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On the Calibration of Digibridges and the Verification of their High-Frequency Specifications

(footnotes in superscript, references in parenthesis)

Part 1, Introduction

Traditionally, resistance calibrations have been made at dc, but the GR/IETLabs Digibridges are calibrated at 1 kHz. Thus it is reasonable to question if this ac calibration is valid. Moreover, some the Digibridges® have specified accuracies to 100 kHz and 200 kHz. It is also reasonable to ask how these accuracies are determined and verified. This memo hopes to answer these questions.

The brief answer is that the Digibridge® specifications have been verified by NIST calibrations. However, there is more that that to say than that.

NIST and other national labs cannot possibly calibrate resistors, capacitors and inductors of all values at all frequencies. Values are scaled by known ratio techniques over very wide ranges. Changes in capacitor and resistor values[2] between official calibrations at different frequencies are determined by extrapolation between these calibrations using the known behavior of the component. This is especially convincing if there is no change between these values. This must be considered valid for if not, NIST would have to make an infinite number of calibrations on each device.

Extrapolation of values to higher frequencies can also be valid, in fact it is encouraged by NIST. In a NBS Technical Note, Jones (1) shows how the values of air[3] capacitors can be extrapolated to higher frequencies by determining their inductance and applying a simple formula. He states that "it is possible for a laboratory to perform its own high frequency calibrations" and that "mutual benefits can accrue" from such independent calibrations. He goes on to suggest that if, the inductance is accurately determined, the value of the capacitor can be determined up to a frequency where the change is 10% by using the formula $C = Co/(1-w^2LCo)$. The tolerance of the value so determined is based on a plus or minus deviation of 10% in the measured value of the inductance. He determined the inductance of GR 1401 and 1402 capacitors by measuring their resonant frequency with a grid-dip meter.

It is argued (3) that a similar extrapolation method can be used for most types of precision resistors, especially small film resistors, particularly if a wide tolerance on the calculated error is used. Moreover, it is recommended that new high-frequency values should not be assigned to the standards (as Jones suggested), but rather the calculated changes be used only to determine the increased tolerances of the high-frequency values. Even though the equivalent circuit of such resistors is somewhat more complicated than that of air capacitors, the frequency errors can be reduced to simple formulas in most cases, see Appendices A, B and C. The high-frequency specifications of the Digibridges® were determined mainly by this method (see part 3).

Part 2, The AC Calibration of Digibridges®

The more accurate Digibridges® have four ranges and are calibrated by four external precision resistors (Vishay type S102). The four internal standard resistors, used to measure the current through the DUT, are of the same values and type. The standards are calibrated by comparison to secondary standards whose values are derived from a dc NIST calibration of a precision 10 kΩ resistor. However, the Digibridge® is made at 1 kHz. The ac-dc difference is assumed to be zero because published specifications for the maximum inductance and capacitance of these resistors would cause errors of less that 1 ppm when used in the equations derived from the equivalent circuit.

At ac, any resistor that is not pure ($Q = 0$) has two equivalent values, series (Rs) and parallel (Rp). The relations ship between then is $Rp = Rs(1 + Q^2)$. The series value of low-valued resistors changes less with frequency while the parallel value of high-valued resistors changes less. If we calculate the 1 kHz error of Rs for low-valued resistors and of Rp for high-values ones, the changes are all less than one part per billion. It is hard to doubt that the dc value may be used in this ac calibration.

Note that the calibration kit includes both an open and a short and both open and short calibrations are made. This removes, almost completely, any capacitance test fixture and resistor mounting and any mutual inductance between the leads as long as they aren't moved.

Part 3. High-Frequency Accuracy Specifications

The high-frequency accuracy specifications were determined before we had high-frequency NIST calibrations on resistors of the same values as those used in the Calibration Kit. I believe GR did have NIST calibrations on many values of GR 1442 Coaxial Resistors but have no idea where there is a record of such calibrations is. (The GR coaxial standards were designed at the suggestion of NBS (NIST) which was working on suitable high-frequency measurement circuits at that time (3).) The Digibridge specifications were determined using these calibrations along with the known behavior of resistors of several other types, including the Vishay resistors. The highest ranges also used air capacitors of known behavior. The resulting specifications are quite broad and, to my knowledge, were never proved too tight.

To understand our confidence in these specifications one should understand how a Digibridge® works. Unlike a manual RCL bridge which has different bridge circuits for the different types of component, Digibridges® use the same circuit to measure any type of component. These instruments measure all the complex components of the voltage across the DUT and across a standard resistor that measures the current. A complex division is used to get complex admittance and well-known calculations are used obtain the parameters that the user has chosen. One might say that the instrument doesn't know what it is measuring until the final parameters are calculated. Therefore, even though it is calibrated by resistors, but it can be checked by any precisely known impedance. (We could calibrate using any type of known impedance if the program were changed appropriately.)

We might note that the Q calibrations are based on a 23 Ω composition of extremely low inductance and a 1404 precision air (nitrogen) capacitor of very low D value. It is interesting to note that the Q values thus obtained agree well with calculated values using the Vishay "typical" capacitance specification of 0.5 pF and an inductance of .08 uH just below the Vishay specified maximum of 0.1 uH .

The Digibridges® use the same detector for both measurements on the DUT and standard resistor. Thus the gain, or phase, of the detector is cancelled in the division and does not affect the accuracy. Changes in accuracy over time are thus only due to changes in the values of the internal standards.

The Digibridges® are calibrated at only 1 kHz, but constants are determined from measurements at higher frequencies that are applied to a formula for high-frequency corrections. This is necessary because there are capacitors across the internal standards to keep the input circuit stable under all conditions and thus the internal standards are, in effect, complex impedances.

Part 4. NIST High-Frequency Calibrations

QuadTech developed some new impedance meters that extend in frequency up to 1 MHz which put a strain on their ability to get accurate calibrations. There we (I was consulting with QT then) made special coaxial resistance standards, similar to the GR 1442s, with values equal to those of the 1689 Calibration Kit. Some of these were sent NIST twice where they were calibrated at 1 MHz (at 100 kHz for the 95 kΩ unit) on the special NIST Twin-T circuit (3). We also measured some of them at 1 MHz on a HP 4284-A and on a GR1687 1 MHz Digibridge®. A table of measured values is in Appendix D. (Unfortunately this table is not very presentable, it wasn't intended to be shown publicly. I do not have the original NIST certificates, maybe QT does.).

These measurements might be summed up by the following table.

Resistor Value	R Tolerance At 1 MHz	1689 R Spec at 100 kHz	Q Tolerance At 1 MHz	1689 Q Spec At 100 kHz
25Ω	negligible	0.31%	.0004	.003
374 Ω	0.014%	0.31%	.0004	.003
5.9 kΩ	0.03%	0.31%	.003	.003
	At 100 kHz	At 20 kHz	At 100 kHz	At 20 kHz
95 kΩ	0.04%	0.51%	.003	.005

Note the tolerance on the measurements is given at a higher frequency than the corresponding 1689 specification. When this is considered, the measured tolerances are well within the 1689 specs. This shows that these special calibrated standards could be used to check the 1689 accuracy. I don't have a record of measurements on a 1689 using these standards, but I assume that many some such measurements were made and they were all within the 1689 specifications..

Conclusion

It is hoped that this memo and it appendices give satisfactory answers to those initial questions. The arguments used are not all completely rigorous, but the many, many measurements that I and other engineers have made on these instruments has convince us that their accuracy specifications are adequate.

Footnotes:

1. In this memo, by “high-frequency” we mean frequencies between 1 kHz and 1 MHz.
2. We don’t suggest that inductor values be extrapolated between frequencies.
3. By “air capacitor” we mean a capacitor with a dielectric of dry air or other inert gas.
4. A discussion of series and parallel equivalent circuits is given in any GR bridge manual.

References:

1. Jones, R.N., “A Technique for Extrapolating the 1 kHz Values of Secondary Capacitance Standards to Higher Frequencies”, NBS Technical Note 201, November 1963.

2. Hall, H. P,, “Another Treaceability Path for Capacitance Measurements”, *GR Experimenter,* March/June 1970, p8

3. Huntley, L.E. and Jones, R.N., “Lumped Parameter Impedance Measurements”, Proc. IEEE, June 1967, p900

Appendices:

A. “Frequency Response of Standard Resistors”
B. “Resistance Measurements: AC vs DC”
C. “ Using Digibridges for “DC” Resistance Measurements”
D. Values of HF Standards