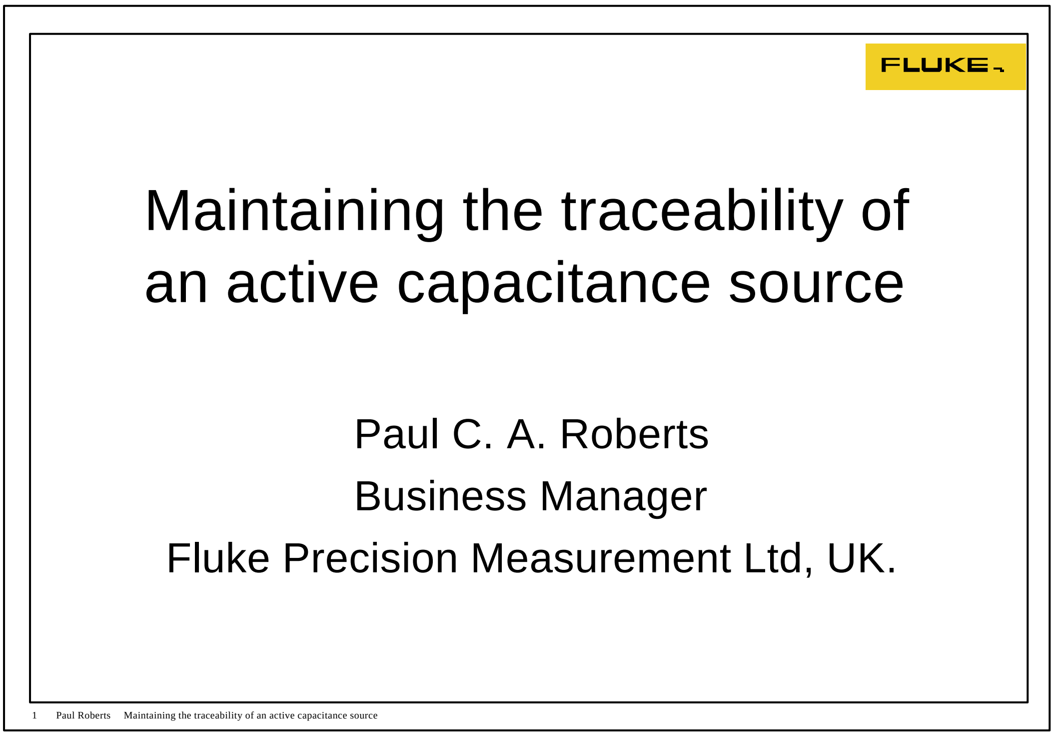
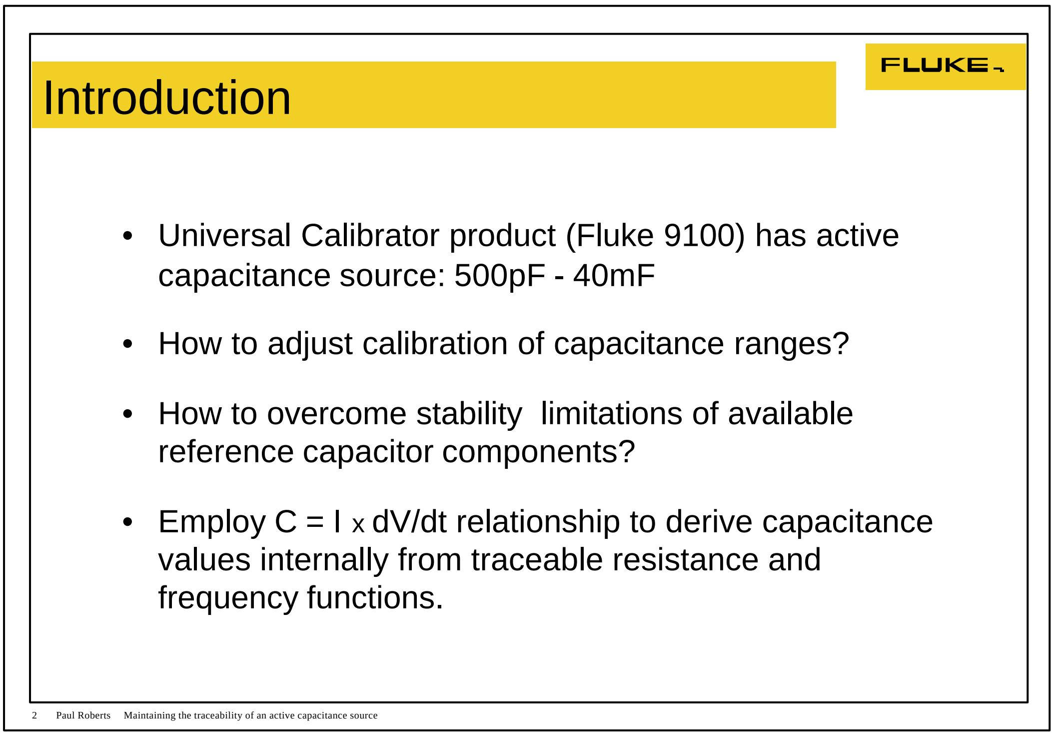


Maintaining the traceability of an active capacitance source

Paul C. A. Roberts
Business Manager
Fluke Precision Measurement Ltd, UK.

Abstract:

A high accuracy active capacitance source relies on a number of fixed capacitors that act as references. Because these capacitors suffer a small amount of drift with time and temperature, a novel impedance transfer technique has been developed to provide automatic drift compensation. This technique relates the capacitance values to voltage, resistance and time references which have much better stability than the capacitors themselves. Being based on the fundamental equation $C = I \times t/V$ the impedance transfer is fully traceable. Traceability can be demonstrated by direct comparison of the active capacitance source against external standards.



Introduction

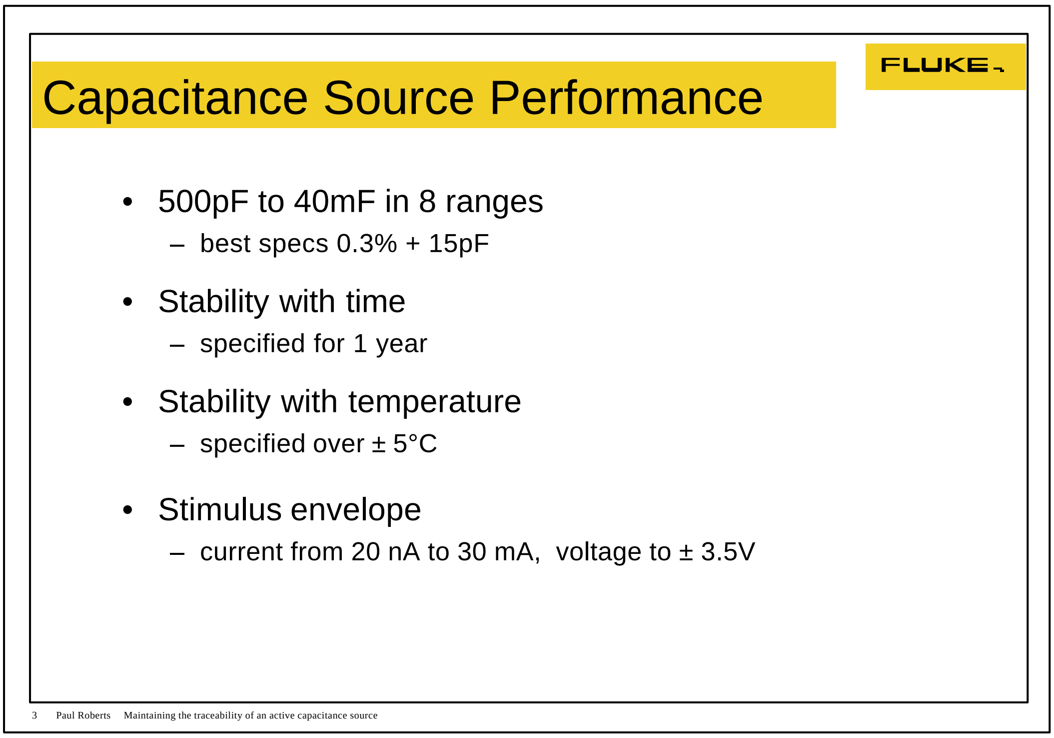
- Universal Calibrator product (Fluke 9100) has active capacitance source: 500pF - 40mF
- How to adjust calibration of capacitance ranges?
- How to overcome stability limitations of available reference capacitor components?
- Employ $C = I \times dV/dt$ relationship to derive capacitance values internally from traceable resistance and frequency functions.

The Fluke model 9100 Universal Calibrator has a capacitance function which generates continuously variable capacitance values from 500pF to 40mF in 8 ranges. The intended application of this function is the calibration of handheld dmms and component testers having capacitance measurement capability.

Traditional capacitance measurement techniques such as transformer bridges and LCR meters are generally not suitable for such a wide range of values. Their cost and complexity also prevent them from being widely available.

In a practical realization of a circuit design, the limitations of available components must be considered. Stability of capacitors constructed from the various dielectric materials available are not adequate to meet the performance requirements of this capacitance source.

A traceable method for maintaining the calibration accuracy of the capacitance source to overcome both limitations described above has been developed. It uses an internal impedance transfer technique based on the relationship $C=IxdV/dt$ to internally derive values for the capacitance ranges from the resistance and frequency functions of the instrument.



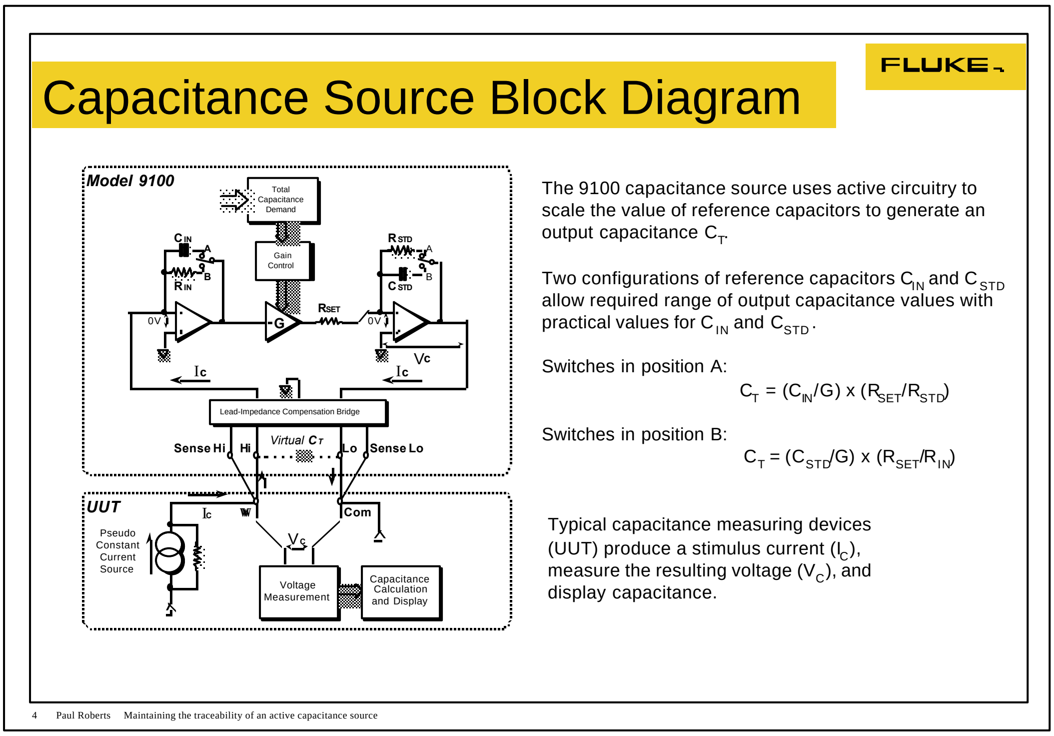
Capacitance Source Performance

- 500pF to 40mF in 8 ranges
  - best specs 0.3% + 15pF
- Stability with time
  - specified for 1 year
- Stability with temperature
  - specified over ± 5°C
- Stimulus envelope
  - current from 20 nA to 30 mA, voltage to ± 3.5V

Each capacitance range provides continuously variable output values over a 10:1 range. The best specifications are 0.3% + 15pF for the lower and middle values increasing to 1% + 60uF for values between 4mF and 40mF.

The specifications apply for a period of 1 year and a temperature range of plus and minus 5 °C from a nominal calibration temperature of 23 °C.

Active circuitry is used to scale values of a number of reference capacitors, and therefore limitations on excitation voltages and currents exist. The capacitance source is designed to operate over the range of stimuli presented by the intended workload. Excitation current capability is from 20 nA to 30 mA with an allowable discharge current of 100 mA and a voltage swing of up to 7 V.



Capacitance Source Block Diagram

The 9100 capacitance source uses active circuitry to scale the value of reference capacitors to generate an output capacitance C_T.

Two configurations of reference capacitors C_{IN} and C_{STD} allow required range of output capacitance values with practical values for C_{IN} and C_{STD}.

Switches in position A:

$$C_T = (C_{IN}/G) \times (R_{SET}/R_{STD})$$

Switches in position B:

$$C_T = (C_{STD}/G) \times (R_{SET}/R_{IN})$$

Typical capacitance measuring devices (UUT) produce a stimulus current (I_C), measure the resulting voltage (V_C), and display capacitance.

The 9100 will produce a voltage (V_C) in response to a stimulus current (I_C) being sourced from the UUT - typically a handheld dmm or component tester with capacitance measurement capability.

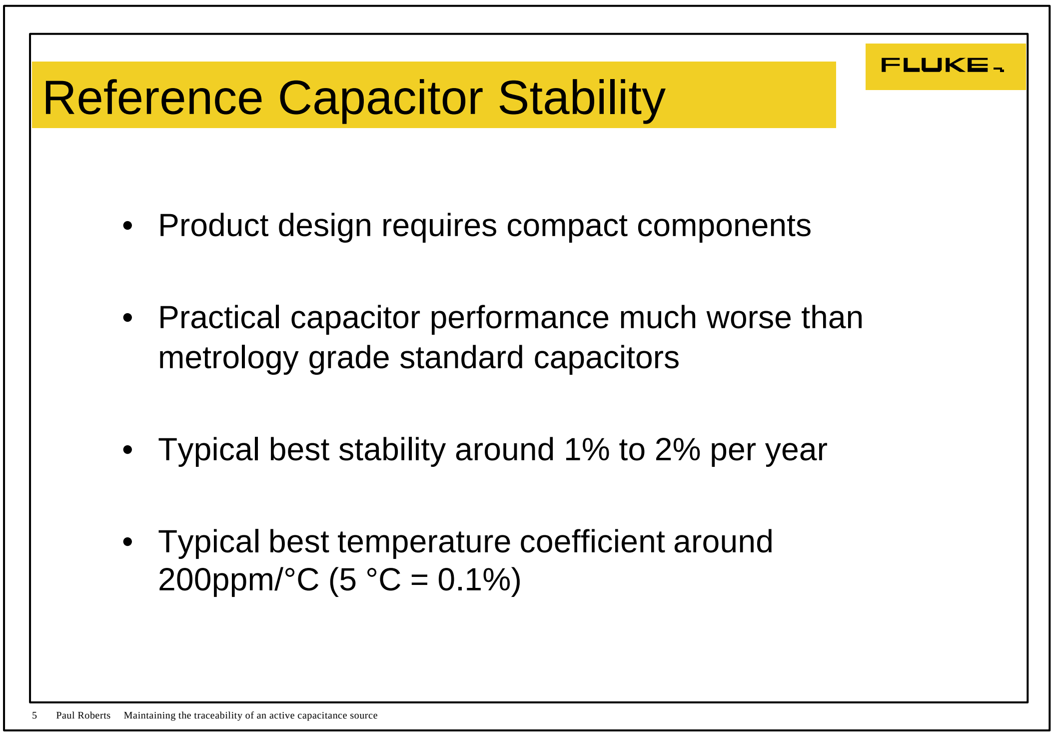
The instantaneous voltage (v_c) is derived from the instantaneous value of the stimulus current (i_c) modified by the Total Capacitance Demand (C_T) set on the 9100 display (including any offset or deviation variations) $dv_c/dt = i_c/C_T$.

The effect is that of placing virtual capacitance of the value C_T between the front panel Hi and Lo terminals of the 9100 which is effectively the reference capacitor C_{IN} or C_{STD} scaled by an appropriate factor. At high values the effects of series lead impedance is significant, and a 4-wire connection feature is incorporated.

Consider the switches at position 'A':

The UUT drives stimulus current I_C into C_{IN} via the Hi terminal, and draws I_C via the Lo terminal. The value of C_{IN} can be one of five possible values, selected automatically to to accommodate the range of stimulus currents. the system gain is set by the 'Total Capacitance Demand' set value (C_T), transferred by DAC to control the gain of amplifier 'G'. The final amplifier is switched in decade values. The overall result is an output voltage (V_C) satisfying $dv_c/dt = i_c/C_T$, placed across the Hi and Lo terminals, while sourcing the same instantaneous values of i_c , drawn by the UUT Lo terminal.

The value of the virtual capacitance with the switches in position 'A' is given by:
$C_T = (C_{IN}/G) \times (R_{SET}/R_{STD})$, and with switches in position B: $C_T = (C_{STD}/G) \times (R_{SET}/R_{IN})$.



Reference Capacitor Stability

- Product design requires compact components
- Practical capacitor performance much worse than metrology grade standard capacitors
- Typical best stability around 1% to 2% per year
- Typical best temperature coefficient around 200ppm/°C (5 °C = 0.1%)

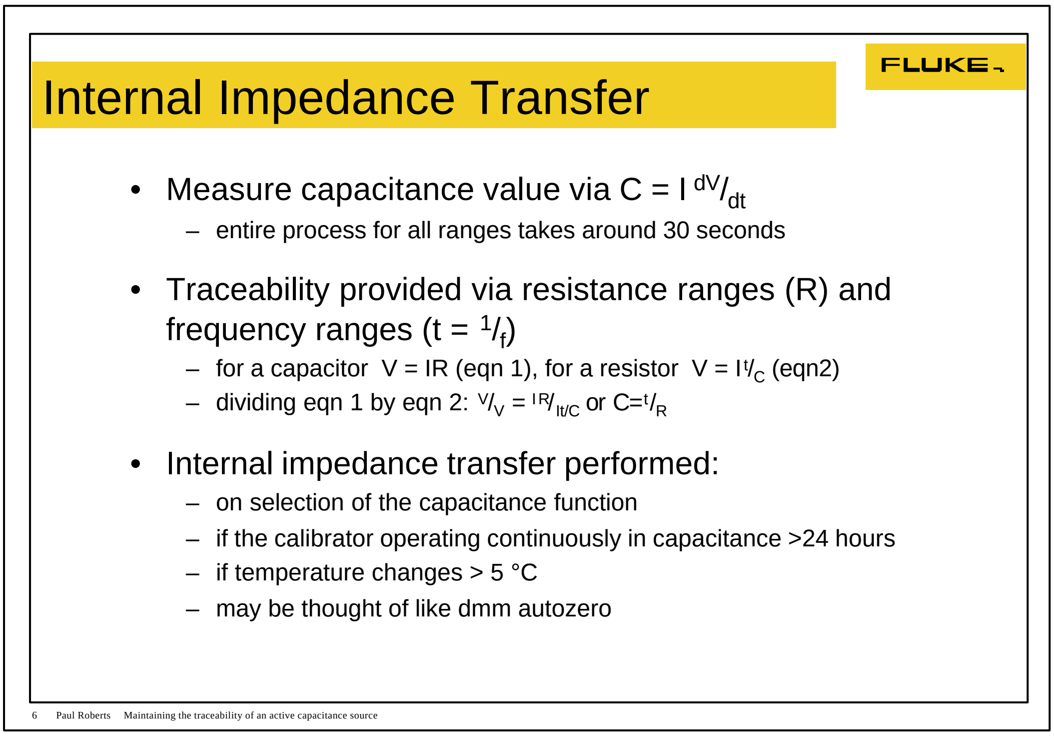
In a practical realization of a circuit design, the limitations of available components must be considered. Product mechanical design limits physical size. Use of capacitors common as metrology standards is impossible and appropriate values are not available.

Stability of capacitors is dependent on the properties of the various dielectric materials from which they are constructed. Even the better materials such as polycarbonate and polypropylene are not adequate to meet the performance requirements of this capacitance source.

Typical values for polycarbonate capacitors are:

1% to 2% per year stability.

200ppm/ °C temperature coefficient, contributing 0.1% over 5 °C.



Internal Impedance Transfer

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- Measure capacitance value via $C = I\,{}^{dV}/_{dt}$
  - entire process for all ranges takes around 30 seconds
- Traceability provided via resistance ranges (R) and frequency ranges ($t = {}^{1}/_{f}$)
  - for a capacitor $V = IR$ (eqn 1), for a resistor $V = I{}^{t}/_{C}$ (eqn2)
  - dividing eqn 1 by eqn 2: ${}^{V}/_{V} = {}^{IR}/_{It/C}$ or $C={}^{t}/_{R}$
- Internal impedance transfer performed:
  - on selection of the capacitance function
  - if the calibrator operating continuously in capacitance >24 hours
  - if temperature changes > 5 °C
  - may be thought of like dmm autozero

The technique chosen is based on the same principle as most handheld capacitance measuring instruments: the value of capacitance is calculated from the change in voltage produced by allowing the capacitor to charge for a given time from a constant current.

The error contributions of the current source and voltage measurement used to measure the capacitance value can be eliminated by using the same current source and voltage measuring device to measure a resistance value provided by the instrument's resistance function.

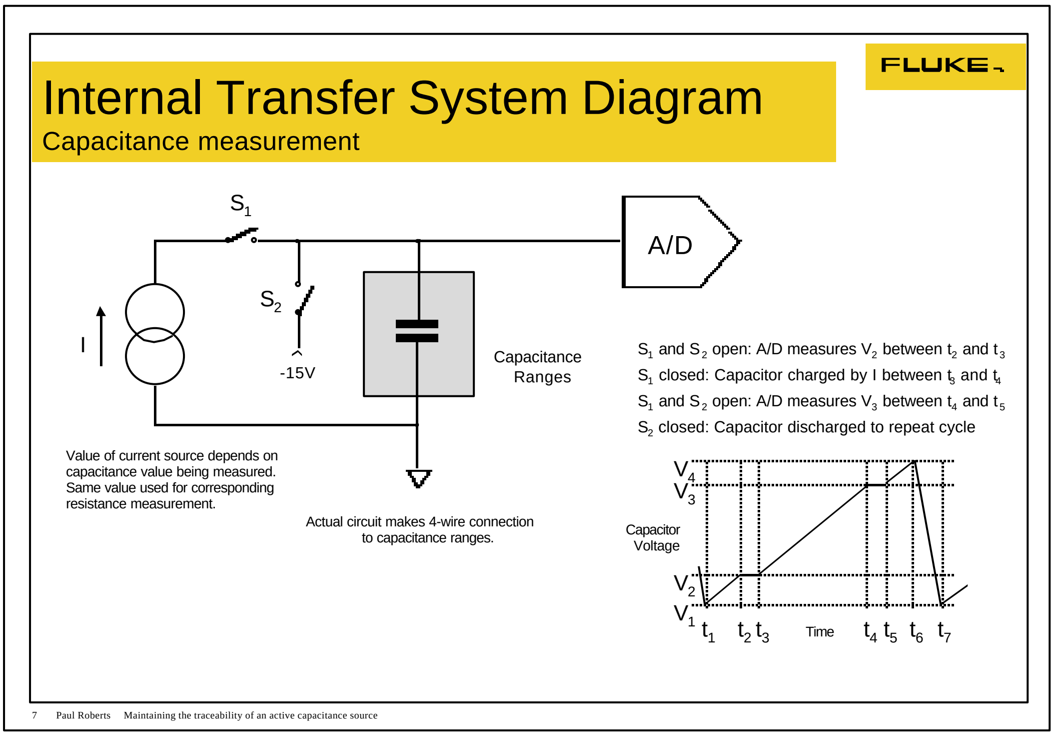
This 'internal impedance transfer' process derives a capacitance value from the resistance and time (frequency) reference circuits, which are calibrated against external standards, providing traceability for the calibration of the capacitance value.

An 'internal impedance transfer' is initiated automatically when the instrument user selects the capacitance function, and takes around 30 seconds to complete.

If the instrument is left continuously operating in the capacitance function for more than 24 hours, the instrument automatically initiates another 'internal impedance transfer' once every 24 hours.

The instrument's internal temperature sensor is used to monitor temperature changes and automatically initiates an 'internal impedance transfer' if the temperature deviates by more than 5 °C from that at which the last impedance transfer was performed.

Operation of the 'internal impedance transfer' is entirely transparent to the user, and may be likened to the operation of an Autozero or True Ohms system which automatically corrects for drifts and errors.



Internal Transfer System Diagram

Capacitance measurement

S_1 and S_2 open: A/D measures V_2 between t_2 and t_3
S_1 closed: Capacitor charged by I between t_3 and t_4
S_1 and S_2 open: A/D measures V_3 between t_4 and t_5
S_2 closed: Capacitor discharged to repeat cycle

Value of current source depends on capacitance value being measured. Same value used for corresponding resistance measurement.

Actual circuit makes 4-wire connection to capacitance ranges.

The capacitance measurement makes use of a current source and A/D provided as part of the instrument's internal selftest circuits.

The value of current I depends on the capacitance range being measured.

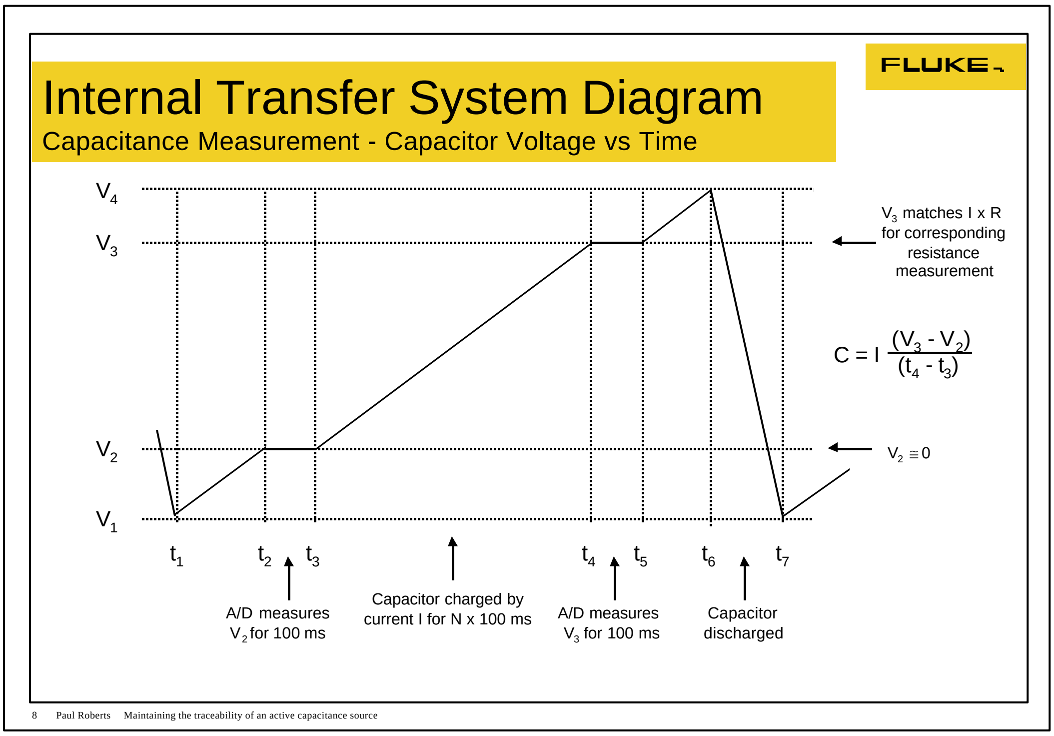
The capacitance function provides a 4-wire connection capability, required to avoid significant lead errors for the higher capacitance values. For simplicity, 4-wire connections are not shown in this diagram.

The capacitor is initially discharged toward the negative power supply rail by closing S_2. This enables the charging cycle to begin at a capacitor voltage below analog common (0V) at time t_1.

Charging begins by S_1 closing, and the capacitor voltage ramps up as the capacitor is charged by current I. When the capacitor voltage is approximately zero, S_1 opens and the capacitor voltage remains constant while the A/D samples and measures its actual voltage (V_2) between t_2 and t_3.

Charging continues with S_1 closing again, and continues for a fixed period of time from t_3 to t_4. At t_4, S_1 opens and the capacitor voltage remains constant while the A/D samples and measures the voltage (V_3) between t_4 and t_5. .

To complete the cycle S_1 closes until the capacitor voltage reaches V_4, when S_1 opens and S_2 closes to discharge the capacitor.



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Internal Transfer System Diagram

Capacitance Measurement - Capacitor Voltage vs Time

V_3 matches I x R for corresponding resistance measurement

$$C = I\,\frac{(V_3 - V_2)}{(t_4 - t_3)}$$

$V_2 \cong 0$

A/D measures V_2 for 100 ms

Capacitor charged by current I for N x 100 ms

A/D measures V_3 for 100 ms

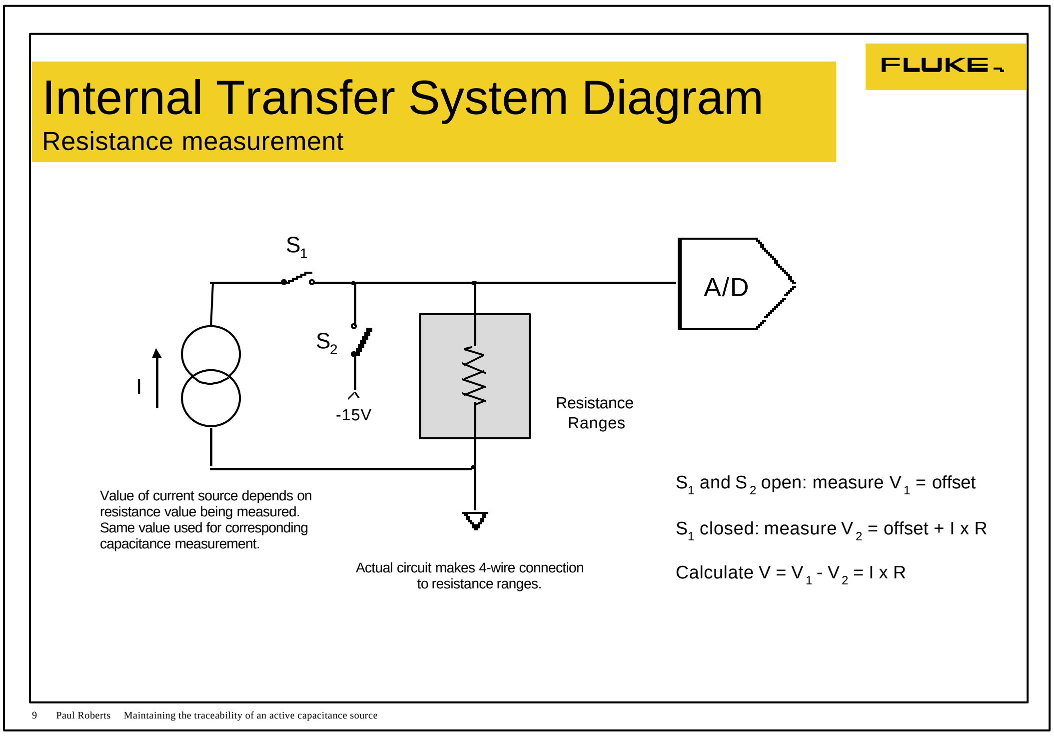
Capacitor discharged

Timing for the capacitance measurement is derived from the instrument's master crystal frequency reference, also used to provide the time/frequency functions.

A/D sample times and capacitor charging times are chosen to be an integral number of line periods for both 50 Hz and 60 Hz power supplies, providing rejection of any line frequency noise present - the effective integration within the A/D and during capacitor charging of any sinusoidal signal present will be equal to zero if the integration time is a multiple of the sinusoid period.

V_2 is arranged to be approximately zero and V_3 is arranged to match I x R for the subsequent resistance measurement to provide similar signal levels in both capacitance and resistance measurement steps. This allows canceling of error contributions.

Capacitance value can be calculated from the time $(t_4 - t_3)$, voltage $(V_3 - V_2)$, and current I. The relationship between voltage and current is also calculated from the subsequent resistance measurement. Therefore the voltage measurement and current source accuracies can be eliminated form the derived capacitance value, which is then based on the traceable calibration of the resistance and time functions.



Internal Transfer System Diagram

Resistance measurement

Value of current source depends on resistance value being measured. Same value used for corresponding capacitance measurement.

Actual circuit makes 4-wire connection to resistance ranges.

S_1 and S_2 open: measure V_1 = offset

S_1 closed: measure V_2 = offset + I x R

Calculate $V = V_1 - V_2 = I \times R$

The resistance measurement makes use of a current source and A/D provided as part of the instrument's internal selftest circuits.

The resistance value is chosen to give a similar voltage to the charging voltage change during the corresponding capacitance measurement

The value of current I depends on the resistance value being measured, and is equal to that used for the corresponding capacitance measurement.

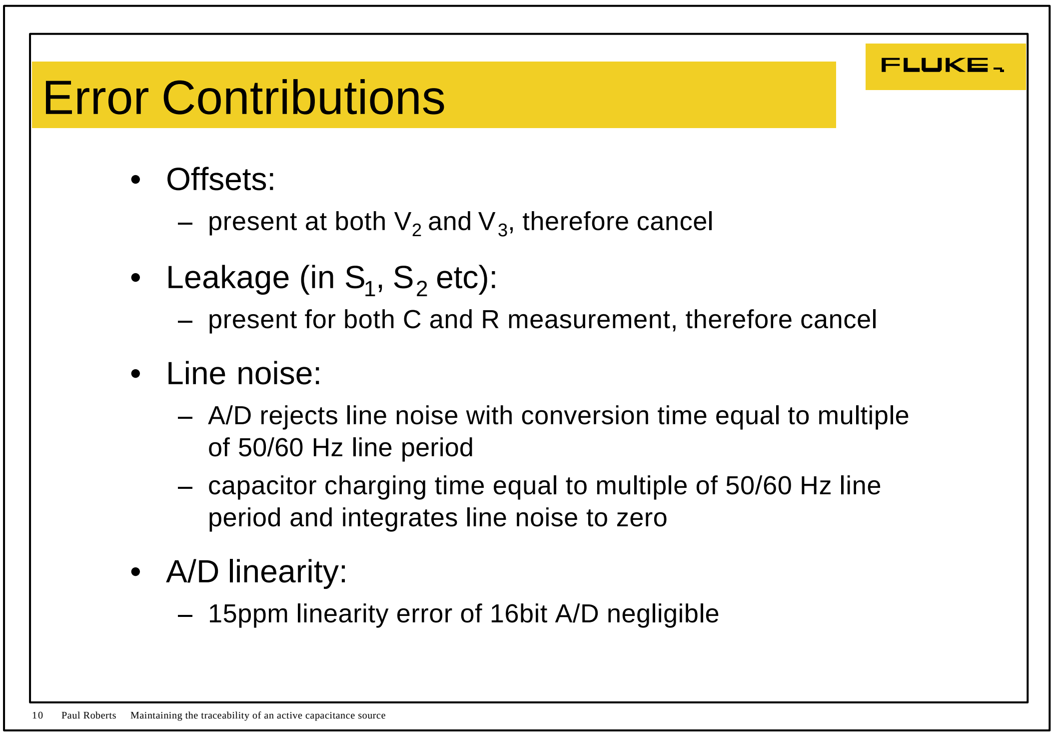
The resistance function provides a 4-wire connection capability, required to avoid significant lead errors for the lower resistance values. For simplicity, 4-wire connections are not shown in this diagram.

S2 is not used for resistance measurement. S1 is opened and the A/D measures any offset present (V1).

A/D conversion time is a multiple of 50/60 Hz line periods to reject line noise.

S1 then closes and the A/D measures V2 = I x R The value of R is calculated and is checked against a value resulting from the same measurement which is taken and stored at the time of external resistance calibration adjustment.

The A/D measurements form both resistance and capacitance measurement phases are used to calculate a value for the capacitance dependent only on the accuracy of the resistance ranges and time/frequency reference.



Error Contributions

- Offsets:
  - present at both V_2 and V_3, therefore cancel
- Leakage (in S_1, S_2 etc):
  - present for both C and R measurement, therefore cancel
- Line noise:
  - A/D rejects line noise with conversion time equal to multiple of 50/60 Hz line period
  - capacitor charging time equal to multiple of 50/60 Hz line period and integrates line noise to zero
- A/D linearity:
  - 15ppm linearity error of 16bit A/D negligible

Offset voltages in the A/D circuit will be present for measurements of the lower and upper ramp voltages (V_1 and V_2) during the capacitance measurement cycle, and will therefore cancel. A/D offset voltages also cancel during the resistance measurement phase.

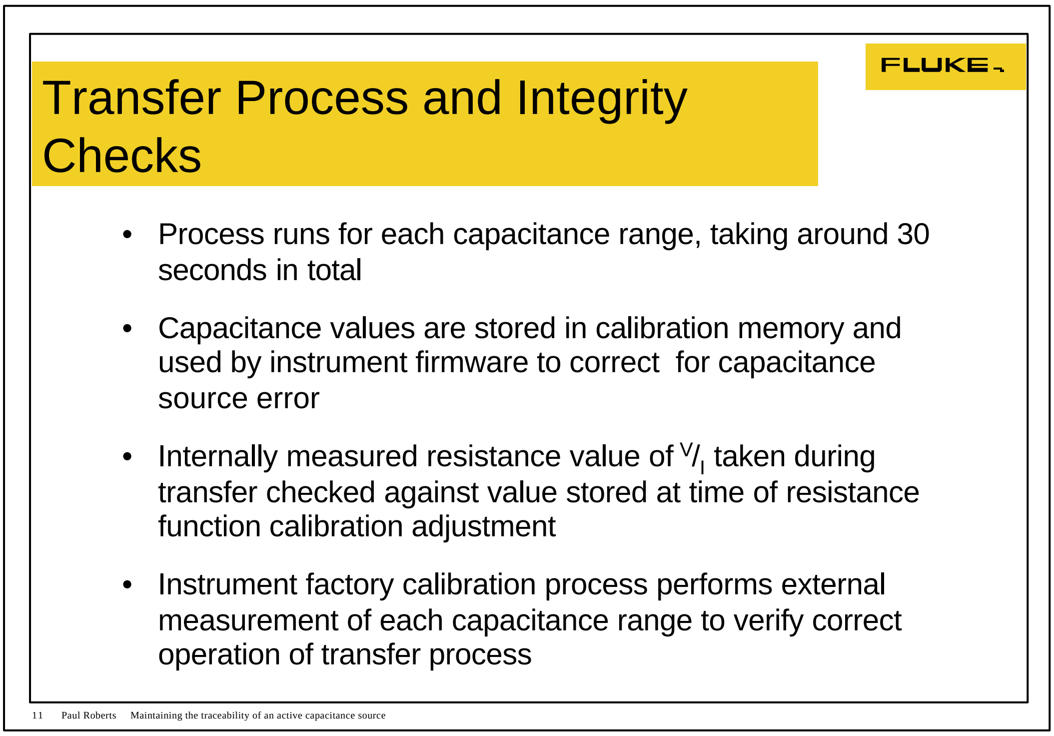
Leakage currents present in the switches (S_1 and S_2) and circuit tracking will be present for both capacitance and resistance measurement cycles. The voltage swing for capacitance and resistance measurement cycles are matched, and the effect of leakages will cancel.

Any power line frequency noise present during the time that the A/D is measuring the voltages on the capacitance or resistance will potentially give an error. By making the A/D sampling time equal to an integral number of power line cycles the effect is eliminated - the A/D effectively integrates the sinusoidal line waveform, which will be zero for a complete line cycle. The A/D sample time is chosen to be a multiple of both 50 Hz and 60 Hz. The same approach is taken for capacitor charging by making the charge time an integral number of line periods.

The A/D linearity error contributes directly to the error of the transfer process. However, the linearity performance of the 16bit A/D employed is better than 15ppm, and is therefore negligible.

Timing is derived from the crystal referenced master clock, and the contribution for long term stability is negligible.

The dominant error source is the stability of the resistance function, effectively used as a reference of V/I. This is more than an order of magnitude better than the performance specifications for the capacitance function.



Transfer Process and Integrity Checks

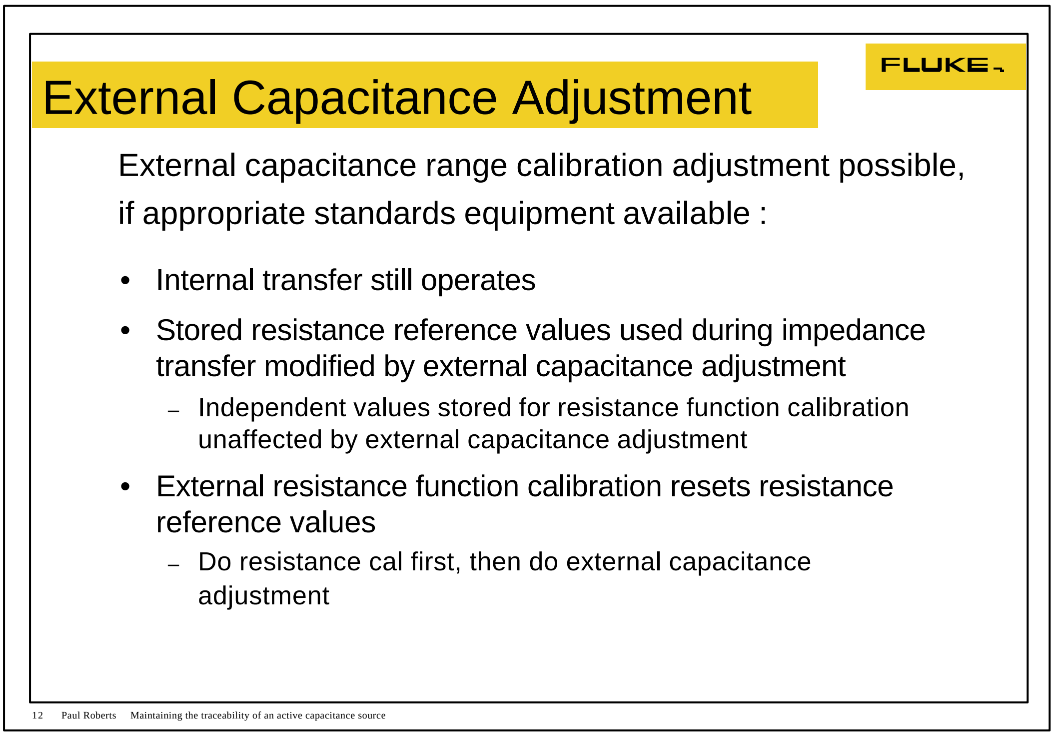
- Process runs for each capacitance range, taking around 30 seconds in total
- Capacitance values are stored in calibration memory and used by instrument firmware to correct for capacitance source error
- Internally measured resistance value of $^{V}/_{I}$ taken during transfer checked against value stored at time of resistance function calibration adjustment
- Instrument factory calibration process performs external measurement of each capacitance range to verify correct operation of transfer process

When the 'internal impedance transfer' process is performed, each capacitance range is measured, taking a total of around 30 seconds.

The values derived for each capacitance range are stored in calibration memory and are used by the instrument's firmware to correct for the capacitance source errors and ensure an accurate capacitance value is delivered to the calibrator terminals, equal to the value demanded by the user front panel controls or GPIB commands.

During the calibration adjustment of the resistance function against external standards (typically a long scale dmm), the internal current source and A/D are used to measure the resistance values used during 'internal impedance transfer' and the results are stored in calibration memory. When an 'internal impedance transfer' is performed the value of resistance measured at that time are compared with the stored values as a cross check to ensure correct operation of the transfer process.

At the time of factory calibration the instrument's capacitance ranges are measured against external standards. This measurement is performed to verify the correct operation of the internal impedance transfer, using an automated system employing a similar voltage ramp technique. This automated calibration system carries NAMAS (UKAS) accreditation and has been described in papers given at the IEEE in the UK and at CPEM '94 in Denver, USA.



External Capacitance Adjustment

External capacitance range calibration adjustment possible, if appropriate standards equipment available :

- Internal transfer still operates
- Stored resistance reference values used during impedance transfer modified by external capacitance adjustment
  - Independent values stored for resistance function calibration unaffected by external capacitance adjustment
- External resistance function calibration resets resistance reference values
  - Do resistance cal first, then do external capacitance adjustment

The instrument is capable of having the capacitance function calibration adjusted against external standards.

If appropriate calibration equipment is available, the user may individually adjust each capacitance range.

To overcome the effects of drift in the reference capacitors with time and temperature the 'internal impedance transfer' process still operates.

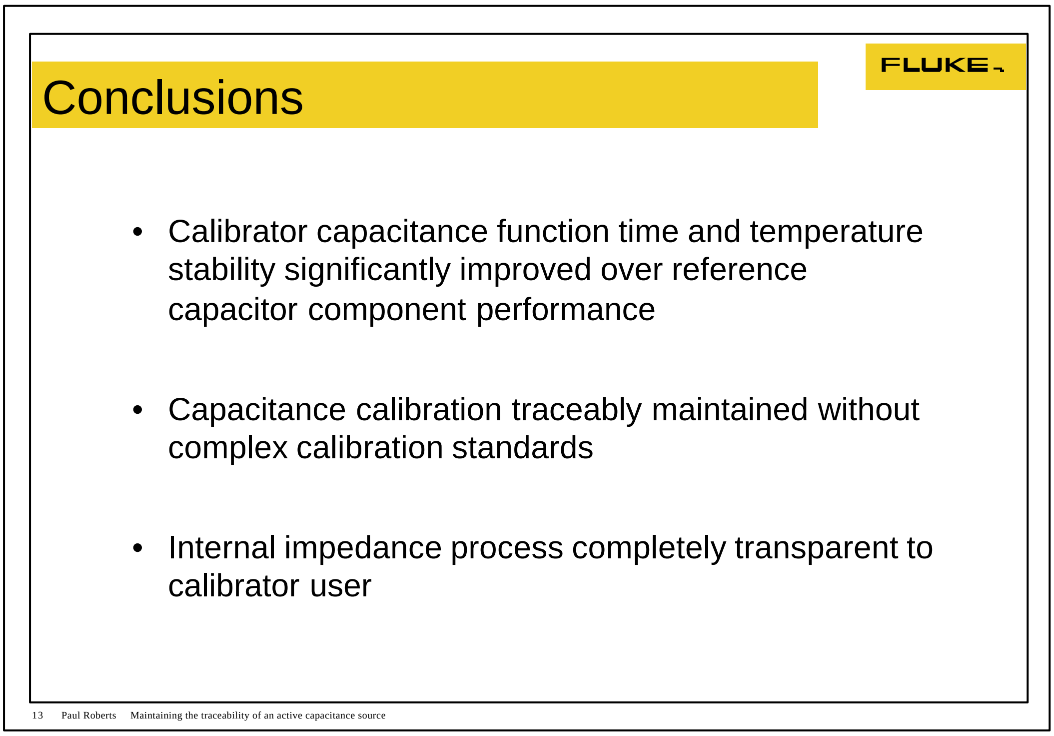
When the resistance function itself is calibrated against external standards, the resistance reference values stored for use by the 'internal impedance transfer' process is updated. Calibration data for use by the resistance function is stored separately.

When a capacitance range is adjusted against external standards the resistance reference value stored in calibration memory for the corresponding resistance value used in the impedance transfer is modified to take account of the externally measured error.

All subsequent 'internal impedance transfer' processes will be relative to this modified resistance reference value and will therefore reflect the externally calibrated capacitance value.

If a resistance range is adjusted, any modified reference resistance values from an external capacitance adjustment will therefore be lost.

If external capacitance adjustment is to be performed, resistance function calibration adjustment must be performed first.



Conclusions

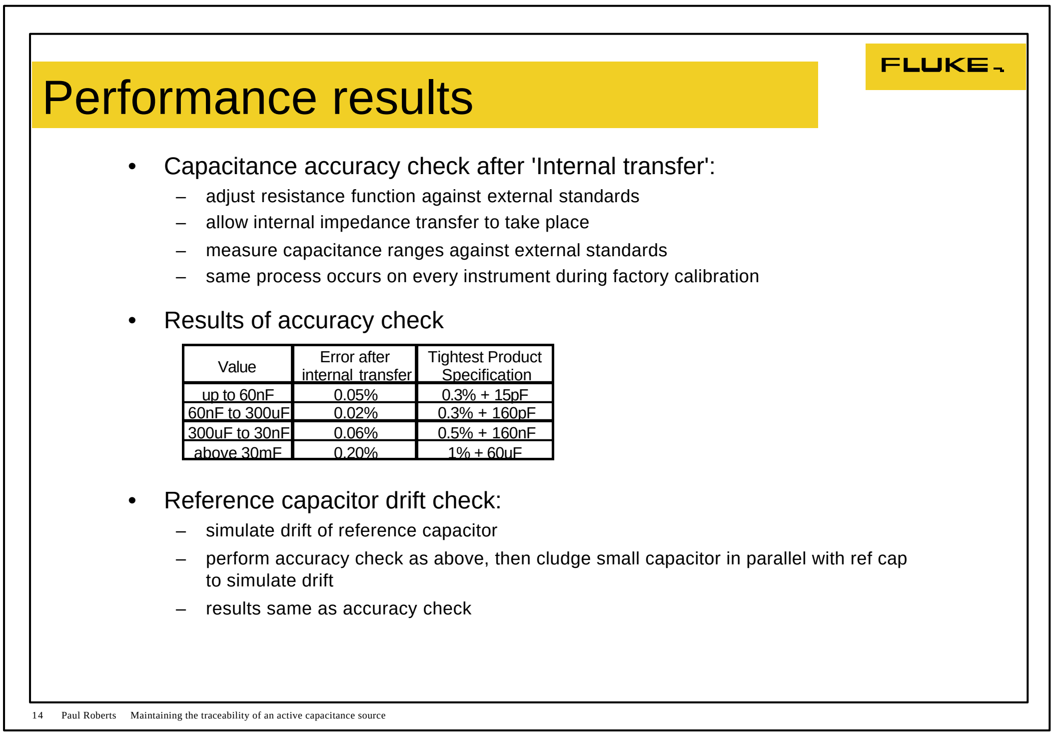
- Calibrator capacitance function time and temperature stability significantly improved over reference capacitor component performance
- Capacitance calibration traceably maintained without complex calibration standards
- Internal impedance process completely transparent to calibrator user

By using an internal impedance transfer process, the capacitance function of the calibrator can be traceably maintained at accuracy and stability levels significantly improved over the performance of the capacitance reference components.

This approach eliminates the need for complex, expensive and time consuming techniques for capacitance calibration adjustment.

Performance of the instrument is considerably enhanced with a completely user transparent process.

However, facilities exist within the instrument to allow calibration adjustment of the capacitance ranges against traditional standards with appropriate capability if the user so chooses.



Performance results

- Capacitance accuracy check after 'Internal transfer':
  - adjust resistance function against external standards
  - allow internal impedance transfer to take place
  - measure capacitance ranges against external standards
  - same process occurs on every instrument during factory calibration
- Results of accuracy check

Value	Error after internal transfer	Tightest Product Specification
up to 60nF	0.05%	0.3% + 15pF
60nF to 300uF	0.02%	0.3% + 160pF
300uF to 30nF	0.06%	0.5% + 160nF
above 30mF	0.20%	1% + 60uF

- Reference capacitor drift check:
  - simulate drift of reference capacitor
  - perform accuracy check as above, then cludge small capacitor in parallel with ref cap to simulate drift
  - results same as accuracy check

The internal transfer process may be tested by measuring the capacitance ranges against external standards. This will demonstrate the residual error remaining on each capacitance range after internal transfer.

At the time of calibration at the factory and service centres, the capacitance function is measured against external standards to verify the internal transfer process.

The results are contained within the calibration certificates issued with every 9100 calibrator, and the values quoted above are typical.

To simulate the effect of drift in the reference capacitors and the correct functioning of firmware , tests have been performed which involve changing the reference capacitor values:

An instrument was calibrated in the normal way and internal impedance transfer allowed to operate. Correct operation of the transfer was confirmed by external capacitance measurement. The reference capacitor values were deliberately changed by several percent by adding 'cludge' components in parallel with the reference capacitors. internal impedance transfer was allowed to run again and the external capacitance measurement repeated. Residual errors after internal transfer were found to be similar to those obtained before modifying the reference capacitor values, demonstrating successfully the ability of the internal transfer process to compensate for reference capacitor time and temperature drift.