# FLUKE ®

## Calibration

# How many calibrators do you need to meet ISO 9000?

## Application Note

## Abstract

Modern quality standards are all about monitoring, controlling and documenting processes. Technology is providing ever more sophisticated multifunction tools to do that job at affordable prices. The prospect of supporting the calibration of these tools, as well as the more traditional ones, can be quite daunting.

This application note describes the design and development of a new class of multi-product calibrator and related tools for managing a burgeoning calibration workload in the ISO 9000 environment.

## Introduction

Emerging quality standards—specifically the ISO 9000 series—are changing the nature of electrical calibration. More and more companies that have never really calibrated are finding it necessary to establish calibration programs to support their quality systems.

These changes in calibration fall into three categories:

- **Changes in *who* is performing calibrations.**
  Many companies first recognize they need a program for calibrating electronic measurement tools when they begin pursuing ISO 9000 registration. Throughout the world, particularly in the countries of the European Community and Asia, registration to ISO 9000 is a fast growing requirement for any producer engaged in international trade, or selling to other exporters. Without ISO 9000, many markets are inaccessible.
- **Changes in *what* is being calibrated.**
  Rather than the traditional calibration world's higher accuracy tools, emerging calibration labs need to support a vast array of common electrical tools. These include handheld digital and analog multimeters, temperature indicators and oscilloscopes. In addition, power measurement is a growing application, particularly in the area of power quality and harmonics analysis. The requirement for calibration support for these measurement tools is increasing.

The Fluke 5500A Multi-Product Calibrator.

- **Obstacles in *how* calibration requirements are being met.**
  Surprisingly, the calibration system, once it is in place, is not a substantial roadblock to registration. However, documentation, procedures and traceability are the challenges to achieving ISO 9000 registration.[1]

Many companies new to calibration feel it is important to control the calibration process within their facilities. Concerns center around control over the process, quality, timely turnaround time and a perceived inability to audit outside service providers. Yet most believe that a large amount of expensive equipment and skilled technicians are required, making it difficult to cover enough workload to achieve a reasonable return on the equipment investment.

What historical trends led up to these changes in calibration operations and workload? What implications might these changes have on the design and development of a new electrical calibrator?

[1] "Identifying the Barriers to Registration," *Quality Systems Update*, September, 1993.

## Calibration trends since 1940: an historical perspective[2]

Most electrical calibrators have been developed to meet the calibration requirements of new or existing workload. As that workload has changed so has the design of the calibrators intended to support it.

Since the middle 1940s, there have been two distinct trends in the development of measurement tools and the calibrators used to calibrate them traceable to recognized national standards:

### The trend toward reducing uncertainty

Since the end of World War II, technical advances have permitted measurement scientists to reduce uncertainty dramatically. In the 1940s working measurements were made with an analog iron-vane or D'Arsonval meter. With care, uncertainties were in the range of 0.5 % of full scale, or 5000 ppm. As shown in Figure 1, that 5000 ppm in 1940 became 100 ppm by 1960, 10 ppm by 1970 and 2 ppm today.

### The trend toward increasing functionality

Hand in hand with decreasing measurement uncertainty was the increasing integration of measurement functions within an instrument. Single function analog voltmeters evolved into portable multimeters for measuring voltage, current and resistance. The digital revolution brought us the fast digital voltmeter that could be controlled by a computer. The digital voltmeter eventually expanded to include new functions and capabilities. As Figures 2 and 3 show, the single function direct voltage meter of 1940 has evolved to the ubiquitous handheld digital multimeter (DMM) with as many as ten or more functions, all in a rugged, portable and inexpensive package. The integration of features continues with a new generation of hybrid, handheld test tools like power harmonics analyzers, oscilloscope/DMM combinations like Fluke's ScopeMeter® test tool, documenting process
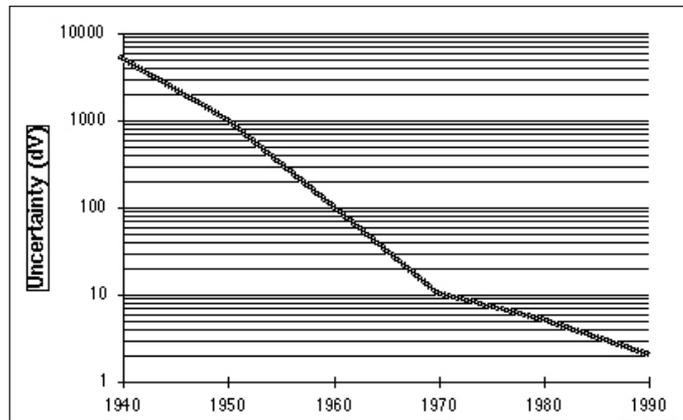


Figure 1. The trend toward lower uncertainties in working measurements.
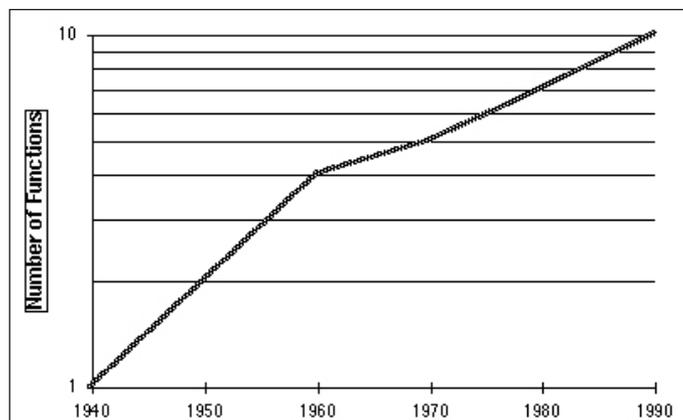


Figure 2. The trend toward increasing functionality in working measurement tools.

calibrators, portable data loggers and so forth.

The one thing these trends have in common is that at the leading edge of these advances in uncertainty and functionality, calibration support becomes a real challenge. How do you support a working voltmeter that can routinely measure direct voltage with uncertainties of ± 2 ppm? How many calibrators are required to calibrate a common handheld DMM with 10 measurement functions?

[2] Johnston, Craig and Corely, Ginger, "Voltmeters and Calibrators: A History and Review of Their Parallel Development," *Measurements and Control*, December, 1985.
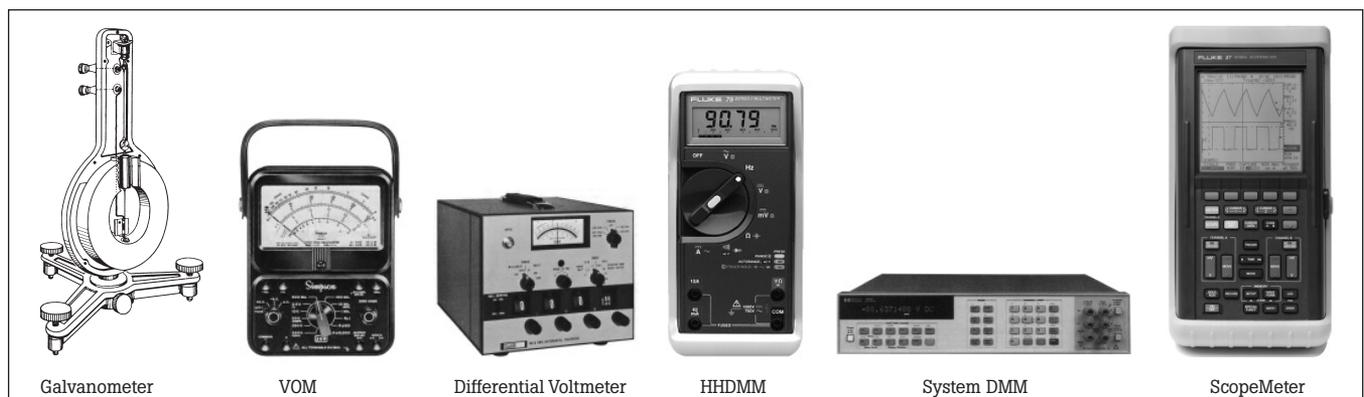


| Galvanometer | VOM | Differential Voltmeter | HHDMM | System DMM | ScopeMeter |

Figure 3. Examples of increasing functionality in electronic test tools.

## The workload "created" by ISO 9000

In the recent past, the bias in the calibration world was toward supporting a low measurement uncertainty workload. Applications consisted of defined programs in the aerospace and defense industries, where state-of-the-art performance goals required the lowest measurement uncertainty. Vendors were required by contract to comply with the government standard MIL-STD-45662A. So the equipment and technical skill required was relatively easy to justify.

But much of the workload "created" by ISO 9000 is different. There are more tools with more functions. Most have not been subject to calibration recall in the past. The traditional calibration equipment commonly available was not designed to support that workload efficiently.

The workload is also changing rapidly. As the electrical and electronic content in everyday products increases, new test instruments are developed to address design, test and troubleshooting applications. For the ISO 9000 company establishing a calibration program, there are more kinds of test instruments in more hands today, with the promise of more and different kinds of products coming tomorrow. And if those instruments affect the quality of a product or service, they must be documented as calibrated with traceability to recognized national standards.

## More than handheld DMMs

Many test instruments share common multimeter functions—measurement of direct and alternating voltage and current, resistance, capacitance and frequency. But the calibration requirement is mushrooming beyond DMMs.

There is a fast growing need to calibrate thermocouple and RTD indicators found in electronic thermometers, chart recorders, process calibrators and data loggers.

Next to DMMs and tools like them, oscilloscopes to 200 MHz bandwidth account for the second largest type of electrical calibration workload, most of which have not been rigorously calibrated. They can be quite challenging to support. Required are a sinewave generator with precise amplitude control, a fast pulse generator to check bandwidth, as well as a squarewave generator for amplitude calibration and a time mark generator.

Finally, line power measurement tools like watt meters and power harmonics analyzers require the ability to generate "phantom" power through simultaneous output of voltage and current or dual voltages. In alternating voltage/current/power modes, phase control is necessary. And for power harmonics, the ability to generate several harmonics of the fundamental frequency is also required.

## How many calibrators does it take to support this workload?

A traditional meter calibrator will support many of the voltage, current and resistance requirements. But two of them phase-locked together, plus a phase meter, are required for power calibration. A thermocouple simulator is needed for temperature. Capacitance is traditionally supported through the use of standard capacitors or RCL meters. For multiple waveforms and oscilloscope calibration, several specialized function or signal generators are needed.

Each calibrator itself requires calibration support. Some can be automated, but most can only be used in manual mode. For the new lab, purchase of all the required equipment can be quite expensive.

Clearly, to meet the workload requirements of a rather diverse number of calibration labs, a new kind of calibrator is required. This new class of instrument will need to:

- Integrate an unprecedented number of calibration functions to maximize its workload coverage.

- Provide tools for dealing with documentation and control of procedures, results and traceability to nationally recognized standards.

- Be cost effective in terms of purchase, support and operator training.

## The design of a new class of multi-product calibrator

This application note describes the design of a new class of calibrator, the multi-product calibrator or MPC. The Fluke 5500A is slightly over one cubic foot, weighs less than 20 kilograms, and integrates a level of functionality never before seen in one package:

- DC volts, 100 nV to 1000V, 40 ppm uncertainty.
- AC volts, 1 mV to 1000V, 10 Hz to 500 kHz.
- DC and ac current, to 11 A.
- Variable resistance, 0 Ω to 330 MΩ.
- Variable capacitance, 330 pF to 1 mF.
- Temperature simulation and measurement, nine thermocouple types.
- RTD simulation, three types.
- Power into phantom loads, up to 11 kW.
- Multiple waveforms and extended bandwidth from 0.01 Hz to 2 MHz.
- Complete oscilloscope calibration, including a 250 MHz leveled sinewave generator.

The block diagram of the 5500A is similar to the

multifunction calibrators of the past, but with some important additions. Key elements in the 5500A block diagram are precision digital-to-analog converters (DACs), arbitrary waveform generators, voltage and current amplifiers, and circuits used for resistance and capacitance generation. See Figures 4 and 5. The details of each of these blocks are not described here, but we will look at each block from the user perspective and how the design of each block was chosen to meet changing customer needs.

## Precision Digital-to-Analog Converters (DACs)

These circuits determine the overall "best" accuracy of the instrument. They are composed of a dc reference amplifier and two pulse-width-modulated DACs. These circuit elements determine not only the basic uncertainty of the calibrator, but also the secondary characteristics of noise and linearity. Leveraging the very linear pulse-width-modulated DAC from the 5700A Calibrator, two pulse-width-modulated DACs are implemented with a high level of integration and surface mount construction. These two precision DACs occupy less printed circuit board area than the one 5700A DAC. Shrinking the physical size of the DACs did not sacrifice performance. Noise and linearity characteristics are approximately ten times better than what is required of this class of calibrator.

The precision DACs are used for a variety of functions, including dc voltage, dual channel outputs, and temperature simulation. A proprietary isothermal block is combined with one of the DACs to simulate nine different thermocouple types. The isothermal block is a fast settling design with excellent isothermality. The thermal emfs of the entire system are less than 2 µV, to yield uncertainty down to 0.10 °C.

## Arbitrary waveform generator

At the heart of the 5500A are the two arbitrary waveform generators used to create multiple waveforms. A direct digital synthesis (DDS) circuit (patent pending) is used to create the sinewaves commonly used in calibration. It is also used to generate other waveforms not normally found in a precision calibrator, but nevertheless used in calibration: triangle waves for verifying frequency counter functions, square waves and time marks for calibration of oscilloscopes, and a "truncated sinewave" used to verify the harmonics performance of the new generation of power harmonics analyzers.
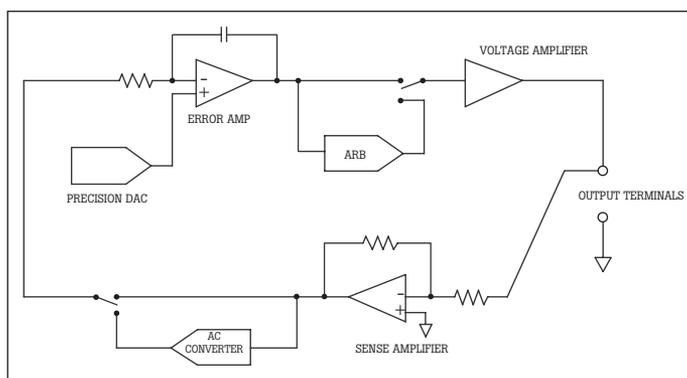
By adding a second channel to the DDS



Figure 4. Precision voltage channel of the 5500A Multi-Product Calibrator.
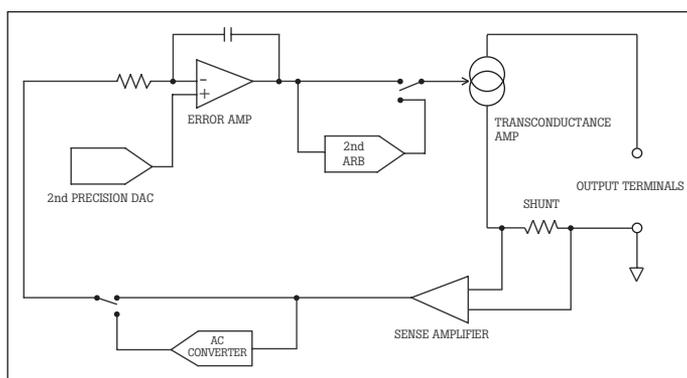


Figure 5. Precision current channel of the 5500A Multi-Product Calibrator.

circuitry and the second precision DAC, two channels of phase related waveforms are generated. The resolution of the phase is determined by the length of the wave table. In this case, it is 14 bits, which gives 0.02° phase resolution. Furthermore, the arbitrary waveform generator is used to create harmonics of the primary channel, which again is used for verifying the power harmonics analyzers. The arbitrary waveform generators are also used to generate very low frequency waveforms (down to .01 Hz), which can be used to check the linearity of chart recorders.

## Voltage and current amplifiers

Several customer demands drove the design of these amplifiers. Most modern DMMs have very high input impedance in voltage and very low input shunts in current. However, most users have a diverse inventory of measurement tools to support, not just DMMs. This equipment may include current clamps, older analog meters, and chart recorders. The input impedance of some of these devices can be as low as hundreds of kΩs. Careful attention was made to assure the MPC could drive these loads with good load

regulation without jeopardizing accuracy. There are both analog and software control loops for excellent load regulation. Where even more drive capability is needed, the 5500A provides an interface to the 5725A Boost Amplifier.

Most DMMs today can measure up to 10 A, so the MPC was designed to output 11 A to provide for some overranging. Several design aspects should be noted here. The voltage burden requirement of most DMMs is fairly benign in this range, typically less than 0.5 V. To calibrate current clamps, a multi-turn coil is often used. A 50 turn coil combined with the current clamp can create an inductive load of up to 200 µH. At 60 Hz, the reactance of 200 µH is 0.075 Ω. At 10 A, compliance of greater than 0.75 V is necessary. The MPC used a lightweight linear power supply with a novel (patent applied for) pre-regulator to meet this requirement, without compromising portability goals. A switching power supply is one alternative to minimize weight, but they can introduce undesirable noise.

Combining the two amplifiers with the DDS, the MPC is capable of sourcing power into phantom loads. The MPC can generate up to 11 kW and drive electronic wattmeters as well as many analog meters.

## Resistance and capacitance

Two requirements drove the design of these circuits. One, there is simply too wide a diversity of DMMs to only offer discrete resistance values. Gone are the days of full scales at "1s," and even "1.9s." Now, calibration procedures for DMMs use resistors starting at 100 Ω, 190 Ω, 290 Ω, 330 Ω, 390 Ω, etc. The other requirement is to calibrate RTD devices, which can be simulated using variable resistance.

In the 5500A MPC, we chose a synthesized resistance technique. To understand how this works, first look at how a DMM makes a resistance measurement. As shown in Figure 6, it solves Ohms law, $V = I * R$ by injecting a current into a resistor and measuring the resulting voltage across the resistor. Now, imagine "tricking" the voltmeter into thinking there is a different voltage across the resistor, for the same amount of
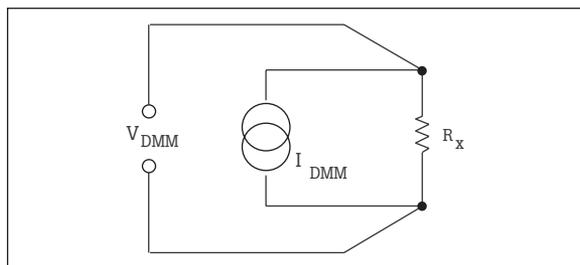
current. This is done by adding a voltage source, $V_s$, in series with the reference resistor, $R_{ref}$. $V_s$ has an output voltage of ($I_{DMM}$ x $R_{ref}$) times a selectable gain "A". The resistor now can look like the one shown in Figure 7. This dependent voltage source is varied by "A" so that the DMM "sees" a different voltage and therefore a different resistance.

A synthesized resistance scheme can present several problems. One concerns the amount of current the unit under calibration puts out when making resistance measurements.

Most handheld DMMs use less than 1 mA, but a Simpson 260 analog meter, for example, will output 120 mA in its lowest range. On the other extreme, the higher end bench/system DMMs can use more than 10 V to make MΩ measurements.

The 5500A addressed this problem by using a large number of discrete resistors (there are 16 reference resistors), and voltage sources that can handle over 100 mA and large compliance voltages. There are other subtle problems that had to be addressed, for example, the switching noise of many DMMs. Many DMMs expand upon the simple Ohm's law scheme depicted above by measuring various internal and external nodes. This can induce voltage spikes which have been known to upset other synthesized resistance sources.

The MPC also uses a synthesis technique to generate capacitance. Referring to Figure 7, if $R_{ref}$ is replaced with $C_{ref}$, any value of capacitance can be generated by controlling the dependent voltage source. There are 13 reference capacitors within the 5500A. A third parameter comes into play here. Handheld DMMs typically use a dc "charge/discharge" method of measuring capacitance, solving the equation $I = C \, dv/dt$. The unknown capacitor is charged with a dc current for a fixed amount of time, then the resulting voltage is measured. AC RCL meters, on the other hand, excite the capacitor with an ac voltage and determine the amplitude and phase of the resulting current. The ac bandwidth of the voltage source is important, in order to behave well into these meters.

Another point is to design in proper isolation of the capacitor such that the ac RCL meters work
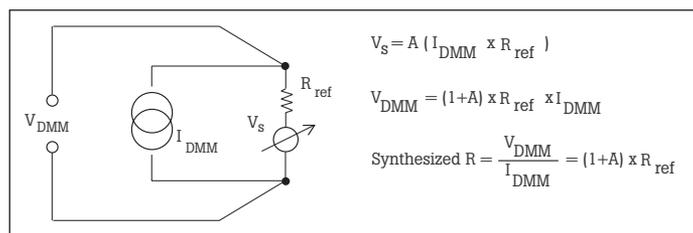


Figure 6. The DMM supplies a known current across $R_x$ the unknown resistance, and measures the resulting voltage.



$$V_s = A \, ( I_{DMM} \text{ x } R_{ref} )$$

$$V_{DMM} = (1+A) \text{ x } R_{ref} \text{ x} I_{DMM}$$

$$\text{Synthesized R} = \frac{V_{DMM}}{I_{DMM}} = (1+A) \text{ x } R_{ref}$$

Figure 7. Resistance values can be synthesized by putting a dependent voltage source in series with a reference resistor, $R_{ref}$.

properly. Typical RCL meters rely on a float-ing capacitor because of their virtual grounding technique. See Figure 8. This is a very important point from a calibration workload viewpoint and also a traceability perspective. The 5500A capacitance traceability path is made using higher end, more accurate ac RCL meters.

## Expansion capability

Several analog and digital busses are built into the 5500A, for additional flexibility in workload coverage. The 5500A-SC is an optional card that plugs into the mainframe. It adds the functional-ity and performance of a complete oscilloscope calibration system, with amplitude, fast edge, time marks, and a leveled sinewave generator. The 5500A also has a 5725A Boost Amplifier connector, to allow more drive capability in volt-age and current that may be needed for older analog meters. There is also an IEEE–488 port and two RS–232 ports, including one RS–232 "pass through" port used for controlling serial instruments.

## Documentation

The new class of multi–product calibrators is a very cost–effective, versatile hardware solu-tion for the changing world of calibration. It is, however, only part of the total package. Calibra-tion, especially with the acceptance of the new quality standards, also requires documentation and traceability.

5500/CAL is a Microsoft Windows® software application that satisfies three critical aspects of calibration system documentation and reporting requirements:

- **Documented procedures.** The package is shipped with over 1500 representative pro-cedures, virtually all of which can be run as is. These procedures document the calibration of a wide variety of DMMs, current clamps, wattmeters, process calibrators, oscilloscopes, data loggers and thermometers, from over 30 different manufacturers. They can be easily edited for calibration of other instruments or to meet other calibration requirements.

- **Traceability.** 5500/CAL maintains information on the calibration status and traceability of the MPC and other standards used to perform calibration procedures.

- **Documented calibration results.** 5500/CAL produces detailed test results, includ-ing as-found/as-left reports and calibration certificates. Format may be customized to meet individual requirements. Data is compat-ible with metrology asset data management
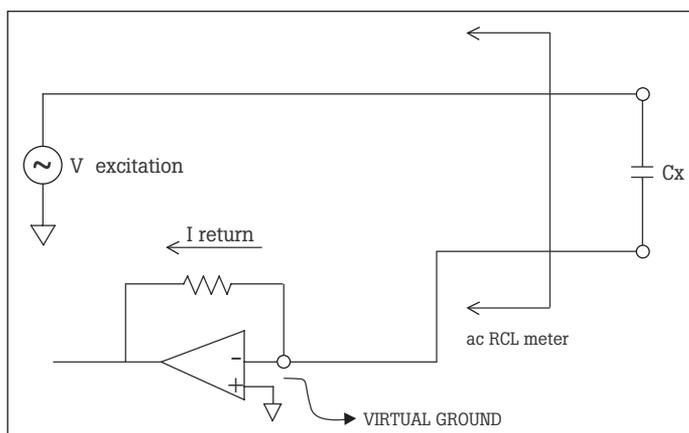


Figure 8. An ac RCL meter requires that the capacitor being measured "floats."

software like Fluke's MET/TRACK® for addi-tional information management, sorting and reporting.

5500/CAL controls the MPC and a DMM via an RS–232 connection. This reduces the complex-ity normally associated with PCs and IEEE–488 interfaces, reduces cost and permits use with a subnotebook computer in on–site calibration applications.

## Summary

The 5500A MPC represents a new generation of electrical calibra-tion tools. It integrates an unprecedented number of calibration functions in a single instrument. It is light weight and rugged and can be used over a relatively wide temperature range in on-site applications. Its accompanying 5500/CAL software streamlines the process of documenting calibration procedures, performing those calibrations under computer control, and collecting and reporting the results and the traceability of all instruments used. The 5500A is relatively inexpensive and easy to use, maximizing return on investment while minimizing operator training requirements.

For increased performance, the 5520A Multi–Product Calibrator expands workload coverage even further, with improved accuracy in nearly all areas and with additional features and functions.

**Fluke Calibration.** *Precision, performance, confidence.*™

| Electrical | RF | Temperature | Pressure | Flow | Software |
|------------|-----|-------------|----------|------|----------|