware blocks is demonstrated, including the mathematical functions (with e.g. the correction functions and values). Beside this, the hardware blocks have been evaluated on critical points with respect to traceability and reliability.

1.3.2 Evaluation Conditions

Three institutes on three different locations in Europe evaluated the instrument. The measurements have been performed in laboratory environment such as a cage of Faraday to reduce the influence of electromagnetic fields. All laboratories control the environmental conditions to similar values in order to be able to compare the results.
The main environmental conditions were:

Temperature	= (23 ± 0,5)°C
Humidity	= (50 ± 20)%
Main power	= 230V, 50Hz

Note that the instrument is evaluated under laboratory conditions ± 0,5°C while the conditions for the temperature for the specifications is ± 5°C. This means that the measurement results of this study will be better than if the temperature conditions of the specifications were used during the study.

All measurement standards or references used to perform the measurements on the MFC are traceable to primary and/or (inter)national measurement standards. All three institutes are members of Euromet, where the quality of measurement is ensured via inter-laboratory comparisons on the primary or secondary level. In general all measurements are performed with high accuracy measurement equipment to ensure that the contribution of the used reference has a minimum influence compared to the specification of the MFC.

1.3.3 Expected results

The MFC is an instrument used worldwide with a new approach to calibration. Due to the different use in accredited and not accredited laboratories the project is carried out to harmonize the use and the maintenance of this instrument. Therefore, the consortium takes into account the requirements of the EN 45001 Standard for Calibration and Testing laboratories. It is expected from the project that the consortium can give its conclusions on traceability and accuracy by making use of the Artifact Calibration. With the knowledge from the evaluation it is expected that the consortium can give recommendations for the use of the instrument were the user can fulfill the requirements not only necessary for accreditation but also for a metrological sound use of the instrument.
The consortium expects to give its knowledge and experience to the European cooperation for Accreditation (EA). This can lead to a harmonization of the use of the instruments in accredited laboratories.

1.4 Project restrictions

During this project some features and options are not measured or investigated.

- The influence of the main power on the Fluke 5700A output value.
- The influence of the environment on the Fluke 5700A output value. So no study is done of the influence of temperature (see also above in the paragraph "Evaluation conditions"), or humidity, or external (EMC) radiation.
- The (long-term) stability, since that is not directly related to the Artifact Cal concept.
- The wide band option that can be used to extend the frequency range.
- The Fluke 5725A external amplifier that can be used to extend the voltage and current ranges.
- The two-wire mode of the resistance function, because four-wire resistance is more accurate and therefore more representative for the capabilities of the calibrator. For the same reason, also the two-wire compensation circuit is not studied.
- The auxiliary current binding post.

It should be realized that the measurements and tests are taken as samples of all measurements that can be performed on the calibrator. However, the consortium has prepared the project with great care, and selected the measurement and evaluation points such that reliable conclusions and recommendations could be given concerning the Artifact Cal calibration method of the calibrator.

In addition, the group of three calibrators is a small sample of the group available and operational worldwide. So, more tests or measurements on another calibrator can lead to slightly different conclusions, especially if the tests are done in a different environment. However, the consortium has the opinion that there is no reason to believe that the results of the present project should not be representative for all Fluke 5700A series II calibrators with the same hardware and firmware version.

Finally, it is noted that the evaluation of the firmware never could be a 100% complete given the large amount of code. However, the general setup of the firmware was studied and more critical parts were studied in detail, so that the essential part of the firmware was covered in the present study. With this, the main aim of the firmware evaluation could be realized, namely to increase the confidence in the correct functioning of the calibrator.

1.5 Vocabulary

The vocabulary used in this document are based on the interpretation given in the 'International Vocabulary of Basic and General Terms in Metrology' (ISO- International Organization for Standardization, Switzerland 1993, ISBN 92-67-01075-1).

We want to note here explicity that 'calibration' in the interpretation of the VIM mentioned above, in our situation means a comparison between the unknown calibrator and another (known) reference instrument or standard. The interpretation in the Fluke manual of calibration means that during this comparison the instrument in not only measured but also adjusted to the nominal value if needed.

Furthermore, in the Fluke manual and also in this report, the word 'verification' is sometimes used instead of the more correct term 'calibration'. Essentially verification is similar to calibration, with in addition the aim to verify the results against some reference or expectation (like e.g. the specification of the instrument).

2 Fluke 5700A Series II calibrator

2.1 General information

The aim of the multifunction calibrator Fluke 5700A is to be used as reference standard for the calibration of a wide variety of electrical measurement instruments. There are multiple functions in the calibrator available in different ranges to cover most types of instruments; DC and AC Voltage, DC and AC Current and Resistance. The instrument can be used for the calibration of frequency with low accuracy. By making use of other features in the calibrator, like phase locking, special functions can be activated.

All functions are built into one instrument. There is an option available for extension of the frequency range (Wideband option). Also, an external amplifier Fluke 5725A can be used to extend the voltage and current ranges. These options were not subject of the present evaluation.

The instrument is equipped with internal software (firmware) to control the output function but also to carry out the internal calibration, the so-called Artifact Calibration. With this feature, the manufacturer states that the instrument will be adjusted within the 24 hours specification by making use of just 3 standards; one 10 V voltage reference and two reference resistors (1Ω and 10kΩ). These standards must be traceable to primary reference standards. It is recommended by the manufacturer to perform this adjustment at the interval related to the specification needed, with an additional full verification every 2 years with traceable measurement standards.

For the evaluation of the calibrator all experts have studied these functional blocks for the internal operation of the instrument to determine the traceability chain. During the measurements, special control commands are used to check and influence the internal calibration constants.

The instruments evaluated in the present study were three Fluke 5700A series II calibrators. Reason for selecting this calibrator, is that it is closer to the older 5700A (non-series II) calibrator of which thousands are in use in calibration laboratories than the new 5720 calibrator that has the best specifications. The 5700A series II calibrators used here had all regular functions included, except for the wideband option. The software version is 1.0+B+* as is printed in the calibration and check reports. The serial numbers of the three calibrators studied are 6450605, 6450606, and 6465606.

To have an efficient evaluation, the work on the calibrator was divided following the four metrological functions: DC Voltage and linearity, AC Voltage, DC and AC Current, and Resistance. Furthermore, firmware is treated as a separate (fifth) function.

Each function is realized by the combination of several functional (sub) blocks. Every hardware metrological (sub) block contains active and passive parts such as amplifiers, relay switches and digital to analog converters. A firmware (sub) block contains software procedures, which in turn use sub-procedures for the different sub-tasks or sub-functions.

Dividing the instrument into functional blocks greatly helped the evaluation. It for example made it easier to check the traceability chain set up by the Artifact Cal process, to check whether non-calibrated elements (blocks) were used on critical parts during the calibration, to make an overview of the total firmware structure, etc.

2.2 Specifications

The global capabilities of the calibrator are:
- DC Voltage to 1100V
- DC Current to 2,2A
- AC Voltage to 1100V, with output available from 10Hz to 1,2MHz
- AC Current to 2,2A, with output available from 10Hz to 10kHz
- Resistance in values of $1 \times 10^n \Omega$ and $1{,}9 \times 10^n \Omega$ to 100 MΩ

The total specifications are given in large specification tables and are not summarized in this report. This report contains the relevant specifications given per functional blo [illegible] so that they can be compared with the measurement results.

The specifications in the calibrator manual are given for the 95% as well as 99% confidence level. For the measurements, the 95% confidence level has been used as reference, since that most closely compares with the "k = 2 factor" used by national metrology institutes when expressing the total uncertainty of measurement results. This practice also is recommended by the European accreditation organizations (EA).

However, the ratio between both specification levels is not everywhere 1,3 but on several locations it is smaller. Basic reason for this is that the factor 1,3 only appears for results that have a normal distribution and have the means centered on the nominal value. So, on these occasions where in the manual the ratio in specifications is less than 1,3 these assumptions were not valid (especially the assumption of having the results of the Artifact Cal measurement centered on the mean). In these cases, the 95% specifications could not be as "aggressive" as the 99% specifications.

2.3 Firmware

The calibrator makes use of three different software applications, available from the instrument's keyboard or via the IEEE interface for remote control.
These three applications are:

- ***Artifact Cal***

The Artifact Calibration is performed by the firmware application 'Artifact Cal'. According to the manufacturer the instrument will adjust itself within its 24 hours specifications. The firmware uses the reference values of the three externally connected measurement standards. The operator connects one by one these external references to calibrate the internal references. Subsequently, the calibrator carries out the internal calibration procedure, using the new values of the internal references. By using the switch matrix board, the different functional blocks, including the internal references, are connected to each other and measurements are made. From these measurements the new calibration constants are calculated for each function. After finishing this, the operator can save the new constants in the memory. So there is no hardware adjustment on the circuit boards, only software adjustments are used for the correct output value. The calibration constants are stored in the memory of the instrument. Also the old values are still stored in the memory (only the previous set and the default set of constants). The results can be printed and stored as history of the instrument to demonstrate the long-term behavior of the instrument.

- ***CalCheck***

To check if the instrument has drifted from its original values, the operator can perform an internal check measurement by using the CalCheck application. All functional blocks are checked with the internal calibration procedure but the values are not stored in the memory. The results of this check can be printed and stored for archiving the history of the instrument. The values in the list provide the operator with information about the drift in relation to its specifications.

- ***SelfTest/SelfDiagnostics***

The SelfTest and SelfDiagnostics can be used to check the instrument memory and digital and analog functions of the calibrator. If there is a fault detected, the operator will be informed by messages on the display while the manual give a more extensive description.

2.4 Fluke 5700A series II versus the Fluke 5700A and 5720A

The Fluke 5700A series II calibrator is the improved version of the Fluke 5700A calibrator. The major differences related to Artifact Cal are:

- ***Artifact Calibration***

The 5720/5700 Series II calibrators have improved Artifact Calibration on a number of ranges, to minimize biases. Furthermore, they have improved interpolation algorithms in AC voltage, particularly at higher frequencies; corrections for the level dependent AC/DC differences at low frequencies (low frequency AC-sensor correction). A new interpolation algorithm is also used for lower AC current ranges.

- ***Hardware and circuitry design.***

The 5720/5700 Series II calibrator has a modification to the in-guard microprocessor circuitry to minimize noise in the mV DC ranges. Also, because of the tighter specifications of the 5720A, there may be more selected components in the calibrator than in the 5700A.

3 Functional Descriptions

3.1 DC voltage

The Fluke 5700A calibrator uses the following functional blocks for the DC Voltage function:

Digital-to-analog-converter with voltage references:	all ranges
5:1 Divider and buffer:	2.2V range
10:1 Passive Divider:	220mV range
20X Power Amplifier:	220V range
100X High Voltage amplifier:	1000V range

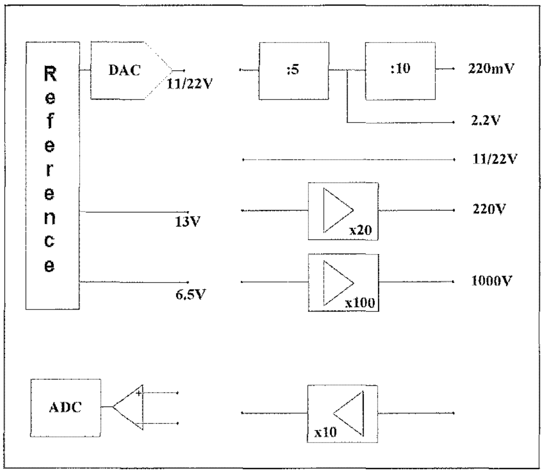


Figure 3.1 Block diagram of the DC Voltage function

Figure 3.1 shows a simplified block diagram of the DC Voltage function of the 5700A. On the top left are the voltage references and the Digital-to-analog-converter (DAC), on the right are the various dividers and amplifiers to obtain the different ranges. Furthermore there is additional hardware used only for artifact calibration shown in the lower part.

The reference voltage of 13V is scaled by the DAC to the desired value. Using a gain of either one or two the DAC output voltage ranges up to 11V or 22V. A buffer in the DAC enables these voltages to be directly routed to the output by the switch matrix. To obtain the other voltage ranges the DAC voltage is divided or amplified using resistive dividers or power amplifiers. Resistive dividers in the feedback network determine the gain of the power amplifiers.

3.2 AC Voltage

The significant building blocks of the Fluke 5700 series II calibrator AC voltage generation function are identified as follows:

- 10Hz - 1,2MHz frequency controlled oscillator with fixed amplitude.
- 0,22V - 22V gain-controlled amplifier.
- Power amplifier for the 220V and 1200V range.
- Active attenuator for the 2,2V and 22V range.
- Active attenuator for the 220V and 1200V range.
- Resistive dividers for the mV ranges.
- AC-DC thermal sensor assembly.
- AC-AC thermal sensor assembly.
- Resistive attenuators for the AC/AC thermal sensor.
- DCV DAC assembly.
- Software corrections

The interrelationship between the above-identified building blocks is shown in figure 3.2.

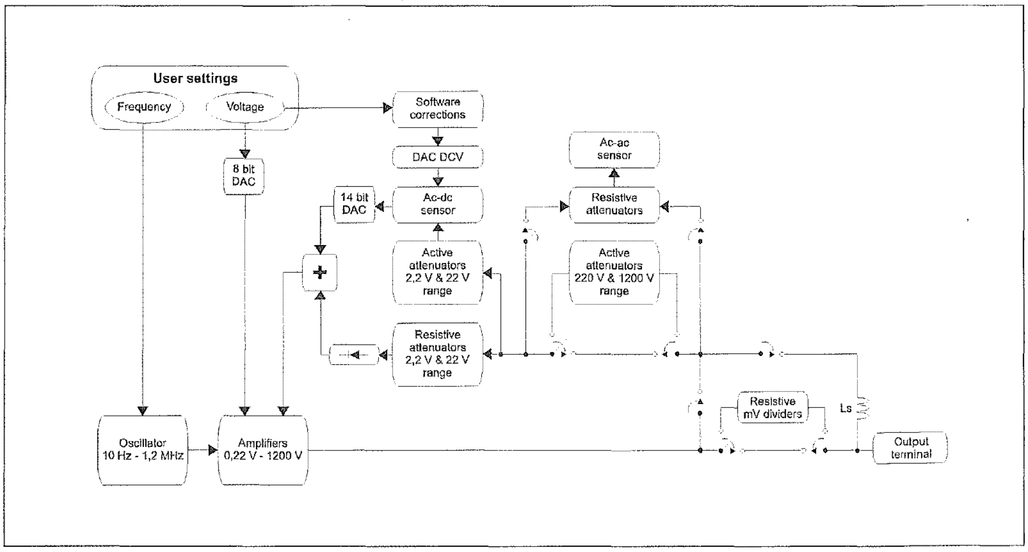


Figure 3.2 Simplified block diagram of the AC voltage generation function

The AC-AC thermal sensor and its resistive attenuators are only used during the Artifact Cal procedure.

3.2.1 *Oscillator frequency control*

The main oscillator is a quadrature RC oscillator type. The frequency control is made in three steps. First there are five selectable ranges: 100 Hz, 1 kHz, 10 kHz, 100 kHz and 1 MHz. Then there is an 8 bit resistive DAC that provides course control within a chosen range. The frequency fine control is made by phase locking to an internal high-resolution square wave frequency generator. The frequency of this generator is derived from a low-level 8 MHz crystal oscillator.

3.2.2 *Oscillator gain control*

The main oscillator has a rough fixed output voltage. The amplitude control of the output voltage is obtained by the use of a gain-controlled amplifier. The amplifier gain is controllable for output voltages between 0,22V and 22V in two ranges, the 2,2V and the 22V range. Within each range a coarse setting is made by an 8 bit resistive DAC. The DAC operates in conjunction with a gain control multiplier circuit. This multiplier provides a small linear control range of several DAC counts. The Oscillator Control assembly controls the multiplier and includes a fast regulation loop that acts by sensing the output voltage with a rectifying amplifier. This provides short-term stability with fast load regulation. There is also a fine control of the output voltage. The fine control is made by AC-DC transfer measurements, comparing the output AC voltage of the amplifier with a DC voltage generated by the DAC assembly. The DC voltage is corrected for the AC-DC-difference at the selected AC voltage level and frequency. The AC-DC transfer provides long term DC voltage stability.

A power amplifier generates higher voltages for the 220V range. By connecting the output of the power amplifier to a transformer, voltages for the 1100V range are generated.
The mV ranges are generated by the use of resistive voltage dividers. The dividers are connected to the 2,2V range or the 22V range. The AC-DC transfer control provides the most accurate control of the output voltage. The AC-DC transfer measurements are made with a solid state thermal sensor circuit. The output AC voltages at different ranges are attenuated to the AC-DC thermal sensor circuit by active attenuators for the 2,2V, 22V, 220V and 1100V range.

3.2.3 2,2V AC and 22V AC range

The figure 3.3 shows a simplified schematic diagram of the AC-DC and the AC-AC sensor circuit.

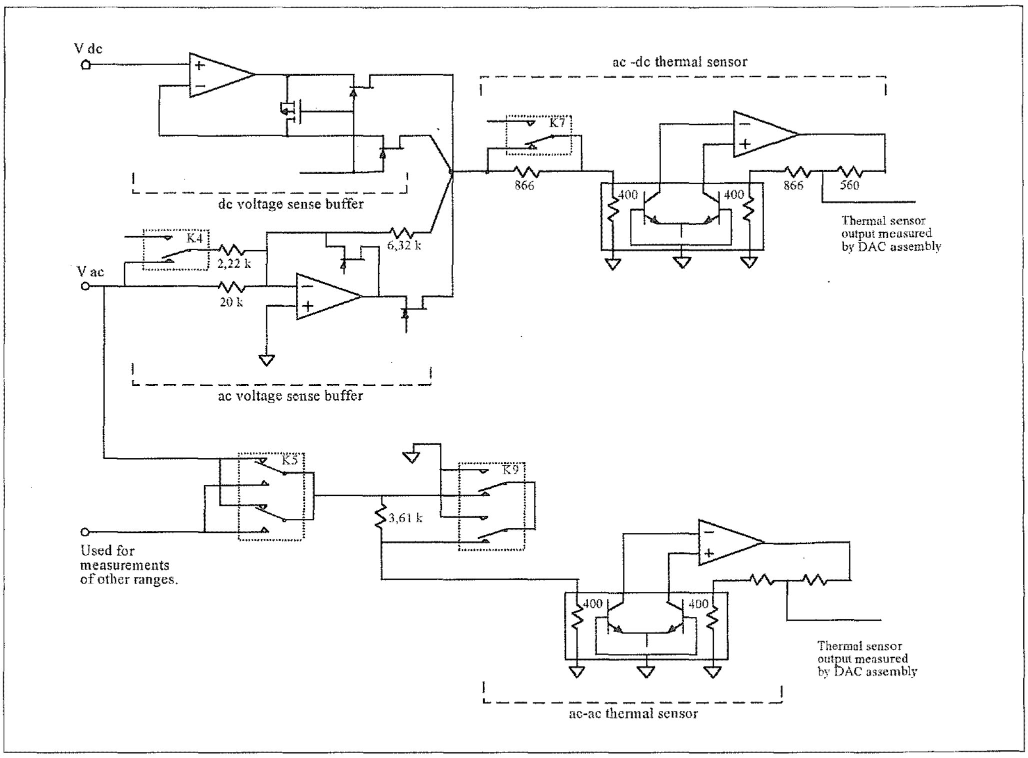


Figure 3.3 Simplified schematic diagram of the AC-DC and the AC-AC sensor circuits

The AC sense buffer is realized through an inverting amplifier with selectable gain, being either -3,16 or -0,316. In this way the AC sense buffer acts as an amplifier with gain -3,16 for the 2,2V range and as an active attenuator with voltage division ratio 3,16:1 for the 22V range.

The thermal sensor essentially measures the temperature of the sensor input resistor being also the heater resistor. The temperature of the heater resistor is a function that is approximately proportional to the square of the input voltage. A full decade input voltage range would give a too small signal to noise ratio when the heater resistor temperature is measured at the low end of the range. Therefore the 2,2V range is sub divided into two sub ranges. The low sub range ranges from 0,22V to 0,7V and the high sub range from 0,7V to 2,2V. By the use of relay K7 the 866Ω resistor is shorted for the low sub range and the relay K7 is left open for the high sub range. In the high sub range the 866Ω resistor and the 400Ω heater resistor forms a voltage divider with the ratio 3,16:1, which squared corresponds to a heater resistor temperature ratio of 10:1. The 22V range is correspondingly divided into sub ranges 2,2V to 7V and 7V to 22V.

3.2.4 The 220V AC range

The 220V AC range covers voltages from 22V to 220V. This range is achieved by connecting the output of the oscillator, configured for the 22V range, to the input of the Power Amplifier, PA. The gain of the PA is set to -10. The PA is used for both the AC and DC voltage generation in the 220V range. See also page 2-92 to 2-95 in the 5700A Service Manual.

3.2.5 The 1100V AC range

Calibrator AC voltages between 220V and 1100V are generated by connecting the output of the PA to the input of a transformer. The -100 gain of the PA - transformer combination is established with a feed back resistor of 500kΩ from the output of the transformer, the 1100V AC output sense of the calibrator, in conjunction with the 4.99kΩ input resistor of the PA. The oscillator output assembly drives the input of the PA, where the oscillator control assembly senses the transformer output voltage through the 1100V ac sense attenuator. The 1100V AC attenuator is basically the same circuit as the DC High Voltage Amplifier, HVA. It is only configured to give a 100:1attenuation instead of a 1:100 amplification. This is achieved by shifting the positions of the input and feed back resistors of the HVA. The attenuator input resistance is 7MΩ and the feed back resistance is 70kΩ. The two resistors and the HVA are located on a temperature controlled hybrid circuit, HR7.

3.2.6 The AC mV ranges

The mV AC ranges are generated with resistive voltage dividers connected to 2,2V or the 22V AC range. The resistive dividers are the same as for the DC mV ranges. There is a divider with 10:1 division ratio and a second divider with 100:1 division ratio. The 10:1 divider in combination with the 2,2V oscillator range is used to generate the 220mV AC range. The combination of the 100:1 and the 10:1 divider represents a divider with 1000:1 division ratio. The 1000:1 divider is used in combination with the 2,2mV and the 22mV oscillator ranges to generate the 2,2mV and 22mV AC ranges. The divider outputs are not sensed by the oscillator control. The output resistance of the calibrator mV ranges is approximately 50Ω.

3.3 Resistance

For realization of the resistance function, the Fluke 5700A calibrator contains a set of resistors with values $1*10^x$ Ω and $1,9*10^x$ Ω in the range of 1Ω up to 100MΩ and a short. Using a large number of relays, the specific resistance selected by the operator is connected to the output binding posts.

To obtain high accuracy the resistors all have four-wire connections, except for the 100MΩ resistor where lead resistance plays an insignificant role. The EX SNS button on the front panel of the calibrator selects the four-wire mode. In this study only the four-wire resistance function is evaluated since this function gives the user the highest accuracy.
The functional block diagram is rather straightforward and given in Figure 3.4.

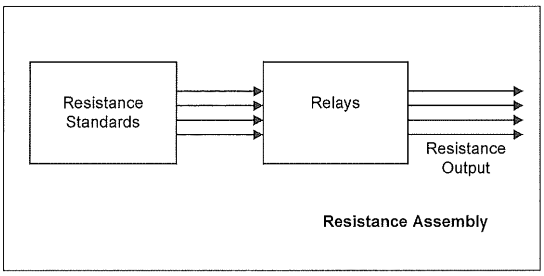


Figure 3.4 Block diagram of the resistance function

It is important to note that the resistance values are not electronically generated or simulated. This in practice has the consequence that the actual value of any resistor can not be changed. The output display of the calibrator always shows the 'true value' of the resistance selected, being the value of the resistance determined in the last Artifact Cal.

Physically the resistors are located on two assemblies: the 'Ohms Main Assembly' and the 'Ohms Cal Assembly'. The main assembly contains the main part of the resistors, namely those in the range of 10Ω to 100 MΩ. The values are arranged in two strings, one for decade values and the other for the multiples of 1,9; these are the left side and right side strings of Figure 3.5 respectively.

The schematic of Figure 3.5 also shows in more detail how the resistors are switched and connected to the output terminals. For example, to output any resistor first relays K1 and K2 are put in the reset position. Then, for selecting a decade resistor below 1 MΩ for example, relays K15 and K16 are reset. Finally, a last set of relays selects the final resistor, like K18A and K20A for the 10kΩ resistor.

The 100MΩ resistance is realized by putting a 90MΩ resistor in series with the decade string. Note that the high side of the 90MΩ is only connected to the 'INT OUT HI' – the 100MΩ resistance is only available in two-wire connection.

The relays that are used on both ohms boards are mainly latching relays because of their very low thermal EMF. Latching relays also are profitable because they only need to be powered during switching, which helps reducing thermal gradients along the ohms boards. On a few locations were particularly high leakage resistance is required, (low voltage) reed relays are used, for example in the connections of the high value resistors above 10MΩ. The use of the resistor strings helps reducing the number of relays needed for switching the resistors to the output terminals.

The resistances with values from 10Ω to 19MΩ on the ohm main assembly are hermetically sealed thin film resistors. They are contained in three separate networks, see parts Z1, Z2, and Z3 on Figure 7.10 of the Service Manual. Part Z1 contains all resistors up to 1,9kΩ. Higher values are in Z2 and Z3 that contain the decade values and 1,9 multiples respectively. The 90MΩ resistor for realization of the 100 MΩ resistance value is a coated (but not sealed) thin film resistor. Temperature coefficients of the resistors are made low since the calibrator is specified at ± 5°C around the calibration temperature (of e.g. 22°C or 23°C). The design of the resistors aims for a zero temperature coefficient at 22°C.

The temperature coefficient (TC) of the thin film networks increases slowly to 1 ppm/°C at about 8°C from the zero TC temperature of 22°C. The 90MΩ resistor that makes up most of the 100MΩ resistor has a TC of 10 ppm/°C or less. Practical experience from Fluke indicates that the 1Ω and 1,9Ω resistors have a temperature coefficient of a few ppm per °C at 22°C. In all cases, the effect of the TC on the resistance value is small compared to the specifications.

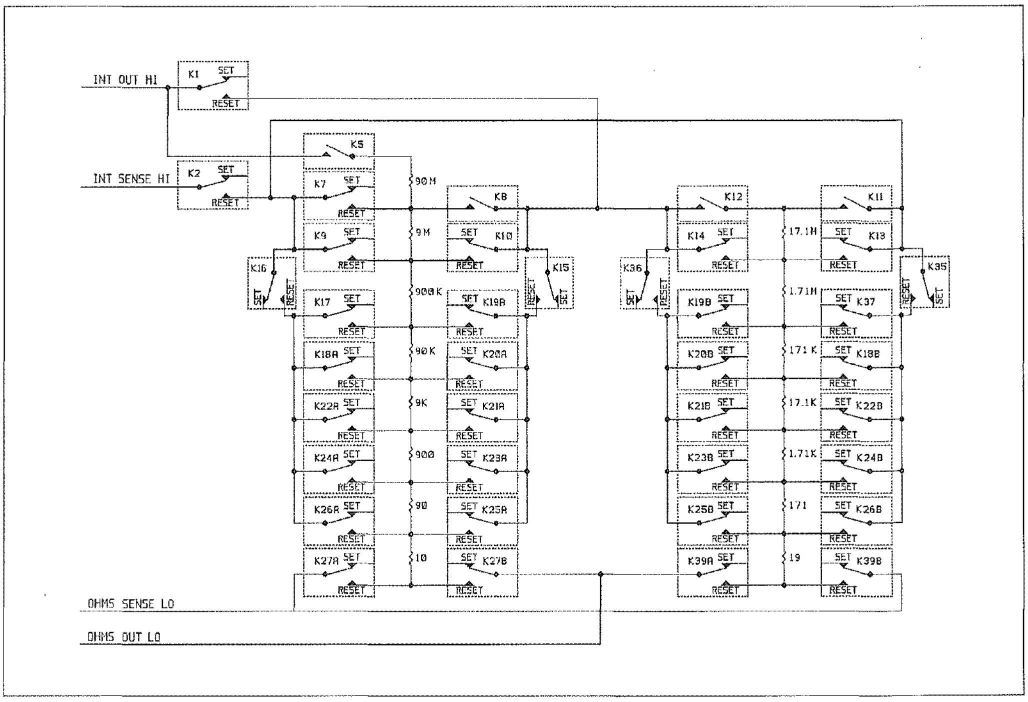


Figure 3.5 Ohms main assembly simplified schematic, showing the two strings of resistors, one for the decade values and one for the multiples of 1,9

The ohms cal assembly contains the low value resistors 1,9Ω, 1Ω, and short resistance. The 1,9Ω resistor is realized by placing two 3,8Ω resistors in parallel. Similarly the 1Ω resistor is realized by placing four 4Ω resistors in parallel. The ohms cal assembly also contains the two-wire compensation circuit and the electronics needed for calibration of the resistances during the Artifact Cal procedure. Among others this is 10:1 resistance divider (part Z5), that consists of a 10kΩ and a 90kΩ resistor. The 10kΩ resistor also is the internal 10kΩ reference standard of the calibrator, that is calibrated against the 10kΩ external reference standard.

The 1Ω, 1,9Ω, and short resistance also have four wire connections, similar to the resistors of the main ohms board shown in figure 3.5. The sense and out Hi connections of these resistors are guided via switches to the corresponding connections of the main board where they are available for connection to the output binding posts. The sense and out Lo connections of all resistors are guided via the ohms cal board to the output binding posts. Note that the use of four wire connections to the resistance elements in the calibrator eliminates the possible contribution of contact resistances of relays to the resistance value available at the output binding terminals.

3.4 DC and AC Current

The current function in the Fluke 5700A series II Calibrator is derived from an input voltage combined with an trans-conductance amplifier and a feedback control loop. In Figure 3.6 the block diagram of the current function is given. Depending which function is selected (IDC or IDC), a DC or AC voltage is used as input voltage. The trans-conductance amplifier converts the voltage into a current. This amplifier also selects one out of four available current ranges (220µA, 2,2mA, 22mA or 220mA). A fifth current range (2,2A) is also available, it is generated by a current amplification of the 22mA output current. The feedback loop measures the generated current through a voltage drop over a shunt resistor and uses this to control the amplitude of the input voltage.

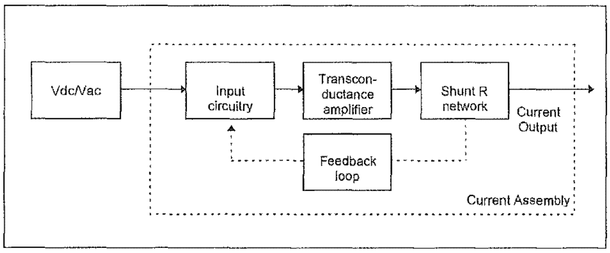


Figure 3.6 Block diagram of the current function

The block diagram in Figure 3.6 is given in more detail in Figure 3.7 [Service manual]. The current assembly (which is combined with the high-resolution oscillator assembly on a single board) generates the DC and AC currents in the range of 220µA to 220mA. The main building blocks are the input circuitry consisting of the divider Z1 and the complementary drive circuit, the trans conductance amplifier, the shunt resistor network and the feedback loop. Some extra circuitry is added, like the current input switching unit, the current output switching unit, the current guard buffer, the compliance limiter and the current/compliance voltage monitor.

The input voltage of the current assembly is selected from the DAC assembly (VDC) or the Oscillator Output assembly (VAC), depending on the required current function. The input voltage used is always configured in its 22V range. The complementary drive circuit provides the single-ended output DC amplifier on hybrid *HR2* to the output transconductance amplifiers. The *HR2* assembly consists of an op-amp mounted on a heated-substrate, bonded to the shunt resistor network.

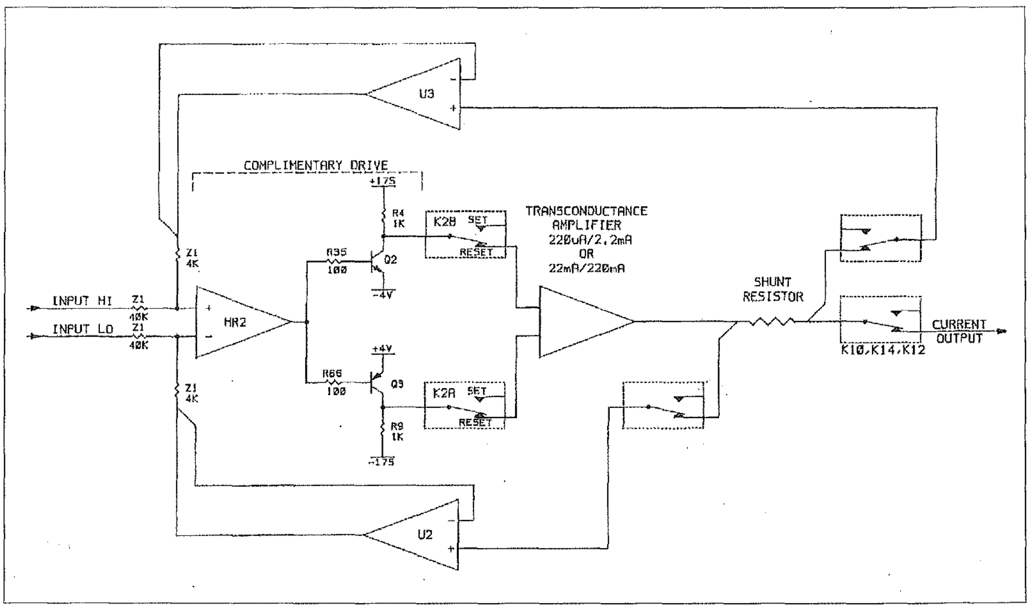


Figure 3.7 Simplified current assembly schematic

The trans-conductance amplifier is built around two amplifiers forming the 220:A/ 2,2µA range and the 22mA/220mA range. The required current range selects different amplification in the circuits. The feedback loop uses a shunt resistor network to sense the output current in the selected current range, the corresponding shunt resistor is given in Table 3.1.

Range	Shunt R
220µA	10kΩ
2,2mA	1kΩ
22mA	100Ω
220mA	10Ω

Table 3.1 Shunt resistor values for the different current ranges

The output current will generate a 2,2V full-scale voltage drop over the appropriate shunt resistor. This signal is fed back to the input by the precision dual 10:1 matched voltage divider network *Z1*. The input signal is compared to this feedback signal and any difference is amplified and applied to the complementary drive circuit and in turn to the transconductance amplifier to complete the feedback loop.

Therefore, with the 22V full scale input and the 10:1 divider, the voltage across the shunt network is forced to 2.2V by the feedback loop. The 2,2V across the shunt is developed by the full-scale output current on any of the four ranges. By programming the input voltage over a 10:1 range, the output current will follow by a 10:1 ratio. By switching between the shunt resistors, four 10:1 ranges give a total output range of 220µA to 220mA.

The 2,2A current is generated by using an extra current amplification. The current assembly is set to 22mA range with its output direct connected to the High Voltage/High Current assembly. This assembly has an amplifier which amplifies the 22mA by 100 to generate the 2,2A.

3.5 Firmware

The documentation of firmware development has evolved over the years since the 5700A was released. At the beginning of the 5700A firmware development, after the Firmware Requirement Specification (SRS) was completed, a Firmware Design Description (SDD) was written. Once the skeleton of the source code was completed, the SDD was not maintained. Fluke considered that the source code was adequately documented for internal firmware maintenance purposes. Also the difficulty of maintaining parallel sets of documentation did not justify the benefits. This firmware development procedure was documented in so-called Standard Operation Procedures (SOP's).

This practice has been changed for the later developed products like the 5790A and 5500A instruments so that a high-level document describing the relationship between subsystems was maintained, and the remainder of the SDD can be generated from the source code comments using a automated tool developed by Fluke. This modified procedure documented conforms to ISO9001, to which Fluke is certified. Because the 5700A Series II and 5720A are substantially similar to the 5700A, and because minimizing changes to correctly functioning code was considered wise by Fluke, a new SDD was not written, nor was the source code adapted to facilitate automatic SDD generation.

3.5.1 Validation and Verification

The validation and verification of the internal 5700 firmware has been accomplished by Fluke through the implementation and execution of a number of test programs and test plans. The error free operation of the original 5700A was tested over the remote interface using a program called RIFT (Remote InterFace Test), while front panel and analog testing of the original 5700A were done on an ad hoc basis by the entire project team and by running representative instruments through final calibration and verification in the factory. Testing of later versions was targeted to detect problems caused by the specific changes to the firmware from the previous version.

The firmware development team performs the inspections of the design and source code modules. Validation of subsequent releases of the firmware is done in a similar way. Formal documentation exists at the highest level but is sparse on details.

The 5700A series II and 5720A source code was verified by a test suite using a newer remote testing tool, RTest, and subsequent releases are also verified in this manner.

The differences between the original 5700A and 5700A series II/5720A code were inspected by the development team and one outside engineer who was part of the original 5700A firmware team. 5700A series II and 5720A firmware defects and enhancement requests are tracked using the Scopus ProTeam firmware package. Changes to the source code are tracked using a RCS (Revision Control System).

The original development team maintains the firmware for at least one year after release. Maintenance eventually passes on to manufacturing engineering. The transfer of control is done informally as dictated by availability of the original team members.

3.5.2 *Internal Communication*

The Fluke 5700A SeriesII calibrator is controlled by two processors: the Main CPU and the Inguard CPU connected to each other via a fiber optic link. See Fig. 3.8.

The communication protocol via the fiber optic link is a proprietary derivative of the SDLC protocol, with numbered packets, dropped packet detection and retransmission.

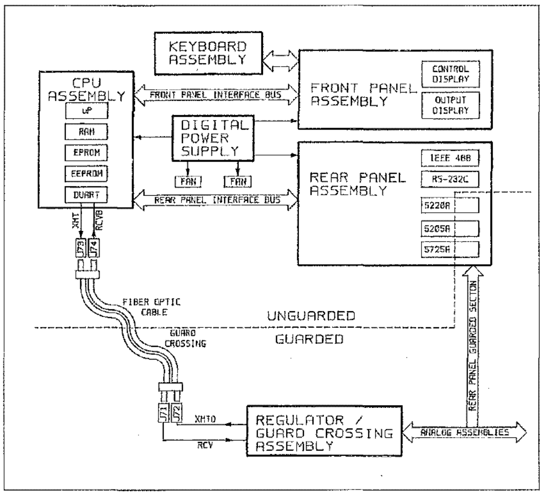


Figure 3.8 Block diagram

The communication link is actively maintained, and if either processor detects that the other is not communicating, it shuts down the instrument to a safe state and, in the case of the Main CPU, notifies the outside world.

Fluke developed the real time operating system, used in both the Main and Inguard CPUs. It is called YUK, and is also found, in other instruments. It is a lightweight, non-preemptive, non-prioritized multi-tasking kernel with simple semaphore and resource control. Its simplicity makes it suitable for instruments with a wide range of complexity; because it is non-preemptive.

3.5.3 *Firmware Versions and Overview*

The evaluated firmware versions of the 5700A Series II are:

- The main CPU firmware, which was evaluated during the glass box tests, had version number 1.3 (dated 19-dec-1996). The Fluke 5700 instruments, that were used for black box firmware tests, had main CPU firmware version 1.0 installed (dated 1-may-1996). The firmware does'nt differ in many points between version 1.0 and 1.3.
- The Inguard CPU is version B, dated 8-apr-1996.

The following numbers are to the nearest thousand lines or bytes.

CPU Firmware	No. of lines source code	Size of compiled code
Main	60 k	562 k
Inguard	3 k	14 k

Table 3.2

The source code for each CPU of the 5700A is divided into "subsystems"; each contained in a single directory. Each subsystem consists of one or more source code files and is assigned a prefix, which is used in the names of files and all functions, variable names, custom data types (such as structure definitions), etc. which are global in scope.
The firmware programs are executed in parallel in ten separate tasks that communicate with each other. The tasks are as follows:

MXTTASK	guard crossing transmit task
MXRTASK	guard crossing receive task
MBXTTASK	boost (only in a 5725 system) crossing transmit task
MBXRTASK	boost (only in a 5725 system) crossing receive task
OPMAN	normal operation, calibration, monitor, etc. task)
FP	front panel task
REM	remote task
REM_MON	does SRQs and print error messages in serial verbose mode
WATCHDOG	
REPORT	serial report printer

3.5.4 *Main CPU Firmware*

The main CPU source code is divided in subsystems as listed in table 3.3.

Acronym	Description	Acronym	Description
High Level		**High Level**	
EX	Command executive	SCA	Self Calibration
FP	Front Panel	SDI	SelfDiagnostics
OPM	Operations Manager	REM	Remote Interface (IEEE & Serial)
MON	Output real-time monitor	RPT	Calibration Reports
NRM	Normal Operation	STA	Instrument State Manager
Mid Level		**Mid Level**	
CCO	Calibration Constants Manager	SEQ	Hardware Control Sequencer
CNF	Configuration Database	VF	Value Finder (computes DAQ settings using cal constants
ERR	Error manager		
Low Level		**Low Level**	
Air	Low Airflow detection	OTD	Output Display
BX	Boost (5725A)serial protocol	RTC	Real Time Clock
DMD	Dot Matrix Display	SER	Serial Interface
GO	Power On Initialization	TIM	Timer
GX	Guard Crossing Serial Protocol	UT	Miscellaneous Utilities
K	Operating System Kernel	WD	Watchdog Timer Caretaker
KBD	Keyboard		

Table 3.3 CPU source code subsystems

EX executes commands sent in from FP or REM, and deals with conditions reported by OPM. EX and OPM maintain STA, which indicates both the present and the goal state (the two differ during a transition – for example, from one output value to another). EX also starts RPT printing a calibration report, when one is requested. MON, NRM, SCA, and SDI are subsidiary to OPM; that is, the Operations Manager task invokes the top level Normal operation, Self-calibration, Self-diagnostics, Monitor routines.

3.5.5 *Inguard CPU Firmware*

The Inguard CPU source code is a single subsystem that handles the low-level interface to the analog hardware. It can be divided in three logical units: Serial protocol, Virtual register interface and Relay refresh.

4 Artifact Calibration Description and Discussion

4.1 DC Voltage & Linearity Artifact Calibration

Calibration against an external 10V standard is performed using the switch matrix to build up the required connections and an analog-to digital-converter (ADC) to measure voltage differences. A so called "cal zero" amplifier is used to increase the resolution of the ADC when measuring offsets (see also figure 3.1). Calibration is required for the voltages of the references and for the gain and offset of the DAC, the dividers and the amplifiers. The offset and gain values of the various building blocks are stored as calibration constants in non-violable memory.

4.1.1 Digital-to-analog-converter

The digital-to-analog-converter (DAC) consists of two pulse-width-modulators (PWM), one for coarse adjustment and one for fine tuning. After summing and filtering the PWM-outputs, the signal is multiplied by one or two and buffered to obtain 11V or 22V output voltage. For calibrating the DAC, the ratio of the two PWM-gains is determined to ensure smooth transition from coarse to fine adjustment. The linearity of the DAC is checked by measuring the 6.5V reference in the 22V-range and comparing the result with the value measured in the 11V range. This is done after these ranges have been calibrated.

4.1.2 11V and 22V-Range

The zero values of the 11V and the 22V range are determined using the internal ADC as a null detector connected to the output via the cal zero amplifier. The DAC is adjusted to obtain zero reading at the ADC and the corresponding setting is stored as offset value. Finally the 11V and the 22V range gains are calibrated against the external 10V reference standard. As with the offset measurement, the DAC is again adjusted to obtain zero difference between output and external standard. From this setting the gain is calculated.

4.1.3 Internal reference voltages

Using the calibrated the DAC and the ADC-null detector, the values of the internal reference voltages (6,5V buffered and un-buffered as well as 13V buffered and un-buffered) are measured in the same way as the DAC gain was calibrated.

4.1.3 Internal reference voltages

Using the calibrated the DAC and the ADC-null detector, the values of the internal reference voltages (6,5V buffered and un-buffered as well as 13V buffered and un-buffered) are measured in the same way as the DAC gain was calibrated.

4.1.4 2.2V Range

The 5:1 divider used for the 2.2V range is made up of a hybrid resistive divider followed by a precision buffer amplifier. Calibration involves determining both offset and gain. First the ADC null-detector is connected to the divider output and the DAC to the input. The DAC setting for zero reading gives the offset.

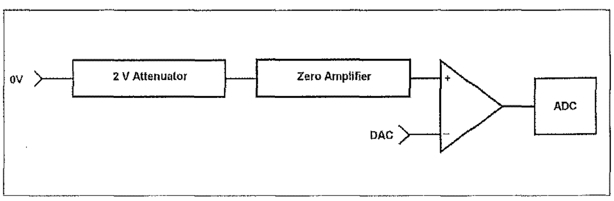


Figure 4.1 2,2V attenuator offset calibration

To calibrate the gain, the divider input is connected to the 13V buffered reference and the output is measured using the DAC and the ADC null-detector. From the calibrated reference voltage and the measured output voltage the gain is calculated.

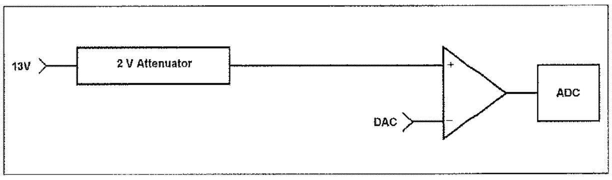


Figure 4.2 2,2V attenuator gain calibration

4.1.5 *Cal Zero Amplifier*

The 5:1 divider is then used to calibrate the gain of ten of the cal zero amplifier. First the offset of the combo of 5:1 divider and cal zero amplifier is calibrated as described before.

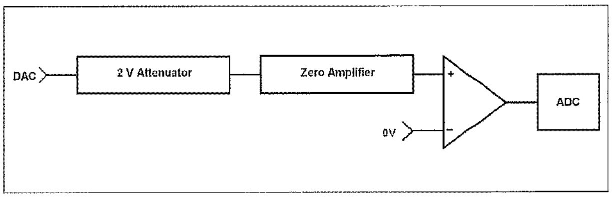


Figure 4.3 Combo of 2V attenuator and cal zero amplifier offset calibration

Then the DAC is connected to the 5:1 divider input. The output voltage of the cal zero amplifier is compared to the 6.5V buffered reference using the ADC. The DAC is then adjusted to achieve a null reading at the ADC and the gain of the cal zero amplifier is calculated.

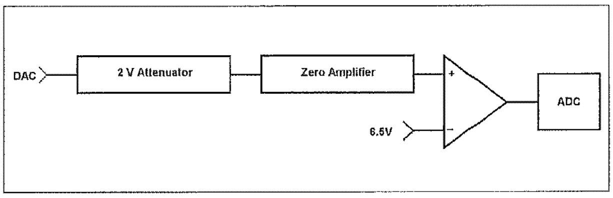


Figure 4.4 Cal zero amplifier gain calibration

4.1.6 *220mV Range*

The 220mV range is derived from the 2.2V range using a 10:1 passive divider. The offset is calibrated in the same way as for the 2.2V range.

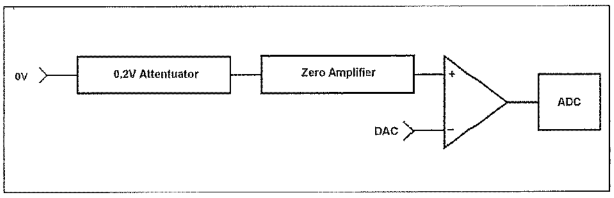


Figure 4.5 220mV attenuator offset calibration

The gain is measured by canceling the attenuation of the divider using calibrated gain of ten of the cal-zero-amplifier. For this measurement the input of the 10:1 passive divider is connected to the DAC output, which is set to 2.2V. The cal zero amplifier's input is connected to the 220mV output and its output (again nominally 2.2V) is compared to the DAC output with the ADC.

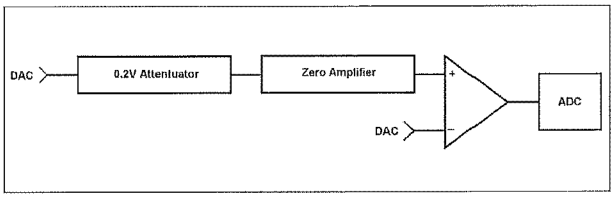


Figure 4.6 220mV attenuator gain calibration

4.1.7 *220V-Range*

The x20 power amplifier used in the 220-V-range is calibrated using an auxiliary resistive divider with a ratio of 8:1. First the offset of the power amplifier is determined as described earlier using the DAC and ADC.

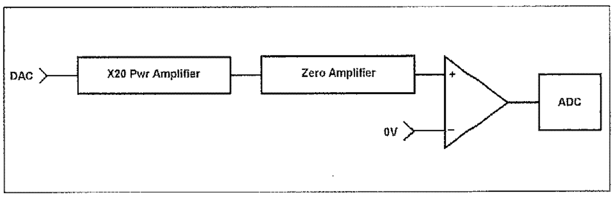


Figure 4.7 x20 power amplifier offset calibration

Then the auxiliary divider is calibrated for offset and gain. The offset is calibrated as described before.

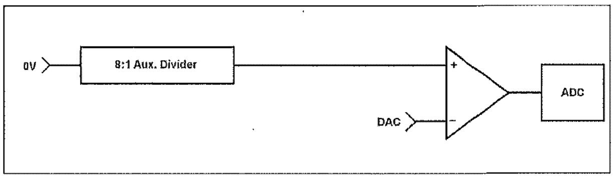


Figure 4.8 8:1 auxiliary divider offset calibration

To calibrate the gain, the 13V buffered reference is connected to the input of the auxiliary divider producing 1.625V at the output, which are measured using the DAC and ADC.

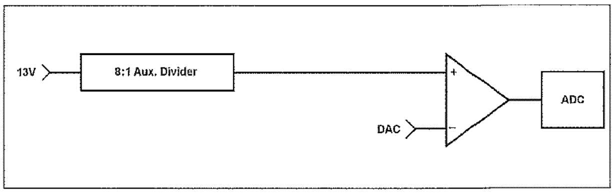


Figure 4.9 8:1 auxiliary divider gain calibration

Now the gain of the power amplifier is calibrated by connecting the 6.5V buffered reference to its input producing 130V at its output. This output voltage is attenuated by the auxiliary resistive divider and measured using the DAC and ADC

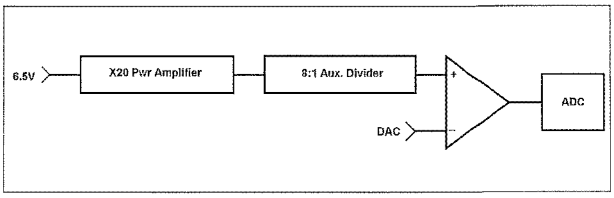


Figure 4.10 x20 power amplifier gain calibration

4.1.8 *1000-V-range*

The x100 high voltage amplifier used in the 1000V range is also calibrated for offset and gain. The offset calibration is straightforward using the DAC and ADC.

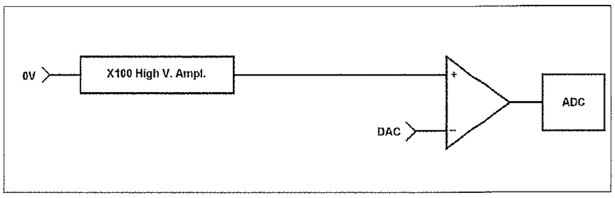


Figure 4.11 x100 high voltage ampl. offset calibration

The gain is calibrated via the ratio of the gain resistors. These resistors are exchanged to give a gain of 0,01 instead of 100. Then a voltage of 130V is generated by the x20 power amplifier fed from the 6.5V buffered reference. This voltage is applied to the input and the corresponding 1.3V output voltage is measured using the DAC and ADC.

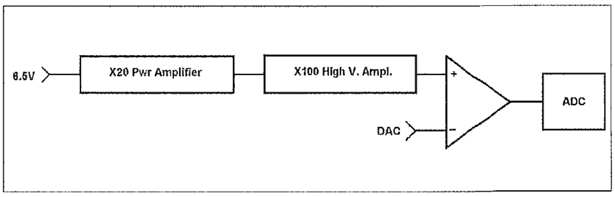


Figure 4.12 x100 HighVoltage ampl. gain calibration

4.1.9 *Traceability chain*

The internal reference voltages are measured using an external 10-V-standard and are therefore traceable to this standard. Then the calibration procedure uses only voltage ratios to calibrate the DC ranges. In this way all DC voltages are traceable to the external standard.

4.2 AC Voltage Artifact Calibration

4.2.1 *Oscillator frequency*

The demand of frequency accuracy is not very high during calibration of High Performance Voltmeters, therefore is the frequency of the oscillator not calibrated during the Artifact Cal procedure.

4.2.2 Oscillator gain control

The Artifact Cal procedure measures the offsets and the DC attenuation ratios of the active attenuators. It also uses the internal primary 6,5V DC and 13V DC references as well as the internal DAC assembly in combination with an analogue to digital converter, ADC, to generate and measure precision DC voltages.

The frequency flatness of the different attenuators in combination with the AC-DC thermal sensor circuit are compared with a second internal thermal sensor circuit with passive, resistive, attenuators. The Artifact Cal procedure adjusts the software frequency flatness corrections to make the frequency flatness response of the AC voltage function equal to the AC-AC sensor circuit frequency flatness.

The Artifact Cal procedure resets any prior Range Calibration adjustments. The Range Calibration is a feature of the calibrator allowing the adjustment of an additional gain multiplier for each range. The Artifact Cal procedure does not record if it changes these gain multipliers.

4.2.3 2,2V AC and 22V AC range

- ***Offset and Gain Measurements***

The offset and gain measurements of the AC-DC sensor circuit are made at dc voltage and considered as valid for frequencies up to 1kHz. AC-AC characterisation is made for frequencies above 1kHz. The offset measurement starts with the precision DC voltage DAC set to zero voltage with DAC sense at the input of the AC sense buffer. The setting of the DAC is called V_{in1}.

With the DAC set to zero voltage and the AC sense buffer set to the 2,2V range, the output of the AC sense buffer is measured by the ADC circuit on the DAC assembly. The output offset voltage from the AC voltage sense buffer is lead to the input of the ADC circuit by a relay and a JFET transistor. The input zero volt setting of the DAC is stored as V_{in1}. The measured offset voltage is stored in memory as V_{out1}.
The primary 6,5V DC reference is connected to the DC voltage sense buffer and the output of the AC-DC thermal sensor is measured by the DAC assembly, in the same way as a DC measurement in an AC-DC transfer measurement. The thermal sensor output voltage is stored as VTDC. The DAC is set to 2V at the input of the AC sense buffer and the DAC output is adjusted until the sensor output equals VTDC. The DAC setting is stored as V_{in2} and the 6,5V reference value is stored as V_{out2}. The gain G is calculated as:

$$G = \frac{V_{out2} - V_{out1}}{V_{in2} - V_{in1}} \qquad (4.1)$$

The offset and gain of the 22V range are measured by an identical procedure.

The offset and gain are not measured at the voltage sub ranges 0,22V to 0,7V and 2,2V to 7V, thus the influence of relay K7 is not measured during the Artifact Cal procedure at the 2,2V and the 22V range measurements. Since the DC sense buffer circuit offset is not measured there is an error introduced in the gain measurement of the AC sense buffer. Based on the specification of the buffer amplifier, LT1007, the error is estimated to be in the order of 3 ppm, which is negligible compared to the instrument specification.

In a traditional AC-DC transfer measurement, the DC voltage is measured with both positive and negative polarity. This is done to minimise errors due to DC offset in the input circuit and thermo-electric effects in the sensor. As the AC-DC measurements both during normal AC voltage operation and during the Artifact Cal procedure, measures only the positive polarity of the applied DC voltage, it is the stability of the thermal sensor DC offset that is crucial for long term AC voltage accuracy.

- ***Frequency Flatness measurement procedure***

The frequency flatness of the AC-DC sensor circuit is compared to a second thermal sensor circuit by AC-AC measurements. The measurement procedure starts with the setting of an AC voltage at a low frequency. The low frequency is 220Hz for the flatness measurement at all voltage ranges, except for the 1100V range where the low frequency is 110Hz.

The low frequency voltage, 2V for the 2,2V range, is connected to both the AC-DC sensor circuit and the second sensor input. The second sensor is called the AC-AC sensor. An AC-DC transfer measurement is performed with the AC-DC sensor circuit. The DAC assembly takes a reading of the AC-AC sensor output. The AC voltage frequency is changed to the first higher measurement point. The voltage is adjusted until the AC-AC sensor output voltage is the same as for the low frequency measurement, the resolution of the adjustment is approximately 2 ppm. The output of the AC-DC sensor is measured and the relative difference of this measurement and the AC-DC sensor measurement at the low frequency is calculated and the shift of the corresponding flatness constant is calculated and stored in memory. The AC voltage frequency is changed to the next higher frequency and the procedure starts again.

The low frequency measurement is only done once in the beginning of the flatness measurement procedure. This emphasis the demand for stability of both thermal sensor circuits during the flatness measurement procedure. The flatness measurement shows the relative difference of the frequency responses of the two thermal sensor circuits.

The flatness measurement plane of reference is different than the plane of reference during normal AC voltage operation, which is at the instrument output terminal, see also Figure 4.13. The input of the AC sense buffer and the input of the AC-AC sensor are during the flatness measurement directly connected to an internal connection point of the

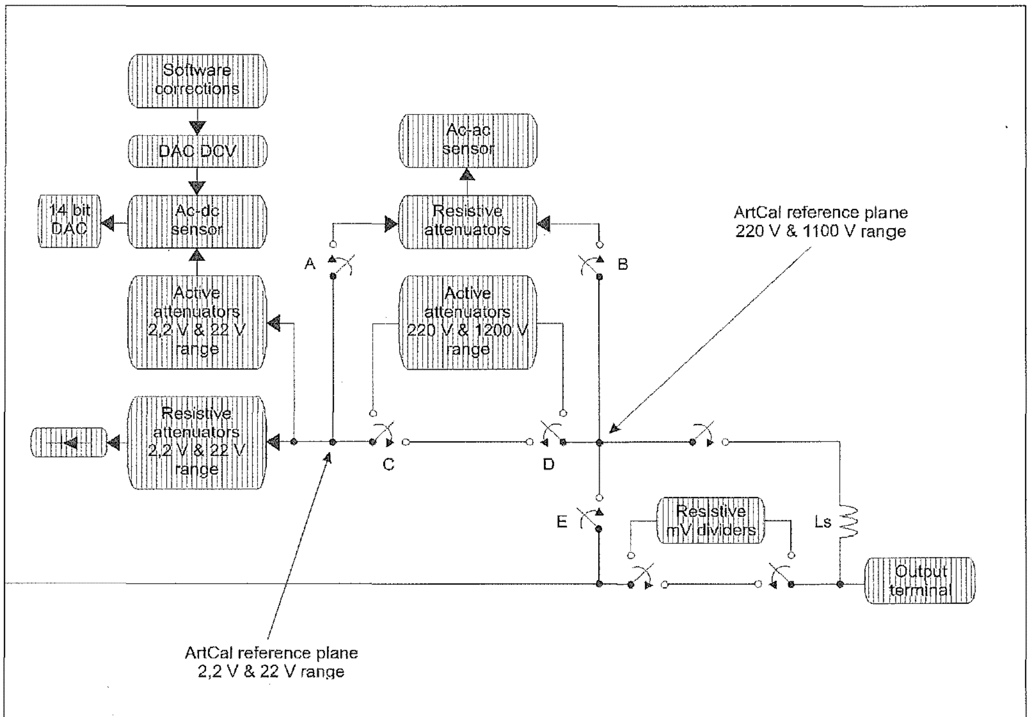


Figure 4.13 Simplified schematic diagram of Artifact Cal reference planes

calibrator. During normal operation of the calibrator, the AC-DC thermal sensor circuit senses the output voltage at the output terminal binding post of the calibrator through relays K19 B, K18 A, K25, K26, K13 and K15 in the Switch Matrix assembly, through relays K2 and K3 in the Analog Mother Board assembly, through a toroid and also through an inductor L2 at the front panel terminal. The different sense lead path introduces a frequency response deviation. The deviation is more significant at higher frequencies due to change in impedance of the input lead to the AC sense buffer. The stability of the deviation depends mainly on the stability of the inductor L2 and the toroid. There is also an inductance arising from the geometrical dimensions and layout of the sense lead. The total sense lead inductance is shown as Ls in Figure 4.13. The error due to geometrical instability is estimated to be negligible. Also the error due to change of the skin effect in the relays and sense leads are estimated to be negligible compared to the calibrator specification.

In this schematic diagram, which is a part of Figure 3.2, relays A, C, D and E are closed for the Artifact Cal calibration of the 2,2V and the 22V ranges. Other shown relays are left open. For the Artifact Cal calibration of the 220V and 1100V range, relays C and D switches in the appropriate active attenuator, relays B and E are closed and the other schematically shown relays are left open.

The input resistance of the ac sense buffer amplifier is 2kΩ for the 2,2V range and 20kΩ for the 22V range. The contact resistances of the relays connecting the AC sense buffer to the front binding post will introduce a frequency independent error. The specifications for this (K4) relay contact-resistance are

- Initial: less than 200 mΩ
- End of life: less than 1Ω

A contact resistance instability of 50 mΩ would correspond to an error in the order of 20 ppm at the 2,2V range. Considering the best specification of the Fluke 5700 on the 2,2V range, which is 63 ppm for k=2, the relay contact resistance variation should be less than 50mΩ. However, the short term instabilities of this contact resistance is possible to verify by making repeated measurements of for example 1V AC at the 2,2V range, switching between the 2,2V range and the 22V range between measurements. Measurements of the test calibrators show relative variations due to relay K4 contact resistance which are less than 2 ppm. These measurements correspond to contact resistance variations less than 5 mΩ. Since the "End of life" contact resistance is specified 5 times higher than the initial contact resistance, the instability of the contact resistance is likely to increase with time and use of the calibrator. However, the relay is specified for at least 5.10^6 operations.

In the 22V range the AC-AC sensor input attenuation circuit consists of a resistor, 3,61 kΩ, in series with the 400Ω heater resistor. In the 2,2V range the 3,61kΩ resistor is shorted by a relay, K9. There is also an input select relay, K5, which connects the input to the sense lead common with the AC-DC sensor. The K5 and K9 relays are of the same model as K4. Assuming a contact resistance variation of 5mΩ from operation to operation of one relay would lead to a total variation of 7mΩ for two relays (Root of sum of squares calculation). However, the relays are only operated once before a complete flatness measurement which means that it is only the frequency response change due to the 7mΩ contact resistance that is of interest. The relative error due to a skin effect change that corresponds to different contact resistances is estimated to be less than 3 ppm at 1MHz.
The relative error due to RC-filter effect is estimated to be less than 0,1 ppm. The instabilities due to contact resistance variations are negligible compared to the specification.

The full range frequency flatness correction constants for the AC-DC thermal circuit are adjusted by the Artifact Cal procedure to bring the measured flatness difference between the AC-DC sensor circuit and the AC-AC sensor circuit to zero. The adjusted AC voltage flatness constants are stored in non-volatile memory. All calibration constants are listed in appendix C in the calibrator operator manual.

- ***The thermal sensor low frequency error***

The sensor low frequency error is related to the time constant of the sensor. The shorter time constant, the faster the temperature response of the sensor input heater resistor. The time constant is related to the heat capacity of the heater resistor. A short time constant is desirable for a fast AC output voltage settling of the calibrator, however, choosing a too short time constant will make the heater resistor temperature, to some extent, follow the instantaneous power due to the input AC voltage. When this happens the sensor looses some of its true RMS sense function and an error is introduced. For a given time constant the error increases with lower frequency and with higher AC voltage amplitude.

The calibrator does correct for the sensor low frequency error. This is an enhancement compared to earlier models of the Fluke 5700 calibrator. The correction factor LCF is calculated as follows:

$$LCF = 1 - LNC\left(\frac{Voltage\_Level}{Frequency \bullet Voltage\_Sub\_Range\_max}\right)^2 \qquad (4.2)$$

Where LNC is the calibration constant A4FH with default value 0,02431807. This constant is measured and adjusted during the Artifact Cal procedure. By measuring 0,6V and 10Hz in both sub ranges to the 2,2V range, the 0,22V - 0,7V range and the 0,7V - 2,2V range, this constant is calculated and updated during Artifact Cal.

- ***Convergence constants***

During normal operation of the calibrator the AC-DC sensor controls the 0,22V - 22V amplifier with a 14 bit DAC. The initial setting of the 14 bit DAC is determined by a calculation that involves corrections for the AC voltage frequency and amplitude. The corrections are based on Artifact Cal measurements at maximum and minimum voltage of each range. These measurements are made before the flatness measurements in the Artifact Cal procedure. Thus the Artifact Cal procedure uses the active and maybe old flatness constants and sets the calibrator for the desired voltage and frequency. It adjusts the 14 bit DAC by AC-DC measurements and when the AC-DC difference is sufficiently small, the Artifact Cal procedure stores the setting of the 14 bit DAC in non-volatile memory as a convergence constant.

The following formula shows how the start value for the 14 bit DAC is calculated.

$$DAC\ value = Cval + \frac{Vval}{scaledV} \qquad (4.3)$$

Cval is a linear interpolation between convergence constants.

Vval is a linear interpolation between 1/V convergence constants, which corrects for the calibrator AC voltage level dependence.

scaledV is the voltage for the AC range 2,2V or 22V. For other ranges, the range gain factor is applied. (E.g. Calibration constant A1G for the 2,2mV range).

The convergence constants are used to calculate the start value for the 14 bit DAC whenever the calibrator is set to output an AC voltage. This is done to make the AC-DC adjustment process converge more rapidly.

- ***The AC Xfer ON/OFF Choice***

In the operator manual page 4-12, there is a short description of the AC Xfer Choice feature and how to access it on the Special function menu.

According to the manual, setting an AC voltage, with the AC Xfer OFF feature enabled, will inhibit internal transfers from being made after the output has settled. Changing the calibrator's output will reinitiate transfers until the output has settled. There are some errors in the description:

- It is written: "The AC Xfer Choice feature activates another soft-key that lets you turn off the monitoring system that makes adjustments for load changes." The full description should be as follows: "The rectifier feedback loop always maintains the AC sense function and keeps making adjustments for load changes. The AC-DC transfer adjustment process, called monitoring system, that is turned off can be viewed as a process that, when activated, corrects for and eliminates the drift in the rectifier feedback loop circuitry".
- It is written: "The AC Xfer OFF feature is available only in the ranges below 220V, at frequencies below 120kHz." But should be: "The AC Xfer OFF feature is also available for all available frequencies on the 220V range, 10Hz to 1MHz."

The manual does not tell that when the AC Xfer Choice is not available for the user, the calibrator is automatically set to turn off the AC-DC transfers once the output is settled. It is done in the same way as when the user sets the instrument to AC Xfer = OFF, the only difference is the settled criteria, which is looser. The calibrator automatically turns off the transfers because the transfers generate too much noise on the output voltage at the higher frequencies.

If the user sets the AC Xfer = OFF, the AC output voltage is considered settled when the last AC-DC measurement and adjustment is less than 7,5 ppm. For voltages where the calibrator by it self turns off the AC-DC transfers, the corresponding settled criteria is 30 ppm.

When the AC-DC transfers are turned off, the settled criteria of 30 ppm represents an AC voltage uncertainty contribution. Considering the 30 ppm as a max. AC-DC error with rectangular probability distribution, leads to a calculated 1σ uncertainty of 17 ppm.

The following table shows for what voltage ranges the AC Xfer choice = OFF is available to the user, the corresponding AC voltage uncertainties (1 σ) due to the settled criteria and the corresponding voltage range's smallest specification (1 σ).

AC voltage uncertainties due to the settled criteria						
	Frequency range 10 Hz - 119,99 kHz			Frequency range 120,00 kHz - 1MHz		
Voltage Range (V)	AC Xfer choice = OFF available (Yes/No)	Settled 1 σ uncert. (ppm)	Smallest 1 σ Spec. (ppm)	AC Xfer choice = OFF available (Yes/No)	Settled 1 σ uncert. (ppm)	Smallest 1 σ Spec. (ppm)
2,2 m	No (*)	17	1023	No	17	3406
22 m	No (*)	17	156	No	17	723
220 m	Yes	4	61	No	17	507
2,2	Yes	4	31	No	17	205
22	Yes	4	31	No	17	234
220	Yes	4	34	Yes	4	854
1100	Yes (**)	4	34			

Table 4.1 AC voltage uncertainties due to the settled criteria

(*) The calibrator falsely presents the user with the display option of making the Xfer choice. The default setting incorrectly shows Xfer = ON. The AC-DC transfers are always automatically turned off for the 2,2mV and the 22mV range, because the transfers generates to much noise.

(**) The frequency range is limited, 15Hz to 1KHz.

The worst case is the 17 ppm uncertainty compared to the 156 ppm 1 σ specification on the 22mV range. Adding the 17 ppm to the specification, by a root-of-sum-of-squares calculation, increases the specification figure with only 1 ppm, which means a 2 ppm increase to the 95% confidence level specification figure. The settled criteria uncertainty is considered negligible.

When the AC Xfer choice is available to the user, the default instrument setting is AC Xfer = ON. In this case, when the settled criteria is reached and the "unsettled" character u in the display is switched off, the transfer process continues. The process continues but with a lower rate, it makes approximately one transfer every seven seconds. Thus, in this case the settled criteria does not correspond to a final settled uncertainty as the continuing transfer process is likely to decrease the AC-DC difference.

The transfers are automatically turned off for a large part of the calibrator's possible AC voltage settings, leaving the AC voltage not monitored by the AC-DC process. The calibrator specification does not explicitly limit the length of time a set AC voltage will still be within specification. The specification, which is without this type of time limit, indicates that the Artifact Cal procedure measuring the AC-DC transfer circuits, is less relevant for these not monitored AC voltages.

There is an implicit limitation to the continuous use of a calibrator once set to output an AC voltage, the specification requirement of performing the DC zeros calibration at least every 30 days. However, the DC zeros uncertainties are negligible compared to the AC voltage specification at the not monitored AC voltages.

Regardless of the AC voltage frequency the calibrator initially makes AC-DC transfer adjustments when the calibrator is set to output an AC voltage. Thus, the convergence constants should have no effect on the output voltage accuracy.

• ***Conclusions***

The AC voltage frequency flatness is measured and adjusted against the AC-AC internal thermal sensor. As the second sensor is not measured against external standards during the Artifact Cal procedure the stability of the second sensor must be verified by traceable external calibration of the AC voltage function.

The second thermal sensor input circuit is passive, as there is no amplifier involved. However, the input select relay and the range select relay will have some influence on the stability of the frequency flatness of the second thermal sensor circuit. To determine this influence, repeated Artifact Cal measurements will be performed in the test measurements. The results of the other measurements are presented in chapter 5.

The long-term drift of the Artifact Cal procedure dedicated internal reference and measurement circuits, e.g. the AC-AC reference sensor, will be outside the scope of the project.

The AC input circuit of the AC-DC sensor consists of an amplifier with selectable gain. The different solution of the input circuit of the reference thermal sensor gives a more independent measurement of the AC voltage. The passive solution of the reference sensor gives a more reliable frequency response with respect to ageing and malfunction.

The AC voltage deviation due to different reference planes, different sense paths, during the Artifact Cal procedure compared to normal operation is determined by measurements presented in chapter 5 as well.

As for the dc offset and gain measurements, the sub ranges 0,22V to 0,7V and 2,2V to 7V are not measured for frequency response, thus the influence of shorting the 866Ω resistor with relay K7 is not measured at the 2,2V range and the 22V range Artifact Cal measurements.

Convergence constants are adjusted by the Artifact Cal procedure. They are used to calculate the AC-DC transfer process start value for the 14 bit DAC. The convergence constants shall not influence the output voltage accuracy. This is verified in the glass box evaluation measurements.

For some voltage-frequency combinations the AC-DC transfer process is automatically turned off, once the output AC voltage is settled. As the specification does not limit the time of use of a once settled voltage, this makes the relevancy for performing the Artifact Cal procedure for these voltages not so clear.

4.2.4 *The 220V AC range*

- ***Offset and DC gain measurements***

The DC offset and gain measurements of the PA are discussed and evaluated in chapter 4.1.7 of this report. The measured PA is used to determine the DC attenuation of the 220V AC range attenuator.

The 220V AC attenuator consists of an operational amplifier, U4, set for an inverting gain of -0.01. The input resistor value is 400kΩ and the feedback resistor value is 4kΩ.

The offset of the attenuator is measured with the non-inverting input of U4 connected to common.

The PA is set to output -130V as in the DC measurement of the PA. The output of the PA is connected to the input of the AC attenuator. The PA senses the generated -130V DC voltage close to the input of the ac attenuator. There is one relay connector, K16B, between the sense point and the 400kΩ input resistor of the AC attenuator. The K16B relay is used to switch between the PA DC output and the PA AC sense. The specified contact resistance and the thermal EMF of this relay is considered to give a negligible error in this measurement.

The DAC assembly measures the 1,3V DC output of the attenuator and the system software computes the DC attenuation of the AC attenuator.

- ***Frequency flatness measurements***

The Frequency flatness of the 220V AC range attenuator is compared to the AC-AC sensor circuit at 22V. Measurements are made up to 1MHz. The frequency flatness measurements are made in an identical procedure as for the 2,2 and 22V ranges. The PA is set to 22V and the output is connected to both the AC attenuator input and the AC-AC sensor circuit. The output of the AC attenuator is connected to the oscillator control assembly, thus providing feedback as in normal operation. The output voltage of the AC attenuator is 0,22V and is measured at the low end of the 2,2V range of the AC-DC sensor circuitry. The low range measurement results in less resolution compared to the flatness calibration of the 2,2V and the 22Vrange. The oscillator is adjusted to make the readings at different frequencies of the AC-AC sensor equal. The adjustments of the oscillator is used in the same way as for the lower voltage ranges to adjust the 220V AC range full scale flatness constants.

As for the lower voltage ranges the AC-AC sensor senses the PA output voltage at a different reference plane than the 220V AC attenuator does during normal calibrator operation mode. The different sense reference planes results in a frequency response deviation. The same reasons as for the lower voltage ranges are also applicable for this voltage range and the 1100V AC range discussed in the following chapter.

- ***Conclusions***

The AC attenuator is measured at the low end of the range and therefore the specified voltage dependence of the attenuator has to be sufficiently low.

4.2.5 *The 1100 ACV range*

- ***Offset and DC gain measurements***

The DC offset and gain measurements of the HR7 hybrid, the HVA, is covered in chapter 4.1.8 this report. This gives both the DC HVA gain and the 1100V AC attenuator DC attenuation.

• *Frequency flatness measurements*

The AC voltage frequency flatness of the 1100V AC attenuator is measured by comparison with the AC-AC thermal sensor circuit. The high voltage output and sense are connected together by relay K11 on the High Voltage / High current assembly. The high voltage output is also connected to the AC-AC thermal sensor circuit by relays K10, K8A and resistor Z6. The resistance of Z6 is 399.6kΩ. In normal calibrator operation the high voltage sense is connected to the front panel binding posts by relays K3, K2 and K10 on the Analog mother board. Errors due to different relays and sense current paths are estimated to be negligible for the high voltage frequency range 15Hz to 1kHz. The AC-AC comparison is made in a similar way as for the lower voltage ranges. The first reference measurement is made at 695V and 130Hz. The measurements at higher frequencies results in adjustments of the flatness constants. The adjustments is presented as full scale shifts in the Artifact Cal print-out report.

• *Conclusions*

Since the offset and gain measurements are made at 130V DC and the frequency flatness measurements are made at 695V the voltage dependence of the 1100V AC attenuator should be low compared to specification.

4.2.6 The AC mV ranges

• ***Offset and DC voltage division ratio measurements***

For the Artifact Cal procedure measuring the DC offset and the DC division ratio of the mV dividers please see chapter 4.1.6.

• *Frequency flatness measurements*

The frequency flatness of the mV range dividers is not measured during the Artifact Cal procedure. The figures that are presented as AC voltage Full Scale Shifts of the mV ranges in the Artifact Cal print-out report are based on the frequency flatness measurements of the 2,2V range and the 22V range in combination with the DC voltage measurements of the dividers.

4.2.7 Traceability chain

The AC voltage of the calibrator is determined by the DC voltage, the oscillator frequency and the frequency response of the internal amplifiers and attenuators. Of these parameters it is only the DC voltage of the calibrator that is measured using an external traceably calibrated reference standard. In the Artifact Cal procedure the frequency flatness of the AC-DC sensor and the active attenuators are calibrated and adjusted with the AC-AC sensor as reference. But on each range only one of the two sub-ranges are calibrated for the frequency response. Due to this fact and since neither the frequency response of the AC-AC sensor nor the frequency is calibrated using external standards it is concluded that the AC voltage is not traceably calibrated by the Artifact Cal procedure. A block diagram, Figure 4.14 illustrates the traceability chain.

The dotted lines in the figure show Artifact Cal connections. The solid lines show the connections during normal operation. This illustrates the different measurement reference planes during the Artifact Cal procedure and during Normal operation. The significance of this is investigated in the glass box test.

Since the Artifact Cal procedure makes software adjustments of the ACV function of the calibrator, based on comparisons between the two internal thermal sensor circuits, this would at first look as if the Artifact Cal procedure breaks the traceability chain. However, traceability to the last performed traceable external calibration, Full Verification, can be retained by storing, saving, all the relevant software constant values at the time of the Full Verification and after the Artifact Cal adjustment procedure has

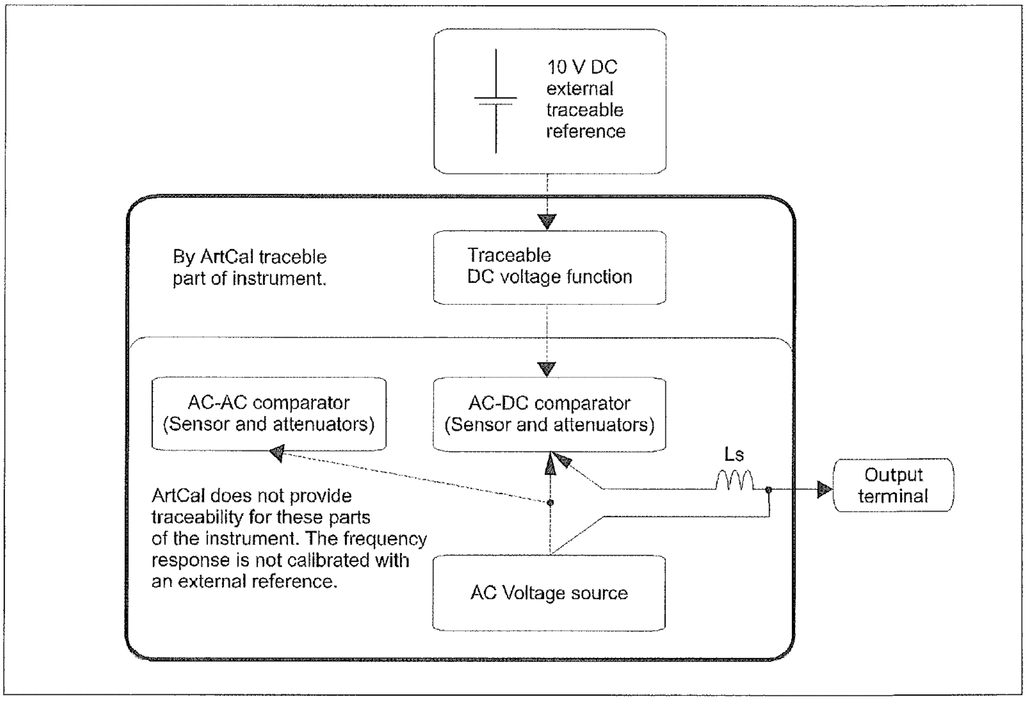


Figure 4.14 Traceability chain of ACV function

been performed. Then since no hardware adjustments are performed by Artifact Cal and since it is in principle possible to restore the exact set of software constants that were valid at the time of Full Verification, it is possible to reset the instrument to the performance that would have been if no Artifact Cal had been performed at all. Thus: eliminate the effect of Artifact Cal.

By measuring the instrument output voltage with the Artifact Cal-adjusted set of constants active and also measure with the Full Verification constants active, it is possible to measure the effect of the Artifact Cal procedure at any possible voltage-frequency combination.

Assuming that there is, which is investigated in the opaque and the glass box tests, a predictable output voltage response to changes in the constant values, it is in principle not necessary to measure the output voltage difference due to the Artifact Cal procedure. The effect of changes to the constant values could be calculated using the same calculations as the instrument software uses to calculate the precision DAC setting during normal operation. This software takes the user set voltage, the user set frequency and the software constants as input and calculates the precision DAC setting. The output voltage change could be calculated as the difference of the calculated DAC setting with the Artifact Cal adjusted constants and the calculated setting with the Full verification constants. In fact, there is almost such a feature built into the instrument. The instrument Artifact Cal print out report software routines performs a calculation of the full scale voltage shifts at each range. However, only the full scale voltage shifts are presented in the Artifact Cal print out report, and since also the thermal sensor low frequency voltage level correction constant is adjusted by Artifact Cal, the necessity of also documenting the minimum scale shifts is evident. The performance of the Artifact Cal report software will be investigated in the opaque box measurements and in the glass box measurements.

- ***Conclusions***

The Artifact Cal procedure does not provide a traceable calibration of the output AC voltage of the instrument. This is due to the two following facts:

1. The frequency response of the AC voltage is not calibrated with an external, traceable AC voltage reference, a reference with stated uncertainties.

2. The Artifact Cal measurement reference plane is not at the instrument output terminals.

It is in principle possible to perfectly determine the effect of the Artifact Cal adjustment procedure by calculation. Given this possibility, the Artifact Cal procedure does not break the traceability chain.

4.3 Resistance Artifact Calibration

The basic calibration principle that is used in calibrating all resistors of the Fluke 5700A calibrator is comparing voltages across a known and an unknown resistor that are both fed by the same current. This current is either delivered by the internal voltage reference (for the resistors of 10Ω and higher values), or by the DC current assembly (for the 1Ω and 1,9Ω resistors). The measurement of the separate voltages is done fully similar to that during the DC voltage calibration. Extra relays are available on the ohms main and cal boards for making all the required connections in the calibration process.

Calibration is required of all resistance values that are available during normal use at the output binding posts.

The resistance and ratio values that are measured during calibration are stored in non-volatile memory at the end of the calibration process. Each resistance has its own symbolic name, which can be logically derived from the resistance value. For example, the constant R10 denotes the value of the 10Ω resistor, and R1_9M denotes the value of the 1,9MΩ resistor. The constant RS10K holds the value of the 10kΩ internal reference resistor.

4.3.1 *Calibration for resistances above 10Ω*

In Fig 4.15, a schematic setup is given of the calibration method that the 5700A calibrator uses for calibration `of resistance values of 10Ω and higher.

As can be seen, the known resistor is placed in series with the unknown resistor and connected to a voltage source. Subsequently the three voltages V1 to V3 are each compared to the voltage of the DAC assembly output. For each voltage, V_{DAC} is adjusted until the ADC converter reads the same voltage as the offset voltage of the ohms cal board x75 preamplifier. At that moment, V_{DAC} equals the voltage to be measured. Since the linearity of DAC assembly is very good and checked during the DC voltage calibration, the ratio of (V1 - V2) and V3 is equal to the ratio of R_X and R_S.

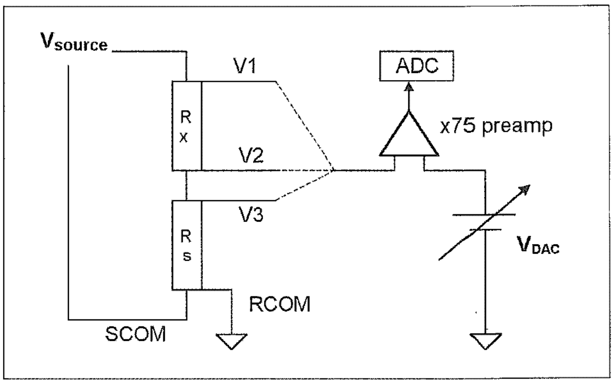


Figure 4.15 Calibration principle for resistance in the 5700A calibrator of 10W and higher

The low side of the R_S resistor is not measured, since the both the DA converter and the AC converter use the same low as reference (RCOM line in the circuit diagrams of the Fluke 5700A documentation). Since this low is separated from the low line for the voltage source (SCOM), no voltage drop is expected to occur along the RCOM line.

The measurement scheme as indicated above is used for calibration of resistances of 10Ω and higher and is slightly different for each range of resistors. In fact, only for the calibration of the internal 10kΩ and 19kΩ resistors the scheme is used as indicated. For all other resistance values one of the voltage measurements (V3) is not performed. This can indeed be done since the resistors are realized in two strings, which make the lines 2 and 3 coincide (see the schematic of Figure 3.5). So once the 10kΩ and 19kΩ resistor of the two strings are calibrated, up scaling and down scaling is done with only two voltage measurements. Note that for calibration of the 1kΩ resistor, Rs is the 1kΩ unknown resistor and (R_x + R_s) together form the 10kΩ known resistor. After the voltage measurements, R1K is calculated via R1K = R10K * V2 / V1. Similarly, for calibration of the 100kΩ resistor, Rs is the 10kΩ known resistor and (R_x + R_s) together form the 100kΩ unknown resistor. And R100K is calculated as equal to R10K * V1 / V2. Above 1MΩ, the current noise of the pre-amp on the ohms cal board becomes a significant factor. Therefore, for these resistance values a low bias input current FET op-amp (located on the ohms main board) is switched ahead of this ohms cal board pre-amp.

The voltage source is located on the ohms cal assembly and uses the buffered 13V zener voltage as voltage reference. Note that the absolute value of the voltage source is not important; only the stability during the calibration is relevant. In the region below 1kΩ, the voltage source can not source 10V since that would cause to much dissipation in the resistors. Therefore, the output of the source is divided to 5V and 2V respectively. In order to still have the full resolution of the DAC in the calibration process, for the measurement of V2 the output of the DAC is divided with a 1:10 divider before it is connected to the pre-amp. The divider used is the 10kΩ / 90kΩ divider (element Z5, described in par.3.3) which is first calibrated before use here. Calculation of the value of – for example – the 100Ω resistor now is R100 = R1K * DividerRatio * V2 / V1. The constant containing the value of the DividerRatio is named RDIV_1.

The constants RDIV10, RDIV5, and RDIV2, contain the divider ratio on the ohms cal board (resistance elements in Z1 in front of op-amp U1), used to divide the 13V reference voltage to the value used during resistance calibration, which is 10V, 5V,and 2V respectively. The exact values of these constants do not need to be known. They are measured during calibration, but only to speed up the convergence of the resistance calibration themselves.

4.3.2 *Calibration of 1Ω and 1,9Ω resistance*

In Figure 4.16, a schematic setup is given of the calibration method that the 5700A calibrator uses for calibration of resistance values of 1Ω and 1,9Ω.

As can be seen in Figure 4.16, both the known and unknown resistors are again put in series but now they are fed by a current source. The current source used for the low value resistance calibration is that of the current assembly. This assembly uses the 10Ω resistor of the ohms main assembly as reference standard (200mA range), to supply 130mA and 65mA for the calibration of the 1Ω and 1,9Ω resistor respectively. The voltages across the resistors is 0,13V and is amplified by 75 by the differential amplifier on the ohms cal board to approximately 9,75V before it is sent to the DAC assembly for comparison with the DAC via another differential amplifier located on the DAC assembly. For correct voltage measurement, the common mode error of the preamplifier is measured first and in the final calculations subtracted from the voltage across the resistor.

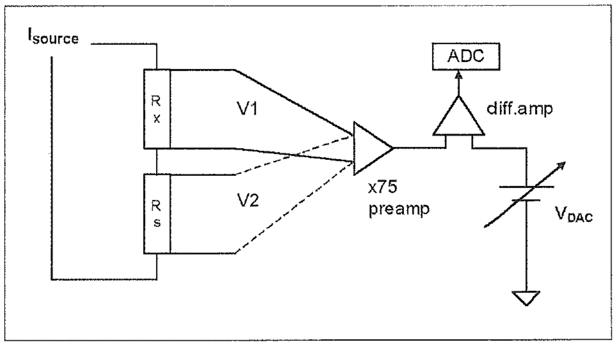


Figure 4.16 Calibration principle for resistance in the 5700A calibrator of 1Ω and 1,9Ω.

Both the 1Ω and 1,9Ω internal standard are calibrated against the 1Ω external reference standard.

4.3.3 *Traceability Chain*

Starting from the externally connected 10kΩ reference, the internal 10kΩ resistor located on the ohms cal assembly (part of the 1:10 divider Z5) is calibrated. From this resistor then the 10kΩ and the 19kΩ resistors of the ohms main assembly are calibrated. Once the 10kΩ resistor of the main assembly is calibrated, it is used as reference for calibration stepping up to 100MΩ and stepping down to 10Ω. Similarly the 19kΩ resistor is used for stepping up to 19MΩ and down to 19Ω.

The 1Ω and 1,9Ω resistors are both directly measured against an external 1Ω standard. The short is not calibrated.

Since the calibration process only relies on the linearity of the DA converter (that was previously checked in the DC voltage calibration), all non-zero resistance values are traceable to the 1Ω and 10kΩ external reference standards.

4.4 DC and AC Current Artifact Calibration

If the calibrator generates a current, an input voltage for the current assembly is calculated depending on the stored calibration constants. The relevant constants for DC are the current offset or zero (Z) and gain (G), and for AC it also includes the frequency response constants. In the relation is given between an input voltage and an output current for DC. During the Artifact Cal procedure the constants Z and G are measured for each current range and are stored in the memory. Furthermore, the frequency response is measured for different frequencies and it is also stored.

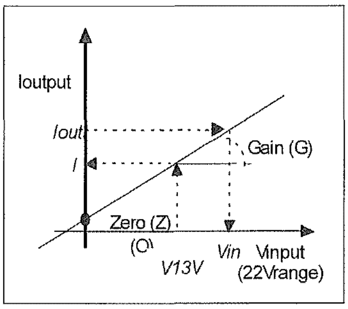


Figure 4.17. (DC) Current generation by using the calibration constants Z(ero) and G(ain).

The traceability of the current output is reached by measuring a voltage over a known resistance. The implementation of this principle is used in the internal calibration procedure which consists of three separate steps:

- current zero calibration (DC)
- current gain calibration (DC)
- current frequency response calibration (AC)

During the calibration, also other parts of the calibrator system are used, such as the resistors on the Ohms Main assembly, the DAC and ADC circuit on the DAC assembly, the RMS converter on the Oscillator Control assembly, next to the current assembly.

For the current calibration, it is assumed that all these other circuits used are working properly and the components used (i.e. the resistors) have traceable values.

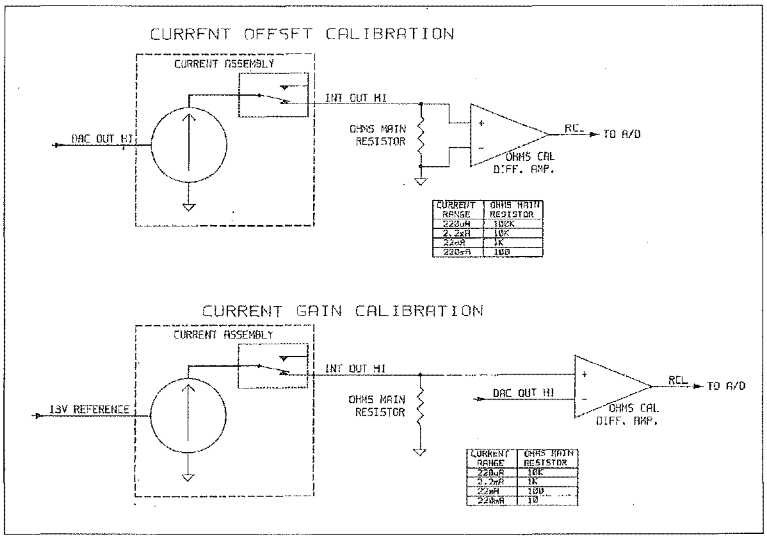


Figure 4.18 Internal set-up of the current gain and zero calibration

4.4.1 *Current zero calibration*

The current zero calibration of a specific range is performed by configuring the current assembly in its DC range with the input from the DAC assembly set to 0V. The output of the current assembly is routed to the Ohms Main assembly where it is connected to a calibrated resistor.

A differential amplifier in combination resistor with the ADC circuit on de DAC assembly measures the voltage across this. In Figure 4.18 this set-up is schematically given.

The actual calibration takes places in two steps. First, a checkpoint reading is made by measuring the voltage drop across the resistance without connecting the current assembly to the resistor and by switching off the relay. Second, the DAC is reconnected and is adjusted until it has the same reading as the check reading. This second reading determines the zero of the specific current range.

Each range has its own resistor on the Ohm Main assembly, the lower table in Figure 4.18 gives the resistance value for the zero calibration in the second column. The zero calibration is traceable from the resistors on the Ohms Main assembly and the voltage measurement of the DAC assembly.

Critical path

During the zero calibration, the current is routed to the Ohm Mains assembly through different relays. Compared to the normal operation, this can introduce extra leakage current.

4.4.2 Current gain calibration

For the gain calibration, the calibrator uses the same principle as the zero calibration, measuring the current by a voltage drop over a known resistor. Also in Figure 4.18, the set-up is schematically given.

The 13V reference standard is connected as input voltage of the current assembly. The output current is routed to one of the calibrated resistors on the Ohms Main assembly. The lower table in Figure 4.18 (column 3) points out for the gain calibration the value of this resistor depending which range will be calibrated. A differential amplifier is used to measure the voltage over the resistor. The positive input is connected to the resistor and the negative input to the output of the DAC assembly. The output of the differential amplifier is connected to the ADC circuit in the DAC assembly. The DAC output is adjusted until a zero reading is achieved. This determines the exact voltage drop across the resistor. The exact gain is calculated from this reading and the results of the zero calibration.

Critical path

The gain calibration is performed at 60% of the current range full scale.
During the zero calibration, the current is routed to the Ohm Mains assembly through different relays. Compared to the normal operation, this can introduce extra leakage current.

4.4.3 Current frequency response calibration

The third step of the current internal calibration process is the characterization of the current for its frequency response. The current assembly is configured for the AC current function with the input from the Oscillator Output assembly set to 20V at low frequency (220Hz). The appropriate shunt resistor is connected. The AC voltage drop is measured by the 400Ω RMS sensor on the Oscillator Control assembly. A DC reading of the RMS sensor is taken and stored together with the Oscillator output level. Furthermore the frequency is increased and the Oscillator output level is adjusted to obtain the same DC output reading of the RMS sensor as the previous one. Also this level is stored in the memory. This procedure is repeated several times to characterize the frequency range up to 10kHz.

Critical path

The absolute level of the AC current at low frequencies is set to the level of the DC current, no correction for a frequency dependence of the shunts is applied. It is assumed that the AC/DC error of the shunt and the RMS sensor is small compare to the uncertainty of the range. For the shunts, frequency independence is assumed; this was determined by design and confirmed by testing during development of the calibrator.

During the frequency response calibration, the feedback loop is interrupted. The shunt resistor is used to measure the AC current without any frequency correction. A voltage follower (U22 in figure 7-7, pg. 7-28 [Service manual], buffers the voltage over the shunt resistor). This circuit is only used during calibration and is not checked for any change during operation.

During the operation of the calibrator, the RMS converter used for the AC/AC calibration is not measured for any time dependence of its frequency response. There is no traceability set for this converter. It will be investigated by the AC Voltage part of the project.

4.4.4 *Current calibration of the 2,2A range*

The calibration of the 2,2A range only consists of the current zero and gain calibration. The frequency response calibration is calculated form the corresponding calibration at the 22mA range. For the calibration the current assembly is configured in the 2,2mA range and the output is routed to the high voltage/high current assembly where the current is amplified 100 times. The maximum power dissipation in the resistor used limits the maximum generated current. This is the main reason to perform the DC calibration of the 2,2A range at a level of 130mA. But, it means that the zero and gain calibration is performed at a factor 10 lower current rate than during normal use.

- ***Zero calibration of the 2,2A range***

The same calibration principle is used as for the zero calibration of the other ranges. The current assembly is set to the 2,2mA range with the input from the DAC set to 0V. The output current is routed to the current amplifier on the High Current assembly after that it is routed to the10Ω resistor of the Ohms Main assembly. First a checkpoint reading is taken without the current assembly and current amplifier connected. Furthermore, everything is reconnected and the DAC input voltage is adjusted to have the same reading as the checkpoint reading.

Critical path

During normal operation, the 22mA range is set for the current generation. Any difference in the zero will cause a difference at the current output of the calibrator.

- ***Gain calibration***

The gain is determined by the configuration as given in Figure 4.19. The 13V internal reference is connected to the current assembly, it generates a 1,3mA output current which is

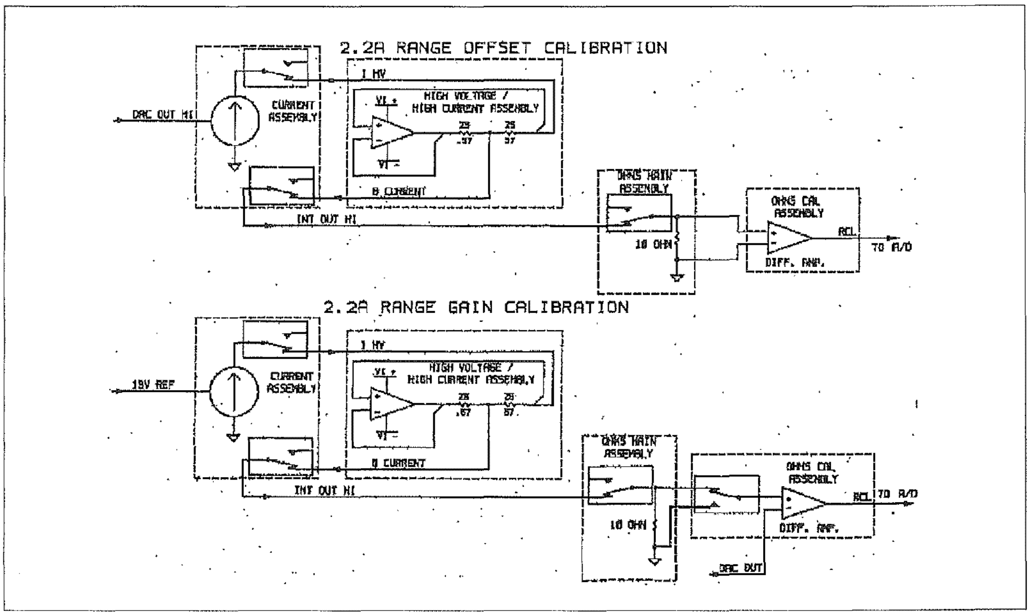


Figure 4.19 Internal set-up of the current gain and zero calibration of the 2,2 A.

amplified by a factor of 100. This current (130mA) is routed to the10Ω resistor of the Ohms Main assembly producing a 1,3V. This signal is compared to the DAC output through a differential amplifier. By adjusting the DAC a null reading is achieved. An extra step is performed by changing the input of the differential amplifier to the other side of the resistor. Both readings of the DAC determine the exact voltage drop over the resistor and with the zero measurement the gain is calculated.

Critical path

The gain calibration is performed at a level which is ten times smaller than the maximum output current of 2,2A. The appendix C of the Operators Manual of the 5700A indicates an extra current gain adjustment constant (I5F7). From the service manual of the Fluke 5700A, no information is given about this adjustment.

A maximum allowable power dissipation in a (10Ω) resistor is 10mW. In case of the gain calibration 170mW is dissipated in the 10Ω resistor instead of the 10mW.

- ***Frequency response calibration***

No frequency response calibration is performed for the 2,2A range.

Critical path

Using the results of the 22mA and the gain and zero calibration, the software computes the calibration constants instead of measuring them. The frequency dependence of the current amplifier is not characterized during the Artifact Cal procedure.

4.5 The current calibration constants

The Artifact Cal procedure determines for each current range 10 calibration constants. These constants has the following symbolic names with x (range 1 to 5) a number of the corresponding current range):

- *IxZ* The zero calibration constant;
- *IxG* The gain calibration constant;
- *IxF1 .. IxF6* The frequency response calibration constants at 0,5k, 1k, 2k, 5k, 7k and 10kHz;
- *IxF7, IxF8* not used for the ranges up to 220 mA, value is set to 1. In the 2,2 A range the IxF7 is used for an extra DC gain adjustment and IxF8 is also set to 1.

Next to these constants, the current function has four extra calibration constants:

- *IGMEAS* The measurement at the bottom of the resistor during gain cal.
- *IMZ* The current monitor circuit zero
- *IMAG* The current monitor circuit AC gain
- *IMDG* The current monitor circuit DC gain

In the next paragraphs the measurements and calculations to determine these calibration constants are discussed. Furthermore, the relations are determined between the internal calibration constants and the external references. To evaluate the Artifact Cal procedure a shift in these parameters will be applied and the result on the calibration constants and the output current will be investigated.

4.5.1 The zero calibration constant

In Figure 2 the measurement setup is given for the determination of the zero calibration constant. The voltage *VDC_zero* is a voltage which compensates the zero current of the current assembly. Equation

$$I\_zero\ (=IxZ) = \frac{-Vdc\_zero}{R\_zero} \qquad (4.4)$$

Under the assumption that the generated offset current remains constant, an applied shift in the external resistance standard (e.g. a shift in the calibration constant of the resistor used, *R_zero*) will cause the same relative shift on the calculated offset current. Thus, the zero calibration constants will have the same relative shift as applied to the resistors. If the shift is in the order of 0,5%, the shift in the zero calibration constant will be measurable. But due to the fact that this is a circuit dependent parameter, this constant doesn't have to be proportional to the applied relative external shift, it is not predictable. On the other hand, the zero output current will not change too much and it is probably not detectable. Table 4.2 shows typical values of the zero calibration constant for the different current ranges.

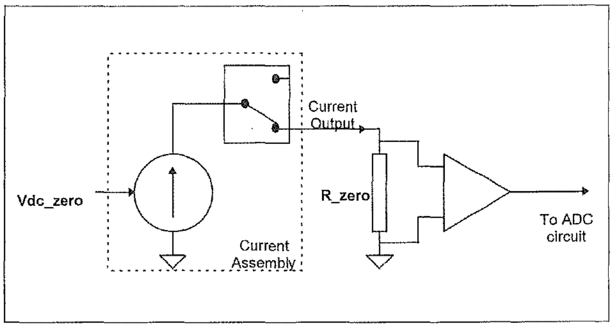


Figure 4.20 DC current zero calibration

Calibration Constant	Value (mA)
I1Z	+8.0801 e-04
I2Z	-4.2860 e-05
I3Z	-2.5047 e-04
I4Z	-2.3133 e-04
I5Z	+3.2010 e-04

Table 4.2 Typical values for the zero calibration constants.

4.5.2 *The gain calibration constant*

The gain calibration constant is measured by the set-up as given in Figure 4.21. This constant *(Gain_I)* is calculated as given by equation.

$$Gain\_I = \frac{\dfrac{V\_gain}{R\_gain} - I\_zero}{V13V\_ref} \Rightarrow \frac{1}{R\_gain} \qquad (4.5)$$

In case the zero current *(I_zero)* can be neglected, the current gain is determined by the values of the two voltages and the resistor. Due to the fact that the voltage *V_gain* is directly derived from the reference voltage, *V13V_ref,* the determination of the gain is only dependent on the resistance *R_gain.* Any external applied change in the voltage reference will have the same relative change in both voltage and this will be canceled out in the gain calculation. Table 4.3 shows typical values for the gain calibration constants for the different current ranges.

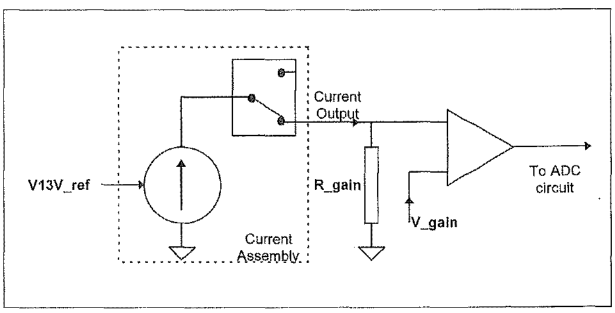


Figure 4.21 DC current gain calibration

Calibration Constant	Value (mA)
I1G	9,99624 e04
I2G	9,99110 e03
I3G	9,98847 e02
I4G	9,98753 e01
I5G	9,98988 e00
I5F7	9,89100 e-01

Table 4.3 Typical values for the gain calibration constants, I5F7 is an extra gain adjustment for the 2,2A range.

On the other hand, a relative shift in the external resistance reference will be seen linear in the gain constants under the assumption that the zero current is neglectable. A relative change of 0,5% in the external resistance reference will be cause the same relative change in the gain calibration constant. It means, the constant will increase from 10e0x to 10,5e0x The measured DC output current *(I_dcout)* is given by the following formula:

$$I\_dcout = Gain\_I * V\_dcin + I\_zero \qquad (4.6)$$

This output current is proportional to a shift in the external voltage reference. On the other hand, if this relative shift has the same absolute value as the shift in the external resistance reference, the output current will remain the same and the influence of both shifts will not be measured.

4.5.3 *The frequency response calibration constants*

The frequency response calibration constants *(IxFn)* are determined by an AC/AC measurement with the RMS converter. These calibration constants are independent of an external shift in the references. The output current *(I acout(fn))* is given by:

$$I\_accout(fn) = Gain\_I * IxFn * V\_acin(fn)\ fn) \qquad (4.7)$$

with x the current range and n the frequency. If no frequency dependence , these frequency constants are equal to 1.

The value of *V_acin* is derived from the external DC voltage reference. It means that *I_acout* is proportional to a relative shift in *V_acin*. The dependence of *V_acin* on the external voltage reference is investigated in the part concerning the AC voltage.

In principle, the same argumentation is used for the AC current dependence on the relative change in the constants as has been given in for the DC current constants.

4.5.4 *Traceability chain*

In Table 4.4 the different internal standards are given which are used during the Artifact Cal procedure for the current function. The last column represents extra requirements during the calibration. These requirements will determine if the application of the

Calibration	Traceable to Voltage	Traceable to Resistance	Extra requirements
Zero		100k, 10k, 1k and 100 W	
Gain	13V internal DC REF	10k, 1k, 100 and 10 W	DAC output linearity
Freq. Response	20V AC REF		20V AC LF absolute AC/DC error of I-shunt AC-AC comparator Buffer Circuit (U22) Freq. dependance of the High Curr. Assembly.

Table 4.4 Traceabilty of the Current Calibration

Artifact Cal feature in the Fluke 5700A is correctly implemented. From this table, it is concluded that the traceability of the DC current function rely on these other standards in combination with the internal software. For AC current, the traceability rely on the frequency response of the current shunts and the AC-AC sensor. In Figure 4.22, this is schematically shown.

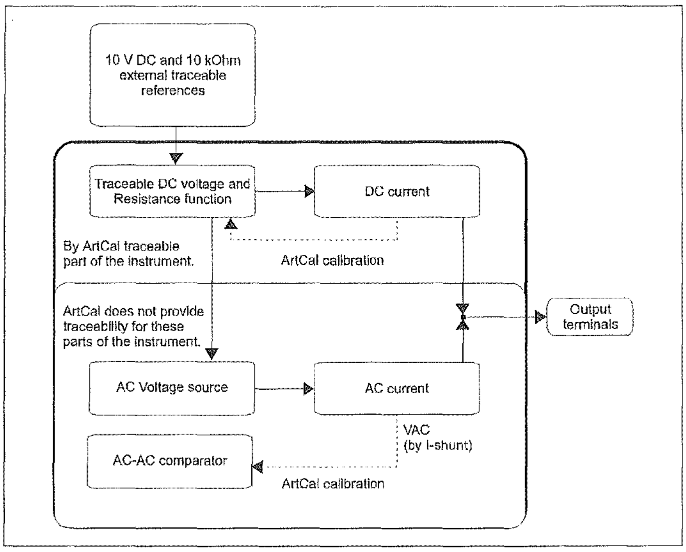


Figure 4.22 Traceability of the current calibration

4.6 Artifact Calibration Firmware

The purpose with this chapter is to identify and study the functional blocks and critical functions of the firmware in the Fluke 5700 Calibrator. Therefore the most important functions to evaluate are judged to be the Artifact Cal function and the function calibration reports.

- **Artifact Cal**, calibration to external standards and internal adjustments (the SCA subsystem). The external calibration is using three external standards: 10V, 1Ω and 10 kΩ. Adjustments are possible to store as constants. It must be completed at the beginning of the calibration cycle.
- **Calibration reports**, the calibrator stores two sets of calibration constants: the set currently in use and the old set from previous calibration. That makes it possible to produce a report of the differences between the present settings and the settings that were in effect before the last calibration.

4.6.1 CPU Assembly Board Functions

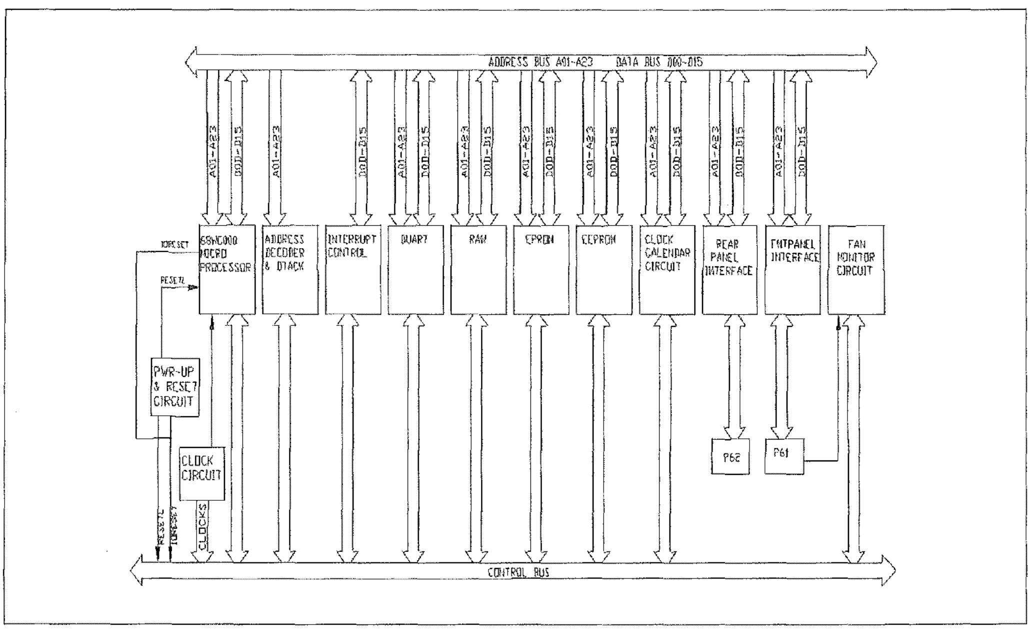


Figure 4.23 CPU Assembly Block diagram

- ***Power-up and reset circuit***

The system could be reset in two different ways, by the hardware and by the firmware. Switch SW1 handles the hardware reset. But the firmware reset, which restores the Calibrator configuration to a default condition, is triggered by RESET button on the front panel.

The reset circuitry consists of line monitor chips (U1, C5, CR1, R3, Z3), switch (SW1) and inverters on U2. At power up, or upon pushing/releasing the switch, an reset pulse is created. This pulse sets the CPU assembly in a known safe condition. The Calibrator is also reset if the power supply falls below 4.5 V.

- ***Clock generation***

The 450 Hz clock is used by the watchdog timer.

- ***Watch dog timer***

Generation of the DOGCLR2 signal is under firmware control. That signal comes from the interrupt controller U10. The signal must come more often than 1.14 s to prevent the watchdog interrupt.

- ***Address decoders and data acknowledge***

Two Programmable Logic Devices (PLDs) accomplish address decoding and data acknowledge generation.

- ***DUART circuit***

The Dual Asynchronous Receiver/transmitter circuit (68C681 DUART) primary task is to provide the asynchronous serial lines, using the fiber optic link, for the communication with the Guarded Digital Controller. The DUART has eight output lines with different functions. Some are used for enabling certain interrupts. The DUART also monitors the EEPROM ready signal and the Fan interrupt signal (FANINT).

- ***Rear Panel Interface***

The Rear Panel Interface and the connector P62 interface the CPU to the rear panel. Several control lines go directly to the connector P62.

- ***Interrupt controller***

The interrupt controller reads incoming interrupts and interrupt control lines, then encodes the highest priority interrupt into the interrupt level for the 68HC000. When the 68HC000 responds to an interrupt request, it asks the interrupt controller for an 8-bit vector that corresponds to the pending interrupt of highest priority.

4.6.2 RAM

Random access memory is contained in three pairs of sockets and are of the type static CMOS RAM.

4.6.3 EEPROM

The calibrator is equipped with a 32 KB EEPROM protected by hardware and firmware against inadvertent writes during power-up and power down sequences, which could corrupt calibration constants stored there by the 68HC000.
It is only possible to write to the EEPROMS when an output enable line, NVMOE,

(non volatile memory output enable) is high. Three diodes and a resistor perform a logical OR function for three signals that controls the line (*NVMOE). The hardware will prevent a write access to the EEPROM at power up, for about 40 ms, and when the power supply drops below 4,5 V or during power glitches.
The NV (non-volatile) firmware subsystem handles the protection of the EEPROM.

4.6.4 *The Guarded digital control circuitry*

The guarded digital control circuitry is built up with the following building blocks:

- The Inguard CPU, being a Hitachi 6303 micro controller 637 A01Y0 CMOS with 16 KB internal CMOS EPROM.
- Inguard Memory. The micro controller has 16 KB of internal EPROM program memory.
- Inguard Watchdog timer using 74HC4020 and part of Programmable Logic Device (PLD).
- Power-up and Reset Circuitry. The line monitor chip (U60) detects three events: 1)power supply falling below 4.5V, 2) reset being initiated, or 3) break being asserted from the break detection circuitry.
- Fiber-Optic Link, isolating the digital and analog circuits from the unguarded CPU assembly (A20). It communicates serial and asynchronously.

4.6.5 *Calibration data Storage in memory*

There are five complete sets of calibration constants; that is, each calibration constant has five replicate values. Each replicate has a primary purpose, although it may be used for other ends. In all five sets, the constants are stored as IEEE double precision floating numbers, which have about 14 digits precision. The five memory sets are:

Name of the set	Description of the set with constants	Type of memory	Physical memory
ACTIVE: (active RAM)	The constants used for normal operation. The set of constants actually used by the 5700 to correct outputs. This is normally a copy of the EEPROM set,	variable & volatile	RAM
EEPROM: (official set)	The "official" set. The constants from the most recent approved self calibration.	Variable but nonvolatile	EEPROM
OLD: (previous set)	The previous "official" set. The set of constants from the self-calibration before the most recent self-calibration.	Variable but nonvolatile	EEPROM
DEFAULT: (default values)	The default values. The original, nominal value of the set of constants, stored by the factory. (The set of constants is also created after reformatting nonvolatile memory).	Invariable & nonvolatile	EPROM
CALCHECK: (cal check RAM)	The set of constants determined by the most recent Cal Check or by the most recent calibration before the constants are saved.	variable & volatile	RAM

Table 4.5 In the standard IEC 1508 t the words "variable" and "invariable" are used to describe the memory type, depending on if it is possible or not to change the data in the memory.
The words "volatile" and "nonvolatile" are used in this report to describe if the data in the memory remains unchanged when the power to the instrument (memory) is cut off.

4.6.6 *Calibration constants storage*

The following subsystems handles the storing of calibration constants.

Short name	Subsystem name	The function of the subsystem
CCO	Calibration constant manager	The CCO subsystem stores and retrieves calibration constants. (It has no knowledge of how the constants are computed or used.)
NV	Nonvolatile memory manager	The NV subsystem holds the default values in ROM, which serve if the integrity of EEPROM is damaged. The CCO subsystem uses the NV subsystem to do the actual storage and retrieval of non-volatile values.

Table 4.6 Subsystems handling Calibration Constants

The storage of calibration constants is handled as follows:

The ACTIVE set is altered during self-calibration, but is resynchronized with the EEPROM set at the end of calibration as follows. First the EEPROM set is copied into the OLD set and the ACTIVE set into the EEPROM set. If the new constants are discarded the EEPROM set is copied into the ACTIVE set again.

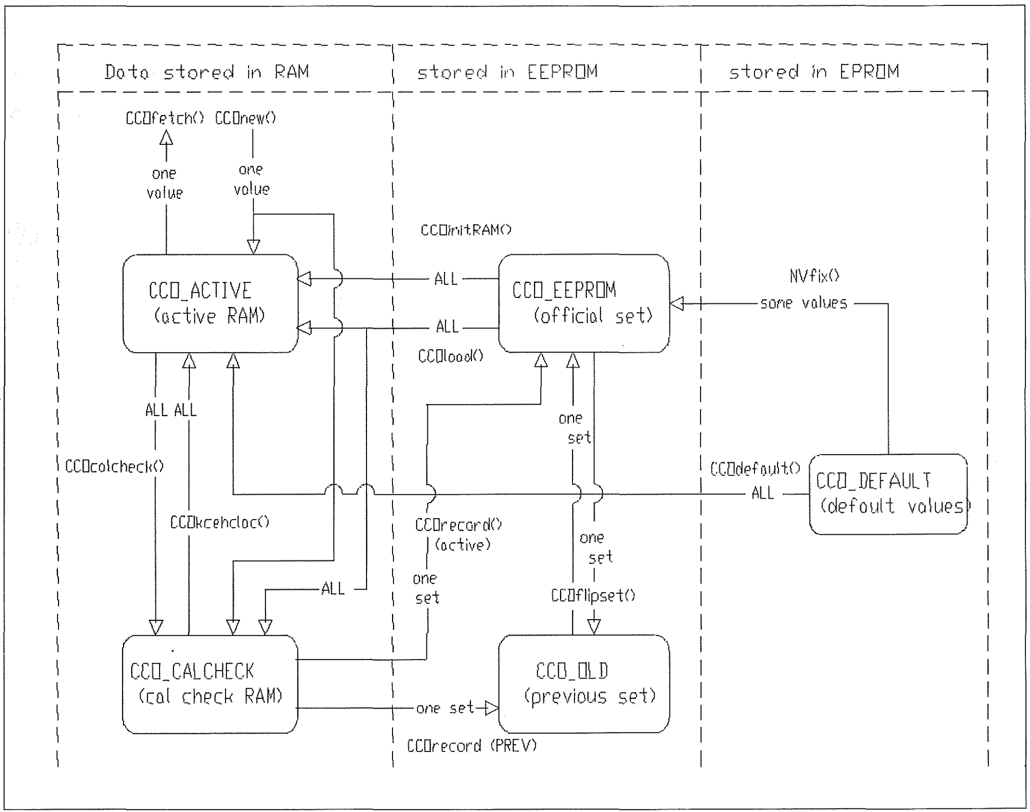


Figure 4.24 Memory block diagram

CCOfetch and CCOnew	provide read/write access to CCO_ACTIVE (CCOnew also writes to calchech RAM)
CCOinit RAM	moves all EEPROM constants to ACTIVE
CCOload	moves all EEPROM constants to both ACTIVE and CALCHECK
CCOcalchecK	moves all ACTIVE constants to CALCHECH
CCOkcehclac	moves all CALCHECH constants to ACTIVE
CCOdefault	moves all DEFAULTS constants to ACTIVE
CCOrecord	moves one set of CALCHECH constants to OLD or EEPROM, depending on its 2nd parameter
CCOflipSet	exchanges the OLD and EEPROM constants

4.6.7 *Self check of Main CPU*

- The instrument does not check the invariable memory or EEPROM containing the firmware, program code, and the default constants.
- No checking is done by the instrument of RAM, used for volatile storing of data and constants.
- At power-up or upon reset (RESET key or *RST command), the EEPROM set is copied into the ACTIVE set. But if a checksum error is encountered in nonvolatile memory an error is reported and the DEFAULT value will then be used. Each value, constant, has its own checksum, so a checksum error only damages one value.
- The communication protocol between the main and Inguard CPUs is a proprietary derivative of the SDLC protocol, with numbered packets, dropped packet detection and retransmission.

- The GO subsystem is the start-up/bootstrap code for the instrument. It is a collection of calls to various subsystem initialization functions containing the following functions:

Main:	main program for startup initialization
Goreset:	Warm RESET the MFC

- The watchdog subsystem consists of one file, which has the following functions:

WDinit:	Initialize watchdog timer driver
WDirqServ:	Watchdog timer time-out interrupt handler and is called if the watchdog goes off, indicating that WDtask missed doing its job for long enough to set off the watchdog. It also handles a power-down interrupt
WDtask:	Watchdog clear task running under the multitasking kernel. It uses a firmware timer to wake it up 4 times per second, at which time it pets the watchdog (it writes to a specific hardware address which resets the watchdog timer).

- The ERR (error) subsystem handles faults detected by the instrument. If the fault occurs as the direct result of user input, e.g. an invalid value entry, the fault is reported back to the source of the error -- either the front panel or remote interface. If the fault occurs asynchronously (e.g. an over-compliance condition is detected), the fault is reported to both the front panel and remote interface. And one of four things happens, depending on which error occurred:

  1) nothing
  2) the output goes to standby
  3) the instrument is reset to the power up (dormant) condition
  4) the instrument considers the error fatal and refuses to do anything more

Fatal errors are also saved in non-volatile memory with the date & time they occurred for later retrieval during instrument repair.

There is one C file, ERRor.c, which contains the following functions:

ERRinit:	Initialize ERRor subsystem.
ERRopen:	Open an Error Channel
ERRget:	Get errnum from ERR Channel
ERRput:	Put error number in the Error Channel
ERRval:	Explain an Error Number
ERRlist:	Send Pretty List of All ERR_VAL Entries to Serial Chan
ERRstring -	Write a formatted Error String into a Buffer
initque -	Initialise error queue
deque -	Dequeue an error

enque -	Enqueue an error
ERRtask:	ERRor handling task.
ERRclearFat:	Clear the Fatal error que
ERRputFat:	Queue a fatal error
ERRgetFat:	Get the list of all fatal errors and date.

The ERRor subsystem provides the following scheme for logging errors which occur anywhere in the system. It provides one incoming channel (calls to ERRput from anywhere in the firmware) to N outgoing channels, one per task which needs to know about system-wide errors. In the Fluke 5700 system there are two tasks which read from the Error Sinks, the front panel task (FP) and the remote monitor task (REM).

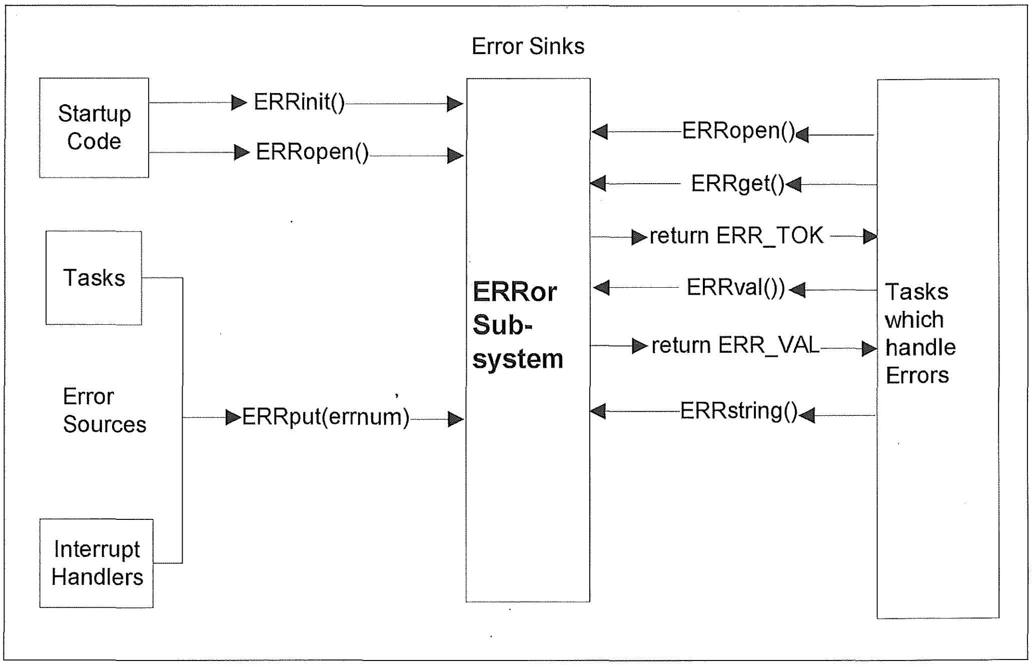


Figure 4.25 Memory block diagram

4.6.8 Self Check of Guarded CPU

No test is done of the guarded CPU assembly. It is considered not necessary to do that because:

1) When using the CalCheck function and by using the self-diagnostic functions the guarded section (the analogue hardware) is checked.
2) The guarded CPU assembly stores no calibration constants.
3) The Communication protocol between them main and the Inguard CPU has error handling.

4.6.9 Self Check of analog switching hardware

The function of the relays used to change range etc. should be checked. A fault in this part of the analogue circuitry may endanger the Artifact Cal function.
The Self-Diagnostic function was constructed with the intention to be used by the operator when he suspects that there is anything wrong with the instrument. The SDI function can then give further information about the cause of the error. The SDI function can also be used as a "check-up" of the instrument.

The Self-Diagnostic Subsystem (SDI) has the objective to find where something is broken in the analog (guarded section) hardware.

4.7 Comparison with a standards lab measurement system

The internal primary voltage references are analog to high precision stand-alone solid state voltage sources in a standards laboratory. The DAC is analog with a 0,22V to 22V DC voltage source with corresponding demands on stability, resolution and linearity. The ADC is comparable with a null detector. The main demands on the ADC are stability and resolution. The thermal sensors in combination with the attenuators are equivalent to AC-DC transfer standards. The internal computer and the software part that is performing the Artifact Cal procedure is comparable with the standards laboratory measurement system computer and software.

With this comparison it is concluded that the internal measurement circuit of the Fluke 5700A series II calibrator comprises the fundamental elements of a traditional laboratory measurement system. It is therefore possible to put corresponding demands on calibration of the internal instruments of the calibrator as for the instruments of a traditional measurement system.

5 *Black Box Measurements*

In the black box measurements, the calibrator was considered as a black box, from which the output is claimed to be within the 24 hour specifications after an Artifact Calibration. The measurements described in this chapter aimed to verify this claim. Even though Les Huntley [ref, 16, 17, and 20] has done a similar evaluation on a large group of Fluke 5700 calibrators, it was felt that the present project would be incomplete without the black box evaluation.

For all calibrator functions and ranges the Black Box tests consisted of the following measurements:

- Self test
- Cal Check
- Conventional calibration of the calibrator output against traceable standards
- Artifact Cal
- Conventional calibration of the calibrator output against traceable standards

5.1 Direct Voltage and Linearity

The DC Voltage and Linearity measurements are mainly based on so-called "opposition measurements" and performed with the following equipment and standards, all traceably calibrated:

- 2ea. Fluke 732A 10V/1V Zener References
- 1ea. Fluke 752A Reference Divider
- 1ea. Null Detector

For the 200mV Voltage range a traceably calibrated HP 3458A High Performance Voltmeter has been used.

Based on the above listed equipment the test uncertainty ratios for the DC Voltage and Linearity tests were 9 (nine) or greater.

The calibrator output measurement results before and after Artifact Calibration of the calibrator are presented in Table 5.1 below.

			Before Artifact Cal.			After Artifact Cal.		
DC Voltage Range (V)	24h spec (ppm)	Test Value (V)	Measured value (V)	Deviation (ppm)	% of 24h Spec (%)	Measured value (V)	Deviation (ppm)	% of 24h Spec (%)
0.2	8.5	0.2	0.1999997	-1.5	-17.65	0.1999991	-4.5	-52.94
2.2	4	2	1.9999986	-0.7	-17.50	1.9999986	-0.7	-17.50
11	3.85	10	9.999999	-0.1	-2.60	9.999999	-0.1	-2.60
22	3.83	20	19.99999	-0.5	-13.05	20.00001	0.5	13.05
220	4.4	200	199.99996	-0.2	-4.55	200.00014	0.7	15.91
1000	6.5	1000	1000.0077	7.7	118.46	1000.0030	3.0	46.15

Table 5.1 DC Voltage output measurement results before and after Artifact Calibration

The linearity of the DC voltage function is mainly given by the linearity of the DAC in its 11V range, since all other ranges are related to this range using dividers and amplifiers. The linearity of the DAC was measured in the 11V range using a string of ten resistors and a 10V standard providing the ten tap voltages 1V, 2V, 3V, ... 10V. The ten 1V voltage differences were measured against 1V out of the calibrator. Adding the values delivered the tap voltages, which in turn were compared to the respective voltages of the calibrator. Through these points a regression line was fitted to get rid of offset and gain errors and measure pure linearity. The mean values and the standard deviation of ten repeated measurements are shown in Table 5.2 and Figure 5.1.

Tap Nr.	Utap	Uout	Deviation from regression
1	0,999989560 V	1,000000106 V	-0,184 µV
2	1,999969137 V	2,000000308 V	-0,132 µV
3	2,999975797 V	3,000000509 V	-0,082 µV
4	3,999961135 V	4,000000826 V	0,085 µV
5	4,999936523 V	5,000001139 V	0,248 µV
6	5,999917955 V	6,000001261 V	0,219 µV
7	6,999909592 V	7,000001378 V	0,185 µV
8	7,999906862 V	8,000001419 V	0,077 µV
9	8,999890393 V	9,000001439 V	-0,054 µV
10	9,999880272 V	10,000001281 V	-0,362 µV

Table 5.2 Deviation Form Regression

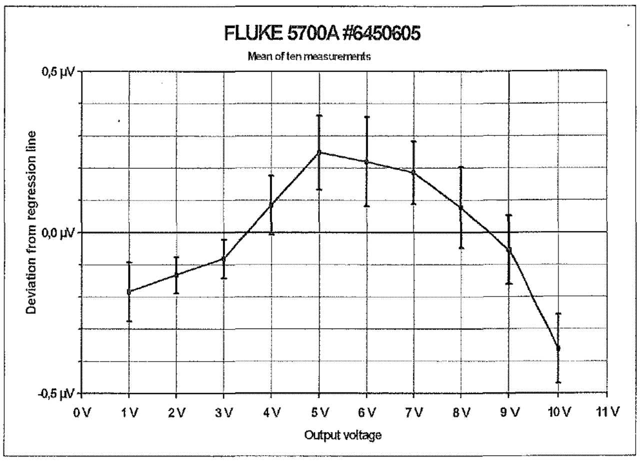


Figure 5.1 Linearity of the DAC in the 11V range

The linearity of the 220V and 1000V ranges was checked with measurements near full range and near 10% of range. In the 220V range and in the 1000V range there are resistive dividers used at fairly high voltages. The self heating of the resistors could lead to a voltage dependence of the dividers and by this to additional non-linearity. Therefore the linearity in these ranges was checked by measuring at about 10%, 50% and 100% of range and fitting a straight line to these points. The deviation from this regression line is given in Table 5.3.

DC Voltage Range (V)	Test Value (V)	Measured Value (V)	Regression (V)	Deviation (ppm)	% of 24h Spec
220V	10	10.000015	10.000010	-0.53	-12.06
	20	20.000035	20.000019	-0.78	-17.74
	100	100.00020	100.000097	-1.04	-23.65
	200	200.00014	200.000194	0.27	6.12
1000V	100	100.000451	100.000287	-1.64	-25.24
	200	200.000840	200.000574	-1.33	-20.47
	1000	1000.00280	1000.00287	0.07	1.07

Table 5.3 Measured output values and deviation from regression

5.2 Alternating Voltage

All ACV measurements using a traceably calibrated Fluke 5790A, were performed at the front panel output terminals of the calibrator, internal sense mode selected. The instrument was also set for local guard and the front panel guard terminal and ground terminal were connected with a shorting bar. All reported measurement results are based on at least three measurements. Measurement uncertainties and specifications are calculated for a confidence level of 95 % (k=2). All test uncertainty ratios, with the Fluke 5790A as reference were 3 (three) or greater. The results of the traceable calibration before and after the Artifact Calibration are presented as percentage of specification in Table 5.4 :

		Output evaluation before and after [presented in ( )] Artifact Cal, Deviation from nominal voltage in % of specification (k=2).											
Range (V)	Voltage (V)	10 Hz	20 Hz	40 Hz	100 Hz	1k Hz	10k Hz	50k Hz	100k Hz	200k Hz	500k Hz	700k Hz	1M Hz
2,2 m	1 m	12 (10)	12(12)	12(12)	13(12)	13(12)	14(13)	35(34)	16(16)	5(5)	36(36)	47(47)	63(62)
22 m	10 m	-15(-15)	-21(-20)	-24(-24)	-24(-24)	-22(-22)	-10(-9)	12(12)	-4(-4)	-32(-32)	-23(-24)	-4(-5)	-2(-4)
220 m	100 m	5(4)	1(0)	-2(-3)	-1(-2)	-3(-3)	1(0)	-1(-2)	-6(-6)	-11(-11)	-5(-6)	-1(2)	0(-1)
2,2	1	6(6)	6(6)	6(5)	2(2)	6(5)	8(8)	6(4)	-2(-1)	-6(-5)	-3(-1)	-3(-2)	-8(-6)
22	3	4(4)				10(14)							
22	6	7(7)				3(7)							
22	10	7(8)				9(14)							
22	20	11(10)	13(15)	21(21)	16(21)	17(22)	17(22)	7(10)	-4(-9)	-11(-9)	-7(-4)	-5(-2)	-7(-4)
220	22												15(14)
220	30										12(12)	7(6)	
220	100	7(6)	6(9)	5(10)	7(10)	5(12)	7(11)	8(11)	-1(0)	-4(-4)			
1000	250		4(4)										
1000	1000			13(13)	16(17)	25(23)							

Table 5.4 AC Voltage output measurement results before and after Artifact Calibration

As can be observed from the measurement data, the deviation from nominal voltage is not significantly decreased, or increased by performing the Artifact Calibration procedure. This does not imply that the Artifact Calibration is not functioning, the Opaque box tests will give better resolution on this but it implies that the drift of the internal AC standards has been very small since the previous Artifact Calibration procedure was performed.

The print-out report of the calibrator shows the full scale shifts of the Artifact Cal adjustment procedure. The following table (Table 5.5) shows the difference between Artifact Cal printed shifts and the shifts according to the traceable calibrations results. A shift according to the traceable calibration is calculated as a shift relative the measured absolute voltage before the Artifact Cal adjustment procedure.

The reason for using a negative sign for the Artifact Cal shifts is that the Artifact Cal print-out report shows shifts of opposite sign to the measured shifts of the output voltage. Taking the opposite sign of the Artifact Cal shift figures into account, the measured shift and the Artifact Cal print-out report shift agrees well.

		(-Artifact Cal printed shifts) - Calibrated shifts, expressed as % of specification (k=2).											
Range (V)	Voltage (V)	10 Hz	20 Hz	40 Hz	100 Hz	1k Hz	10k Hz	50k Hz	100k Hz	200k Hz	500k Hz	700k Hz	1M Hz
2,2 m	1 m	-1	0	0	-1	0	-1	-1	0	0	0	0	0
22 m	10 m	0	1	0	0	0	0	0	0	0	-1	-1	-1
220 m	100 m	0	0	0	0	1	0	0	0	0	-1	-1	-1
2,2	1	0	-1	-2	0	-2	0	0	0	1	2	2	2
22	3	0				4							
22	6	0				4							
22	10	0				5							
22	20	-1	1	5	5	5	5	2	2	2	3	2	3
220	22												0
220	30										0	0	
220	100	0	3	4	3	7	4	1	1	0			
1000	250		0										
1000	1000			0	1	3							

Table 5.5 Difference between Calibrator reported shifts and actual measured shifts after an Artifact Calibration

5.3 Resistance

The measurement set-up used for the black box measurements was relatively simple. A schematic representation is given in Figure 5.2.

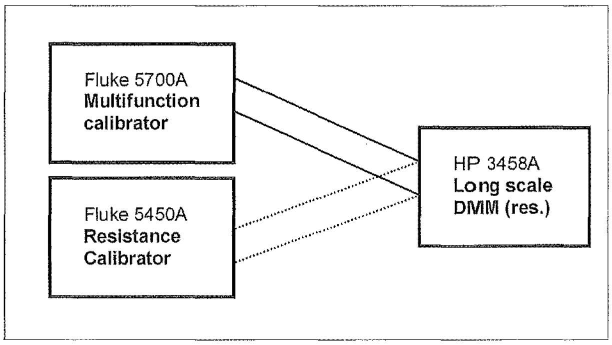


Fig 5.2 Measurement principle resistance

Starting point for the traceability was a Fluke 5450A resistance calibrator, that contains exactly the same resistance values as the Fluke 5700A multifunction calibrator. All resistors of the resistance calibrator were calibrated against resistance reference standards using a current comparator resistance bridge and a potentiometric resistance bridge. For the determination of the exact value of all 5450A resistors at the time of use with the 5700A calibrators, the calibration values were corrected for the drift of the resistors of the Fluke 5450A, as well as for the difference in (internal) temperature between calibration and use.

Calibration of the 5700A calibrators was done using a HP 3458A long scale digital multi meter (DMM) as a transfer device, configured for four wire high-resolution resistance measurements. The DMM first was measuring the 5450A resistance calibrator, then the 5700A calibrator (after an Artifact Calibration was performed), and finally again the 5450A resistance reference. From the DMM measurements resistance ratios were calculated, which were converted to calibration values of the 5700A calibrator using the known values of the resistors of the 5450A. Through this measurement technique a TUR of 2 (two) or higher could be obtained.

The guard of the DMM was connected to the Lo terminal and the offset compensation feature that corrects for possible thermal voltages was on (OCOMP ON). The calibrator was configured for four wire resistance output via the EX SNS button (except for the 100 MΩ resistor, which is only available in two wire output), and external guarding (EX GRD button). At the outside of the calibrator, the guard terminal was connected to the ground (chassis).

Since the resistance function is a passive function, no traceable evaluation has been performed before the Artifact Cal procedure: Artifact Cal is expected only to change the constants stored in memory and not the actual output. This was confirmed in the opaque box and glass box measurements (see the corresponding paragraphs).

The results of the measurements are given in Table 5.6 below. It can be seen that all results are within the 24 hour specifications of the calibrator. Best results are obtained for the middle range, for resistance values between 10Ω and 1MΩ, where the results are within 15% of specification. For the 1Ω and 1,9Ω resistors, as well as for values above 1MΩ, the results are within 50% of specification.

The 1,9MΩ resistor forms the exception with a relatively large deviation between displayed and calibrated value of 85% of specification. Check measurements performed with a potentio-metric resistance bridge (for which the T.U.R. was 3) gave the same deviation. All other resistance values were within 50% of the 24Hr specification, where the middle range values were within 30% of specification. Again the 1,9MΩ resistor was the exception, now with a deviation of 60% of specification.

Value [Ohm]	Display value [ppm]	Calibration Value [ppm]	Difference [% of spec]	Value [Ohm]	Display value [ppm]	Calibration Value [ppm]	Difference [% of spec]
0	0	-0,2	0,4	10 k	5,5	5,7	-2,7
1	-239,4	-262	32,3	19 k	-48,3	-47,9	-5,3
1.9	4,7	-14,9	28,0	100 k	-7,3	-7,4	1,1
10	-31,3	-30,1	-5,7	190 k	11,8	12,8	-11,1
19	-57,6	-57,6	0,0	1 M	-31,8	-30,6	-9,2
100	8,6	9,9	-10,0	1,9 M	-22,9	-11	-85,0
190	-30,6	-30,3	-2,3	10 M	-169,5	-171,1	5,9
1000	-2,9	-2,3	-6,7	19 M	-39,7	-23,3	-46,9
1900	1,3	1,9	-6,7	100 M	7,6	-32,4	44,4

Table 5.6 Results of the resistance value evaluation calibration after Artifact Calibration adjustment

5.4 Current

The measurement set-up used is based on the well-known principle to determine a current by the measurement of a voltage drop over a known resistor. In case of the AC current measurement, the AC/DC current difference of the resistor (shunt) is characterized in advance.

In Figure 5.3 the measurement set-up for DC Current is given. The (DC) DVM is a HP 3458A. The current shunts are standard resistors (Fluke 742A). For the 2,2A range a special low value resistor is used (Burster 1240). The corresponding value of the shunt resistors used is given in Table 7. Through this measurement set up a Test Uncertainty Ratios of 4 to 7 were obtained. The calibrator is configured for internal sense and local guard. The ground of the calibrator is used to ground the signal.

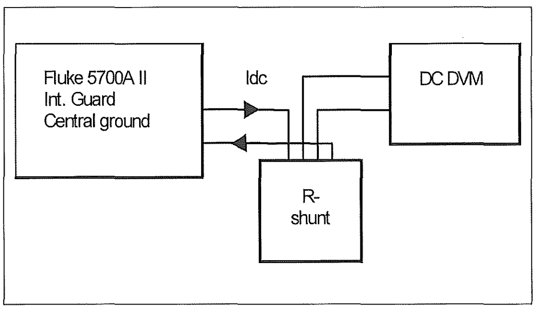


Figure 5.3 DC-current measurement set-up

Range	R_shunt	V_DVM
220 mA	1 kΩ	2V
2,2 mA	100Ω	2V
22 mA	10Ω	0,2V
220 mA	1Ω	0,2V
2,2 A	0,05Ω	100mV

Table 5.7 Resistance values and input voltages of the DVM for the DC current range calibration

The AC current measurement set-up uses the same basic principle as the DC set-up. The DC DVM is replaced by an AC DVM (Datron 4920). The shunts are special designed AC shunts; Tinsley 5685B 1kΩ, for the 220mA range and for the other ranges corresponding Fluke A40 shunts. Before the AC calibration takes place, the DC resistance of the AC current shunt is determined by applying the previously calibrated DC current and measuring the voltage drop over the shunt resistor. The AC current is measured at 7 frequencies, between 10 Hz and 10 kHz. For the AC Current Test Uncertainty Ratios of 2 (two) to 77 were obtained.

The measurement results being the deviation from the nominal value after Artifact Calibration are listed below in Table 5.8 and represented in ppm from nominal as well as a percentage [within ()] of the 24Hr specification.

Range	Current	DC+	DC-	10Hz	20Hz	40Hz	100Hz	1kHz	5kHz	10kHz
220 µA	200 µA	-9 (13)	-9 (13)	86 (13)	39 (6)	15 (4)	7 (2)	-9 (5)	28 (5)	139 (8)
2,2 mA	2 mA	-3 (9)	-4 (10)	15 (3)	2 (0)	-10 (3)	-14 (12)	-22 (19)	-25 (4)	-63 (4)
22 mA	20 mA	-3 (9)	-1 (4)	-42 (7)	-9 (2)	-12 (4)	-6 (5)	-18 (15)	-26 (4)	-15 (1)
220 mA	200 mA	-3 (5)	0 (0)	29 (5)	43 (8)	23 (8)	29 (24)	6 (5)	41 (7)	82 (5)
2,2 A	2 A	-7 (7)	0 (0)		-29 (6)	-27 (5)	-25 (5)	-62 (12)	-136 (21)	84 (1)

Table 5.8 Current measurement results, deviation from nominal after Artifact Calibration

6 Opaque Box Measurements

In the opaque box measurements, the basic knowledge concerning the functional set up and the Artifact Calibration (see Chapters 3 and 4) was used in order to evaluate the Artifact Calibration process into more detail.

For all calibrator functions and ranges the Opaque Box tests consisted of the following measurements:

- Cal Check
- Artifact Cal, where reference values have been entered with an offset
- Calibration of the calibrator output against traceable standards

In this way, the traceability chains could be verified. For example, if the reference value of the 10V standard is given with an offset, all outputs that are derived from this reference should change with the same relative offset. In this case it is DC voltage, AC voltage, DC and AC current; but not resistance since the calibration of the resistors only relies on voltage *ratios*. This similarly holds for the resistance values. A nice example is Artifact Calibration no. 4 in Table 6.2, in which case the current output is not expected to change since current is realised via Ohm's law in the calibrator and both the voltage and resistance reference have the same relative shift in reference value.

6.1 Direct Voltage

The measurements for the opaque box test are performed with an applied shift to the value of the external 10V reference. For this, the value given to the calibrator was changed by first +1% and then by -0,5%. The corresponding changes in the calibration constants were observed and the output voltages were measured against external traceable standards using the results of the black box test as reference. As observed there is a very good agreement with the expected values. Table 6.1 shows the influence on the output voltage.

			Ext. reference Shifted +1%			Ext. reference Shifted -0.5%		
DC Voltage Range (V)	24h spec (ppm)	Test Value (V)	Measured value (V)	Deviation (ppm)	% of 24h Spec (%)	Measured value (V)	Deviation (ppm)	% of 24h Spec (%)
0.2	8.50	0.2	0.1980195	-1.78	-20.94	0,2010051	+0.37	+4.36
2.2	4.00	2	1.980198	-0.01	-0.25	2.0100510	+0.37	+9.27
11	3.85	10	9.90099	-0.01	-0.26	10.050252	+0,07	+1.91
22	3.83	20	19.80197	-0.52	-13.58	20.10050	-0,12	-3.25
220	4.40	200	198.01974	-0.32	-7.27	201.00502	-0,03	-0.58
1000	6.50	1000	990.1001	+1.07	16.46	1005.0261	+0,92	+14.08

Table 6.1 Output Measurements with external reference value shifted by +1% and –0.5%.

6.2 Alternating Voltage

For the Opaque box test, the verification of the Artifact Cal adjustment procedure will be performed by making shifts of the stated values for the externally connected standards and compare the measured AC voltage shifts at the output terminals with the Artifact Cal print-out report shifts.

The shifts as chosen with two different magnitudes in order to verify the linearity of the Artifact Cal adjustment procedure are listed in Table 6.2.

	Applied reference shifts					
Ext. Ref.	Artifact Cal No. 1	Artifact Cal No. 2	Artifact Cal No. 3	Artifact Cal No. 4	Artifact Cal No. 5	Artifact Cal No. 6
10 V	0	1%	0	-0,5%	-0,5%	0
10 kΩ	0	1%	0	-0,5%	+0,5%	0
1 Ω	0	0	1%	-0,5%	+0,5%	0

Table 6.2 Applied reference shifts

Table 6.3, shows the difference, as a percentage of the instruments 24Hr Spec's, between the Artifact Cal print-out report full scale shift figures and the traceably measured shifts at the output terminals after the shifts. Since the results of the Artifact Cal 2,3 and 6 shifts were far more smaller than those of Artifact Cal 4 and 5, are only the results of Artifact Cal 4 and Artifact Cal 5 shifts listed.

		(-Artifact Cal printed Shifts) - Calibrated shifts, % of specification											
		Artifact Cal No. 4						Artifact Cal No. 5					
Range (V)	Voltage (V)	10 Hz	40 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 Hz	40 Hz	1 kHz	10 kHz	100 kHz	1 MHz
2,2 m	1 m	2	2	4	4	4	6	-1	-1	-2	-2	-3	-6
22 m	10 m	0	1	1	0	1	1	0	0	0	1	-1	0
220 m	100 m	1	0	1	-1	-1	-1	0	1	-1	0	1	1
2,2	1	1	0	0	0	-1	-1	-1	0	0	-3	1	1
22	3	0		1				0		-2			
22	20	1	12	11	14	2	-2	0	-11	-11	-13	-3	3
220	100	1	9	10	9	1		-2	-11	-12	-12	-2	
1100	1000		-2	-2					1	0			

Table 6.3 Difference (as % of 24Hr specs) between Artifact Cal reported Shifts and actual output shifts

6.3 Resistance

For the presentation of the results of the opaque box measurements, basically the same procedure was followed as presented by AC voltage, with some simplifications. The shift printed in the Artifact Cal calibration report is compared with the expected shift based on the applied shifts to the value of the relevant external reference standard as presented in Table 6.4. The deviations between printed and expected shifts are given in the table 6.5.

Finally we want to note that since resistance is a passive function, the shift as printed in the Artifact Cal calibration report has the same sign as the sign in the change of output. (For active functions, the Artifact Cal calibration report indicates changes in gain constants and changes in these constants have a sign opposite to the change in actual output.)

	Applied software Shifts (%)					
	no.1	no. 2	no. 3	no. 4	no. 5	no. 6
10V ref.	0	1	0	-0,5	-0,5	0
10kΩ ref.	0	0	1	-0,5	0,5	0
1Ω ref.	0	1	0	-0,5	0,5	0

Table 6.4 Shifts in reference values as entered in calibrator

	Deviation from expected shift [% / spec.]						Deviation from expected shift [% of spec.]				
Resistor	no. 2	no. 3	no. 4	no. 5	no. 6	Resistor	no. 2	no. 3	no. 4	no. 5	no. 6
RS10K	-2,9	-8,0	-4,8	-0,7	-6,4	R10K	-1,7	-5,4	-5,3	-0,9	-5,3
R1	-2,3	-1,2	-4,8	-7,1	-5,8	R19K	3,4	-3,4	-0,7	3,0	-0,6
R1_9	-8,8	-4,3	-5,9	-10,0	-10,4	R100K	3,2	1,6	1,5	4,0	-4,8
R10	-7,4	-7,0	0,6	-2,9	1,3	R190K	5,3	-0,4	1,6	6,6	-1,2
R19	-5,6	-4,8	3,6	0,0	5,2	R1M	6,3	3,6	3,1	6,1	-7,8
R100	-6,1	-8,9	-4,8	-3,5	0,8	R1_9M	7,7	5,0	6,0	9,7	-2,8
R190	-3,2	-5,2	2,8	1,1	7,8	R10M	5,4	3,7	5,0	6,0	-2,9
R1K	-1,7	-6,0	-3,7	-0,1	2,5	R19M	5,4	5,7	6,4	5,6	0,2
R1_9K	-3,8	-11,5	-2,7	-1,4	-0,4	R100M	-2,6	-5,2	-0,3	-2,3	-7,1

Table 6.5 Deviations from the expected shifts as a % of Specification

It can be seen from Table 6.5 that first of all, the assumptions in calculating the expected shift were correct. Secondly, all deviations in printed and expected shift typically are 5% of specification and always less than 12% of specification.

6.4 Current

For the opaque box measurements, the procedure as presented in parograph 6.3 is followed. The external calibration results (the measured shifts) are compared to the one found by the internal calibration and taken from the calibration report generated by the calibrator. Also, the difference between the external calibration and the figures on the calibration report are calculated as % of specification. In this case, all five external shifts are followed by the calibrator. The maximum deviation found is 20% of specs, but in general the values are much smaller, less than 5%. For this reason only the results of the Artifact Cal 2 and 3 Shifts are presented.

		Artifact Cal No. 2 ((- Artifact Cal printed shifts) – Calibrated shifts) as % of specification									Artifact Cal No. 3 ((- Artifact Cal printed shifts) – Calibrated shifts) as % of specification								
Range	Current	DC+	DC-	10Hz	20Hz	40Hz	100Hz	1kHz	5kHz	10kHz	DC+	DC-	10Hz	20Hz	40Hz	100Hz	1kHz	5kHz	10kHz
220 mA	200 mA	0	1	-4	-1	-3	-6	-9	-3	-2	-1	0	5	0	0	2	0	-1	0
2,2 mA	2 mA	0	0	-6	-4	-8	-8	-20	-5	-2	-1	0	7	3	5	2	13	3	1
22 mA	20 mA	0	0	-1	-1	-2	-2	-4	-1	-1	-1	0	2	0	0	0	-1	0	0
220 mA	200 mA	0	0	-2	-1	-2	-2	-5	-1	0	0	-1	2	1	0	0	0	0	0
2,2 A	2A	1	0		-1	0	-1	-4	-2	0	-1	9		0	-1	-1	-1	-1	-2

Table 6.6 The differences between the shifts given by calibration report generated by the calibrator and the external calibrated shifts as % of specs

7 Glass Box Measurements

In the glass box measurements, all available knowledge concerning the calibrator and the Artifact Calibration process was used for very detailed test.

For all Glass Box measurements the following the tests are carried through:

- Repeatability of the Artifact Cal procedure.
- Changes made to the external reference values and their impact on the calibrator output.
- Changes made to critical calibration constants and their impact on the calibrator output.
- If necessary special test and measurements for critical circuitries.

The second activity was done for both the voltage and resistance reference, where reference standards with non-nominal value were used. In this case the linearity of the first step in the Artifact Calibration process was checked.

7.1 Direct Voltage

7.1.1 Repeatability

The Artifact Cal process was repeated 10 times to investigate the scatter in the calibration constants. The measurements indicated that the scatter of the for DC Voltage relevant calibration constants was below 0,5 ppm.

7.1.2 Applying shifts to the external references.

The calculation of the calibration constants was checked by applying external reference voltages with a value of 9,95V (-0,5%) and 10,1V (+1%). Table 7.1 and 7.2 show the influence of shifted external reference voltage on the calibration constants and on the output voltage. References were the black box measurements.

		External Reference Shifted +1%		External Reference Shifted -0.5%	
Calibration constant	Symbolic name	Value	Deviation from +1%	Value	Deviation from -0,5%
10V external reference standard	EXT_10V	+10,1000000 V	-	+9,950000 V	-
6.5V reference true value	KV6	+6,8962974 V	+0,00 ppm	+6,896297 V	+0,00 ppm
13V reference true value	KV13	+13,7913432 V	-0,38 ppm	+13,791338 V	+0,00 ppm
6.5V buffered reference value	BV6	+6,8963459 V	+0,30 ppm	+6,896346 V	+0,30 ppm
13V buffered reference value	BV13	+13,7913947 V	-0,22 ppm	+13,791389 V	+0,17 ppm
11V range positive gain	D3G	3.016,15355015 /V	-0,00 ppm	3.016,15354629 /V	-0,00 ppm
11V range negative gain	D3N	3.016,15283890 /V	+0,44 ppm	3.016,15397771 /V	+0,06 ppm
22V range positive gain	D4G	1.508,07299389 /V	+0,35 ppm	1.508,07352517 /V	-0,00 ppm
22V range negative gain	D4N	1.508,07299389 /V	+0,35 ppm	1.508,07354365 /V	-0,02 ppm

Table 7.1 Calibration constants with external reference voltage shifted by +1% and –0.5%

			External Reference Shifted +1%			External Reference Shifted -0.5%		
DC Voltage Range (V)	24h spec (ppm)	Test Value (V)	Measured value (V)	Deviation from +1% (ppm)	% of 24h Spec (%)	Measured value (V)	Deviation from -0.5% (ppm)	% of 24h Spec (%)
0.2	8.50	0.2	0.1999998	-1.00	-11.76	0.1999994	-3.00	-35.29
2.2	4.00	2	1.9999996	-0.20	-5.00	1.9999985	-0.75	-18.75
11	3.85	10	9.999998	-0.20	-5.19	9.999999	-0.10	-2.60
22	3.83	20	19.99999	-0.50	-13.05	20.00000	-0.05	-1.31
220	4.40	200	200.00009	+0.43	9.77	200.00000	+0.00	0.00
1000	6.50	1000	1000.0016	+1.59	24.46	1000.0026	+2.62	40.31

Table 7.2 Measurements with external reference voltage shifted by +1% and –0.5%

7.1.3 *Applying shifts to internal calibration constants*

The calibration constant "2.2V range gain" (D2G) was changed by +1% using special engineering commands. This affects only the 2,2V range, since the higher ranges do not use the 5:1 divider. The 0,2V range, which uses the 5:1 divider, does not use the gain constant of this divider, but has its own gain constant being the gain of the 5:1 divider and the 10:1 divider connected in series. Analogous to this, the change in the 11V positive gain constant D3G only affects the ranges 0,2V, 2,2V and 11V. The higher ranges except the 22V range are made up using the negative 11V range constant D3N. The table below clearly shows this behavior.

			D2G Constant Shifted +1%			D3G Constant Shifted +1%			D3G & D3N Shifted +1%		
DC Voltage Range (V)	24h spec (ppm)	Test Value (V)	Measured value (V)	Deviation from +1% (ppm)	% of 24h Spec (%)	Measured value (V)	Deviation from +1% (ppm)	% of 24h Spec (%)	Measured value (V)	Deviation from +1% (ppm)	% of 24h Spec (%)
0.2	8.50	0.2	0.1999995	-2.50	-29.41	0.2019995	-2.48	-29.18	0.2019996	-1.98	-23.29
2.2	4.00	2	2.0199997	-0.15	-3.75	2.0200000	+0.00	0.00	2.0199998	-0.10	-2.50
11	3.85	10	9.999999	-0.15	-3.90	10.100011	+1.09	28.31	10.099998	-0.16	-4.16
22	3.83	20	20.000000	+0.10	2.61	20.000000	+0.10	2.61	20.000000	+0.10	2.61
220	4.40	200	200.00011	+0.55	12.50	200.00015	+0.75	17.05	202.00014	+0.69	15.68
1000	6.50	1000	1000.0016	+1.60	24.62	1000.0016	+1.60	24.62	1010.0015	+1.49	22.92

Table 7.3 Measurements with calibration constants D2G, D3G and D3G & D3N individually shifted by +1%

7.2 Alternating Voltage

7.2.1 *Repeatability*

The Artifact Cal procedure was repeated 14 times with stable external reference standards. After each Artifact Cal measurement the resulting new values of the calibrator software calibration constants were obtained with the Print Raw Data function of the calibrator. The mean values and the sample standard deviations of the ACV gain constants, the ACV flatness constants and the sensor low frequency correction were calculated. The results are shown in the following tables.

Artifact Cal measured ACV gain constants		
Range	Mean	StdDev
(V)		(ppm)
2 m	990,33926	1,2
22 m	990,33927	1,2
220 m	10,001051	0,7
2,2	3,1622977	0,5
22	0,31622318	0,0
220	0,010000011	0,3
1100	0,010002231	0,3

Table 7.4 Mean and standard deviation ACV gain constants

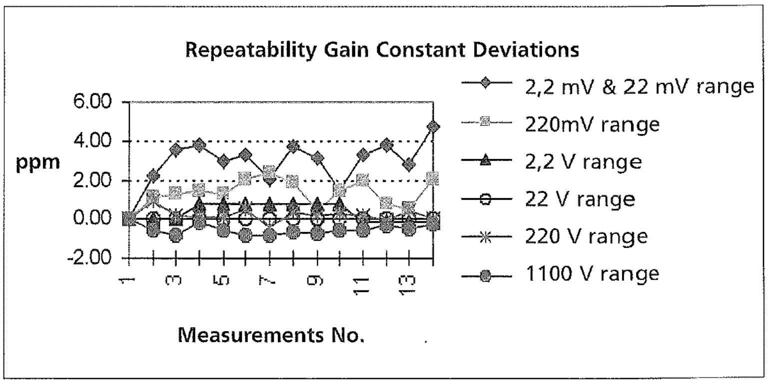


Figure 7.1 Repeatability Gain Constants

Deviation Flatness constants in ppm relative to unity Std Dev. of Artifact Cal measured Constants, presented in ( )																						
Freq. (kHz)	0.3	0.5	0.7	1	5	10	20	50	100	120	120	200	300	400	500	600	700	800	900	1000	1100	1200
Range (V)																						
2,2							0	-15	-43	-129	129	226	317	374	404	409	384	325	216	-27	-358	-517
							(2)	(1)	(3)	(3)	(3)	(3)	(4)	(5)	(5)	(5)	(6)	(6)	(7)	(6)	(7)	(8)
22							1	4	51	114	139	306	450	650	859	1088	1326	1569	1810	1930	4117	4462
							(2)	(1)	(1)	(2)	(3)	(2)	(2)	(2)	(2)	(3)	(3)	(3)	(4)	(5)	(19)	(5)
220					-3	-4	2	-9	-66	-9	29	120	147	-54	-453	-317	8	-3192	-5536	-7565		
					(2)	(2)	(3)	(3)	(3)	(4)	(4)	(5)	(11)	(90	(13)	(18)	(26)	(33)	(30)	(35)		
1100	-21	-97	-207	-438																		
	(1)	(1)	(1)	(2)																		

Table 7.5 Repeatability of Artifact Cal measured ACV flatness constants

The mean value of the Artifact Cal measured AC-DC sensor low frequency constant, A4FH, is 0,02751 and the standard deviation is 0,00117. As the output voltage correction is a function of the A4FH constant, the voltage level and the frequency, the corresponding maximum output voltage standard deviation is calculated to be 12 ppm relative to the nominal voltage.

7.2.2 *Artifact Cal ACV reference plane measurements*

The reference plane for the generated AC voltage during normal user operation of the calibrator is at the front panel output terminals with the calibrator set to internal sense mode. These output conditions are not mentioned as such in the calibrator AC voltage specifications. For the 2,2V range and the 22V range, the reference plane for the Artifact Cal procedure internal AC-AC comparison between the AC-DC thermal sensor and the AC-AC reference thermal sensor is at an internal connection point on the oscillator control PCB, A12. The voltage at this Artifact Cal reference plane is possible to measure by measuring the voltage between test points TP1 and TP2 on the A12 PCB.

The voltage drop between the calibrator output terminals and the Artifact Cal measurement reference plane has been measured at 2V on the 2,2V range and the results are presented in the following Figure 7.2.

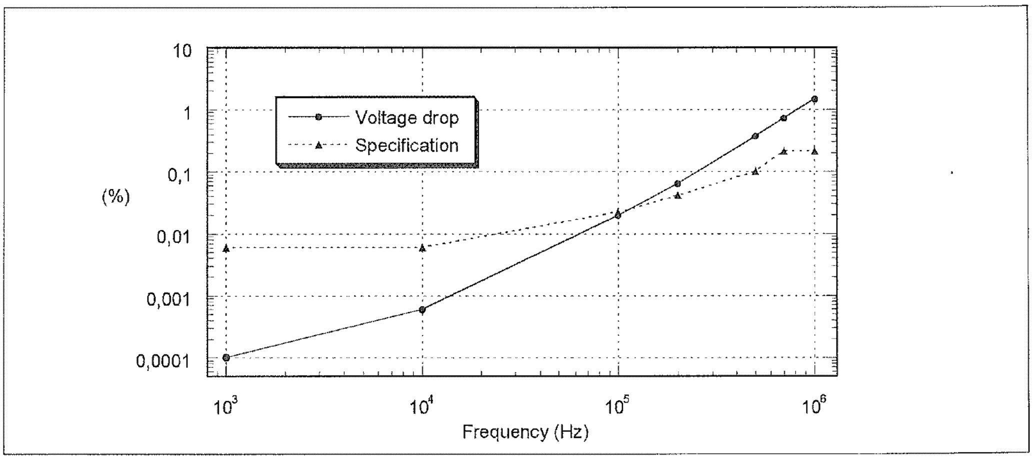


Figure 7.2 Voltage drop between output terminals and Artifact Cal reference plane at the 2,2 V

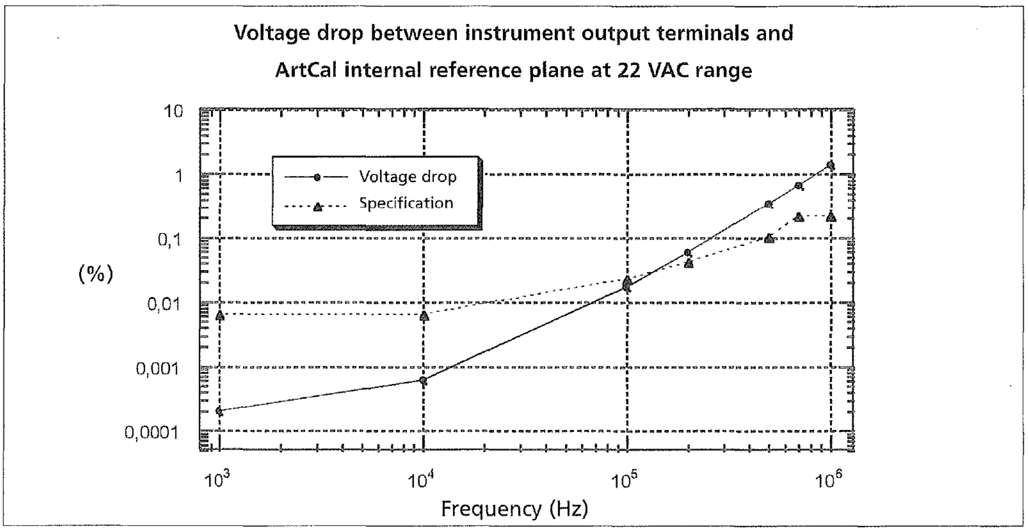


Figure 7.3 Voltage drop between output terminals and Artifact Cal reference plane at the 22V range

Measurements at 20V on the 22V range are also performed and the following figure 7.3 shows the results.

The voltage drop at the 22V range is almost equal to the voltage drop at the 2,2V range. The differences can be explained by different input capacitance of the 2,2V and the 22V range active attenuators at the input of the AC-DC sensor.

There is a factory calibrated software constant for each ACV range that corrects for these errors, they are called Standing Wave Ratio correction factors, SWR constants. The values of these constants are user obtainable with the Artifact Cal Print Raw Data function of the calibrator. For the 2,2V range and the 22V range the constants are A4S and A5S, respectively. The SWR correction factor is for the 22V range applied as shown in the following equation:

$$V^{n+1}_{DAC} = V^{n}_{DAC} \bullet (1 + Frequency^2 \bullet A5S) \qquad (7.1)$$

Where V^n_{DAC} is the precision DAC voltage (DAC counts) without correction for SWR and V^{n+1}_{DAC} is the DAC voltage with the correction applied. Comparing the measured sense lead voltage drops with the calculated SWR correction, using the instrument stored values of A4S (14,4357E-15) and A5S (13,132E-15) gives the following results:

Difference between measured sense lead voltage dropand SWR correction. (ppm)							
Range (V)	1 kHz	10 kHz	100 kHz	200 kHz	500 kHz	700 kHz	1 MHz
2,2	1	5	50	66	84	127	232
22	2	5	34	54	68	107	302

Table 7.6 Comparison of measured sense lead voltage drop and SWR

The differences are negligible compared to specification.

7.2.3 Effect of changes to internal constants that influence ACV

The Artifact Cal procedure uses the internal DC voltage references to calibrate the gain of the precision DAC and stores the result as DAC counts per Volt. The ACV function uses the positive 11V range of the DAC. The gain of the positive 11V range is stored as the D3G constant. The value of this constant was for the instrument under test 3016,1555 (DAC counts/Volt), before shifted. The constant was shifted +1% and measurements showed a corresponding +1% shift in the output voltage.

The DCV gain of the ACV ranges are in principle calibrated with the linearity of the precision DAC as reference. This means that the value of the external 10V DC reference

does not influence the measurement of the DCV gain of the ACV ranges. The gain of the ACV ranges are quantities without dimension. Shifts of +1000 ppm (1%) to the 22 ACV and 0,22 ACV range gain constants, A5G and A3G, were introduced and measurements showed corresponding +1000 ppm shifts in the output voltage.
The frequency flatness constants are measured with the second internal AC-AC sensor circuit as reference. They are not influenced by Artifact Cal DCV gain measurement results. The factory set frequency flatness constants, such as the SWR constant for the 22 V range, A5S, are not measured or adjusted by Artifact Cal. Some gain constants for the mV ranges are written directly in the software code. In Table 7.7, test results from changing flatness constants and convergence constants are presented.

Range (V)	Freq. (Hz)	Type of constant	Const. name	Const. value before change	Const. value after change	Calculated shift of constant (ppm)	Measured shift of output voltage (ppm)	Meas. voltage level (V)	Print Out Report Shifts (ppm)
22	100 k	Flatness	A5F3	0,999994587	1,00099458	1000	1000	20	-1000
22	1 M	Flatness	A5FE	1,003236392	1,00122992	-2000	-2013	20	2000
22	50 k	Converg.	A5C5	1638,91111	1838,91111	+400 (*)	0	20	0
22	500 k	Converg.	A5CC	1715,388888	1415,38889	-600 (*)	-3	20	0
2,2	500 k	1/V Conv.	A4VC	313,13333	1313,13333	+1000 (**)	0	2	0
2,2	"	"	"	"	"	+2000 (**)	1	1	---
2,2	"	"	"	"	"	+9091 (**)	36	0,22	---

Table 7.7 Introduction of shifts to flatness and convergence constants

(*) Estimation based on 14 bit DAC resolution of 2 ppm per count.
(**) Calculated as ((1000 DAC counts).(2 ppm))/(Measured voltage level)

It is noticed that the output voltage follows the shifts made to the flatness constants. It is also noticed that the Print Out Report presents the correct magnitude of the output voltage shift but with the opposite sign. Also, the output voltage is correctly not influenced by the convergence constants.

7.2.4 AC-DC sensor low frequency correction

The AC-DC sensor low frequency constant, A4FH, is adjusted by the Artifact Cal procedure, but the output voltage shifts due to this adjustment is not shown by the Artifact Cal print-out report. The value of the A4FH constant is documented in the Artifact Cal Raw data print-out report.

The formula which the calibrator uses to calculate the Low frequency output voltage Correction Factor, LCF, is applied for frequencies 10Hz to 100Hz only.
In the following, the validity of the formula for the low frequency correction factor is verified. A shift of the AC-DC thermal sensor low frequency constant, A4FH, is introduced. The original, not shifted, A4FH value is 0,027333. Then the value of A4FH is shifted + 200 %, thus becomes now 3*0.027333 = 0,081999.

The measurement goal was to obtain the differences between the calculated proportional output voltage shifts due to the shift of A4FH and the measured values. The differences observed were within the measurement uncertainty, the largest uncertainty at k=2, is 25 ppm at 10Hz and the smallest is 5 ppm at 1000Hz.

The differences between the measured output voltage shifts and the calculated shifts due to the shift of the A4FH constant are negligible compared to the specification.

Although the Artifact Cal print-out report does not show the calculated output voltage shifts, due to shift of the A4FH constant, it is possible to use the given formula for LCF to calculate the output voltage shift and thereby keep the traceability to the last performed external calibration.

7.2.5 *Introducing a hardware frequency response shift and functional testing of the AC-DC transfer process*

To verify that the Artifact Cal procedure correctly adjusts the flatness constants to compensate for a frequency response drift of the AC-DC sensor, a hardware frequency response shift is introduced to the AC-DC sensor circuit.

A large frequency response shift is introduced to the AC-DC sensor circuit by soldering a capacitor C at the input of the thermal sensor. The following figure shows the connection of the capacitor C.

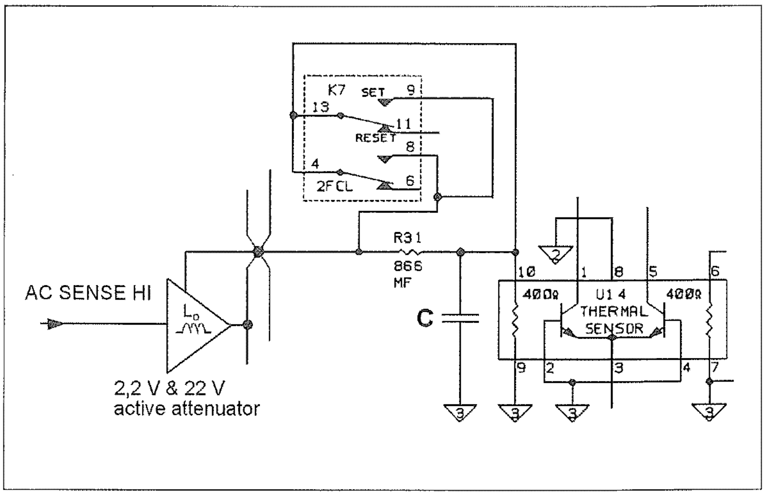


Figure 7.4 Schematic of relay K7 connection and adding a capacitor C to the ac-dc sensor circuit

Adding the capacitor C will, due to the RC filter effect, decrease the thermal sensor input voltage when relay K7 is in the RESET position for the high sub range. When the K7 relay, for the low sub range, is shorting the R31 resistor, adding C will in combination with the output inductance of the AC SENSE active attenuator, L_O, increase the input voltage of the thermal sensor. L_O has been measured to approximately 1,1 µH.

To get an overall picture of the AC-DC transfer process. the capacitor C was added and removed, while the output voltage was continuously measured. As the AC Xfer Choice is enabled at the 220V range and the V-Hz product is limited to $22 \cdot 10^7$ (V*Hz), the measurement point of 22V and 1MHz at the 220V range is chosen for some tests.

The following measurement procedure was performed:

- A) An Artifact Cal procedure was performed with no capacitor added.
- B) The output voltage was measured.
- C) The capacitor was soldered at the AC-DC sensor input.
- D) The output voltage was measured.
- E) An Artifact Cal procedure was performed with the added capacitor.
- F) The output voltage was measured.
- G) The capacitor was removed.
- H) An Artifact Cal procedure was performed with no capacitor added.
- I) The output voltage was measured.

A traceably calibrated Fluke 792A was used to measure the calibrator output voltage. The measurement uncertainties are less than the corresponding uncertainties for the measurements with the Fluke 5790A in the black box- and the opaque box evaluation measurements.

Measurements made at step B and I are compared to evaluate the base stability of the calibrator during the measurement sequence. The largest found difference is 150 ppm at 22V and 1MHz. For frequencies 100kHz and below, the differences are less than 10 ppm. The results of the measurements are shown in the table 7.8a and 7.9b.

Output voltage shift due to the added 80 pF capacitor, measurement D - measurement B.
Shifts in ppm relative nominal voltage.

Range (V)	Voltage (V)	1 kHz	10 kHz	20 kHz	50 kHz	75 kHz	100 kHz	119 kHz	120 kHz	150 kHz	200 kHz	300 kHz	500 kHz	700 kHz	1000 kHz
0,22	0,06	-3	-6	-7	-13	-21	-36	-39	171		474	1072	2989	5852	11887
0,22	0,2	-1	-1	2	29	71	126	178	179		492	1091	3013	5885	11952
2,2	0,6	-2	-2	-5	-8	-16	-23	-36	172		483	1077	2988	5843	11838
2,2	2	-1	0	4	31	69	125	174	176		486	1081	2982	5824	11817
22	6	-1	0	-2	-9	-17	-27	-38	181		477	1082	2984	5826	11824
22	20	2	2	5	31	68	123	173	177		484	1081	2983	5811	11810
220	22	-1	4	-1	-4	-14	-27	-38	-45		-132	-291	-810	-1672	-3360
"	60	-1	4	1	-8	-16	-31	-38	-49	-80	-141				
"	70										495	1110			
"	100	-2	5	7	31	68	118	175	176	271	476				
"	200	-1	7	7	33	71	122								

Table 7.8a Output voltage shift due to added 80 pF capacitor

The measured shifts indicate that the R31 resistor is not shorted for frequencies above 119kHz in the low sub ranges of the ranges 0,22V, 2,2V and 22V. This will make the internal AC-DC transfer measurement resolution lower for these sub ranges. This yields for the 2,2mV and the 22mV range also, as they are divided from the 2,2V and the 22V range. For the 220V range, the R31 resistor is shorted for all frequencies in the low sub range.

The measured output voltage when the calibrator is ArtCal adjusted without any extra capacitor is compared with the measured output voltage when the calibrator is ArtCal adjusted with the 80 pF capacitor. The voltage differences are shown in the following table.

Difference of output voltage when calibrator was ArtCal adjusted
with the 80 pF capacitor and when the calibrator was adjusted without the capacitor, measurement F - measurement B.
Deviation from nominal voltage in ppm

Range (V)	Voltage (V)	1 kHz	10 kHz	20 kHz	50 kHz	75 kHz	100 kHz	119 kHz	120 kHz	150 kHz	200 kHz	300 kHz	500 kHz	700 kHz	1000 kHz
0,22	0,06	-2	-5	-11	-43	-98	-158	-211	-2		-11	-10	-3	19	52
0,22	0,2	-2	-3	-2	-3	-8	1	2	1		5	7	19	42	79
2,2	0,6	0	-1	-7	-39	-94	-147	-210	-34		4	0	7	23	55
2,2	2	0	-1	2	-1	-8	1	2	-1		0	2	0	3	17
22	6	-1	-3	-8	-42	-98	-155	-210	4		2	15	49	111	225
22	20	0	-1	0	-2	-12	-4	1	1		7	13	47	94	217
220	22	2	11	-3	-2	9	-5	-5	3		-7	-6	-11	-91	-169
"	60	1	10	-1	-2	1	0	-6	-5	-5	-19				
"	70										607	1366			
"	100	2	13	3	36	84	149	207	221	344	598				
"	200	1	14	5	39	88	152								

Table 7.8b Difference of output voltage, after ArtCal adjustment with and without 80 pF capacitor

From the measurement results in the above table it is seen that the low sub ranges of the 0,22V, the 2,2V, and the 22V range are not measured by ArtCal for frequencies below 120 kHz. It is also seen that the high sub range of the 220V range is not measured by ArtCal. The ArtCal print-out report shows full scale output voltage shifts and these agrees well within specification, compared with the measured shifts for the voltage ranges 0,22V - 22V, except for the sign. The print-out report full scale shifts are not correct for the 220V range as it is measured at 22V in the low sub range. The print-out report full scale figures yields also for frequencies 120 kHz and above in the low sub ranges of the ranges 0,22V -22V, but not for frequencies below 120 kHz.

However, since the low sub range, where R31 is shorted, is measured by ArtCal at the 220V range measurement, this measurement result could, but not necessarily will, indicate shifts on the low sub ranges on ranges 2,2mV -22V, for frequencies below 120kHz. Also, shifts at the high sub ranges of the 2,2mV - 22V ranges could indicate shifts in the high sub range of the 220V range.

7.2.6 *The resolution of the AC-DC transfer process.*

Figure 7.5 shows the different resolution of the AC-DC transfer process for frequencies below 120,00kHz and for frequencies 120kHz and above.

The measurement series for the 119,99kHz and 120,00kHz shown in the above diagram were performed in the same way and for clarity they are shown in the same diagram. Before each measurement, shown as a dot in the diagram, the calibrator AC-DC transfer process was restarted, the "unstable" character u on the instrument display lit. When the u character was switched off, the measurements of the output voltage were performed and the output voltage was stable within 2 ppm.

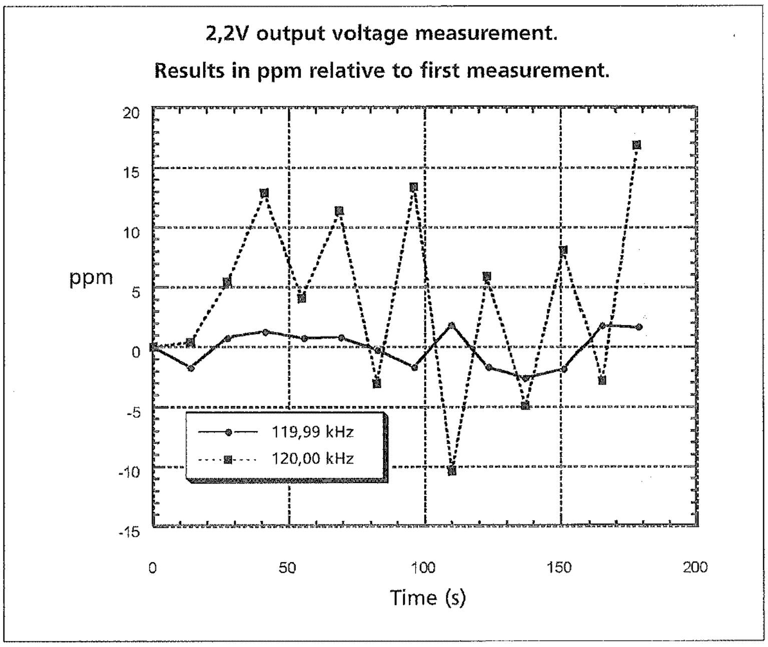


Figure 7.5 AC-DC transfer resolution shift between 119.99 and 120.00kHz

The measurement voltage, 2,2V, is at the low end of the 22V range, where the R31 resistor is shorted for 119,99kHz and not shorted for 120,00kHz. To equalize the conditions of the calibrator the AC Xfer = OFF command was used for 119,99 kHz. The larger standard deviation at 120,00kHz, 7,9 ppm,
compared to 1,5 ppm at 119,99kHz, is due to the following:

- Lower resolution when the R31 resistor is not shorted at the minimum voltage on the 22V range, for frequencies above 119,99kHz.
- Different settled criteria: Final AC-DC adjustment is less than 30 ppm for the 120,00kHz measurements and less than 7,5 ppm for the 119,99kHz measurements.

7.3 Resistance

7.3.1 *Repeatability*

The Artifact Cal procedure was repeated 14 times with stable reference standards. After each calibration, the internal calibration constants were obtained by the print out of the raw data file from the calibrator. The average and standard deviation of the relevant internal calibration constants were calculated. The standard deviations are given in the following table.

Constant	Std.Dev [ppm]	Std.Dev [% of spec]	Constant	Std.Dev [ppm]	Std.Dev [% of spec]
RS10K	0,8	10,7	R10K	0,8	11,2
R1	0,6	0,9	R19K	0,8	11,0
R1_9	1,3	1,8	R100K	0,8	8,9
R10	1,2	5,5	R190K	0,7	8,0
R19	1,1	5,4	R1M	0,9	6,8
R100	1,1	8,1	R1_9M	0,7	5,3
R190	0,9	7,1	R10M	0,9	3,3
R1K	1,0	10,6	R19M	0,9	2,5
R1_9K	0,9	10,3	R100M	1,0	1,1

Table 7.9 Standard deviation of the Artifact Cal measured values of the output resistors R1 through R100M and the internal reference resistor RS10K.

From Table 7.9 it is clear that the Artifact Cal procedure performs a very stable calibration. For all resistors the standard deviation is approximately 1 ppm, which corresponds to at most 11% of specification.

7.3.2 *Use of non-nominal external references*

The linearity of the first calibration step in resistance was checked by applying a non-nominal external 10kΩ reference standard in the Artifact Cal procedure. Two values were used, namely 10,1kΩ and 9,95kΩ which differ +1% and – 0,5% from nominal value respectively.

Using the CAL_REF command (see page 5-21 of the Fluke 5700A Operator manual), via

	Starting value	Deviation from starting value [ppm]		
Resistor	kΩ	10,1 kΩ cal.	9,95 kΩ cal.	10,0 kΩ cal.
RS10K	9.9993364	+0,21	-0,32	-0,04

Table 7.10: Change in value of the RS10K internal 10 kΩ reference standard after three subsequent calibrations using three different values of the external reference standard

a computer connected to the calibrator, the subsequent steps of a normal Artifact Cal were programmed but now with the 10kΩ calibration step repeated several times. Table 7.10 shows the change in the value of the internal 10kΩ reference standard (symbolic name RS10K) after the subsequent calibrations.

The deviations of the starting value are only a few tenths of a ppm. It is clear from these results that the calibrator correctly calibrates the internal 10kΩ standard, even when the external standard is not very close to nominal. The linearity of the calibration thus is very good and also the calculations apparently are done correctly.

7.3.3 *Shift of internal calibration constants / CalCheck*

The glass box measurements also consisted of shifts of some of the internal calibration constants. When any of the resistance constants are changed, the new values are correctly showed on the display of the calibrator. Again, no measurements of these changes were necessary because of the passive nature of the resistance function.

7.3.4 *Leakage resistances*

For the high-ohm values of the resistance function leakage resistances in the calibrator are very important. Therefore, some leakage resistances of the calibrator were determined, as far as was possible without damaging (other) components in the calibrator. For the determination of the leakage resistances a battery operated terra-ohm meter was used with a test voltage of 10V.

First of all, the leakage of the external binding posts to ground was determined with the calibrator in standby mode. The lowest leakage resistance was between the Out Lo terminal and ground, being 0,5TΩ. The leakage resistance of the other binding posts to ground was at least an order of magnitude larger, with the highest value of more than 20TΩ found for the Sense Hi terminal. Leakage between the binding posts was at least 5TΩ. For the 100MΩ resistor this means a parallel resistance of at most 20 ppm, which falls well within the specifications. For the lower value resistors, the leakage is even of less relative importance.

In 'operate' mode, the leakage of the Lo terminals to ground was approximately 100MΩ. This in principle is sufficient, since in practical use one of the Lo terminals will be connected to the guard so there is no need to have that resistance particularly high. It could not be measured what the contribution was of the internal lines and relays to the leakage between the output lines. On the other hand it is noted that the two Ohms boards are located in the calibrator close to the front panel so that the total length of the output line is relatively short.

7.4 Current

7.4.1 *Repeatability*

The Artifact Cal procedure was repeated 14 times with stable reference standards. After each calibration, the internal calibration constants were obtained by the print out of the raw data file from the calibrator. The standard deviation of the relevant internal calibration constant measurements were calculated and were ranking from 1.02 ppm to 3.86 ppm for all current gain, offset and frequency flatness constants. The standard deviations are caused the internal measurement system of the calibrator. The standard deviations are relative small compared to the specifications of the calibrator.

7.4.2 *Shift of internal calibration constants*

In case the DC voltage gain constant of the 22V range is shifted (A5G), it will affect all the current ranges. A nominal measurement is performed including an external current calibration and the running of the Cal Check by the calibrator. This is followed by the shift of the internal constants. Then again an external calibration and Cal Check is carried out. The differences found by the calibration and the Cal Check are calculated relative to the 24h specs.

In the following table the results are given. The measurements show a good agreement with the shifts given by the CalCheck procedure of the Fluke 5700A calibrator.

The current constants has been shifted for as well the gain constants, I2G (2,2mA range) and I4G(220mA range) as the frequency constants, I3Fx (22mA range) and I4Fx

Range	Current	shift of	((-CalCheck shifts)-Measured shifts) as % of spec								
		int. constant	DC+	DC-	10Hz	20Hz	40Hz	100Hz	1kHz	5kHz	10kHz
2,2 mA	1 mA	A5G (+0.5%)	-7	5	-4	-4	-9	-19	-19	-3	-1
22 mA	10 mA	A5G (+0.5%)	1	-3	-3	-2	-5	-8	-10	-3	-1
220 mA	100 mA	A5G (+0.5%)	0	-3	-3	-4	-8	-19	-24	-5	-3

Table 7.11 Shifts of the internal DCV gain constant of the 22V range

(220mA range). The results show have a good agreement for the calibration points. In case of the 22mA range, the 500 Hz point is taken instead of the 100 Hz, because the CalCheck procedure takes 500 Hz as lowest frequency reference point. No deviation was found for this extra measurement point between the external calibration and the internal CalCheck procedure.

Range	Current	shift of	((-CalCheck shifts)-Measured shifts) as % of spec								
		int. constant	DC+	DC-	10Hz	20Hz	40Hz	100/500Hz	1kHz	5kHz	10kHz
2,2 mA	1 mA	I2G (+0.5%)	4	2	0	0	-1	-4	-2	0	0
2,2 mA	2 mA		1	4	0	0	2	11	1	1	-1
22 mA	10 mA	I3F1, I3F2	6	7	2	2	16	1	10	1	1
22 mA	20 mA	and I3F3 (-0.5%)	-10	-5	1	2	12	-5	-2	-1	0
220 mA	200 mA	I4G, I4F4, I4F5	-9	-9	-1	-1	0	0	1	0	0
220 mA	200 mA	and I4F6 +0.25%)	3	12	1	0	3	3	0	1	0

Table 7.12 Shifts of the internal current constants

7.5 Internal Firmware

The firmware of the 5700A has been analyzed on its functions and responsibilities, whereby special attention has been given to those subsystems and routines which have direct or indirect impact on the Artifact Calibration procedures and their results on the output of the calibrator. In relation to this the following functions and circuitry have been identified as critical:

- CPU Assembly
- Guarded Digital Control Circuitry
- Firmware for storing calibration constants
- Self Check of Main and Guarded CPU
- Analog Switching hardware

Additionally in relation to the goal of the project, Artifact Calibration functions and calibration report functions are especially evaluated. For this reason the source code of the critical identified functions and firmware has been analyzed after which practical test have been carried out. The firmware evaluations and tests were performed according the following scheme:

7.5.1 *Calibration Data Storage Check*

The NV Non-Volatile memory manager holds default calibration constant values in EPROM, which serves the integrity when the EEPROM is damaged. The CCO Calibration Constant manager, stores and retrieves calibration constants and uses the NV subsystem to do the actual storage and retrieval of Non-volatile values. The tests carried out verified the handling of the calibration constants and should give resolution whether unintended changes in data are detected and if so, what actions are taken.

The NVget and NVgetPrev attempts to read or get constants (Official set or Previous set resp.)from the EEPROM memory. Every constant has it's own checksum and if the NVeeRead detects a checksum error, it will inform the system. As a result, the corresponding default constant (which is being held in the separate EPROM) will be used.

7.5.2 *In-variable memory Check*

The EPROM contains a checksum, calculated when the firmware was compiled and it covers the entire memory content. The tests investigated if unintended changes in the invariable memory will be detected and if so, what actions are taken.

At Power-Up, or by giving the remote *TST command, the checksum is re-computed and compared with the initial checksum at the time of compilation. The instrument is not allowed to continue unless it passes the checksum test.

7.5.3 *Variable Memory Check*

In the instrument it exists two types of variable memories, RAM memory (being checksum /CRC tested during power-up) and EEPROM memory, which is tested by giving every calibration constant a checksum of its own. When a calibration constant is red from a EEPROM memory a checksum test (CRC) is done. If an error is discovered the default value, got from the invariable EPROM memory, is used instead.

1) The RAM memory is tested during power up by using a checksum calculation.
2) At power up, the calibration constants that reside in the OFFICIAL set in the EEPROM memory are copied to the ACTIVE set in RAM memory. Every calibration constant has its own checksum and if an error occurs the default value from the EPROM memory is used.
3) Parts of the EEPROM memory, the calibration constants in the PREVIOUS set, are also checked when the *TST remote command is given.
4) Parts of the RAM memory, the calibration constants in the ACTIVE set, are also checked when the *TST remote command is given.

Almost the entire RAM memory is checked during startup by the function UTramTest(). The excepted memory area is the top 800 hexadecimal bytes. Those memory bytes are not considered important to check because that memory area is only used during the power-up stage. If a memory fault is detected during start up the instrument is stopped and is not allowed to continue.

The routine testRam(), called by the function UTramTest(), writes different bit pattern to the RAM. After that a bit pattern is written to the RAM a read access is performed. This sequence with write and read to and from memory is so constructed that every bit is tested in the checked memory area of RAM.

At power up the function CCOinitram moves all calibration constants from the official set (EEPROM) to the active set (RAM). To get the calibration constants it uses the function NVget. This function use the function NVeeread() to do the checksum test (CRC) for every value. If a calibration constant is faulty the corresponding default value in EPROM is used instead. An error message is then sent to the system.

The *TST command is an IEEE-488.2 standard remote command intended for a controller to request an instrument to perform a simple self-test. In 5700A the command calls the functions UTromTest() and NVcheck(). The function NVCheck use the function NVeeread() to do a checksum test for a calibrating constant. This test is done for all calibration values in the active set in RAM and in the previous set in EEPROM.

Also for this test it was investigated if unintended changes in the variable memory will be detected. If so, what actions will be taken.

Result: The RAM memory is only checked at startup and not continuously during run-time. Therefore a regular reset is advised (i.e. daily, when the calibrator is switched on continuously) to check the RAM memory.

The EEPROM memory is checked by using a checksum for each calibrating constant, so that a checksum error would only affect one value.

7.5.4 *Data Path Checks*

The guarded and unguarded sections between the digital and analog circuitry are connected via an optical link. The communication protocol between the main and in-guard CPUs is a proprietary derivative of the SDLC protocol, with numbered packets, dropped packet detection and retransmission. Further there is a function "testRam" performing at power up a write and read test accessing RAM. This is done for every bit channel on the data bus. The used RAM area is checked (See also "Invariable memory Checks"). And at power up, the data bus is checked by accessing the RAM.

The tests should indicate whether faults in the internal communication between modules will be indicated and if the data bus between the processor board and the RAM is checked.

During the tests it was observed that the internal communication line between modules as well as the data bus communication between the processor board and the RAM is checked by the firmware.

7.5.5 *Power supply monitoring*

The two actions: power up and power down are handled by the hardware and by the firmware. The firmware deals with it in the WD and GO subsystem. The WD, watchdog, subsystem. The watchdog routine WDiqrServ also handles a power-down interrupt. But in case the power goes down, the routine has not enough time to do anything when the power goes down, (no extra power buffer exists). The GO subsystem is the start-up/bootstrap code for the instrument. It is a collection of calls to various subsystem initialization functions. The file GO.c contains the following:

main: main program for startup initialization
GOreset - Warm RESET the MFC

The power monitoring test investigated what happens if the power supply fails to deliver correct voltage, or if there are fluctuations. This test was practically carried out by lowering, in steps, the input AC line voltage. During the low input voltage the instrument was tested by running the SDI (self diagnostic) test. The instrument specifications for line voltage is +/- 10 % allowed about selectable nominal line voltage. The nominal voltage selected was 230 VAC.

Before the SDI test was started a reset of the instrument was always done. After that a text message was shown on the front panel and that the SDI program had stopped, the SDI program was aborted. A new input voltage was then adjusted and after that a reset was done.

When the input voltage was decreased the only reaction of the instrument was that the front panel gradually went darker. And when the line voltage got as low as 125 VAC the instrument's front panel display became completely dark and the instrument shut down. Based on this, one can conclude that the instrument meets the Fluke voltage specifications for the input line. The watchdog checks the front panel power supply. If a power supply fault is detected the measure taken is an error message.

The hardware prevents that the EEPROMs memories are written into during power up and during power down. During power down a reset signal is generated by the circuit U1 after a voltage drop to 4.5V. This means that the circuit U1 prevents CPU malfunctions, during power up/down sequences, because of undefined supply voltage.

7.5.6 *Program sequence monitoring.*

The tests should indicate how faults in program sequence will be detected. Also they should indicate what actions will be taken when a watchdog alarm is given.
The watchdog subsystem consists of one file WDOG.c, which has the following functions:

1) WDinit: Initialize watchdog timer driver
2) WDirqServ: Watchdog timer timeout interrupt handler and is called if the watchdog goes off, indicating that WDtask missed doing its job for a time long enough to set off the watchdog. The WDiqrServ also handles a power-down interrupt..
3) WDtask: Wtachdog clear task It uses a firmware timer to wake it up 4 times per second, at which time it pets the watchdog (it writes to a specific hardware address which resets the watchdog timer).

When a interrupt occurs the type of interrupt will be checked by the firmware. If it is a valid hardware watchdog interrupt and it has occurred more than five times, then the instrument will be shut down by the routine Utcrash(). Every valid hardware watchdog interrupt will however result into an error message to the error sink. But those watchdog interrupts that are defined to be spurious, by the firmware, are not logged.

Result: The system will not be shut down until six valid hardware interrupts are detected by the watchdog. This watchdog counter, the parameter BarkCount in the routine WDirqServ, is only cleared by a reset of the instrument or by a power down. It is advised to perform a reset of the instrument now and then. To avoid a unnecessary system shut down during operation of the instrument, see also "Variable memory Check".

7.5.7 *Checking of analogue switching hardware*

The Self Diagnostic Subsystem (SDI) is constructed with the intention to be used by the operator when he suspects that there is anything wrong with the instrument. The SDI

Routine	Function of the routine
SDIdacHeater ();	Test of the dac heater regulation
SDIdacRefs ();	Test the dac Reference supplies
SDIdacDac ();	Test the D/A on the dac
SDIdacAdcAmp ();	Test the ADC amplifier on the dac
SDIoscAnalog();	Test of the oscillator analogue
SDIpaAnalog();	Test of power amp Analogue hardware
SDIpaTemp();	Check the power amp Temperature
SDIcurAnalog();	DC current analogue tests
SDIaci4021();	AC current analogue tests
SDIhiresTests();	hi-res analogue tests
SDIswmDigital();	Test of switch matrix digital hardware
SDIswmAnalog();	Test of switch matrix analogue hardware
SDIswmXtraRelays();	Test extra switch matrix relays by using binding posts
SDIswmTemp();	Check the switch matrix Temperature
SDIhvAnalog();	Test of high voltage analogue hardware
SDIwbAnalog();	Test of wideband analogue hardware
SDIrpAnalog();	Test of rear panel analogue hardware
SDIohmsAnalog();	Test of ohms analogue hardware
SDIohmsTwoWireComp();	Diagnostics for checking the Ohms Two wire compensation
SDIwbPresent();	Is wideband present ?
SDIwbAnalog();	Test of wideband analogue hardware

Table 7.13 Routines, checking the hardware

function can then give further information about the cause of the error. It can also be used as a "check-up" of the instrument. This function has the objective to find where something is broken in the analogue (guarded section) hardware.
The table 7.13 lists the diagnostic routines checking the analog hardware.

The following test has been carried out, to investigate if a fault in the analogue switching hardware will be detected.

To simulate a relay malfunction a short was placed between two legs in the K7 (The Switch Matrix printed circuit assembly is analyzed (see figure 7-8 in the Fluke 5700A service manual). This K7 relay connects the 1:100 divider with the 1:10 divider.

The following display messages were observed during fault simulation test in the switch matrix assembly.

Action/Funktion	Display Messages
Power Up	No error messages
Self Test	No error messages
Self Diagnostic Test	A8 : Relay Fault (3819)
Continue of Self Diagnostic Test	No error messages

The fault "3819" is explained in the Fluke Troubleshooting manual in the following way. "A fault occurred while doing relay testing on the Switch Matrix assembly"

The firmware routines, in the SDI subsystem, test the switches in a very ambitious way. Most likely errors in the relays will be normally be detected by the Self Diagnostic test. The fault simulation test confirms that.

7.5.8 *Direct Voltage*

The firmware evaluation for this function was concentrated on:

a) Linearity & the calculation of the calibration constant DACLIN
b) the procedure to measure a voltage ratio by the ADC null detector;
c) the parameters gain and offset used for the 2,2 V range.

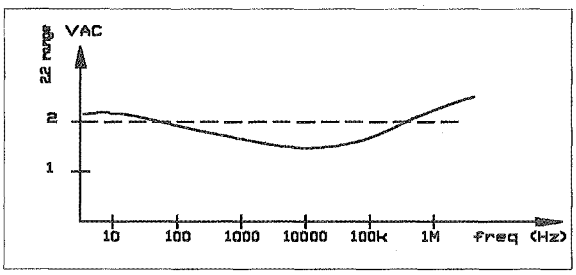
Firmware routines evaluated were:

1) The function SCAint6_5V22V in the file SCAref. c and the SCA subsystem.
2) The function SCAdc2_2Vzero in the file SCAdcv.c and the SCA subsystem.
3) The function SCAdc2_2Vgain in the file SCAdcv.c and the SCA subsystem.

7.5.9 *Alternating Voltage*

The firmware evaluation for AC Voltage was concentrated on:

a) the firmware which handles the determination of the frequency flatness corrections



Frequency flatness correction constants shall adjust the voltage so that it follows the "flat" dashed line.
These constants are measured and stored for some certain frequencies.
For other frequencies the constants are interpolated.

Figure 7.6 Freq. Flatness

b) Evaluation of the firmware which handles the determination of the convergence constants for frequencies above 120 kHz.
During the Artifact Cal procedure the convergence constants are created. The

convergence constants sets the start value DAC which is used to adjust the VAC. The adjustment process is a comparision between VDC and VAC using a thermo-element until the voltages match, VDC=VAC. These constants are measured and stored for some certain frequencies. For other frequencies the constants are interpolated.

Firmware modules analyzed:

1) The routine "SCAac2_2Vflat()" in the file/module SCAacv.c. and the SCA subsystem.
2) The routine " SCAacFlats()" in the file/module SCAacv.c. and the SCA subsystem.
3) The routine " acvFlat()" in the file/module SCAacv.c. and the SCA subsystem.
4) The routine " SCAac2_2V14bit()" in the file/module SCAacv.c. and the SCA subsystem.
5) The routine " ac()" in the file/module VFinder.c. and the VF subsystem.
6) The routine " CNFfreqCorrectc(). In the file CNFrange.txt and the CNF subsystem.
7) The routine "Correct()" in the file in the file/module VFinder.c. and the VF subsystem.
8) The routine cal_lf_linear() in the file/module Vfinder.c and the VF subsystem.
9) The routine " acvAll14bit()" in the file/module SCAacv.c. and the SCA subsystem.
10) The routine " acv14bitDac()" in the file/module SCAacv.c. and the SCA subsystem

The flatness correction calculations have especially been studied. The equation that creates the flatness constant in the routine acvFlats has been checked. As well as normal operation of the flatness calculation has been studied and evaluated.

7.5.10 Resistance

No complete firmware evaluation was planned for the resistance part of Artifact Calibration. The essential element in the resistance calibration are the DC voltage measurements. The evaluation of these are covered in the DC voltage tests. However, a check of the correct calibration figuration and correct formula in the resistance calibration still remains to be done.

Firmware modules analyzed:

1) The function SCAohms10Kstd() in the file SCAohms.c
2) The function grunt(), calibration routine for R≥10Ω, in the file SCAohms and the SCA subsystem.
3) The function groan(), calibration routine for R=1Ω,1.9Ω in the file SCAohms and the SCA subsystem.

7.5.11 Current

Since Current is derived from DC Voltage and Resistance and the impact of these on current are in detail tested and evaluated in the Glass box tests of those individual parameters was the evaluation of the firmware for current concentrated on the calculation of the frequency response of the 2,2A range.

Firmware modules analyzed:

1) The routine " SCAaciFlat2_2A" in the file/module SCAaci.c and the SCA subsystem.
2) The routine " SCAaciFlats" in the file/module SCAaci.c and the SCA subsystem.

7.5.12 Conclusions

All routines as described in paragraph 7.5.1 – 7.5.7. were evaluated and tested and as a result no errors or faults have been found . All DCV, ACV, Resistance and Current firmware routines, were evaluated in cooperation with the respective specialist in DCV, AVC, Resistance and Current measurement techniques and no faults have been found.

8 *Final Observations*

- For Direct Voltage, Direct Current, and Resistance, the Artifact Cal procedure makes a traceable calibration of the calibrator. Thus for these functions, there is an unbroken traceability chain.

- Resistance is a normal passive function, which means that only the values of the resistances stored in memory can be changed by the Artifact Cal procedure and not the actual value at the binding posts.

- The Artifact Cal procedure does not realize a traceable calibration of the AC functions. In the Artifact Cal process, DC external reference standards are used and an internal AC/AC sensor. The latter is not calibrated to an external reference during the Artifact Cal procedure.

  However, the Artifact Cal procedure does increase the confidence in the AC part of the calibrator. It does adjust the calibrator within the 24 hour specification of the calibrator, provided that the characteristics of the internal AC/AC transfer sensor have not changed significantly since the last external verification.

- Another issue concerning traceability is that during the internal measurements of the AC voltage ranges by Artifact Cal, the reference plane differs from the reference plane during normal use (the binding posts). In the firmware of the calibrator, the correction factors AxS (x = 1...6) compensate for this effect. Although it is most unlikely these correction factors change, they are not checked during Artifact Cal.

- The overall results of the black box tests were within 50% of specification, except for the 1,9MΩ resistor and for the 1mV AC voltage at 1MHz where the measured deviation was 63 to 88% of specification.

- From the results of the opaque box tests, it is clear that the traceability chain was realized by Artifact Cal as expected from the theoretical study. Secondly, it is concluded that the Artifact Cal measurement system in the calibrator is very linear. Shifts in the external reference standards were followed within 20% of the 24 hr specification by all functions and ranges concerned.

- The calibrator behaves very stable when kept in a stable environment. This is deduced from the repeatability tests done at (23,0 ± 0,5) °C which showed a maximum standard deviation in the average of 2ppm or 10% of specification for some DC voltage and resistance ranges.

- The linearity of the internal DA converter was found to be better than 0,5ppm, which is sufficient to guarantee correct scaling in the Artifact Cal process.

- When non-nominal external reference standards where used in the first calibration step of the Artifact Cal process, this did not result in significantly different values for the internal standards of the calibrator. This confirms the linearity of the DA converter and furthermore shows that the calculations are done correctly.

- During the evaluation of the source code and testing of the firmware, no errors were found. A general conclusion of the firmware evaluation is that have indeed gained considerable confidence in the correct functioning and Artifact Cal calibration of the calibrator through our study.

- The documentation of the Fluke 5700 series II calibrator is exemplary. Only in two occasions for AC voltage, the documentation did not entirely represent the actual configuration of the calibrator.

  Note of the manufacturer:
  These occasions have been taken as input for future manual improvement.

- The calibration report produced by the Artifact Cal procedure accurately reflects the changes at the binding posts of the calibrator due to the adjustment, except for the opposite sign (in voltage and current). Thus, the Artifact Cal calibration report is very well suited as reference document for building up history of the calibrator.

- Strictly speaking, Artifact Cal is not equal to a (conventional) calibration since it does not produce measurement values (shifts are mentioned in the Artifact Cal calibration report) and uncertainties. Furthermore, it does not make a separate uncertainty evaluation for each measurement it performs.

  However, in practice Artifact Cal measurement values can be deduced using the values of the constants in the raw constants report. Furthermore the specifications may be regarded as the final total uncertainty of the complete Artifact Cal process. Viewed from this side, Artifact Cal is very similar to a calibration (combined with an adjustment).

- CalCheck is verifying those ranges of the calibrator that are derived from the internal voltage and 10 kΩ resistance reference but does not store the results. This makes CalCheck a very useful facility for monitoring the stability of the calibrator between different Artifact Calibrations. CalCheck thus significantly increases the confidence in the calibrator.

- The SelfTest and SelfDiagnostic routines perform very useful checks of firmware and hardware functionality.

9 Recommendations for the user

Correct use of the reports that are provided by the calibrator limits the external measurements that are needed. In a normal situation, the calibrator is externally measured before adjustments are made by the Artifact Cal routine ("as found" data), then the Artifact Cal is performed, after which again an external full calibration is performed ("as left" data). Normally this is needed because Artifact Cal adjusts ranges and only by knowing the value of the adjustment, history of the calibrator can be built up.

In this study, the opaque box tests have shown that the calibrator behaves very linear and that the calibration report can be used by the user to see difference between "as found" data and "as left" data. The shifts reported in the calibration report, indeed are the shifts as actually measured at the output binding posts (except for the opposite sign for voltage and current). Thus only an Artifact Cal and "as left" external measurements are needed to build up a full history of the calibrator for the DC ranges.

The only requirement is that the calibration report and the raw data are stored by the user after the Artifact Cal has been performed.

For the AC ranges it is also necessary to have the calibration report of the external calibration. The Artifact Cal raw data is only needed when something goes wrong in the calibrator. Then the calibration data alone is not sufficient to retain the old history of the instrument (as shifts of the low frequency constants are not included in the Artifact Cal report and some ranges use a combination of multiple constants); in that case only with the raw data the pre-Artifact Cal values can be recalculated. Since this calculation is not trivial, it is advised to ask Fluke for help in such cases.

Note that the results of range calibrations that may have been performed should be stored carefully as well. Artifact Cal automatically resets all range calibration factors to 1 (default value of the additional gain multiplier), and does not record possible changes!

The Artifact Cal report should be stored by the user. The raw data of the constants can be stored by the user or at the calibration institute performing the full verification. This could be accomplished through automatic reading (from the calibrator or text file) of the calibration data, and subsequent processing the data in tables and figures. This should at least be done for the data provided in the calibration report, and preferably as well for the raw data (constants) and CalCheck data.

It is highly recommended that any user of a Fluke 5700A calibrator also does a repeatability test of the Artifact Cal procedure like that done in the glass box tests. It will show the repeatability of the individual instruments Artifact Cal measurements and the influence of the environment of the user's laboratory. The user should combine the noise found in his test with the critical points of the black box tests in this study and check that his instrument does not exceed the specifications.

9.1 Calibration intervals

A very important aspect of the maintenance of any measuring instrument is the calibration interval. By extending this interval the user can significantly reduce the cost of ownership of the instrument, which is especially relevant for instruments like the Fluke 5700A calibrator that have a wide range of capabilities. In this paragraph, we will address the determination of the calibration intervals of the calibrator.

The calibration interval can not be directly derived from the results of the present study alone, but needs to be combined with the specification of the calibrator and general metrological principles. In general, one should remember that

the user of an instrument has to prove himself that the calibration interval he is using for that specific instrument is correct.

In other words, this means that the user should be able to justify the calibration interval he has chosen. It clearly is not sufficient to refer to, for example, the results of the present study alone.

One of the basic metrological requirements for determining and especially for extending calibration intervals is the calibration history of the instrument. So the starting requirement is to store the results of the external calibrations and of the Artifact Cal results (the calibration report provided by the calibrator).

The use of these results is essential to build up history on the effectiveness of the Artifact Cal procedure for an individual calibrator.

Once a certain history of the individual calibrator's behavior is obtained, it is possible to assess to what extent Artifact Cal can replace and reduce the external full calibrations.

The Artifact Cal reports are an essential prerequisite for extending the intervals between the external full calibrations.

When a calibrator has been repaired, it depends on the part(s) that had to be repaired whether the user can still use (part of) the history he has gathered. In this judgment, detailed information from Fluke can be very helpful.

9.2 Full Calibration

A starting point of the calibration history of the calibrator is a full calibration, where for all functions and ranges, the output is measured at the external binding posts. What points exactly are measured depends on the use of the instrument, but the general user may choose to select the points recommended by Fluke (see Service Manual chapter 3 "full verification", page 372). The calibration should at least include all ranges and frequencies (especially for alternating voltage) since separate dividers and amplifiers are used in different ranges and since the frequency response of the AC/AC reference sensor and of the sense part, from the AC/DC sensor to the output binding terminals, is not checked during the Artifact Cal procedure.

It is advised to have any full external calibration preceded by a SelfTest / SelfDiagnostic and an Artifact Cal to check malfunctioning and to adjust the instrument to nominal values before the external calibration starts.

Fluke recommends to use a maximum interval of two years between the full calibrations, and this is considered a good choice. This maximum two year period is independent of the uncertainty level the user wants to maintain the calibrator. There are two reasons for having the full verification at least every two years.

- **The first and most important one is the fact that the AC quantities are not traceably calibrated by Artifact Cal, neither are the time base of the instrument (oscillator frequency) and the short (0 Ω) calibrated. Therefore, these quantities need to be externally checked at certain times.**

- **Another good reason for having a full verification every two years is that this calibration forms an overall rigid check that the calibrator is still functioning correctly. In this sense, the calibration can be compared with the overall check of a calibration setup used in a calibration laboratory as is done in an inter-laboratory comparison.**

It is recommended to run the CalCheck routine on a regular basis, for example every three months, in order to monitor the stability of the calibrator. If significant shifts in the AC voltage are reported, an external full calibration should be done, even when the two year period has not yet passed.

Also, the air filter should be cleaned at a regular interval, since an obstruction causes a rise in the inner temperature of the calibrator and thus may influence the stability and drift rate of the instrument.

9.3 Intermediate Artifact Cal

This section aims to provide the user of the Fluke 5700A with some recipes for the calibration regime of his calibrator. As already noted above, we want to state again that these recipes should be considered as guidelines only.
Based on the results of the measurements in this project, the specific use of the calibrator in a particular laboratory, and the metrological knowledge of the user, any user may choose to use an other calibration regime than those given here below.
The present recipes aim to be a good combination of correct metrology (quality) and reduction of costs (economic aspect). They are valid for both new and older instruments, where for the latter the initial phase with more frequent full external calibrations can be skipped but only if the user has gathered sufficient history.
Two examples of the use of Artifact Cal and full verification are given in Figure 9.1 together with the EAL guideline and the Fluke recommendation.

It is clear from this figure that the results of the present evaluation lead to a significant reduction of the number of full external calibrations (the 'C') compared to the present EA guideline: costs of maintenance are significantly reduced! Note that when the laboratory wants to use the 90d specifications (last row in Fig. 9.1), the calibration results are verified against the 90d specifications, even when this calibration is only performed once a year. Also the non-accredited laboratories may use these "recipies". This will give them a significant benefit in improving the quality of the lab without any significant workload additions.

EA guideline (1 yr)	CAC				CAC				CAC				CAC				CAC				CAC
Fluke recom. (1 yr)	AC				A				AC				A				AC				A
This study (1 yr)	AC				AC				A				AC				A				AC
This study (90 d)	AC	AC	A	AC	A	A	A	AC	A	A	A	A	A	A	A	AC	A	A	A	A	A
	0yr	3m	6m	9m	**1yr**	3m	6m	9m	**2yr**	3m	6m	9m	**3yr**	3m	6m	9m	**4yr**	3m	6m	9m	**4yr**

Figure 9.1 Recipes indicating the Artifact Cal's (A) and full external calibrations (C) needed for maintaining a Fluke 5700A calibrator at a certain specification level. The first three rows concern 1 year specification; the last one 90 day specifications. The last two recipes are based on the results of the present study

The example for the use of 1 year specification indicates that after two full external calibration, normally sufficient history is obtained on the stability of the AC output in order to omit the full external calibration at that moment. Something similar is true for the 90 day specifications, where it seems appropriate to switch to yearly full external calibrations already within the first year of the calibrator – assuming the history of the specific calibrator does not prove the contrary. It is very difficult to expand the last recipe beyond 2 years, since the interval for the full external calibrations then strongly depends on what the history of the first 2 years indicates about the stability of the calibrator.
It depends on the stability of the calibrator whether a user can extend the interval between the Artifact Cal's and / or the full external calibrations. *No matter what interval*

is chosen, the user should always be able to justify his choice with the history of his calibrator.

A final example may be given for the (rare) user that wants to use the calibrator on its 24 hour specifications for the DC functions and on the 1 year specifications for the AC functions. It this case the user should follow the "1 year scheme" of Figure 7 for the full external calibrations, and in addition he should perform an Artifact Cal every day. More frequent full external calibrations are not needed since Artifact Cal performs a traceable calibration for the DC functions.

9.4 Applicability of results

The results of the evaluation described in this report strictly is only applicable to the type of calibrator studied, being the Fluke 5700A series II calibrator, more specifically with the firmware versions 1.0+B+ (as indicated in the reports produced by the calibrator). It is expected that the results are also applicable to later versions of the 5700A series II calibrator, since the product is so mature that only minor changes are expected.

The results of the present study can only with great care be applied to the older Fluke 5700A calibrators, since some significant improvements have been applied in the time between the first generation of Fluke 5700A calibrators and the present Fluke 5700A series II calibrator.

The Fluke 5720 calibrator is an improved version of the series II calibrator, with more selected components, and some improvements in the Artifact Calibration process. In that sense, the Artifact Calibration process will be equivalent to or better than that of the series II calibrator studied here. But since its specifications are tighter than those of the series II calibrator, at least some extra black box measurements are needed by the user before he can apply the results of this study to his calibrator.

In general, we recommend that users of calibrators not evaluated here contact Fluke in order to discuss to what extent the results of this study are applicable to their calibrator.

9.5 Summary

- Full external calibrations should be performed at purchase of the instrument and subsequently at least every two years. This mainly is required to maintain the traceability of the AC functions.

- Each full external calibration preferably is preceded by running SelfTest & SelfDiagnostics to check the functionality of the calibrator and an Artifact Cal to adjust the calibrator close to nominal.

- It is strongly recommended that users of the Fluke 5700A calibrator run the CalCheck routine on a regular basis, for example every three months, in order to monitor the stability of the calibrator and to confirm correct functioning. Correct functioning is furthermore checked by running the SelfTest and SelfDiagnostics routine.

- Examination, evaluation, and storage of the calibration report of the full external calibrations and of the Artifact Cal's calibration and raw data reports forms the necessary basis for building up history of the calibrator. Such history is required to possibly extend the time between successive calibrations.

It is recommended to Fluke to develop a spreadsheet file that helps maintaining the history of the calibrator via the calibration reports. For example, it could include automatic reading (from the calibrator or text file) of the calibration data, and subsequent processing the data in tables and figures.

- Results of range calibrations that may have been performed should be stored carefully. Artifact Cal automatically resets all range calibration factors to 1 (default value of the additional gain multiplier), and does not record possible changes.

- Recipes are given as examples of how the results of the project can be used to determine the interval between Artifact Cal's and full external calibrations. A user of a calibrator should always be able to motivate his choice for his particular calibrator.

- Switching the calibrator on and off every now and then is useful since at start-up a destructive RAM test is done and furthermore the watchdog counter is reset.

- It is highly recommended that any user of a Fluke 5700A calibrator also does a repeatability test of the Artifact Cal procedure like that done in the present glass box tests. It will show what the influence of the environment of the user's laboratory is on the noise of his calibrator.

References

General documents used in the project

1 Fluke 5700A/5720 series II Operators manual (version May 1996)

2 Fluke 5700A/5720 series II Service manual (version June 1996)

3 EN 45001, General criteria for the operation of testing laboratories, CEN/CENELEC, 1989.

4 International vocabulary of basic and general terms in metrology, International Organization for Standardization, 2nd Edition, 1993.

Basic references for the project

1 "Instrument 'Internal Calibration' Reduces Cost of Ownership and Improves Performance", Measurement Science Conference, Irvine, CA, 1987. P. Baldock

2 "Achieving An Ultra Stable Reference For Modern Standards and Calibration Instrumentation", Measurement Science Conference, Irvine, CA, 1987. S.G. Haynes

3 "Advances in Accurate AC Voltage Sources", Measurement Science Conference, Irvine, CA, 1987. L. Eccleston

4 "Simplified Instrument Calibration: Sin or Salvation", in Proc. NCSL Workshop and Symposium, 1987. C.E. Johston

5 "Alternating Voltage Metrology: An Overview; Past, Present, and Future". D.L. Agy

6 "Artifact Calibration". P. Baldock

7 "New Design Developments Simplify Calibrator Support", Measurement Science Conference, 1988. P. Baldock

8 "Internal Calibration, a Measurement Revolution?", in Proc. Measurement Science Conference, 1989. H. Chendall

9 "Evaluation of Calibration Procedures for Fluke 5700 and Hewlett Packard 3458", SP report 1990:47E, 1990. I. Thorèn

10 "In-situ support for deployed multifunction calibrator", in Proc. NCSL Workshop and Symposium, 1991, pp 409-415. M. Aitken

11 "General requirements for electronic measuring instruments", OIML International Document, Edition 1994 (E).

12 "Linear Error Modelling of analog and mixed-signal devices", 1991. G.N. Stenbakken, T.M. Souders

13 "Modelling and test point selection for a thermal transfer standard", in Proc. NCSL Workshop and Symposium, 1993, pp 299-310. A.D. Koffman, H.L. Stott

14 "Efficient Testing Strategies for the Fluke 792A Thermal Transfer Standard -- A Preliminary Study –", 199X. A.D. Koffman, T.M. Souders, G.N. Stenbakken

15 "Application of the NIST testing strategies to a multi range instrument", 1994. A.D. Koffman, T.M. Souders

16 "A Preliminary Assessment of the Effectiveness of 5700A Artifact Calibration", in Proc. NCSL Workshop and Symposium, 1995. L. Huntley

17 "An Assessment of Artifact Calibration Effectiveness for a Multifunction Calibrator". L. Huntley

18 "Artifact Calibration", in Proc. NCSL Workshop and Symposium, 1996, pp 315-322. G. Rietveld

19 "Software verification for measuring instruments: a European approach", OIML Bulletin, Vol. 27, no. 4, pp 5-13. U. Grottker et al.

20 "An Evaluation of Artifact Calibration in the Fluke 5700A Multifunction Calibrator", Fluke Application Note, 1996. L. Huntley

21 "How accurate are AC current calibrators?", Fluke seminar Singapore, 1997. M. Klonz

Nederlands Meetinstituut
P.O. Box 654
2600 AR Delft
The Netherlands

Tel. +31(0)15 269 1500
Fax +31(0)15 261 2971
E-mail NMi@NMi.nl

Physikalisch- Technische Bundesanstalt
Bundesallee 100
Postfach 3345
38023 Braunschweig
Deutschland

Tel. +49 531 592 0
Fax +49 531 592 92 92

SP Swedish National Testing and Research Institute
Physics and Electrotechnics, Electrical Metrology
Box 857
S-501 15 BORAS
Sweden

Tel. +46 33 16 50 00
Fax +46 33 12 50 38

Printed in the Netherlands 10/99
G0480NENA
1543868
ISBN 90-9013322-4