

# ***THE AUSTRALIAN METROLOGIST***

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## ***Metrology in Retrospect:***

**A L Franklin – Manufacturer of  
Precision**

## **A General Technique for Calibrating Metric Instruments**

## **An International Evaluation of the Artifact Calibration Concept**

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## The Metrology Society of India

Our sister society in India continues to seek interactions with the MSA. In their latest communication, they point out an error unwittingly committed by me in my last TAM report. I had said then that the MSI was a small organisation with about 100 members. In fact their members number some 800 in all, with about 500 active. So they are about twice as big as we are! My apologies to both the TAM readership and the MSI for this error.

The MSI has sent to the MSA the two latest copies of their Society journal MAPAN, which contain articles on the following:

\* "Vehicular Pollution in Delhi and its Control in Line with Euro Norms" \* "Present Status of ITS-90 Temperature Standards and Calibration Facilities at NPL, New Delhi." \* "Humidity Generation Using Water-Glycerine Mixtures" \* "News from the BIPM" (T J Quinn) \* "International Comparison of Leak Standards using Calibrated Capillary Leaks" \* "Uncertainty of Measurements Related to Temperature" \* "Lead Assessor and Assessor(s) Role in Laboratory Accreditation."

In addition they donated to the MSA a copy of the Proceedings of the NPL-Industry Interaction meet on Calibration for Quality Assurance (held in New Delhi in October, 1999). Papers at that meeting included:

\* "The Role of the National Physical Laboratory in National Measurement System." \* "Streamlining of Calibration and Testing Services at NPL, New Delhi."

\* "Uncertainty in Dimensional Calibrations." \* "Temperature Standards and their Calibration on ITS-90." \* "Force Measurement and Evaluation of Uncertainty." \* "Pressure Calibration and Estimation of Related Uncertainty." \* "Quality Policy of Industry in Accomplishing its Objectives and Feedback to NPL." \* "Why Does Industry Need Calibration."

I will happily provide to members copies of any of the MAPAN papers or those from these Proceedings on request.

- Laurie Besley Hon. Secretary, MSA

## The Australian Metrologist

is published four times per year by the Metrology Society of Australia Inc., an Association representing the interests of metrologists of all disciplines throughout Australia.

Normal dates of publication are mid-month in February, May, August and November.

All editorial copy should be sent to the editor by the middle of the month prior to publication.

Further information regarding the Metrology Society of Australia may be found on page 25.

## 2000/01 Advertising Rates for The Australian Metrologist

| Space<br>A4 page | One issue<br>issue | Two issues<br>issues | Three/Four<br>issues |
|------------------|--------------------|----------------------|----------------------|
| Full page        | \$400              | \$750                | \$1050               |
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| 1/3 page         | \$150              | \$130                | \$400                |
| 1/4 page         | \$115              | \$215                | \$290                |
| 1/8 page         | \$ 60              | \$110                | \$150                |

**Closing date for copy to be received for TAM is 15th of the month preceding publication.**

**Contact the TAM editor for further details.**

Camera ready artwork is to be supplied. Size and specifications are available from the editor. If extra typesetting etc is required an extra charge will apply. MSA members receive a 10% discount when they place advertisements in TAM.

## MSA Annual General Meeting

The 2000 Annual General Meeting of the Society is to be held at 6 pm on Wednesday, November 8 in the Lehany Theatre of the CSIRO National Measurement Laboratory, Bradfield Road, West Lindfield, NSW.

All members are invited to attend.

One of the purposes of the Annual General Meeting is to elect the national committee of the MSA for the next twelve months. Nominations are called for the position of Vice-President and for the positions of eight (8) ordinary committee members. Nominations must be proposed and seconded by members of the MSA and must be received in writing by the Secretary of the MSA seven (7) days before the AGM. In this case, therefore, nominations close at 6 pm on November 1, 2000.

Further details of the form of the evening will be sent to members in October.

- Laurie Besley, Secretary

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## Still uncertain about uncertainty?

The **National Measurement Laboratory** will be running three day courses on estimation of measurement uncertainty at venues in **Sydney**, 15 – 17 Nov 2000 and **Melbourne**, 4 – 6 Dec 2000.

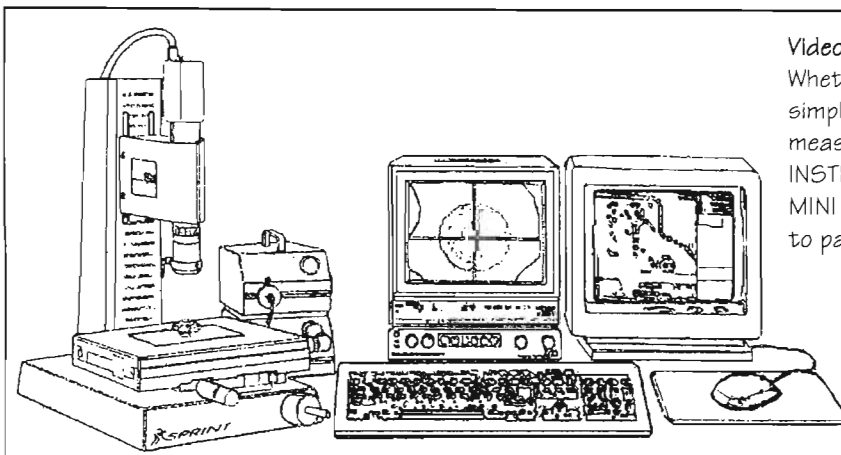
These courses have been successfully run since 1994 and provide a balance between theory and practical work. The emphasis is on the student achieving competence in making uncertainty calculations according to the recommendations of the ISO.

In-house courses of one or three day duration are available on request. To obtain a free brochure on these courses, contact Mrs Jan Brett on.....

*Mail:* National Measurement Laboratory, Melbourne Branch  
CSIRO Telecommunications and Industrial Physics  
Private Bag 33, CLAYTON SOUTH MDC, VIC 3169

*Fax:* 03 9544 1128

*Email:* jan.brett@mst.csiro.au



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## Metrology in Retrospect

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### A.L. Franklin - Manufacturer of Precision

Small-scale manufacturing concerns often last for half a century or so and then pretty much disappear from consciousness. Their products wear out and are replaced. Their documentary files are destroyed. Their histories go unrecorded. This is too often the case but is not always so. The name A.L. Franklin will be familiar to many readers of *The Australian Metrologist*. The firm was founded in Sydney in 1919 and closed its doors for the last time in 1999. The following article provides a brief overview of A.L. Franklin, the man and the firm.

Arthur Louis Franklin was born in Shrewsbury, England, in 1892. A bright and perceptive child, he developed an early fascination for science. A Shrewsbury Corporation Scholarship enabled the twelve-year-old Arthur to attend The Boys' High School there from 1904. He was fortunate in 1908 to secure the post of junior in the Physics Department of the recently founded University of Birmingham, before long becoming personal assistant to Professor J.H. Poynting.

John Henry Poynting (1852-1914) is best known for his work on the flow of energy in electromagnetic fields. He studied at Cambridge and was appointed professor of physics at Mason College in Birmingham in 1880. The College became the University of Birmingham in 1900. During the period Franklin worked with him, Poynting was not only dean of the science faculty, but also a member of Council and vice-president of the Royal Society.

Franklin assisted Poynting in 'preparing the more advanced lectures in Physics' as the professor's letter of reference stated. 'He has been an excellent assistant taking always great interest in the preparation of the experiments & devoting attention to their theory. He has made many pieces of apparatus & has given much time to glass blowing.' Franklin himself recalled Poynting as a 'friend as well as tutor' to whom he owed 'much for the thorough way he taught me the basic principles of accurate observation'. Poynting was himself a designer of instruments for research and lecture demonstration.<sup>1</sup> Clearly Franklin gained an extremely good training in the principles and methods of precision instrument making.

After four years at Birmingham, Franklin was advised for the sake of his health to move to a warmer climate

and so in 1912 the skilled twenty-year-old sailed for Sydney. In the years before the First World War there was no well developed industry for manufacturing scientific instruments in Sydney but Franklin found employment opportunities. The first of these was with the firm of Andrew Thom, maker of scientific apparatus specialising in medical equipment including microbiological incubators. In the six months Franklin worked there, Thom found him to be 'a very high class mechanic... [possessing] a knowledge of theory of Mechanics & Physics that in conjunction with his mechanical abilities should make his services invaluable to any firm with an opening in that direction'.

In the middle of 1913 Franklin sought work 'more suited to my physique and temperament' and joined the newly established electric clock department of Prouds Ltd. He found himself in the curious position that although he was the youngest member of staff he was the only one with technical training. He introduced a number of improvements and at one stage was acting manager.

Apart from his day job, Franklin found his skills in demand by other firms. In 1913 he took a barometer home to repair for Esdailes, beginning a relationship which continued for more than fifty years. Two other firms in Sydney for which Franklin did after-hours work were Elliott Brothers, the wholesale chemists who had an apparatus branch,<sup>2</sup> and the Sydney branch of H.B. Silberberg (subsequently H.B. Selby Ltd). 'I found both these firms anxious to do business and very soon I found all my spare time - which meant most evenings and weekends - fully occupied with instrument work and glassblowing.'

Perhaps understandably, Franklin found that this 'arrangement did not work satisfactorily' and in 1919 took the opportunity of setting up on his own account. He had by then built up a private workshop and when the New South Wales Education Department called for large quantities of scientific equipment following the First World War, Franklin 'was awarded a major share and ceased to be somebody's employee - for good'.

It was necessary to make a decision about the character of the business. Franklin was more interested in metrology and meteorology than optics or electronics. For this he would need a linear dividing engine. 'To the best of my knowledge [Franklin recalled] in 1912 there was only one straight dividing engine in Sydney. It was hand operated and belonged to Esdaile's who made it themselves.' In 1920 Franklin built his own straight dividing engine which he believed to be 'the first automatic dividing engine in Australia, certainly the first made here'.<sup>3</sup> With minor modifications this dividing engine continued in use throughout the life of the firm (and is now preserved in private ownership).

Franklin began his business in the workshop he had developed at his Ashfield home. By the end on 1919

he had also set up factory premises with a staff of three at 265 George Street - H.B. Selby's building. With an expansion to five staff, the factory had moved to Bathurst Street by the middle of 1922 and ten years later moved to Sussex Street, near Pymont Bridge. During the Second World War, the firm was contributing to the war effort. For the security of production the factory was relocated to a would-be furniture factory at Artarmon. This site had a number of difficulties and at the end of the War a site was chosen at Brookvale where a new factory was built. This remained the home of the firm until its closure last year.

Perhaps the most widely known of the firm's products were mercurial barometers. Franklin had made his first barometer - a J-tube instrument - in 1912, shortly before migrating to Sydney. Eventually the firm manufactured a variety of barometers, including several types of Fortin and Kew models. Franklin and his son developed a controlled pressure tank for testing mercurial barometers before the CSIRO had such a facility.

For a period the firm manufactured turret clocks. The first of these was installed in Ashfield Town Hall in 1922. George Julius of the consulting engineers Julius, Poole & Gibson assessed the work for Ashfield Council. 'We have pleasure in stating that the time keeping records on this Clock are excellent, and reflect great credit upon Mr. Franklin, both for his design and workmanship.' Arthur Franklin maintained this clock for more than forty years. A number of other turret clocks followed, the last being for the Cairns Harbour Board in 1948. Arthur's son, Raymond, had joined the firm by this stage and one of his first tasks was work on the Cairns clock.

From 1923 the firm produced chondrometers for measuring grain, including the New South Wales Standard Chondrometer, and later developed a simplified design known as the 'Growers' Personal Chondrometer'. During the Second World War, A.L. Franklin manufactured a variety of items for the military services. Besides rolling parallel rules, the firm manufactured Kew barometers for the Royal Australian Navy and airspeed calibrators and altimeter calibrators for the Royal Australian Air Force. Over the years the firm also manufactured precision weights and test equipment such as flash-point apparatus and penetrometers.

As a manufacturer, Arthur Franklin realised the importance of effective distribution. In 1929 the opportunity arose to establish a third firm in this area (in addition to Elliott Bros. and Selby's). The London firm of Townson & Mercer was approached about the setting up of a local firm with Australian finance. The Australian firm began with a capital value of some £2500, including a 'hard to spare £50' from Franklin. Townson & Mercer (Holdings) Ltd became a highly effective distributor of scientific apparatus and chemicals in Aus-

tralia. Franklin was appointed to the board of directors in 1940 and remained a director until his death. He was proud that Townson & Mercer (Holdings) Ltd became a wholly Australian-owned company 'making a little and distributing a lot of Australian made instruments throughout Australasia'.

In 1957 the firm's laboratory gained official NATA registration in the category of metrology (Reg. No. 232).<sup>4</sup> Two years later the laboratory was also QCB approved, again for metrology. This covered balances, precision weights, and barometers. A.L. Franklin himself was for more than thirty years a member of the Standards Association and in 1965 was elected to Associate Membership of the Australian Institute of Physics.

The firm became A.L. Franklin Pty Ltd in 1960, with four directors, the father and son and their wives. Arthur Franklin remained active in the management of the firm until his 79<sup>th</sup> year. He died early in 1972 and his son Raymond became managing director of the firm. In 1985 Ray Franklin sold the firm but continued to be associated with it as a technical consultant. During this later period there was little development of new products and the firm does not seem to have adapted to a changing market. In 1999 the firm became insolvent and an administrator was appointed. In September 1999 A.L. Franklin Pty Ltd closed and its stock and equipment were sold at auction. While this was a sad end for one of Australia's precision manufacturers, the eighty years that the firm lasted was longer than the span of many comparable small engineering firms and is a tribute to the sound basis on which Arthur Louis Franklin established it.

#### Note:

The research for this article has been undertaken with Dr Matti Keentok of the Department of Mechanical Engineering at the University of Sydney. Much of the source material was provided by Ray Franklin. Matti Keentok is preparing a substantial account of the firm and its products for publication in 2001 and would be pleased to hear from any readers with extensive experience of any A.L. Franklin products. He may be contacted by email: <mattik@mech.eng.usyd.edu.au>.

#### References

- Anon. [Obituary] 'A.L. Franklin', *The Australian Physicist*, vol. 9, May 1972, p. 70
- A.L. Franklin, 'Pioneering in Scientific Instrument Manufacturing', *Convention on Recent Advances in Scientific Instrumentation* (Sydney, 1966)
- <sup>1</sup> A.E. Woodruff, 'Poynting, John Henry', *Dictionary of Scientific Biography*, vol. XI, pp. 122-23.
- <sup>2</sup> The Sydney firm of Elliott Brothers is not to be confused with the important London firm of scientific instrument makers. The Sydney firm were primarily



manufacturing chemists and wholesale druggists. In 1919 they issued a 650-page *Catalogue of Chemical and Scientific Apparatus Balances and Weights, Graduated Instruments and General Laboratory Appliances also Pure Chemicals and Reagents*. Elliott Brothers claimed these were the 'Largest and Most Varied Stocks in Southern Hemisphere'.

<sup>3</sup> There is a circular dividing engine in Adelaide said to have been brought to Australia by Otto Boettger in 1877, but I am not acquainted with its technical characteristics.

<sup>4</sup> This put A.L. Franklin in company with Automatic Totalisators Ltd (118), Cockatoo Docks & Engineering Co. Pty Ltd (91), Commonwealth Government Small Arms Factory (87), Coventry Gauge & Tool Co. (Australia) Pty Ltd (145), and Telephone & Electrical Industries Pty Ltd (43).

## Letter to the Editor

### The Uncertain State of Uncertainties

When the ISO Guide to the Estimation of Uncertainties in Measurement was introduced I had serious concerns about how (and whether), the calibration community would be properly trained and guided in the method. Since then I have seen little to make me believe that my fears were groundless. In some ways I think the situation may be worse than I imagined, because I believe there is a sort of conspiracy of silence, or a cone of ignorance, which suppresses information about the actual situation.

I see a number of groups of people in the measurement community: those who have a good grasp of the subject and are unable to empathise with those who do not, those who have acquired some knowledge of the procedures but who do not really understand what they are doing, and those who have barely a clue. Obviously there will be a gradation rather than distinct boundaries between the groups, but I think they are good descriptions for the sake of discussion.

In these groups, the members of the first will not see a great problem, and will hope that enough training courses of the sort offered at present will eventually win the battle. Most members of the second group will smugly feel that they have defeated this fiery dragon, and will continue complacently, even if the tools they are using are not appropriate for the job. Others in this group will recognise their deficiencies but to safeguard their reputation (and perhaps their jobs), will keep quiet about it. The third group will also understate their ignorance, and hope that they will be enlightened some time in the future.

On top of this we have a dearth of local rules on appropriate methods in different situations. As the in-

imitable Max Purss said at a recent workshop he conducted, even the experts disagree about many points. At the same time we are seeing the beginnings of some ISO standards which specify their own approaches (see for example ISO 14253 Part 2 on Dimensional and Geometric Product Specification and Verification). On top of all this NATA is about to replace Guide 25 with ISO 17025, a standard that mentions the need for uncertainties at least a dozen times. Soon assessors will each begin to impose their own ideas on the laboratories that they assess, perhaps differing from other assessors, so generating bewilderment and confusion.

I know that this sounds like a bureaucratic response, but I think it is time for a committee of inquiry. Let's bring out into the open the views of the whole measurement community. Let's assess the needs and requirements of testing laboratories and different fields of testing and calibration. We need to know what the problems are before we can address them.

Now this is a topic that should concern every member of MSA, so what do you think? In your view, am I being alarmist or do you also see a problem out there? Do you agree with my suggestion, or is an inquiry a waste of time? Who should be responsible for any inquiry, and who should be represented? Would all those not afflicted with terminal apathy please respond to me or to The Editor, so that we can determine whether we put the idea in the little round filing cabinet or not.

Jeffrey Tapping  
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### New range of Touch Trigger Probes available to Australian CMM Users

Most CMMs in Australia use touch trigger probes manufactured by Renishaw in the UK. An attractively priced alternative from America has now become available on the Australian market offering a range of probes and accessories. Further information is available from Asteg Sales Pty Ltd. Ph 02 9677 2249 Fax 02 9677 0287. Renishaw probes are available from John Hart Pty Ltd in most state capitals.

### Measurement and Safety

Test Safe Australia hosted a most interesting MSA visit for the NSW branch on Tuesday August 8. They even managed to provide mild weather that added to the visit. The meeting was attended by 17 enthusiastic members and their colleagues. Test Safe Australia is a testing and research centre dedicated to the improvement of both public and workplace safety in hazardous industrial sites, underground mines and general industry. (continued page 12)

## IMEKO NEWS

As part of the MSA's membership of the International Measurement Confederation, IMEKO, TAM publishes reports from time to time of the activities of that body. There is much happening within IMEKO that is of interest to our membership.

### New IMEKO Technical Committee on Environmental Measurements

This new committee, TC-19, is in the process of being formed. Its nominated chairman is Prof. Scot Smith of the University of Florida, USA. The scope of the committee includes the following:

- Analytical measurements in air, water and soil and in a variety of other materials and the development of analytical methods for measuring pollutants in them.
- Instrumental methods for the measurement of environmental noise and vibration pollution.
- Remote-sensing methods for the measurement of environmental pollution.

TC-19 plans to meet at Vienna, Austria in September, 2000 and then hold their first symposium in Budapest, Hungary in September, 2002.

The MSA invites any member interested in representing the Society on IMEKO

TC-19 to contact the MSA President, Jim Gardner.

### Measurement

The latest copies of the IMEKO journal *Measurement* contain the following articles. If any member would like a copy of any of these please contact the Secretary, Laurie Besley, who will be pleased to supply them.

#### Vol. 27, No 1, January 2000

Polygon-based large diameter measurement with modular gauges

Adaptive photodetectors: novel approach for vibration measurements.

Lock-in measurement of bio-impedance variations.

Vibration measurements for diagnosis of structural defects on human teeth.

Requirement of a robust method for the precise determination of the contact point in the depth sensing hardness test.

Particular aspects in the calibration and application of strain gauge torque measuring devices for quasi-static alternate torque loading

Potential measurements on electric contacts.

#### Vol. 27, No 2, March 2000

Beyond the representational viewpoint: a new formulation of measurement.

Measurement and analysis of surface myoelectric signals during fatigued cyclic dynamic contractions.

Datacloud fusion in three-dimensional laser comparator.

Thermochromic liquid crystal based sensing system for analysis of air flow.

Vibration measurements of tools inside fluids by laser Doppler techniques: uncertainty analysis.

Measurement of gait parameters from free-moving subjects.

Measurement of electrode-tissue interface characteristics during high current transcranial pulse electrical stimulation.

#### Vol. 27, No 3, April 2000

Data acquisition systems for non-periodic signals with real-time data compression.

Measurement concepts: from classical transducers to new MEMS.

Impact of measurement and standards infrastructure on the national economy and international trade.

Performance of two electromagnetic flowmeters mounted downstream of a 90° mitre bend/reducer combination.

Analysis of ultrawide-band detected partial discharges by means of a multiresolution digital signal-processing method.

### Events

Events sponsored by IMEKO that are coming up this year:

16<sup>th</sup> IMEKO World Congress

Vienna, Austria

September 25-28, 2000



# A GENERAL TECHNIQUE FOR CALIBRATING METRIC INSTRUMENTS

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## ABSTRACT

A metric scale allows an attribute of an object to be expressed in terms of a real number multiplied by the value assigned to the same attribute of a standard artefact (the metric). Two classes of metric instruments are identified, namely direct reading instruments, which directly indicate the value of the attribute of a single object on the appropriate metric scale, and ratio-metric instruments, which indicate a dimensionless ratio of the same attribute of two objects. If a set of artefacts can be combined while retaining the definition of the specified attribute, then it is possible to calibrate metric instruments thoroughly over a wide operating range with minimal information on the artefacts. The technique is demonstrated by application to direct reading mass balances, which may be calibrated with several masses, only one of which has a known value, and ratio-metric resistance bridges, which may be calibrated with a few resistors of unknown value.

## 1. INTRODUCTION

### Metric scales

The results of all measurements are recorded as symbols that place the result on a measurement scale. The scale and system of symbols often has underlying mathematical properties that enable mathematical operations on the symbols so we can draw conclusions or make predictions. A huge number of measurement scales have been developed for different purposes, and a number of classifications systems have been developed [1]. For scales used in the physical sciences a common classification based on the mathematical properties of the scales is as follows:

*Nominal scales* use symbols to rename attributes and only the equality of two measurements can be established. Examples include catalogue numbers, numbers on football jerseys, and the names of the elements in the periodic table.

*Ordinal scales* enable both order and equality to be established. Examples include the Moh hardness scale, and the Beaufort wind strength scale. Many chemical tests are carried out on ordinal scales.

*Interval scales* enable meaningful interpretation of intervals or differences, and therefore addition and subtraction of different results is meaningful. Such scales include many time and calendar systems; also latitude and longitude are measured on interval scales.

*Metric scales* have the properties of interval scales plus the additional property of a natural or meaningful zero. This means that the mathematical operations of scalar multiplication and division are meaningful, and the ratio of two measurements is meaningful.

It is the ratio property that sets metric scales apart from other scales, as they can be defined in terms of a single standard artefact (the metric) and a real number (a dimensionless ratio). That is, the result  $a$  of any measurement of a metric attribute  $A$  of any artefact  $X$  can be expressed as a real number  $r$  times the same attribute of a standard artefact

$$a = A(X) = \rho A(X_s) \quad \dots(1)$$

With the adoption of the Metric Treaty, signatory nations agreed to the adoption of a single definition for the metric (or unit of measurement) for a number of commonly measured physical attributes. The SI system now defines a system of metric scales and quantities that enable us to use all of the rules of normal algebra and real numbers to model physical systems [2]. All measurements on the SI metric scales can be represented as

$$a = A(X) = \rho A(X_{SI}) \quad \dots(2)$$

so a measurement result consists of a real number times the unit. Thus for example an object of length 3 m has three times the length of the SI defined metre. Similar statements about ratios on non-metric scales, such as the 20<sup>th</sup> of May is twice the 10<sup>th</sup> of May, are meaningless. Metrology is literally the study of ratios.

### Metric Instruments

There are two common types of metric instruments in use. Direct reading instruments are the most common and indicate an estimate of the attribute  $a = \rho A(X_{SI})$  directly. Common examples of this type include digital voltmeters which indicate all of the readings in terms of the appropriate units e.g. volts, amperes, and ohms.

Ratio-metric instruments report the ratio of two measurands  $\rho = a_1 / a_2$  often with the expectation that the user will complete the measurement by multiplying the ratio by the value associated with the second artefact and hence converting the result to the appropriate metric scale:

$$a_1 = \rho a_2 \quad \dots(3)$$

Ratio-metric instruments are often associated with very high accuracy measurements, for example resistance bridges, frequency (event) counters, and many types of direct reading instruments are based on analogue-



to-digital converters, which measure the ratio of two voltages.

Traditionally metric instruments are calibrated by preparing a small number of calibrated artefacts (standards) and subjecting them to measurement with the instrument. This method requires a compromise between the number of standards that are affordable and the number of standards required to characterise the instrument's response. For high precision instruments in particular, the cost of the standards becomes prohibitive and instruments are often designed to measure near 1:1 ratios or decade ratios to minimise the costs. Calibration of the best of the ratio-metric instruments can be a problem because it is often impractical or impossible to maintain standards at the high level appropriate for calibrating the instruments.

In this paper we describe a method for calibrating metric instruments that thoroughly characterises the instrument's response yet requires at most one calibrated artefact. The method exploits the known inter-relationships between the many combinations of a small number of artefacts. In the case of ratio-metric instruments, the technique enables calibration at a relative accuracy exceeding the uncertainty in the definition of the unit. Section 2 describes the principles underlying the calibration technique. The remaining sections then give examples of the application of the technique to the two types of metric instruments, namely single-pan mass balances and resistance bridges.

## 2. PRINCIPLES OF THE TECHNIQUE

### Direct reading instruments

#### Assessments of non-linear errors

Suppose we have two artefacts  $X_1$  and  $X_2$  and make measurements of the attribute  $A$  of those artefacts

$$a_1 = A(X_1), \quad a_2 = A(X_2) \quad \dots(4)$$

Then we make a third measurement of the attribute of the sum of the two artefacts

$$a_{12} = A(X_1 + X_2) \quad \dots(5)$$

Now because the attribute  $A$  is a metric quantity we expect

$$a_1 + a_2 - a_{12} = 0 \quad \dots(6)$$

In practice there will be small errors in the instrument's response to the artefacts so that

$$a_1 + a_2 - a_{12} = \xi(a_1) + \xi(a_2) - \xi(a_{12}) \quad \dots(7)$$

where  $\xi(a)$  is a function describing the error in the instrument's readings. The three measurements yield one result (7) that provides information on the rela-

tionship between the three error terms, but not enough information to provide a unique value for the three errors. In particular, under some circumstances the right hand side of equation (7) may be zero although each error term is not zero, indicating incorrectly that the instrument is free of error. Now if equation (7) is zero for all possible values of  $A(X_1)$  and  $A(X_2)$  then the instrument error  $\xi(a)$  must be a linear function i.e. a straight-line through zero [3]. Alternatively if the instrument departs from linearity then a sufficient number of measurements of the type implied by equation (7), using different combinations of several artefacts will detect the instrument's departures from linearity.

An important feature of linearity assessments of the kind indicated by (7) is that it is not necessary to know the values of the attributes of the artefacts, only that the artefacts can be combined without error.

### Assessment of linear errors

Since we can detect departures from linearity let us assume for the moment that the errors in the readings are linear i.e.

$$a = A(X) + \xi(a) = A(X)(1 + \epsilon) \quad \dots(8)$$

where ideally for an error free instrument  $\epsilon = 0$ . For a direct reading instrument the error can be determined simply by using the instrument to measure a calibrated artefact

$$a_s' = A(X_s)(1 + \epsilon) = a_s(1 + \epsilon) \quad \dots(9)$$

where  $a_s'$  and  $a_s$  are the indicated and known values of the attribute of the artefact respectively.

Thus the combination of one calibrated artefact and a linearity assessment is enough to detect all types of the errors in the instrument's readings.

### Ratio-metric instruments

#### Assessment of non-linear errors

Suppose we have two artefacts  $X_1$  and  $X_2$  and we make measurements of the ratio of the attribute of these artefacts with respect to that of a third (often a standard) artefact  $X_s$

$$\rho_1 = A(X_1) / A(X_s), \quad \rho_2 = A(X_2) / A(X_s) \quad \dots(10)$$

Then we make a third measurement of the sum of the two artefacts with respect to the third

$$\rho_{12} = A(X_1 + X_2) / A(X_s) \quad \dots(11)$$

Hence, as with the direct reading instrument, we can gather information about the non-linearity of the in-

strument

$$\rho_1 + \rho_2 - \rho_{12} = \xi(\rho_1) + \xi(\rho_2) - \xi(\rho_{12}) \quad \dots(12)$$

where  $\xi(\rho)$  is a function describing the error in the instrument's readings.

### Assessment of linear errors

To determine the linear errors in a ratio-metric instrument we employ a different technique. Again let us assume for the moment that the errors in the readings are linear i.e.

$$\rho_1 = \frac{A(X_1)}{A(X_s)}(1 + \varepsilon) \quad \dots(13)$$

With a ratio-metric instrument it is possible to exchange the artefacts and make a reciprocal measurement

$$\rho_2 = \frac{A(X_s)}{A(X_1)}(1 + \varepsilon) \quad \dots(14)$$

Now ideally the product of the two measurements is equal to 1, but in practice

$$\rho_1 \rho_2 = (1 + \varepsilon)^2 \quad \dots(15)$$

Thus the combination of a 'normal' and a reciprocal measurement will detect linear errors. The combination of a linearity assessment and reciprocal measurements is enough to detect all types of the errors in the instrument's readings. Note in this case that none of the artefacts used to carry out the measurements need to have values that are known. This is a consequence of the reading being a dimensionless ratio.

### The principles of the calibration technique

All of the simple measurements described above are commonly used in a number of fields of metrology to verify the performance of instruments. As described the checks greatly enhance the confidence in an instrument, but they fail to provide the necessary information for a calibration, namely sufficient data to make good estimates of the corrections and uncertainties in the instrument's readings. The linearity check for direct reading instruments illustrates the problem. Equation (7) has five unknown variables associated with it  $A(X_1)$ ,  $A(X_2)$ ,  $x(a_1)$ ,  $x(a_2)$ , and  $x(a_{12})$ , but is based on only three measurements, thus there is insufficient information to determine unique values for the three errors and the two attributes. Such systems are described as underdetermined.

To make a calibration feasible it is necessary to make the system overdetermined, i.e. the number of measurements must exceed the number of variables. The essence of the technique described here is the recog-

nition that it is not necessary to know the error associated with every reading: it is sufficient to characterise the distribution of the errors. Accordingly the number of unknown variables can be reduced substantially by approximating the error function  $x(a)$  by a simple algebraic function with a few unknown parameters. The ideal approximating function is one that leaves a random distribution of residual errors. Often a simple cubic polynomial is sufficient. The number of measurement results available to determine values for the various parameters is also increased by generating a large number of measurements from a small number of artefacts. This is illustrated in the two examples below.

### Method of analysis

The simplest form of analysis is to use the results from the measurements of the single artefacts to predict values for the combinations, and then compare the predicted values with the measured values. However this approach is particularly sensitive to the errors in the measurements that are used to predict the others. A better technique is to use the method of least squares to find values for the artefacts that minimise the variance of the residual errors in all readings. For a direct reading instrument a suitable least squares cost function is

$$s^2 = \frac{1}{N-n} \sum_{i=1}^N (a_{i,meas} - a_{i,calc})^2 \quad \dots(16)$$

where  $a_{i,meas}$  are the  $N$  measurements,  $a_{i,calc}$  are the estimates of the measurements calculated from the fitted or known values of the artefacts, and  $n$  is the number of fitted variables. Note that the variance (16) provides a measure of the accuracy of the instrument that includes a sample of all of the errors over a wide fraction of the operating range of the instrument.

If the instrument has significant departures from ideal behaviour then a correction equation can also be fitted. In this case a suitable least squares cost function is

$$s^2 = \frac{1}{N-n} \sum_{i=1}^N (a_{i,meas} + \Delta a(a_{i,meas}) - a_{i,calc})^2 \quad \dots(17)$$

where  $\Delta a$  is the correction equation, and  $n$  now includes the number of fitted parameters in the equation as well as the number of fitted values for the artefacts. In this case the variance (17) measures the accuracy of the instrument when the readings are corrected. Note that  $N - n$  is the number of degrees of freedom associated with the variance. A suitable correction equation is

$$\Delta a = A + Ba + Ca^2 + Da^3 \quad \dots(18)$$

which includes terms for characterising an offset ( $A$ ), a



linear error (B), a quadratic or weak even-order non-linearity (C) and a cubic or weak odd-order non-linearity (D). Other models of the instrument error may be used if appropriate. While equations (17) and (18) apply to direct reading instruments the discussion and analogous equations apply equally to ratio-metric instruments.

### 3. APPLICATION TO A MASS BALANCE

Balances are possibly the simplest instruments to calibrate using the technique described above, since masses can be combined easily without error simply by placing them on the pan of the balance. If  $M$  masses are used then there are  $2^M$  possible combinations of those masses, including the zero when no masses are used.

Figure 1 summarises the results of the calibration of a single-pan balance of 5 kg capacity and 1 mg resolution. Five masses, of nominal values 2 kg, 1 kg, 1 kg, 500 g and 200 g, were used to generate a total of 32 different measurements. Figure 1(a) shows the residual error as determined by a least squares fit with values fitted for all 5 masses and no correction equation. The large number of readings test the interpolating ability of the balance, and in Figure 1(a) the measurements reveal a distinct non-linearity. This example illustrates how uncalibrated artefacts can be used to assess an instrument's non-linearity.

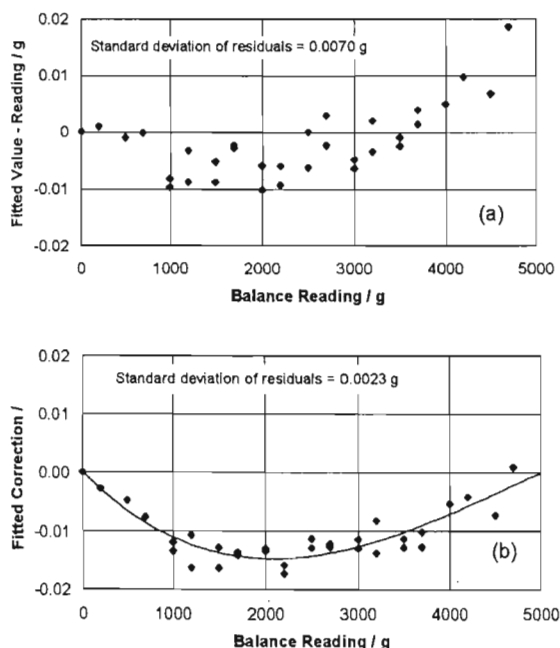


Figure 1. The results of the calibration of balance with a 5 kg capacity and 1 mg resolution, (a) the residual errors when the values for all 5 masses are fitted, (b) the residual errors when the value for one mass is fixed and a correction equation is fitted.

Figure 1(b) shows the same data fitted using a cubic correction equation with no constant term and the value of the 2kg mass fixed to its calibrated value. In this case the least squares analysis of the measurements provides values for the 4 other masses involved. Such values obtained over many balance calibrations can be used for surveillance of the mass of the calibrated artefact, provided the masses involved have sufficient long-term stability. Alternatively, the measurements can serve as a simultaneous calibration of the balance and of the masses (for use elsewhere). A similar example has been suggested by Nielson [4].

This technique has an added advantage in the calibration of large capacity balances, when the availability of calibrated artefacts is limited to small masses. An example is the calibration of a 1500 kg capacity balance using 2x500 kg and 2x200 kg masses, and a calibrated 100 kg mass. However, uncertainty propagation limits how small the calibrated mass  $m$  can be, as the uncertainty in the correction to a reading with mass  $M$  on the balance increases with  $M/m$ , and is proportional to  $M/m$  at large values of this ratio.

### 4. APPLICATION TO A RESISTANCE BRIDGE

Until recently the calibration of resistance thermometry bridges was a long-standing problem in thermometry. The best commercial bridges are ratio-metric and have accuracies approaching  $10^{-8}$  in resistance ratio, accuracy far in excess of the accuracy with which the ohm can be disseminated, especially for alternating current (ac) measurements. The development of the technique described here was the key to solving the problem.

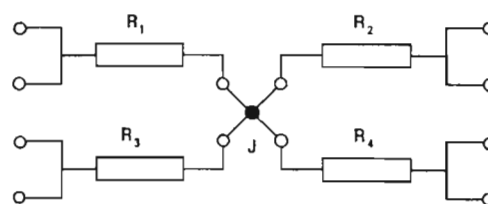


Figure 2. A simplified diagram of the resistor resistance network developed for the calibration of resistance bridges.

Figure 2 shows the four-terminal resistance network developed especially for the calibration of resistance thermometry bridges. The details of its working principles are described in [5]. In its simplest terms it is four resistors connected in such a way that they can be combined in a total of 35 different series and parallel combinations. If it is used in all of its combinations

for both normal and reciprocal measurements then 70 measurements are available to characterise the behaviour of both the bridge and the resistance network. The network itself can be characterised by just four resistance ratios  $R_1/R_S$ ,  $R_2/R_S$ ,  $R_3/R_S$  and  $R_4/R_S$  where  $R_S$  is the resistance of the artefact used to define the ratios (see equation (10)).

Figure 3 summarises the results of a calibration of an 8-digit ac resistance bridge. In this case not all of the 70 resistance ratios were within the range of the bridge, so the data include 34 normal measurements and 10 reciprocal measurements. Figure 3 shows the residuals from a fit of the four base ratios and a 2-parameter correction equation. The results show that the bridge has small offset and linear errors in its readings and that it is performing well inside the manufacturer's specification of  $\pm 2 \times 10^{-7}$ . The most notable feature of this example is that the technique enabled the calibration of the bridge to an accuracy of about  $2 \times 10^{-8}$  in resistance ratio, despite the fact that the values of the four resistors  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  were only known to about 0.01%. Indeed it is the freedom from the need to use calibrated artefacts that makes the calibration of the bridge possible.

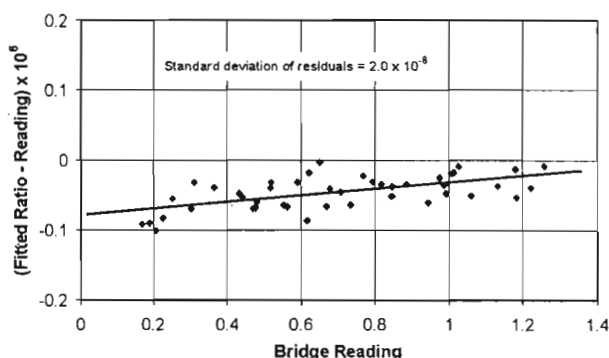


Figure 3. Results of the calibration of an 8-digit resistance bridge.

## 5. DISCUSSION

The calibration technique described and demonstrated here is, in principle, applicable to any metric instrument for which there is an artefact or group of artefacts that can be combined in a large number of ways such that they maintain their definition.

For direct reading instruments only one of the artefacts need be calibrated so the technique provides the means to simultaneously calibrate the instrument and the remaining artefacts. For ratio-metric instruments the technique requires no calibrated artefacts yet enables calibrations at a level far in excess of the uncertainty in the values of the artefacts.

By subjecting the instrument to a large number of

measurements and a least-squares analysis, the technique provides a good measure of the uncertainty associated with the instrument's readings over the whole of the calibration range.

### Constraints on the artefacts

There are a number of factors affecting selection of the artefacts that have an influence on the outcome of the calibration.

The artefacts must be able to realise a sufficient number of combinations to ensure that the number of degrees of freedom associated with the least squares fit is sufficient to yield high confidence in the uncertainties in the fitted values for the various parameters.

The artefacts must be able to be combined without (significant) error. This appears to be the most limiting factor in the application of the technique. While it is obvious how artefacts for extensive quantities such as mass, voltage, and resistances might be combined, it seems unlikely that suitable artefacts can be found for intensive quantities such as pressure, density or temperature.

The artefacts must be stable over the duration of the experiments. This stability requirement is less demanding than that for artefacts used as standards, which may be required to be stable for periods as long as a year or more.

The values of artefacts should be chosen so that the range of combinations covers the operating range of the instrument. A binary sequence of artefacts with the value of the largest artefact near half of the full-scale reading provides a very uniform and wide coverage. If such a sequence is used with direct reading instruments with a  $3 \frac{1}{2}$ ,  $4 \frac{1}{2}$ , ...,  $7 \frac{1}{2}$  digit display, then the value of the largest artefact will also be a convenient decimal multiple or sub-multiple of the SI unit.

For direct reading instruments at least one of the artefacts must be calibrated. The propagation of uncertainties in the calibrated values are minimised if the largest artefacts are the ones calibrated.

For ratio-metric instruments none of the artefacts need be calibrated so long as reciprocal measurements are included in the data. The uncertainties in the values of the fitted coefficients in the correction equation are minimised if both normal measurements and reciprocal measurements are taken near ratios of 1.0.

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## Q & A Column

**Question:** What is the status of the move to redefine the unit of mass from an artefact to a value of Avogadro's number and the mass of a particular type of atom?

**Answer:** By chance part of the answer to this question has recently been posted on the MSA web site. This paragraph tells us what is happening at NML on this project, but not what others are doing. Here is the text taken from the site.

### **"The Avogadro Project, now renamed the Atomic Kilogram Project."**

The project has broadened its focus from manufacture and metrology of silicon spheres to the physical properties of the silicon itself and its surface under the leadership of Dr. Mike Kenny and his team at the CSIRO NML in Lindfield. The CSIRO Division of Manufacturing Science and Technology in Clayton has also had considerable involvement in the project through assisting with the manufacturing of the instrumentation used for the metrology, developing the sophisticated graphical and visualization software used to understand the relationship between the physical and metrological characteristics of silicon spheres, and the X-ray measurements performed to relate these to the silicon crystal orientation."

**Question:** Why do we use 95% confidence levels? It seems to me that a chance of one in twenty of being wrong is a bit big.

**Answer:** Uncertainty intervals calculated according to The Guide to the Expression of Uncertainties in Measurement are derived from an estimated standard deviation of the variation in the result, based on an assumed Gaussian probability distribution of results. Intervals with high confidence, such as 99%, extend well out into the tails of the distribution, which will be represented by only a few data points, even for a large sample size. This means that the boundaries for 99% intervals can change significantly for small changes in the data. On the other hand 95% intervals are much more robust, and are therefore much more reliable. One way of seeing this effect is to look at the tables of Student's t values. The t values are a sort of fudge

factor to allow for lack of knowledge of the standard deviation because of limited sample sizes. For effective degrees of freedom from 10 to 100 the t value adjustment for 99% intervals is about 1.6 times greater than for 95% intervals. (By adjustment I mean the percentage that the value of t is from its final value for infinite degrees of freedom).

**Question:** Does anyone know what the oldest known measuring instrument is?

I cannot claim to have the definitive answer to this, but perhaps Stonehenge would stand a chance, presuming it was designed as a sort of calendar.

This week's new question:

**Q.** I have heard that Henry Ford was responsible for the first slip gauge. What part did he in fact play?

**Note:** The question about the oldest measuring instrument raises an interesting and more general question, namely what is the origin of measuring instruments for each of the main measurement units. We invite your submissions on the first instruments for pressure, temperature, voltage and so on.

- Jeff Tapping

## Measurement and Safety

(from page 5)

It is located at in Western Sydney on approximately 130 acres of land. Test Safe Australia performs the following tests: - High Voltage Testing up to 33kV, Personal Protective Equipment Testing, Calibration, Intrinsic Safety Testing of electrical circuits, Flame Proof Testing of enclosures, Engine Testing, Destructive Rope Testing, Environmental Testing, Explosion Testing, Fire Fighting Training and Fire Testing, Conveyor Belt and Cable Testing for Flammability.

The evening started with a demonstration of how wire ropes used in mines are tested for strength. The rope was a 44mm 15 strand Skip Head Rope. This was an exciting demonstration and we were sorry we did not ask the audience for their estimates ahead of time. The wire broke at 1555 kN which meant it was within specifications. The number of test facilities available at this location made this visit particularly valuable. The meeting ended with a barbecue that rounded off a thoroughly enjoyable evening.

Thanks to Bill Stewart, Laurie Gerisch, Michael Kabriel, Bill Dunn, and Tony Jackson for working late to make the visit both enjoyable and educational. Special thanks go to the cook Kerry Fernandez who did a splendid job.

## An International Evaluation of the Artifact Calibration Concept

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### 1. Abstract

The "Artifact Calibration" concept uses a reduced set of reference standards to adjust an "Artifact Calibration" instrument like a calibrator traceable to legally accepted standards. In many countries around the world, this concept has been accepted within accredited environments, however in Europe, accreditation organizations have shown reluctance to accept the 5700A Artifact Calibration process as well as the manufacturer's recommendations for independent verifications. This results in a higher cost of ownership with the owner of the instrument.

Recently, "Artifact Calibration" was extensively studied by three European National Institutes. This paper describes the AC Voltage portion of the evaluation. It discusses the evaluation approach and results as well as the recommendations to the users of the 5700A calibrator.

### 2. Background

Artifact Calibration as implemented in the Fluke 5700A Series Multi Function Calibrators uses a reduced set of references and standards to adjust the instrument within its specification again. This set of references and standards exists of a 10V DC Voltage reference and two Resistance references of 10k $\Omega$  and 1 $\Omega$  resp. Through internal metrology, three internal references are being measured against the three above mentioned external references. After this, all output parameters and functions are adjusted relatively to the three internal references. AC functions are adjusted using internal ac-dc thermal transfer standards intended for this purpose. After this process the shifts in the calibration factors (used to correct the instrument for nominal outputs or to calculate the exact output value) are available for PC downloading or printing. The whole process is being controlled via internally embedded software ensuring consistency and repeatability.

To ensure the internal metrology is working properly the manufacturer recommends to independently verify the calibrator using a traditional set of measurement standards, such as DC voltage standards and dividers, resistance standards as well as AC voltage and current standards, and associated equipment. The benefits are obvious: consistency in the calibrator's calibration process and less calibrator downtime. The use of artifact calibrated equipment within such accredited environments has been accepted by national institutes as well as laboratory accreditation bodies throughout the world. However in Europe the concept is only accepted

if the user of such artifact calibrated equipment performs an independent verification prior to and after the artifact calibration. This results in a higher cost of ownership of the instrument and thus higher costs for the industry. Since many users of such calibrators are looking for optimizing their calibration facilities, there has been a continuous discussion between industry, national institutes, accreditation bodies and suppliers of such "Artifact Calibration" equipment. To serve these discussions a project has been set-up and carried through by three European national institutes and a supplier of artifact calibrated equipment.

### 3. Project Goal

The project goal was to verify independently from the manufacturer, whether the 5700A artifact calibration process brings back the calibrator within its 24hr specification as claimed by the manufacturer. On top of this evaluation the three partners wanted to evaluate the traceability chain realized by the artifact calibration so that the users of 5700A calibrators can utilize the artifact calibration feature and follow the manufacturer's recommendations within accredited environments.

### 4. Project Partners and Approach

To carry out the project within a relatively short time (January 1997 – April 1998) a consortium of three national institutes within Europe has been formed. Each consortium member had a special assignment covering the technical evaluation of the 5700A sections/functionality affected by the Artifact Calibration concept. The three institutes and their project assignments/responsibilities were:

- Netherlands Measurement institute-Van Swinden Laboratory B.V., NMi-VSL, The Netherlands  
Project Coordinator, Current & Resistance
- Physikalische Technische Bundesanstalt, PTB, Germany  
DC Voltage and Linearity.
- Swedish National Testing and Research Institute, SP, Sweden.  
AC Voltage and Firmware

The evaluation has been set up in three phases, which simulated as closely as possible the evaluation of a calibration laboratory, seeking for accreditation. Therefore the evaluation has been performed through measurements:



- with absolute traceability towards international accepted standards and
- within the scope of international standards like EN45001 and ISO Guide 25.

The three phases, are as follows and described in comparison to the laboratory evaluation:

**Black Box:** The calibrator output has been evaluated against the 24Hr specification (95% confidence level, as mentioned in the Operators manual) after a normal Artifact Calibration has been carried out.

*This phase is equivalent to the inter-laboratory comparison where the laboratory must perform measurements to demonstrate the results are within the laboratory's "Best Measurement Capabilities".*

**Opaque Box:** The calibrator output has been evaluated against the 24Hr specification (95% confidence level, as mentioned in the operators manual) after a nonstandard Artifact Calibration has been carried out where the values of the references are entered into the calibrator had an offset from the real values. The result should be such that the calibrator output values follow the offsets in a predictable way, based on the calibrator's internal metrology principles. Through these measurements the internal metrology principles and the traceability chain are evaluated.

*The opaque box phase is equivalent and comparable to the assessment of the used equipment and their impact on the total measurement system in the laboratory.*

**Glass Box:** The calibrator output has been evaluated after hardware and software parameters have been manipulated. The evaluation is made between the actual traceable results and the predicted results, based on the manipulated hardware and software parameters. This evaluation gives a clear view on the internal procedures used with the artifact calibration and their impact on the calibrator's traceability as well as a clear and detailed view on the functionality of the calibrator.

*This phase is equivalent to the assessment of the used calibration procedures and their impact on the traceability within the laboratory.*

Three randomly selected 5700A Series II calibrators have been made available by Fluke, which were individually delivered to the three national institutes. After each institute completed its measurements on their instrument, the instrument rotated to another consortium member. Through this system of rotating the instruments, each consortium member could perform his measurements on two different calibrators.

## 5. Evaluation Conditions

The instruments have been evaluated by the three consortium members under environmental conditions of  $23 \pm 0.5^\circ\text{C}$ ,  $50 \pm 20\%$  RH, with mains power of 230V @ 50Hz.

All measurement standards and references used during the evaluation were traceable to primary and/or national measurement standards. In general all measurements are carried through with high accuracy measurement equipment to ensure the contribution of the used reference has minimum influence compared to the specification of the calibrator.

## 6. Black Box Measurements and Evaluations

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

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

### Black Box Alternating Voltage Results

All ACV measurements made were performed using a traceably calibrated Fluke 5790A, where some of the measurements were performed with a traceably calibrated Fluke 792A with comparably lower measurement uncertainties.

The measurements 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 terminals 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 1.

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.**

| Range | Voltage | Output evaluation before and after [presented in ( )] Artifact Cal,<br>Deviation from nominal voltage in % of specification (k=2). |          |          |          |          |         |        |        |          |          |        |        |
|-------|---------|------------------------------------------------------------------------------------------------------------------------------------|----------|----------|----------|----------|---------|--------|--------|----------|----------|--------|--------|
|       |         | 10                                                                                                                                 | 20       | 40       | 100      | 1k       | 10k     | 50k    | 100k   | 200k     | 500k     | 700k   | 1M     |
| (V)   | (V)     | Hz                                                                                                                                 | Hz       | Hz       | Hz       | Hz       | Hz      | Hz     | Hz     | Hz       | Hz       | Hz     | 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 1: Black Box Test AC Voltage output measurement results before and after Artifact Calibration

The printout report of the calibrator shows the full scale shifts of the Artifact Cal adjustment procedure. Table 2 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 printout 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.

## 7. Opaque Box Measurements and Evaluations

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

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

In all there were six Artifact Calibrations each with evaluation of the results. The first and sixth Artifact Calibrations had no offsets applied to either the 10V, 1 ohm and 10 kOhm values. The second through fifth each had different combinations of the three artifacts

| Range | Voltage | (-Artifact Cal printed shifts) - Calibrated shifts,<br>expressed as % of specification (k=2). |    |    |     |    |     |     |      |      |      |      |    |
|-------|---------|-----------------------------------------------------------------------------------------------|----|----|-----|----|-----|-----|------|------|------|------|----|
|       |         | 10                                                                                            | 20 | 40 | 100 | 1k | 10k | 50k | 100k | 200k | 500k | 700k | 1M |
| (V)   | (V)     | Hz                                                                                            | Hz | Hz | Hz  | Hz | Hz  | Hz  | Hz   | Hz   | Hz   | Hz   | 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 2: Black Box Test Difference between Calibrator reported shifts and actual measured shifts after to Artifact Calibration



|           |             | (-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 3: Difference (as % of 24Hr specs) between Artifact Cal reported Shifts and actual output shifts

having differing shifted values.

### Opaque Box Alternating Voltage Results

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 were chosen with two different magnitudes in order to verify the linearity of the Artifact Cal adjustment.

Table 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.

| Artifact Cal measured ACV gain constants |             |              |
|------------------------------------------|-------------|--------------|
| Range (V)                                | Mean        | StdDev (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 4: Glass Box Test - Mean and standard deviation ACV gain constants

| Deviation Flatness constants in ppm relative to unity<br>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 |
| Range (V)                                                                                                              |     |     |      |      |     |     |     |     |     |      |     |     |      |     |      |      |      |       |       |      |
| 2.2                                                                                                                    |     |     |      |      |     |     | 0   | -15 | -43 | -129 | 129 | 226 | 317  | 374 | 404  | 409  | 384  | 325   | 216   | -27  |
|                                                                                                                        |     |     |      |      |     |     | (2) | (1) | (3) | (3)  | (3) | (3) | (4)  | (5) | (5)  | (5)  | (6)  | (6)   | (7)   | (6)  |
| 22                                                                                                                     |     |     |      |      |     |     | 1   | 4   | 51  | 114  | 139 | 306 | 450  | 650 | 859  | 1088 | 1326 | 1569  | 1810  | -358 |
|                                                                                                                        |     |     |      |      |     |     | (2) | (1) | (1) | (2)  | (2) | (2) | (2)  | (2) | (3)  | (3)  | (3)  | (3)   | (4)   | (7)  |
| 220                                                                                                                    |     |     |      |      | -3  | -4  | 2   | -9  | -66 | -9   | 29  | 120 | 147  | -54 | -453 | -317 | 8    | -3192 | -5536 | 4117 |
|                                                                                                                        |     |     |      |      | (2) | (2) | (3) | (3) | (3) | (4)  | (4) | (5) | (11) | (9) | (13) | (18) | (26) | (33)  | (30)  | (5)  |
| 1100                                                                                                                   | -21 | -97 | -207 | -438 |     |     |     |     |     |      |     |     |      |     |      |      |      |       |       | -517 |
|                                                                                                                        | (1) | (1) | (1)  | (2)  |     |     |     |     |     |      |     |     |      |     |      |      |      |       |       | (8)  |

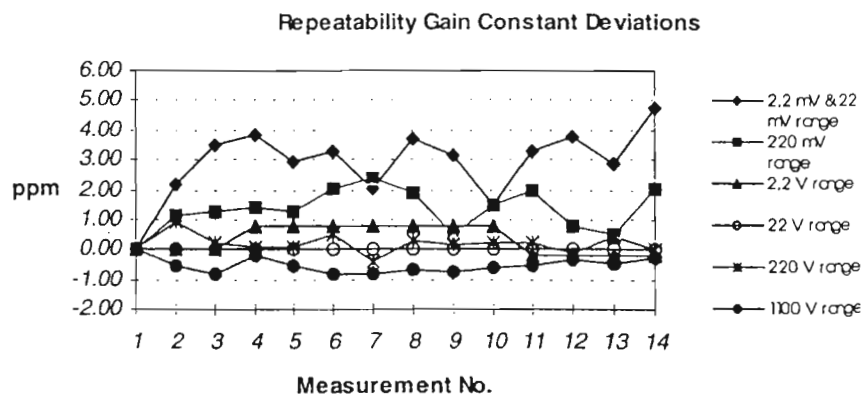
Table 5: Glass Box Test - Repeatability of Artifact Cal measured ACV flatness constants

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.

### 8. Glass Box Measurements and Evaluations

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 circuitry's.



### Glass Box Alternating Voltage Results

- 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 Tables 4 and 5.

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.

- 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 local sense mode. For the 2.2 V range and the 22 V 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 2 V on the 2.2 V range and the results are presented in the following diagram, Figure 1.

The voltage drop at the 22 V range is almost equal to the voltage drop at the 2.2 V range. The differences can be explained by different input capacitance of the 2.2 V and the 22 V range active attenuators at the input of the ac-dc sensor.

Measurements at 20 V on the 22 V range are also performed and Figure 2 shows the results.

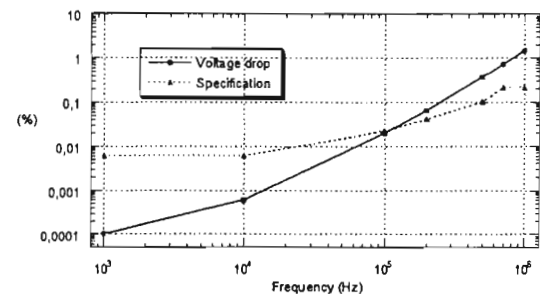


Figure 1: Glass Box Test - Voltage drop between output terminals and Artifact Cal reference plane at 2.2 V range

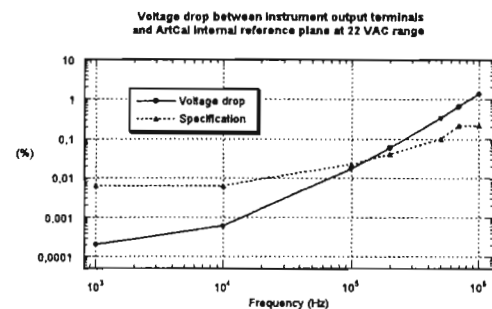


Figure 2: Glass Box Test - Voltage drop between output terminals and Artifact Cal reference plane at the 22 V range

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 2.2 V range and the 22 V range the constants are A4S and A5S, respectively. The SWR correction factor is for the 22 V range applied as shown in the following equation:

$$V^{n+1}_{DAC} = V^n_{DAC} \cdot (1 + \text{Frequency}^2 \cdot A5S)$$

Equation (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 results shown in Table 6.

| Difference between measured sense lead voltage drop and 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 6: Glass Box Test - Comparison of measured sense lead voltage drop and SWR correction



The differences are negligible compared to specification.

- Effect of changes to internal constants that influence ACV

The Artifact Cal procedure uses the internal VDC references to calibrate the gain of the precision DAC and stores the result as DAC counts per Volt. The ACV function uses the positive 11 V range of the DAC. The gain of the positive 11 V 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 gains 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 10 VDC reference does not influence the measurement of the DCV gain of the ACV ranges. The gains 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, test results from changing flatness constants and convergence constants are presented.

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.

- 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 printout report.

The formula that the calibrator uses to calculate the Low frequency output voltage Correction Factor, LCF, is applied for frequencies 10 Hz to 100 Hz 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  $3 \times 0.027333 = 0.081999$ .

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 10 Hz and the smallest is 5 ppm at 1000 Hz.

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

| Range (V) | Freq. (Hz) | Type of constant | Constant name | Constant value before change | Constant value after change | Calculated shift of Constant (ppm) | Measured Shift of output Voltage (ppm) | Measured 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                       | ---                           |

(\*) Estimation based on 14 bit DAC resolution of 2 ppm per count.

(\*\*) Calculated as  $((1000 \text{ DAC counts}) \cdot (2 \text{ ppm})) / (\text{Measured voltage level})$

Table 7: Glass Box Test - Introduction of shifts to flatness and convergence constants

| Output voltage of Artifact Cal adjusted calibrator with no added capacitor C, measurement B |                |          |           |           |           |           |            |            |            |            |            |            |            |            |             |
|---------------------------------------------------------------------------------------------|----------------|----------|-----------|-----------|-----------|-----------|------------|------------|------------|------------|------------|------------|------------|------------|-------------|
| Deviation from nominal voltage in ppm                                                       |                |          |           |           |           |           |            |            |            |            |            |            |            |            |             |
| Range<br>(V)                                                                                | Voltage<br>(V) | 1<br>kHz | 10<br>kHz | 20<br>kHz | 50<br>kHz | 75<br>kHz | 100<br>kHz | 119<br>kHz | 120<br>kHz | 150<br>kHz | 200<br>kHz | 300<br>kHz | 500<br>kHz | 700<br>kHz | 1000<br>kHz |
| 0.22                                                                                        | 0.06           | -3       | 8         | 10        | 45        | 56        | 68         | 66         | -38        |            | -21        | 122        | 266        | 436        | 782         |
| 0.22                                                                                        | 0.2            | 6        | 10        | 10        | 9         | -14       | -24        | -35        | -51        |            | -60        | -54        | 93         | 170        | 409         |
| 2.2                                                                                         | 0.6            | -3       | -3        | 5         | 20        | 32        | 55         | 72         | -41        |            | -36        | -67        | -25        | -100       | -288        |
| 2.2                                                                                         | 2              | 6        | 7         | 9         | 5         | -9        | -16        | -21        | -41        |            | -40        | -46        | -48        | -127       | -319        |
| 22                                                                                          | 6              | 1        | -2        | 1         | 12        | 34        | 54         | 71         | -59        |            | -51        | -55        | -4         | 35         | 142         |
| 22                                                                                          | 20             | 9        | 11        | 12        | 6         | 2         | -10        | -17        | -44        |            | -43        | -44        | -26        | -42        | -154        |
| 220                                                                                         | 22             | 4        | -4        | 4         | 5         | -13       | -18        | -39        | 38         |            | 74         | 149        | 297        | 1658       | 4000        |
| "                                                                                           | 60             | -6       | -11       | -2        | 12        | 5         | 9          | -2         | 82         | 107        | 169        |            |            |            |             |
| "                                                                                           | 70             | -3       | -9        | 1         | -3        | -30       | -55        | -88        | -174       | -191       | -194       | -174       |            |            |             |
| "                                                                                           | 100            | 1        | -3        | 6         | 4         | -23       | -40        | -70        | -155       | -164       | -152       |            |            |            |             |
| "                                                                                           | 200            | 2        | -2        | 6         | 1         | -29       | -47        |            |            |            |            |            |            |            |             |
| Output voltage of calibrator with added 80 pF capacitor, measurement D.                     |                |          |           |           |           |           |            |            |            |            |            |            |            |            |             |
| Deviation from nominal voltage in ppm                                                       |                |          |           |           |           |           |            |            |            |            |            |            |            |            |             |
| Range<br>(V)                                                                                | Voltage<br>(V) | 1<br>kHz | 10<br>kHz | 20<br>kHz | 50<br>kHz | 75<br>kHz | 100<br>kHz | 119<br>kHz | 120<br>kHz | 150<br>kHz | 200<br>kHz | 300<br>kHz | 500<br>kHz | 700<br>kHz | 1000<br>kHz |
| 0.22                                                                                        | 0.06           | -6       | 2         | 3         | 32        | 35        | 32         | 27         | 133        |            | 453        | 1194       | 3255       | 6288       | 12669       |
| 0.22                                                                                        | 0.2            | 5        | 9         | 12        | 38        | 57        | 102        | 143        | 128        |            | 432        | 1037       | 3106       | 6055       | 12361       |
| 2.2                                                                                         | 0.6            | -5       | -5        | 0         | 12        | 16        | 32         | 36         | 131        |            | 447        | 1010       | 2963       | 5743       | 11550       |
| 2.2                                                                                         | 2              | 5        | 7         | 13        | 36        | 60        | 109        | 153        | 135        |            | 446        | 1035       | 2934       | 5697       | 11498       |
| 22                                                                                          | 6              | 0        | -2        | -1        | 3         | 17        | 27         | 33         | 122        |            | 426        | 1027       | 2980       | 5861       | 11966       |
| 22                                                                                          | 20             | 11       | 13        | 17        | 37        | 70        | 113        | 156        | 133        |            | 441        | 1037       | 2957       | 5769       | 11656       |
| 220                                                                                         | 22             | 3        | 0         | 3         | 1         | -27       | -45        | -77        | -7         |            | -58        | -142       | -513       | -14        | 640         |
| "                                                                                           | 60             | -7       | -7        | -1        | 4         | -11       | -22        | -40        | 33         | 27         | 28         |            |            |            |             |
| "                                                                                           | 70             |          |           |           |           |           |            |            |            |            | 301        | 936        |            |            |             |
| "                                                                                           | 100            | -1       | 2         | 13        | 35        | 45        | 78         | 105        | 21         | 107        | 324        |            |            |            |             |
| "                                                                                           | 200            | 1        | 5         | 13        | 34        | 42        | 75         |            |            |            |            |            |            |            |             |
| Output voltage shift due to the added 80 pF capacitor, measurement D.                       |                |          |           |           |           |           |            |            |            |            |            |            |            |            |             |
| Shifts in ppm relative nominal voltage.                                                     |                |          |           |           |           |           |            |            |            |            |            |            |            |            |             |
| Range<br>(V)                                                                                | Voltage<br>(V) | 1<br>kHz | 10<br>kHz | 20<br>kHz | 50<br>kHz | 75<br>kHz | 100<br>kHz | 119<br>kHz | 120<br>kHz | 150<br>kHz | 200<br>kHz | 300<br>kHz | 500<br>kHz | 700<br>kHz | 1000<br>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 8: Output voltage shift due to added 80 pF capacitor

performed external calibration.

- 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 hardware frequency response shift is introduced to the ac-dc sensor circuit by soldering a capacitor C at the input of the thermal sensor. The Figure 3, it shows the connection of the capacitor C.

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,  $L_0$ , increase the input voltage of the thermal sensor.  $L_0$  has been measured to approximately 1.1  $\mu\text{H}$ .

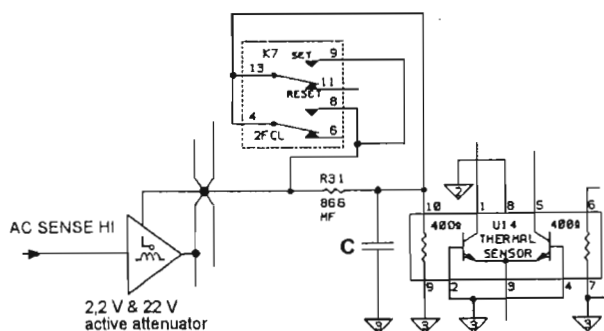


Figure 3: Schematic of relay K7 connection and adding a capacitor C to the ac-dc sensor circuit.

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 220 V range and the V-Hz product is limited to  $2.2 \cdot 10^7$  (V\*Hz), the measurement point of 22 V and 1 MHz at the 220 V range is chosen for some tests.

The following measurement procedure was performed:

- An Artifact Cal procedure was performed with no capacitor added.
- The output voltage was measured.
- The capacitor was soldered at the ac-dc sensor input.
- The output voltage was measured.
- An Artifact Cal procedure was performed with the added capacitor.
- The output voltage was measured.
- The capacitor was removed.
- An Artifact Cal procedure was performed with no capacitor added.
- 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 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 22 V and 1 MHz. For frequencies 100 kHz and below, the differences are less than 10 ppm. The measurement results are shown in Table 8.

The measured shifts indicate that the R31 resistor is not shorted for frequencies above 119 kHz in the low sub ranges of the ranges 0.22 V, 2.2 V and 22 V. This will make the internal ac-dc transfer measurement resolution lower for these sub ranges. This yields for the 2.2 mV and the 22 mV range also, as they are divided from the 2.2 V and the 22 V range. For the 220 V range, the R31 resistor is shorted for all frequencies in the low sub range.

- The resolution of the ac-dc transfer process.

Figure 4 shows the different resolution of the ac-dc transfer process for frequencies below 120.00 kHz and for frequencies 120 kHz and above.

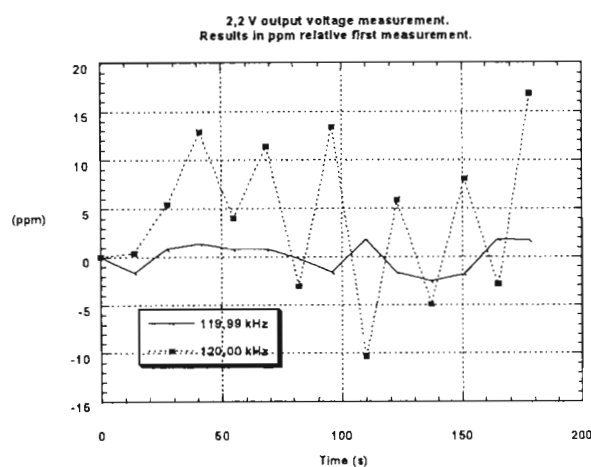


Figure 4: AC-DC transfer resolution shift between 119.99 and 120.00 kHz

The measurement series for the 119.99 kHz and 120.00 kHz 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. When the u character was switched off the output voltage was stable within 2 PPM.

The measurement voltage, 2.2 V, is at the low end of the 22 V range, where the R31 resistor is shorted for 119.99 kHz and not shorted for 120.00 kHz. To equalize the conditions of the calibrator the AC Xfer = OFF command was used for 119.99 kHz. The larger standard deviation at 120.00 kHz, 7.9 ppm, compared to 1.5 PPM at 119.99 kHz, is due to the following:

- Lower resolution when the R31 resistor is not shorted at the minimum voltage on the 22 V range, for frequencies above 119.99 kHz.
- Different settled criteria: Final ac-dc adjustment is less than 30 ppm for the 120.00 kHz measurements



and less than 7.5 PPM for the 119.99 kHz measurements.

### 9. 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. However, 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 observed 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  $AxS$  ( $x = 1 \dots 6$ ) compensate for this effect. Although it is most unlikely these correction factors change, there are not checked during Artifact Cal.

➤ From the results of the opaque box tests, it is clear that Artifact Cal as expected from the theoretical study realized the traceability chain. 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 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  $(23.0 \pm 0.5)^\circ\text{C}$  which showed a maximum standard deviation in the average of 2 PPM or 10 % of specification for some DC voltage and resistance ranges.

➤ The calibration report produced by the Artifact Cal procedure accurately reflects the changes at the binding posts of the calibrator due to the calibration, except for the opposite sign. 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 calibrating those ranges of the calibrator that are derived from the internal voltage and 10 k $\Omega$  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.

### 10. 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. 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 user stores the calibration report and the raw data 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 user should store the Artifact Cal report. 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 do a repeatability test of the Artifact Cal procedures 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 (given in the previous chapter) and check that his instrument does not exceed the specifications.

### • 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 need 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 motivate 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.*

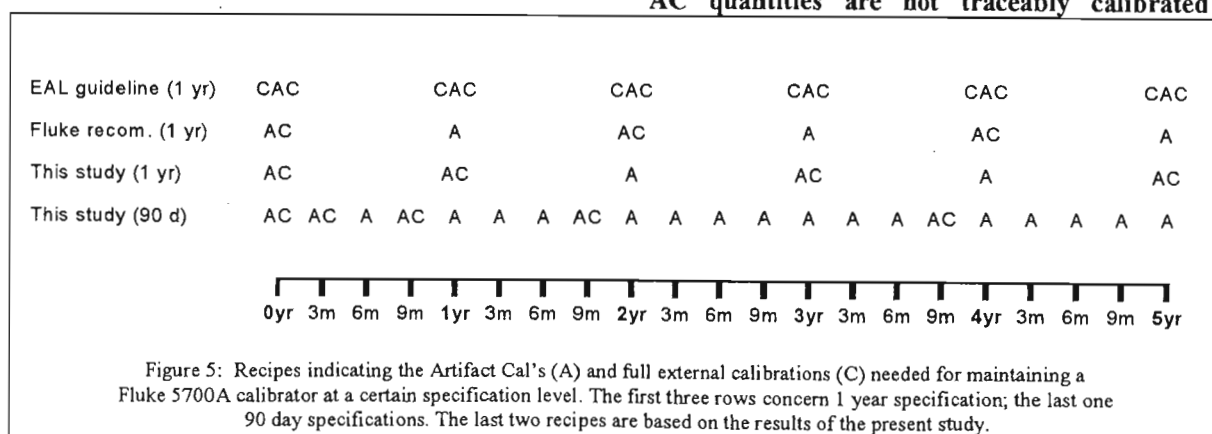
When a calibrator has been repaired, it depends on the part(s) that had to be repaired whether the user can still use (part of) the history he has gathered. In this judgment, detailed information from Fluke can be very helpful.

### • 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.

Fluke recommends using 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 ( $0\ \Omega$ ) 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.

#### • Intermediate Artifact Cal

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 another calibration regime than those given here.

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 5 together with the EAL guideline and the Fluke recommendation.

The example for the use of 1-year specification indicates that after two full external calibrations, 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. In this case the user should follow the "1 year scheme" of Figure 5 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.

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## References

Leading reference for this paper:

"Artifact Calibration, An Evaluation of the Fluke 5700A Series II Calibrator"

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**General documents used in the project were:**

- 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.
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