Supporting New Calibrators with Existing Equipment

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Abstract

New calibrators are being introduced not only with new functions and better performance, but also with expanded output ranges. These calibrators can present some new challenges for the cal lab. Resistance up to 1GΩ, capacitance up to 100mF and AC current to 30kHz can be measured, but at what cost? This paper will present one approach to making these tests without huge investments in capital equipment. Data presented will demonstrate that, with a modest investment, you can extend the capability of your existing instrumentation to get the performance necessary to test state-of-the-art calibrators.

Introduction

For many cal labs, calibrating the calibrator requires expensive equipment that is difficult to justify, both in terms of cost of acquisition and maintenance costs. Recently, new calibrators have been introduced with expanded output ranges that exacerbates this problem, requiring new equipment for a handful of calibration and verification points. However, resistance up to 1GΩ, capacitance up to 100mF and AC current to 30kHz can be measured inexpensively, probably with equipment that is already in your lab.

First, this paper will present a very accurate method for measuring capacitance from 100μF to 100mF. Next, it will discuss techniques for measuring the extremes of resistance. Finally, it will describe an approach for measuring high frequency AC current.

Examples presented will demonstrate that, with little or no investment, using instrumentation that likely already exists in your lab (e.g. Fluke 5700A, Hewlett-Packard 3458A, and some standard resistors), it is possible to get the performance necessary to calibrate and verify state-of-the-art calibrators. Error analysis for each of the measurement methods will be discussed, and Test Uncertainty Ratios (TUR) for the intended workload will be calculated. Unless otherwise noted, all specifications quoted herein are the manufacturer's 90-day published specifications, which are at 99% confidence levels. It is beyond the scope of this paper to go into detail on confidence levels and how they affect TURs. Refer to reference [1], particularly chapters 20 and 31, for more information about analyzing specifications and confidence levels.

Capacitance

Newer calibrators provide precision synthesized capacitance outputs ranging from hundreds of picofarads up to 110mF. Typical midband uncertainties are 0.2%, increasing to 1% for outputs above 33mF.

A number of manufacturers market a variety of precision benchtop LCR meters suitable for calibrating these capacitance standards with adequate uncertainty. Relatively inexpensive units are available that provide up to 0.1% midband uncertainty. High-end meters provide up to 0.05% midband uncertainty. But, regardless of price, performance or features, all these instruments have one thing in common: their specifications degrade rapidly for higher values of capacitance. Typical specifications for a 0.1% LCR meter are shown in Figure 1. Note that for capacitances as low as 100 μF, the spec increases tenfold to 1.0%. At 1mF, another tenfold increase occurs, to 10%. Above 10mF, there are unspecified regions, and above 70mF, the meter is completely unspecified. The reason for this is that, regardless of the technique employed by the meter to make the measurement (i.e., charge/discharge, bridge, or frequency response in a RC circuit), the accuracy of the meter is inversely proportional to the excitation frequency of the test signal. The lower this frequency is, the higher the resultant uncertainty will be.

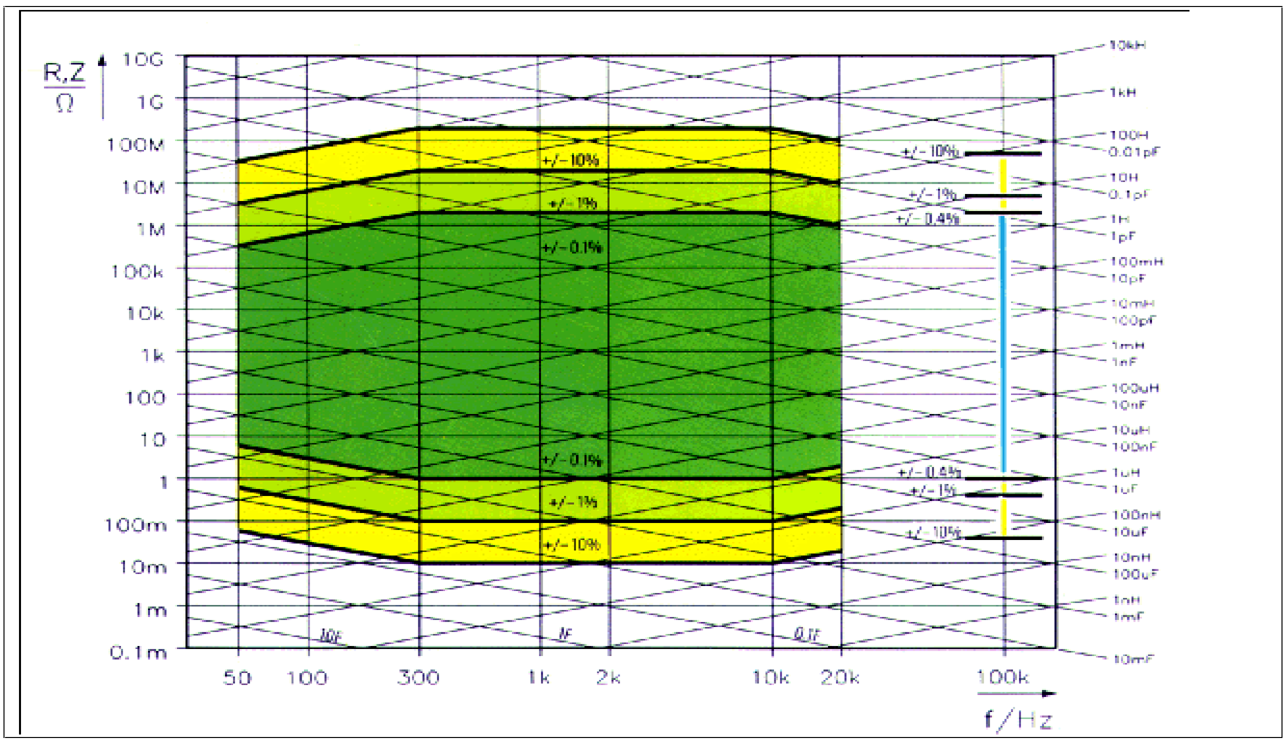


Figure 1. Typical Specifications for a LCR Meter

By definition, capacitance is the product of an applied current and the ratio of the charging time to the charging voltage:

$$C = I * \frac{dv}{dt}$$

Thus, another valid technique for measuring capacitance is to simply apply a known current across a device and measure the voltage change over a known time interval. The obvious drawback to this approach is acquiring a precision current source and a DMM with sufficient voltage and time base accuracy to make this measurement. At low capacitances, it will be very difficult to compete with the specifications of off-the-shelf LCR meters. The system described in Reference [2] is one example, but requires an extremely accurate, custom designed current source and precision timing circuitry.

However, as the magnitude of the capacitance increases, this technique not only proves to have superior accuracy, it is the only method that can be used. A Fluke 5700A can provide a current source of sufficient accuracy, and the HP 3458A DMM has both sufficient voltage and time base accuracy to measure the charging voltage over a precision time interval. The useful range for this technique is limited by the 5700A DC current source. Below 10% of its lowest output range of 200 μ A, the floor error begins to dominate the spec. Output noise and uncertainty of the current source leads to unacceptable TURs. As a general rule of thumb, 100 μ F is the transition point. Above this value, an LCR meter's accuracy degrades significantly. Below this value, the current source's noise and uncertainty dominate. Figure 2 plots the measurement variation of a 109 μ F capacitor measured with an LCR meter at 50Hz. Figure 3 plots the same capacitor measured using the charge technique at 30 μ A. The two methods yield virtually identical noise, less than 40 ppm, or about 2% of the spec. (In these plots, the y-axis upper and lower bounds are compressed to 5% of spec to illustrate the comparable noise.)

Figure 2. 109uF Measured Using LCR Meter at 50 Hz

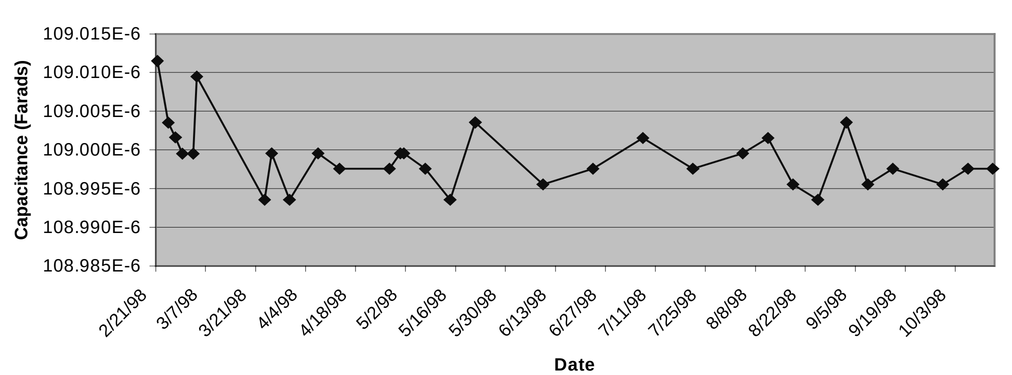
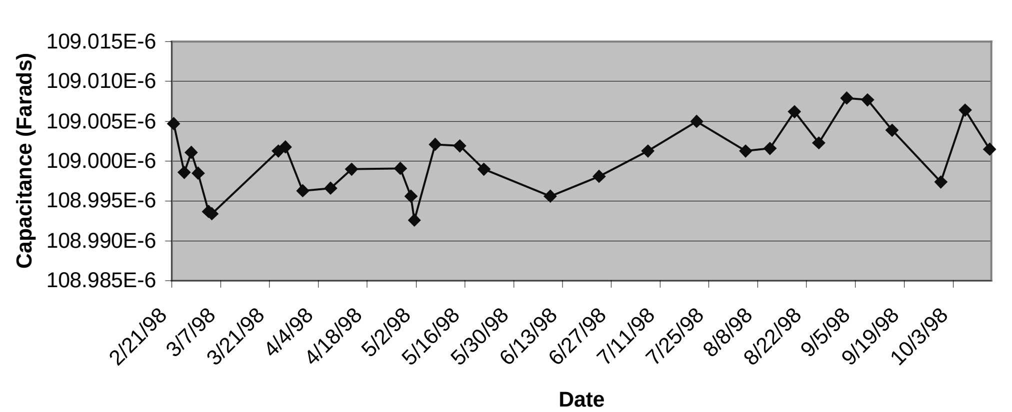


Figure 3. 109 uF Measured with Charge Method at 30 uA



For this technique, the amplitude of the current is typically chosen to limit compliance voltage across the capacitor under test to 3 V over a charging interval of 10 seconds. Computer control of the instruments is essential to eliminate manual timing uncertainties. The HP 3458A is locked on the 10 V range, since range changes will affect the timing and linearity of the data. The meter is programmed to take 100 samples at 100mS-aperture width (total 10 seconds) on a trigger command. The readings are stored internally to the meter and retrieved after the measurement cycle is completed. The 5700A is programmed to the predetermined DCI level and set to operate. As soon as the calibrator's remote status indicates a settled condition, the computer triggers the HP 3458A reading sequence. Voltage sensing is performed at the calibrator output. Figure 4 shows the measurement set-up.

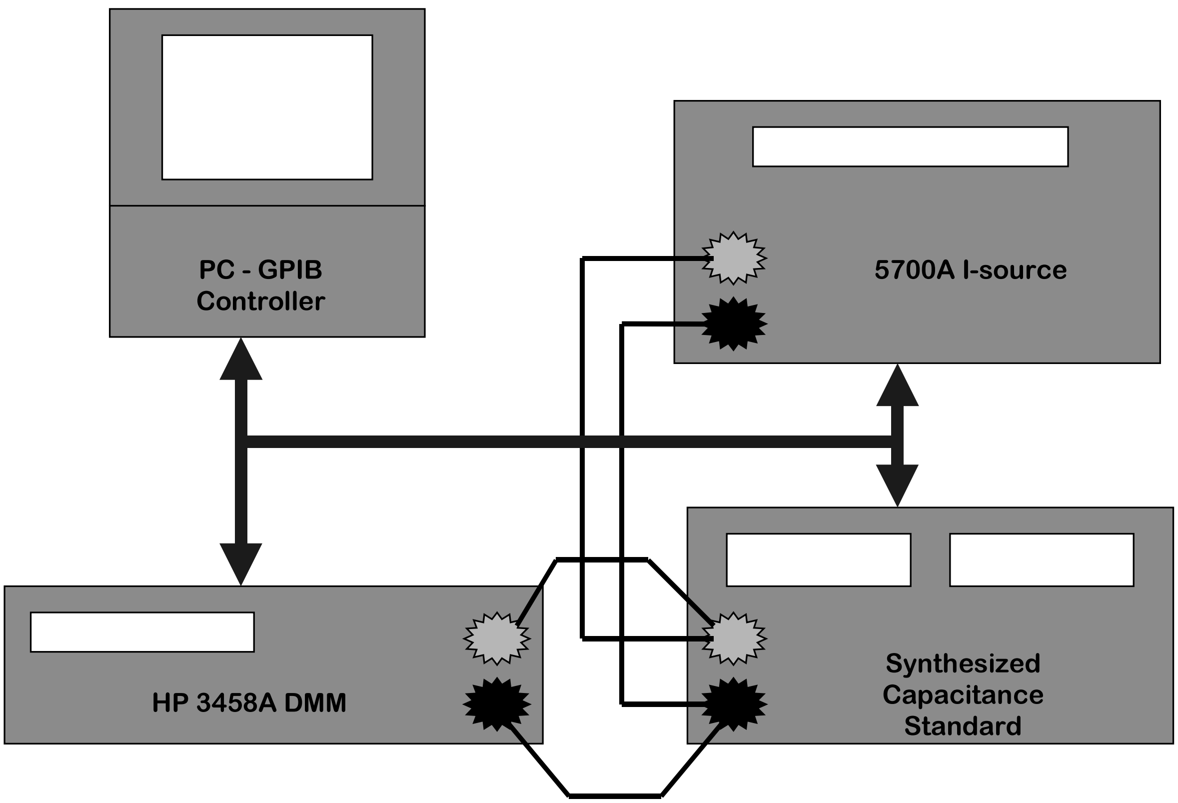


Figure 4. High Capacitance Measurement Set-up

At the completion of the measurement, the 5700A is set to standby and the computer retrieves the data from the HP 3458A. A linear regression routine examines the data for linearity and noise about the regression line; if it meets linearity limits, the capacitance is simply computed as the product of the DC current and the ratio of the time interval (10 seconds) divided by $(V_{final} - V_{initial})$.

Error Analysis Example: 3mF tested at 800 μA

- 5700A DCI, 2.0mA range: 50 ppm + 10nA; at 800 μA: 62.5 ppm.
- HP 3458A DCV, 10V range: 4.1 ppm of reading + 0.05 ppm of range.

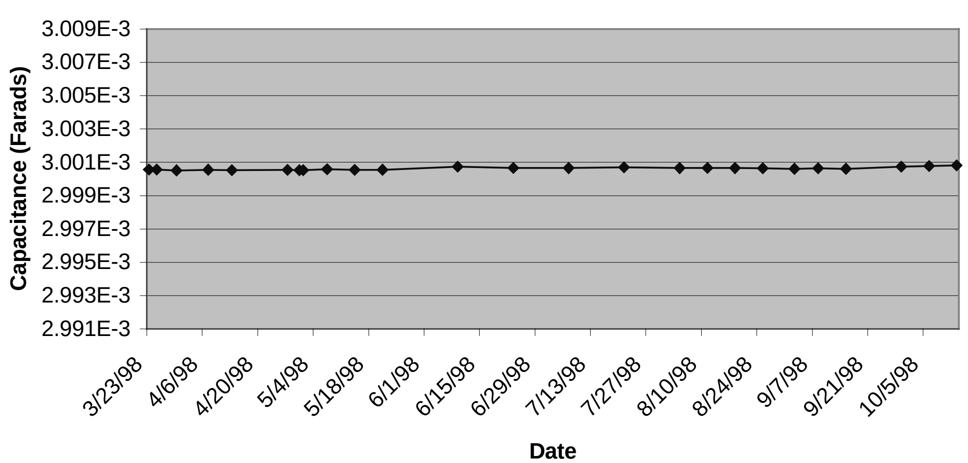
- HP 3458A time base uncertainty: 100 ppm.
- UUT (Fluke 5520A) 3.0mF: 0.44%

While the HP 3458A DCV accuracy is not specified for sample rates other than NPLC of 100, testing indicates the DMM is within 25 ppm for the fast sample rate. Adding the error terms yields (62.5 ppm + 25 ppm + 100 ppm) = 187.5 ppm, or 0.0187%, for a TUR > 20:1. A number of other error sources can contribute to this measurement uncertainty. The DMM has a number of possible error sources: linearity, uncertainty on the 10 V range at 2% of full scale, uncertainty in fast sample mode and internal trigger timing uncertainty were all of concern. Also, the current source accuracy is not independent of the continuously changing compliance voltage. Tests were performed to quantify each of these error sources, and none were found to contribute more than 0.02%. This is not significant relative to the workload.

The accuracy of synthesized capacitors is also dependent on the measurement technique. References [3] and [4] go into detail about measurement errors associated with synthesized impedances.

Figure 5 plots a 3mF capacitor on a scale of the actual spec. Measured at 800 μA, the noise is less than 30 ppm. By comparison, the LCR meter uncertainty at this amplitude is 1%.

Figure 5. 3mF Measured with Charge Method at 800uA



Resistance

Newer calibrators provide precision synthesized resistance outputs ranging from milliohms to 1.1GΩ. Typical midband uncertainties are 25 ppm, increasing to 0.25% for outputs up to 400MΩ and 1% for higher resistances.

The HP 3458A provides adequate TUR for midband resistance calibration of these standards. At the low and high-end extremes of the calibrator's resistance output, the TURs become marginal or unacceptable. Limitations of this meter, along with other error sources (i.e., offsets at low levels, leakages at high levels), make direct resistance measurement unacceptable.

Once again, the Fluke 5700A comes to the rescue. For low level resistance, the 5700A can source a higher, more stable current than the current source used in the HP 3458A ohms converter. The higher current leads to a higher compliance voltage, which also increases the accuracy of the measurement. Fluke 742A resistance standards can be used to calibrate the current source at time of use. Figure 6 shows the measurement set-up.

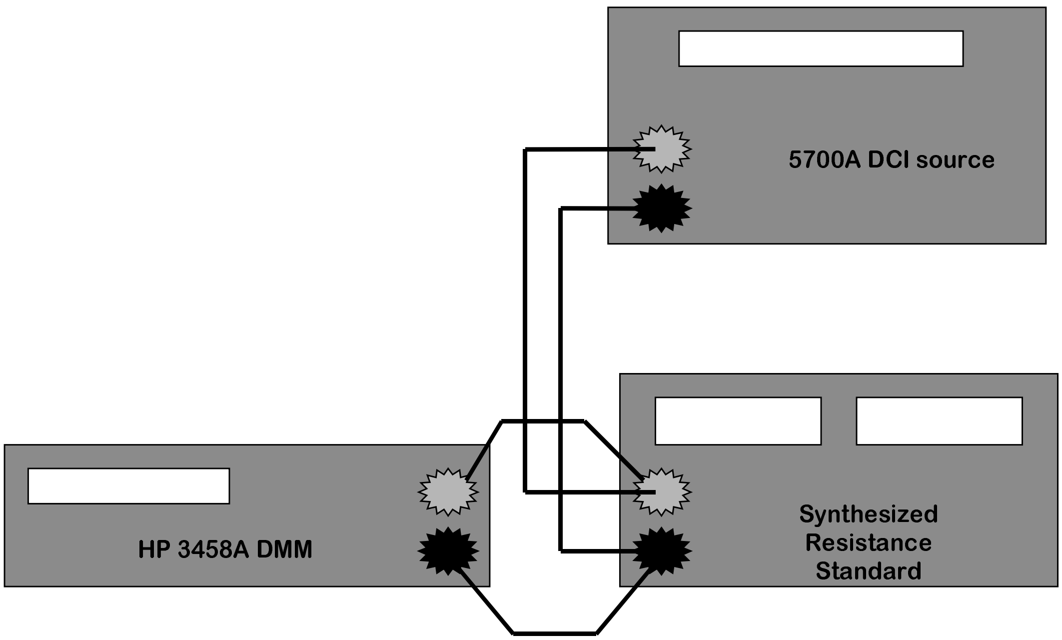


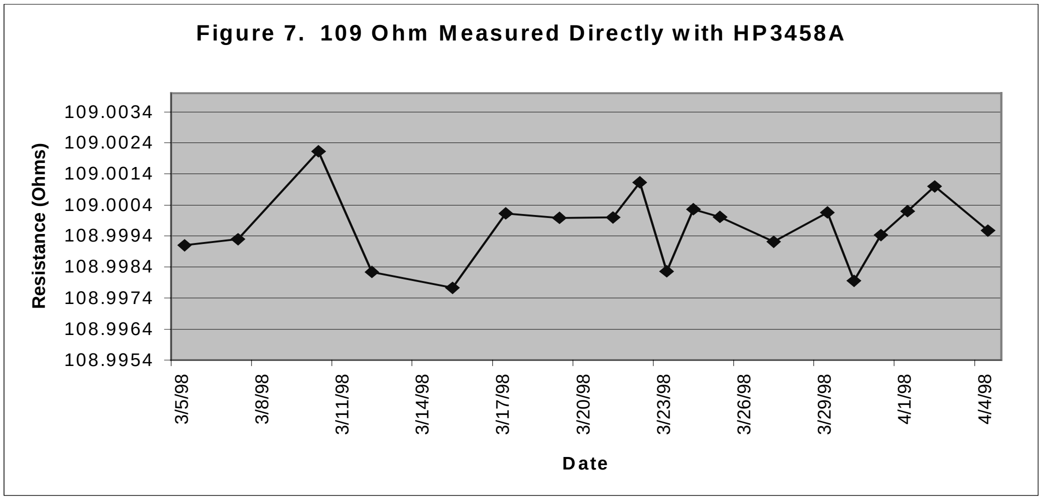
Figure 6. Low Resistance Measurement Set-up

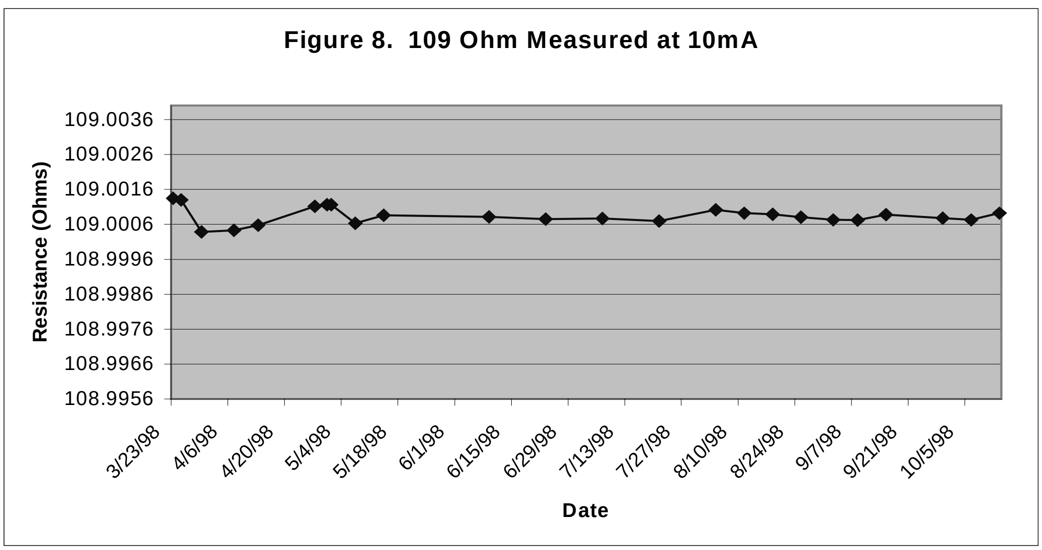
Error Analysis Example: $100\,\Omega$ tested at 10mA

- 742A-$100\,\Omega$: 1 ppm cal error, 4ppm/6mo stability.
- HP 3458A DCV, 1.0V: 4.9 ppm.

Sourcing 10mA from the 5700A into a 742A-$100\,\Omega$ and measuring the resultant compliance voltage with the HP 3458A yields a root-sum-square error of $\sqrt{5\,ppm^2 + 4.9\,ppm^2} = 7\,ppm$ for the current source. Sourcing the now-characterized current through the UUT $100\,\Omega$ and again measuring the resultant compliance voltage with the HP 3458A yields a root-sum-square error of $\sqrt{7\,ppm^2 + 4.9\,ppm^2} = 8.5\,ppm$. This provides a 4:1 TUR for the UUT $100\,\Omega$ resistor specified at 36 ppm, a significant improvement over the 2:1 TUR when using the HP 3458A directly in resistance mode. (The Fluke 5520A $100\,\Omega$ specification is 36 ppm; the HP 3458A $100\,\Omega$ specification is 15 ppm.). The 5700A DC current short-term stability error is negligible over short time periods, but can be verified by re-measuring the 742A.

Figure 7 is a plot of the measurement variation using the HP 3458A directly at 100Ω. Figure 8 plots the same measurement using a 10mA DC current from the 5700A, with the compliance voltage (1.0V) sensed by the HP 3458A.





For the highest resistance ranges, the HP 3458A current source in the ohms converter is only 500nA. The repeatability of the ohms converter on the 1GΩ range is very poor, leading to a published spec of 0.5%. Also, very high-level resistance measurement is prone to time-variant leakage paths induced by temperature and humidity changes. It was discovered, however, that the HP 3458A current source for high resistance measurement has extremely good short-term stability. This lends itself to making very accurate transfer measurements. The Fluke 5700A can source very accurate cardinal point resistors up to 100MΩ. Measurements International, Inc. also supplies resistance standards. (Their model 9331S/1G 1GΩ-standard specifies 30 ppm ±15 ppm/6-month stability.) By measuring the known resistance standard, either from the 5700A or an external standard, then transferring to the unknown resistance in the calibrator, extremely stable and accurate measurements can be achieved. Figure 9 shows the measurement set-up.

Figure 10 is a plot of the measurement variation using the HP 3458A directly at 100MΩ. Figure 11 plots the same measurement by transferring from a precision 100MΩ standard resistor.

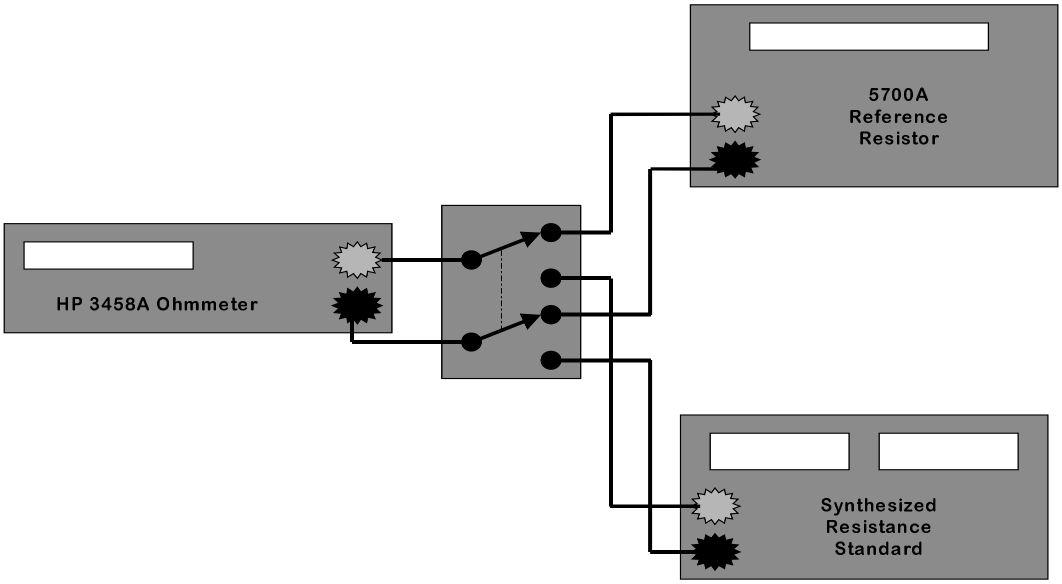
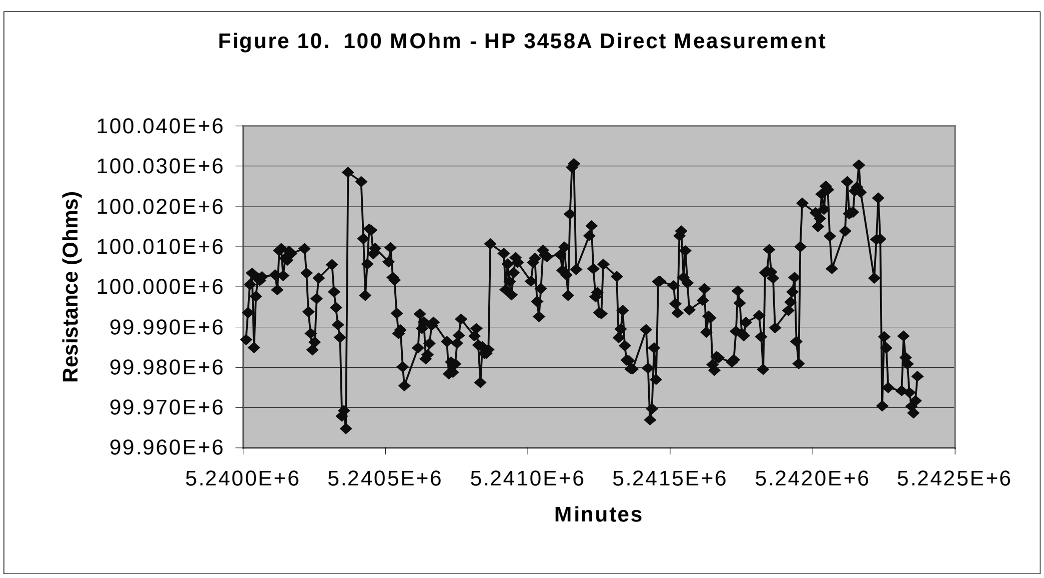


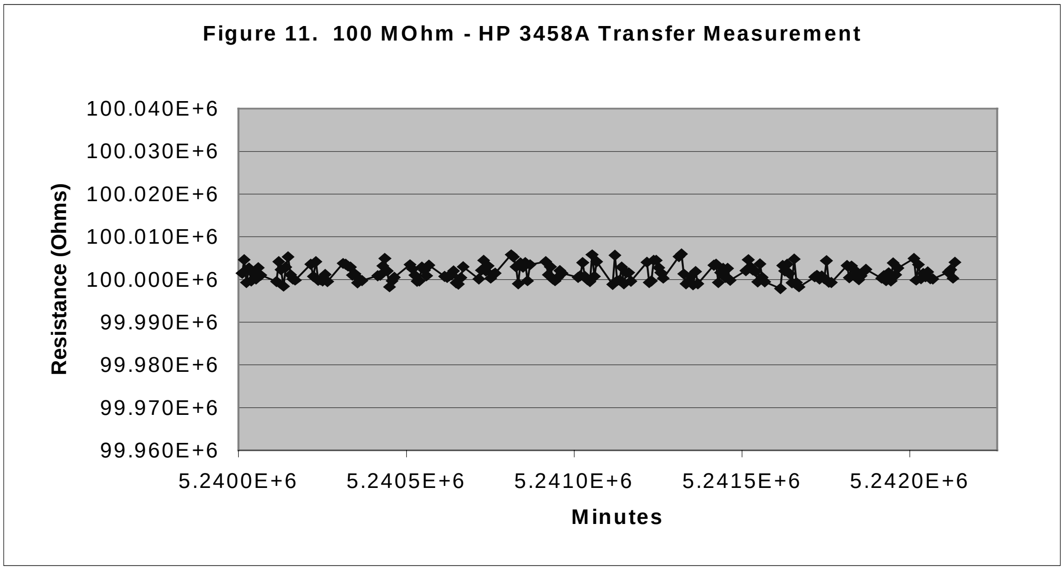
Figure 9. High Resistance Measurement Set-up

Error Analysis Example: 100MΩ transfer measurement

- 5700A 100MΩ specification: 120 ppm.
- Short term repeatability (See figure 11): < 20 ppm.
- Transfer Uncertainty: 12 ppm

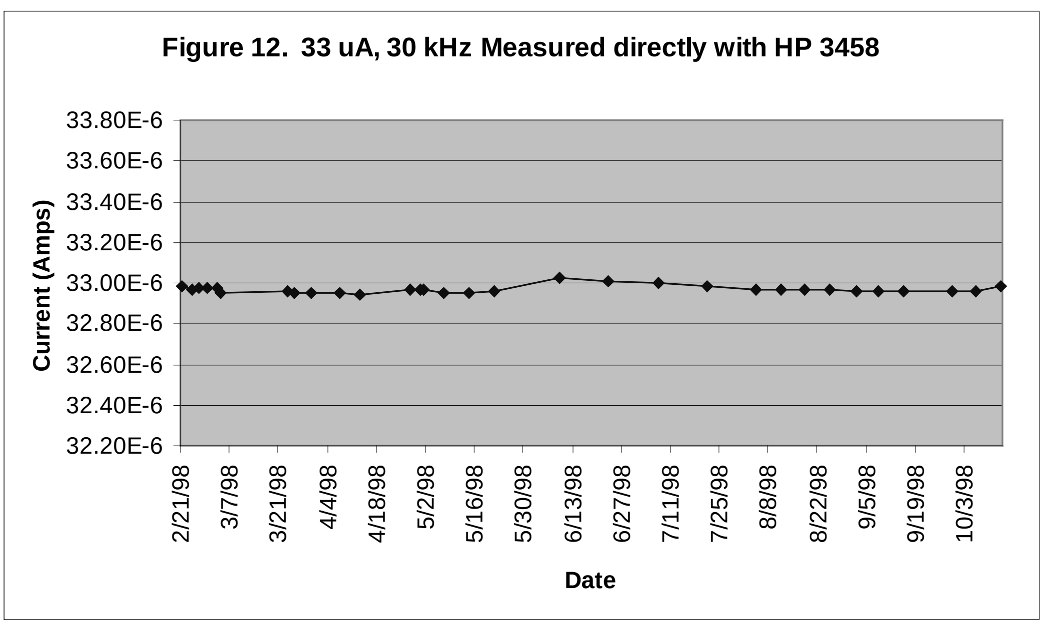
Total Uncertainty: $\sqrt{120\,ppm^2 + 20\,ppm^2 + 12\,ppm^2} = 122\,ppm$ for a TUR of 3.5:1. (The Fluke 5520A 100MΩ specification is 430 ppm; The HP 3458A specification at 100MΩ is 510 ppm.)





AC Current

The Fluke 5520A calibrator provides low level AC current up to 30kHz, with midband uncertainties of 0.16% to 10kHz and 0.32% to 30kHz. The HP 3458A AC current function isn't even specified above 5kHz on the 100 μ A range. Other ranges specify "typical" performance only above 5kHz. In addition to the shortcomings of the meter, AC current is traditionally a fairly difficult parameter to measure in a system environment. The parasitic capacitance of even short cable lengths induce significant leakage errors for low-level, high frequency AC current.



Fortunately, while the HP 3458A AC current absolute uncertainty is relatively poor, it was discovered that the long-term stability and repeatability is quite good. Hence, characterizing the meter (and the associated measurement system) at the currents and frequencies required leads to greatly simplified AC current measurements.

Characterization requires a 5700A and discrete metal film resistors. Using metal film resistors for shunts, an AC/DC current transfer can be performed, effectively transferring DC current accuracy to AC current at specific frequencies. The HP 3458A is used to sense the DC and AC voltage. Once the calibrator's AC current error is known, a correction factor can be determined for the HP 3458A and system interconnects. Figure 12 shows a plot of the measurement variation using the HP 3458A directly at 33 μ A, 30kHz, with corrections applied. Figure 13 is a plot of the corrections applied to this measurement over a 7-month period for 10kHz; figure 14 is a plot of the corrections at 30kHz. Note that at 10kHz, the nominal error is 1.1%; at 30kHz, the nominal error is 5%. Figure 15 shows the measurement set-up.

Figure 13. HP 3458A Corrections at 33 uA, 10 kHz

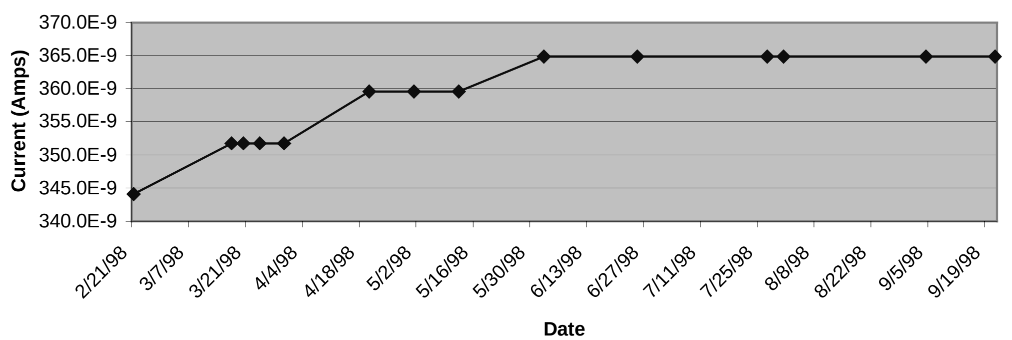
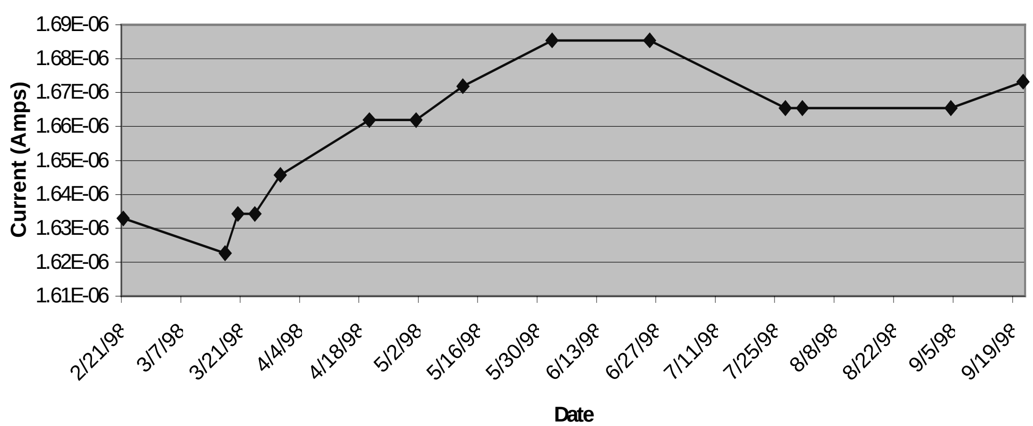


Figure 14. HP 3458A Corrections at 33 uA 30 kHz



Error Analysis Example: 33 μA measured at 10kHz and 30kHz

The 5520A spec at 33 μA, 10kHz is 1.2%; at 30kHz, it is 2.4%. For a 2kΩ metal film resistor, typical parasitic shunt capacitance is 2pF, and series inductance is 10nH. At 10kHz, the equivalent shunt reactance is 8MΩ, and series reactance is 0.6mΩ. At 30kHz, this increases to 2.6MΩ and 1.9mΩ, respectively. These parasitics contribute less than 1 ppm of error and can be neglected. Using a HP 3458A for the detector causes additional errors, since the ACV input impedance is specified as 1MΩ with < 140pF. At 10kHz, this capacitive reactance contributes 0.0155% error, but at 30kHz the error is 0.139%. (See reference [5] for a derivation of these error terms.) Also, at 2kΩ the 1MΩ input impedance will contribute 0.2% error, since in DCV mode the error caused by the input impedance (> 10GΩ) is negligible. Note that as the current increases and the shunt value decreases, these error terms also decrease. At 200Ω, the reactance of the 140pF contributes just 14 ppm, and the error from the 1MΩ input impedance drops to 0.02%. Using a Fluke 5790A as the detector instead of the HP 3458A further reduces errors, since this instrument specifies 10MΩ with < 100pF input impedance.

The 5700A DC current uncertainty at 33 μA is 353 ppm. The HP 3458A DCV uncertainty at 66mV (2kΩ * 33 μA) is 9.5 ppm. Hence the DC current uncertainty (worst case) is (353 + 9.5) = 363 ppm. (The HP 3458A could also be used to measure the 2kΩ shunt accuracy. The resistance uncertainty of the HP 3458A at 2kΩ is 10.5 ppm. This would lead to a DC current shunt error at DC of (10.5 ppm + 9.5 ppm) = 20 ppm.)

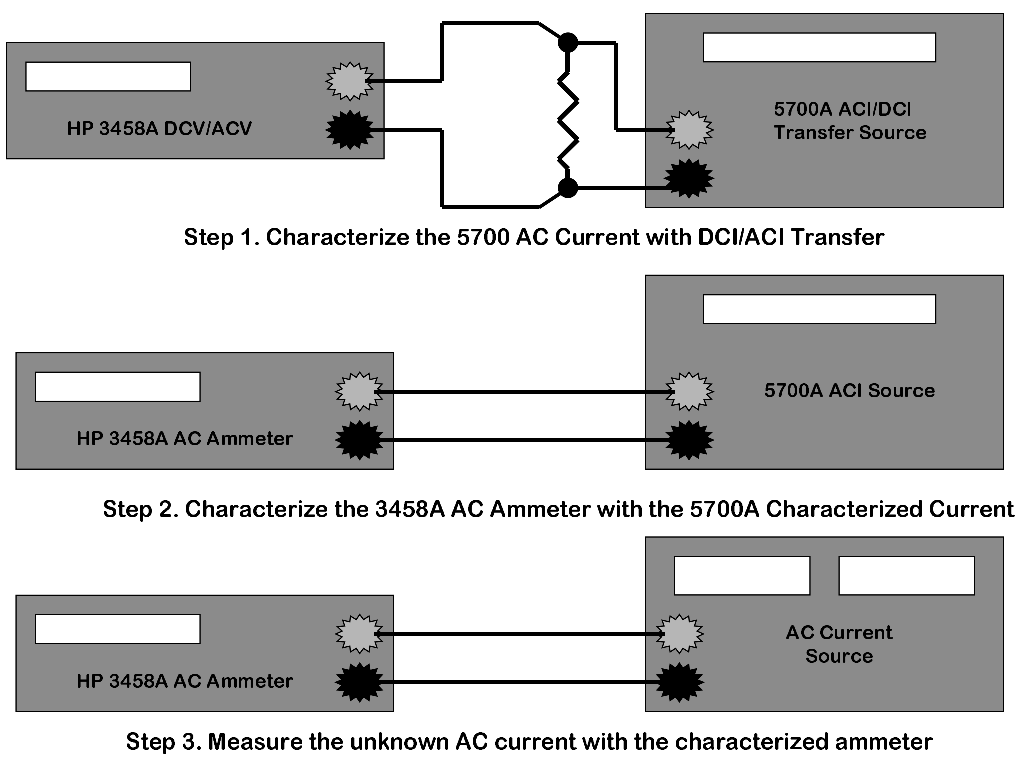


Figure 15. High Frequency AC Current Measurement Set-up

At 10kHz, the HP 3458A ACV uncertainty (synchronous mode) is 170 ppm, and the total measurement error (worst case) is 170 + 363 = 533 ppm (0.053%). Total transfer error is therefore (0.053% + 0.2% + 0.0155%) = 0.268%. The standard deviation of the correction (HP 3458A variation) over a 7-month period is 0.021% (See figure 13). As this is a random term, it is safe to RSS this with the transfer error for a total error of 0.270% or a TUR of > 4:1.

At 30kHz, the 5520A calibrator has to be used for the shunt characterization, since the 5700A AC current is limited to 10kHz. At 33 μA DC, the 5520A specification is 726 ppm, and the DC current uncertainty (worst case) is 726 + 9.5 ppm = 736 ppm. At 30kHz, the HP 3458A uncertainty (synchronous mode) is 330 ppm, and the total measurement error (worst case) is 330 + 736 = 1066 ppm (0.107%). Total transfer error is therefore (0.107% + 0.2% + 0.139%) = 0.446%. RSSing with the standard deviation of the correction (HP 3458A ACI variation) over a 7-month period (0.061% - See figure 14) yields 0.45% or a TUR of > 5:1.

Conclusion

This paper has demonstrated how, with little or no investment in new equipment, you can extend the capability of your lab. First, a very accurate method for measuring capacitance from 100 μF to 100mF was presented. Data presented proved an uncertainty of several hundred ppm, providing a very generous TUR for the workload. Next, techniques for measuring the extremes of resistance were discussed. The analysis here showed a twofold improvement in TUR for low values of resistance and an acceptable TUR for high resistance. Finally, a time saving approach for measuring high frequency AC current was described. Error analysis using this method demonstrated that characterizing a digital ammeter provided a TUR in excess of 4:1.

References:

[1] Fluke Corporation, “*Calibration: Philosophy in Practice*”, Second Addition, 1994

[2] Crisp, Peter B., Roberts, Paul C. A., Bargroff, Keith P., "*Automated Measurement of Capacitance From 500pF to 40mF*", 1994 NCSL Workshop and Symposium, pp. 219 - 223.

[3] Nordeng, Arnold E., "*New Advances in Generating Variable Impedance For Calibration*", 1995 Measurement Science Conference Symposium and Workshop, Anaheim, CA, January 26, 27, Session 2B.

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[5] Fluke Corporation, “*5700A Service Manual*”, Rev. 7 (8/94), pp. 3-36 to 3-37