A New Method for the Calibration of the mV Ranges of an AC Measurement Standard

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Abstract
Presented are different methods for the calibration of an AC Measurement Standard from 20 mV to 2 mV, 10 Hz to 1 MHz. The two methods currently used for this calibration are the comparison to an AC/DC Transfer Standard and the use of the bootstrap method given in the manufacturer's service manual. A new method has been developed using the AC/DC Transfer Standard with a resistive voltage divider in a way that gives better Test Uncertainty Ratios (TURs) then the current methods. This paper describes these methods, sources of error and ways of reducing these errors. Also shown are test results comparing the methods [1].

1. Introduction

The Fluke 5790A AC Measurement Standard [2] is calibrated in the Fluke Labs by comparison to a Fluke 792A AC/DC Transfer Standard on all ranges from 1 kV down to the 70 mV range but is not used to verify the 20 mV range and below. The reason for this is low test uncertainty ratios (TURs) and noise. Instead the bootstrap method as given in the service manual is used. Tests run during the development of the 5790A showed this method to work with adequate TURs but some labs and accrediting bodies have been hesitant to accept this method without further verification. So a new method was developed which gives excellent results that can be used instead. This method uses a resistive voltage divider in conjunction with the 792A. This paper presents the challenges encountered in developing the divider method and how they were overcome. Once developed the divider method was used to evaluate the bootstrap method. This testing is still ongoing but the results so far indicate that the bootstrap method does work as originally intended The testing has also revealed ways of improving the method to get better results if so desired. Lastly test results with the different methods are presented.

2. Direct Measurements with 792A

The 5790A is verified on the 70 mV range and above by connecting the input of a 792A to the input of the 5790A under test using a type N TEE and driving both with the output of a calibrator such as the 5700A. The calibrator supplies both the AC and DC Voltage needed for the test. The most important requirement for the 792A is that its uncertainties be low enough to give a good TUR at all the test points. At the time this product was developed the uncertainties for the 792A on its 20 mV range resulted in low TURs so it could not be used to do these ranges. The better uncertainties available today on the 20 mV range does result in acceptable TURs at 20 mV and may also at 6 mV and 2 mV depending on where the 792A is calibrated.

Another consideration when using the 792A is noise in the measurement, both low frequency and high frequency. Since the 792A is an AC/DC device, the calibrator must supply a rather low level of DC Voltage. Since most calibrators have a 100 mV to 300 mV as their lowest DCV range, supplying DCV at 20 mV and below has a significant floor error since the voltage is at tenth scale to one hundredth scale. Also any DC offset voltage drift during the test is not entirely cancelled by the polarity reversal that is done. These offsets comes from the Thermal EMF voltages of the connections and offset voltages in the instruments. There is also a problem with high frequency noise. Most calibrators output some high frequency noise on the DC output and when operating near the bottom of the range this noise can add significantly to the RMS value of the DC Voltage. The 792A operates to 1 MHz and so it will respond to noise up to several MHz. This places an error in the DC Measurement. There are ways of overcoming the noise problems so a direct measurement with the 792A is possible down to 2 mV but the details of this are not part of this paper.

3. Measurement with 792A and Resistive Voltage Divider

Using a 792A with a resistive voltage divider can provide a way to measure a 5790A down to the 2.2 mV range with good TURs even when the 792A doesn't have a calibration with low enough uncertainties to do a direct measurement. Figure 1 shows a simplified diagram of how such a divider is used. It is connected between the output of the calibrator and the input of the 5790A under test (UUT). The 792A is connected to the input of the divider. An appropriate division ratio is used to allow the calibrator to operate at a high enough voltage that it performs well and also where the uncertainties of the 792A are low. At the same time it provides the mV signal with a good signal to noise ratio. Before the divider is used, its division ratio at each test frequency is determined using the 792A. The voltage applied to the UUT is found by multiplying the input voltage as measured by the 792A times the division ratio for that frequency.

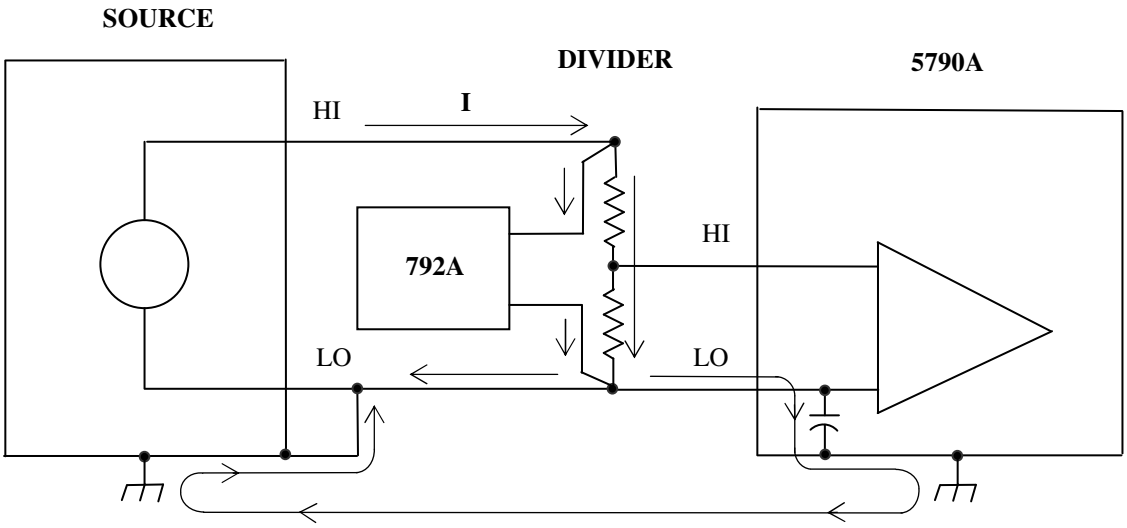

Figure 1. Simplified diagram of divider connections and current flow.

The divider is calibrated with the 792A before it is used. The 792A is first used to characterize the UUT at the voltage level the divider will be putting out when calibrated. Then the divider is connected as shown in Figure 1 and the 792A measures the input voltage to the divider while the characterized UUT measures the output voltage. From these two voltages the division ratio is found. This process is repeated for all the test frequencies. It was desired to have one division ratio work over the 20 mV to 2 mV range and still be able to calibrate it at a high enough voltage to get low uncertainties. A division ratio of 100:1 was picked as the best choice. This allows the input voltage to be between 2 V and 0.2 V which works well for both the calibrator and the 792A. The voltage at which the divider is calibrated is a compromise between two factors. The higher the voltage the better to minimize the errors when characterizing the UUT but if it is too high then there is a problem with the power dissipation within the divider. It was found that an input of 10 V with an output of 100 mV or an input of 6 V with an output of 60 mV was the best choice. Of these two choices the 6 V in is the best if the uncertainties of the 792A are low enough at 60 mV; if not then use 10 V in and 100 mV out.

4. Design problems to overcome with the divider method

There were several problems to be overcome designing a divider that would perform to the desired uncertainty[3]. Figure 1 shows the flow of current between the devices. Most of the current that flows through the divider and 792A input impedance returns through the Source LO connection back to the calibrator but some of it can also flow through the UUT LO path due to the capacitance between the LO and ground. At low frequencies this current is very small and the common mode rejection of the UUT is very high so it contributes no significant error. As the frequency goes up the current increases through the capacitance and the common mode rejection of the UUT decreases so that above 100 kHz or so a significant error can occur. For a typical divider setup this error will be very significant at 1MHz so something must be done to reduce this current. Figure 2, on the next page, shows what was done to accomplish this.

First the cable from the divider to the source is kept as short as possible and uses large gauge wire, one foot of #18 wire in our case. Secondly a short heavy braid strap is connected between the source Ground terminal and the 5790A Guard terminal and the 5790A is set to EXT GRD. Figure 2 shows the connections for a 5790A that has the Guard Modification. For a 5790A that doesn't have the modification this strap should be connected to the Ground terminal on the 5790A and the 5790A set to INT GRD. The 5700A was also set to EXT GRD and its Guard connection brought to the divider and connected to the divider output low after the common mode choke. Tests showed that this was the best connection scheme and almost any deviation from this gave poor results at 1 MHz.

Next a common mode choke was placed on the output of the divider. This choke places inductance in series with the common mode current while not affecting the normal mode current flowing through the HI and LO leads of the UUT. Care should be taken when building the choke to minimize the normal mode inductance introduced by the windings. A good way to do this is to use coax. Our unit was built by winding a few turns of miniature coax through a very high mu ferrite core. The inductance in series with the common mode current needs to be about 150 µH to 250 µH at 1 MHz. If the core has a high Q then there will be a problem around 100 kHz where the inductance of the choke resonates with the capacitance in the 5790A. This forms a

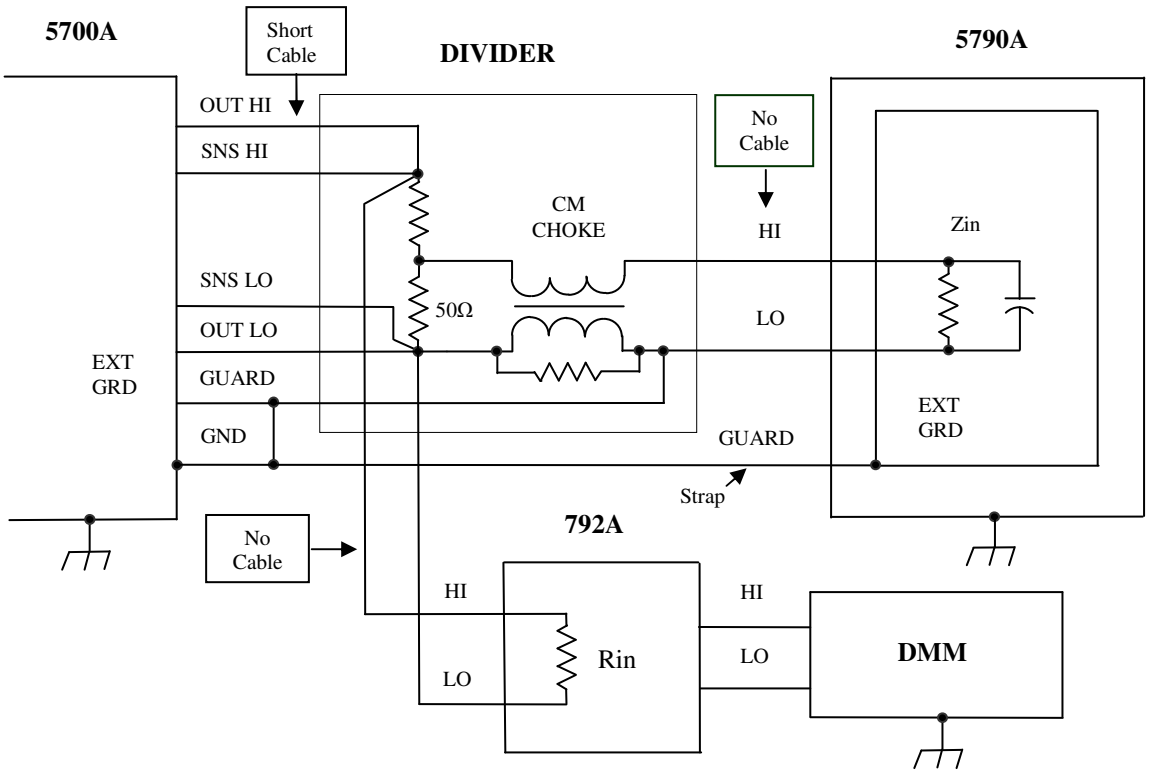

Figure 2. Complete diagram of divider and connections

series resonant circuit where the series impedance goes to near zero. This allows a lot of current to flow through the LO path to the 5790A at the resonant frequency. To greatly reduce this effect a resistor can be placed across the choke on the LO side which reduces the Q of the series circuit. The value depends on the Q, but for a high Q core, 75 Ohms is a good choice.

Another way of dealing with the common mode current is to break the current path between the UUT and ground. Normally the UUT is grounded through the power cord and also can be grounded by means of mounting hardware if installed in a rack. There is also a path to ground through the IEEE-488 cable. If the UUT can be isolated from ground well enough then the divider would not need a common mode choke. To break the path through the power cord the UUT could be powered off a battery and inverter. Test would need to be run to ensure that any switching transients from the inverter did not affect the UUT measurements. Another way is through the use of a very low capacitance isolation transformer. This transformer would need to have very low capacitance from its secondary to ground. Not all types of isolation transformers on the market have particularly low capacitance from secondary to ground. To isolate the IEEE-488 connection an IEEE-488 isolator could be used, but again it is the low capacitance to ground that is important, not just the isolation across the unit. If possible try and get the total capacitance to ground to less than 100 pF.

In some setups it was also found that a common mode choke between the 792A DC output and the DMM input gave better results at 2 mV and 1 MHz. This choke can be made by winding a

few turns of the cable on a ferrite core. To determine if it is needed, take measurements with and without it and if there is a significant difference then use it.

Another consideration is the value of the resistors in the divider and what range of values is best. The higher the resistance, the less power is dissipated in the upper arm of the divider. The lower the resistance the less the effect the UUT input loading has on the divider output. The divider doesn't need to have a flat frequency response since its response is measured, so the upper arm can consist of a large number of resistors in parallel to handle the power. Our divider, built to be calibrated at 10 V, used forty 1/8 W metal film resistors in parallel. An output resistance of 50 Ohms, which makes the upper arm about 5 kOhms, is the upper limit of resistance to use. With 50 Ohms the error in the measurement at 1 MHz due to the change in loading from the range on which it was calibrated to the range on which it is used on can be significant. Data will be presented later in this paper on this. A lower resistance like 20 Ohms or less would reduce this error but increase the power dissipated in the upper arm.

Another consideration is to keep the lead length of the connections between the 792A and the input of the divider as short as possible. The 792A has a low input impedance on its 2 V range and above so it draws more current than the divider does. This input Z also changes significantly with range, which changes the current it draws and the voltage drop across the leads. The divider was built so the 792A connects directly to the divider housing without any cable and uses a layout inside the housing to keep the leads very short. If the divider is calibrated at 10 V in, the input Z of the 792A is 4 kOhms. When the divider is used to calibrate a UUT the input voltage is first set to 2 V to get 20 mV out. If the 792A is set to the 2.2 V range its input Z is 420 Ohms. This large a shift in resistance and thus current drawn by the 792A caused a noticeable shift in the results at 1 MHz. For better results the 2 V should be measured on the 7 V range where the input resistance is 1200 Ohms. The best results can be obtained by calibrating the divider with 6 V in and 60 mV out. This places the 792A on the 7 V range when calibrating the divider and then the 792A can stay on this same range to measure the 2 V input. Using 6 V to calibrate the divider also reduces the power the divider must handle. The next range down on the 5790A is the 7 mV range which requires an input of 600 mV. Here the 700 mV range of the 792A is used which has a high input Z so the current drawn goes way down and is no longer a problem.

Another consideration is the DC connection. Since the 792A is an AC/DC device an accurately known DC voltage must be presented to the input of the divider. The 792A and divider draw enough current that a four wire connection may be needed right to the input of the divider so remote sensing can be used.

The loading of the divider output resistance by the UUT input Z was mentioned earlier. The affect this loading has on the division ratio at each frequency is accounted for in the calibration of the divider but only for the UUT range on which it was calibrated. There is some shift in the loading from range to range which would change the ratio. The amount of change goes up with frequency so the biggest change is at 1 MHz. The amount of change also differs from UUT to UUT. To account for this the loading of each frequency above 100 kHz on each range can be measured. From this, the shift in the divider ratio can be determined and corrections applied. In a previous paper,[4] a description was given as to how to measure the loading of an AC Voltmeter. The connection diagram in that paper was for a 792A.

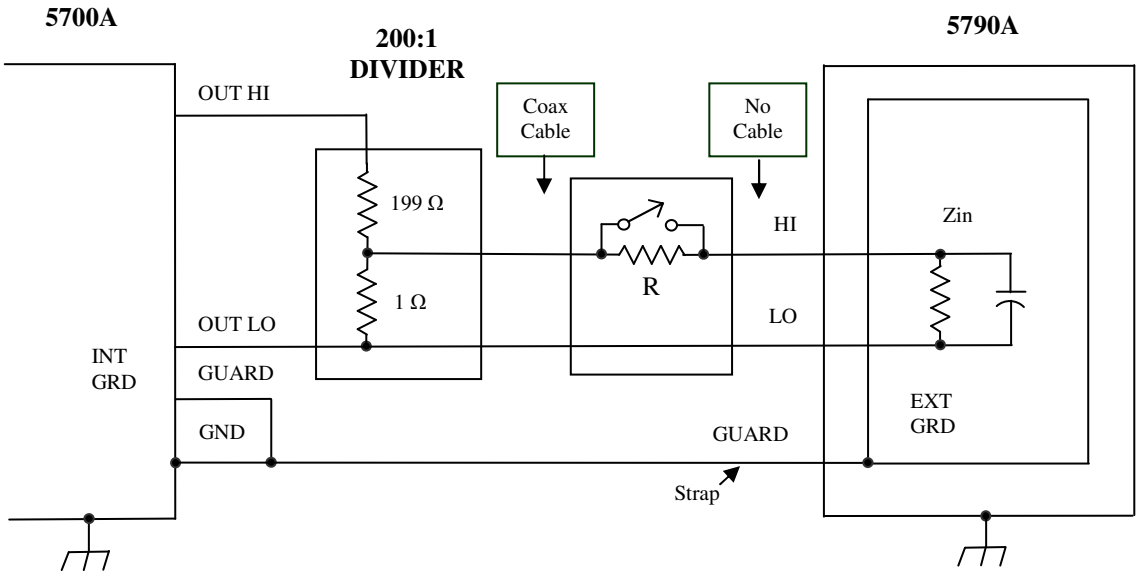

Figure 3. Diagram for the measurement of 5790A loading

Figure 3 shows the setup that should be used for a 579A that has the guard modification. For a unit without the guard modification, connect the braid strap to the Ground terminal instead of the Guard terminal and use Internal Guard. Here again following this connection scheme is very important to the success of the measurements at high frequencies. As mentioned in the referenced paper this technique depends on the use of a low output Z source. Since most sources are 50 Ohms output Z in the mV ranges a divider can be built with a low output resistance to supply the voltage. Figure 3 shows a 200:1 divider with a 1 Ohm output Z that can be built using inexpensive resistors. A large number of resistors can be paralleled to handle the power in the upper arm. The resistor with the switch across it must be placed right at the UUT input and its value should be same as the output resistance of the divider in Figure 2. The 200:1 divider shown in Figure 3 can be placed at the source output terminals and connected with a coaxial cable to the resistor with the switch. A common mode choke will probably not be needed as the measurement process only depends on the change in the UUT reading when the switch is closed. An alternative to correcting for the loading change would be to use an average change for the UUT and put an uncertainty component in the uncertainty analysis for the variation of this change from unit to unit. Data on this will be presently later in this paper that shows that this uncertainty is only really significant at 1 MHz.

5. The bootstrap method

The bootstrap method as given in the 5790A service manual was developed as a means of calibrating the 20 mV range and below because, at the time of the 5790A product development, the uncertainties available on the 792A were not low enough to allow for acceptable TURs in this range. At that time tests were run to determine the magnitude of the errors in the bootstrap method and the specifications were adjusted to insure that this method gave acceptable TURs. With the development of the divider method as described above it became possible to look again

at the sources of error in the bootstrap method and determine their magnitude using a method with good TURs. This process is still under way and the full results will be published later. Sufficient work has been done though to identify the two major sources of error and ways of determining their magnitudes so corrections can be made to the results. This has resulted in an enhanced bootstrap method that has better TURs.

The major error contributor at low frequencies was found to be the linearity error from full scale to the bottom of the range, which is one-third scale. In other words the error in proportional parts at full scale was not the same as at one-third scale. The bootstrap method depends on this linearity error to be within certain limits for the method to work with acceptable uncertainties. The bootstrap method starts by measuring the error of the 70 mV range at 60 mV using the 792A. Then with the UUT still on the 70 mV Range, 20 mV is sourced at all the test frequencies and readings taken from the UUT. Next the range is changed to the 22 mV range and readings taken again at 20 mV at all the test frequencies. The shift in the readings in proportional parts at 20 mV between the ranges is the error of the 22 mV range relative to the error at the bottom of the 70 mV Range. The error at the top of the 70 mV range is known in proportional parts so if the range is linear the two errors can be added together to get the 20 mV error. To what degree the 70 mV range is not linear, causes an error in the measurement of the 22 mV range at full scale. Measurements were made using the divider to determine this linearity error and the results showed that the error was relatively constant over the low frequency range of 10 Hz to 100 kHz. It was also found that a good determination of the linearity error could be made using measurements made with DC voltage. The 5790A is not specified for DC operation at 20 mV and below but it is DC coupled on these ranges so DC measurements can be made. By adding an extra step to the bootstrap method for each range, most of the linearity error can be determined and a correction made. This extra step involves applying +DC and –DC at 60 mV and 20 mV on the 70 mV range. The average of the +DC and the –DC is taken for each level. The average is taken to cancel significant DC offset voltages that are present. The linearity error in proportional parts is determined by taking the error from nominal in proportional parts at 20 mV and subtract the error from nominal in proportional parts at 60 mV. This correction is then applied to all frequencies. The same process is then done on the 22 mV range when doing the 7 mV Range and on the 7 mV Range when doing the 2.2 mV Range. It should be noted that when applying the DC voltage, noise and short term drift of the offset voltages can make it difficult to get a good measurement so it is generally required to average multiple readings in each polarity and reverse the polarity more than once. Measurements on a number of units showed that the maximum error that the linearity error contributed to the calibration of any of the ranges was about 40% of the specification for that range with the average around 15%. Using the DC measurements reduced this error to less than 10% in most cases. Again this is some what preliminary results.

The major error contributor of the bootstrap method at high frequency is the change in the loading of the UUT from range to range. The source of voltage for this test is a calibrator which has a 50 Ohm output impedance. This 50 Ohms is loaded by the input Z of the UUT. Its input Z decreases as the frequency goes up and also changes some between ranges for the same frequency. So in the example given above for calibrating the 22 mV range from the 70 mV range, the 20 mV as measured on the 70 mV range can change when the UUT is switched to the 22 mV range if the loading of the UUT changes between the two ranges. The amount of this change is different from instrument to instrument but test on a number of units showed that at

most it contributed an error that was about 15% of the 5790A specification with the average being about 6%. This is small enough that it isn't worth measuring the loading of each unit under test but instead an uncertainty component can be put in the uncertainty analysis for this. In the next section results of testing of the loading of a sample of 5790As will be given to give an idea of the typical shift and the variance of this shift.

6. Test results – divider design

One of the most important parts of the design of the divider is the use of a common mode choke that will effectively reduce the level of common mode current going through the UUT LO lead. Figure 4 shows the results of testing done on a UUT at 2 mV using a divider with a CM Choke with adequate inductance and without any choke. For this particular setup three turns on the ferrite core was sufficient to get good results so that at 1 MHz the measured error was close to zero. On the other hand, making the same measurement without a choke resulted in a measured error that exceeded the 5790A specification at 1 MHz. In both cases the divider was calibrated at 10 V before being used to make the measurements. There are two ways to determine how much inductance is needed for a particular setup. One way is to add turns to the core until adding more turns doesn't change the measurement outcome at 2 mV and 1 MHz. The other way is to start without a choke on the output of the divider but have isolation on the UUT power and IEEE-488 Port so no common mode current can flow through the unit. Take measurements, then remove the isolation and add the choke and repeat the measurements. If there is enough inductance then there will be little difference in the results.

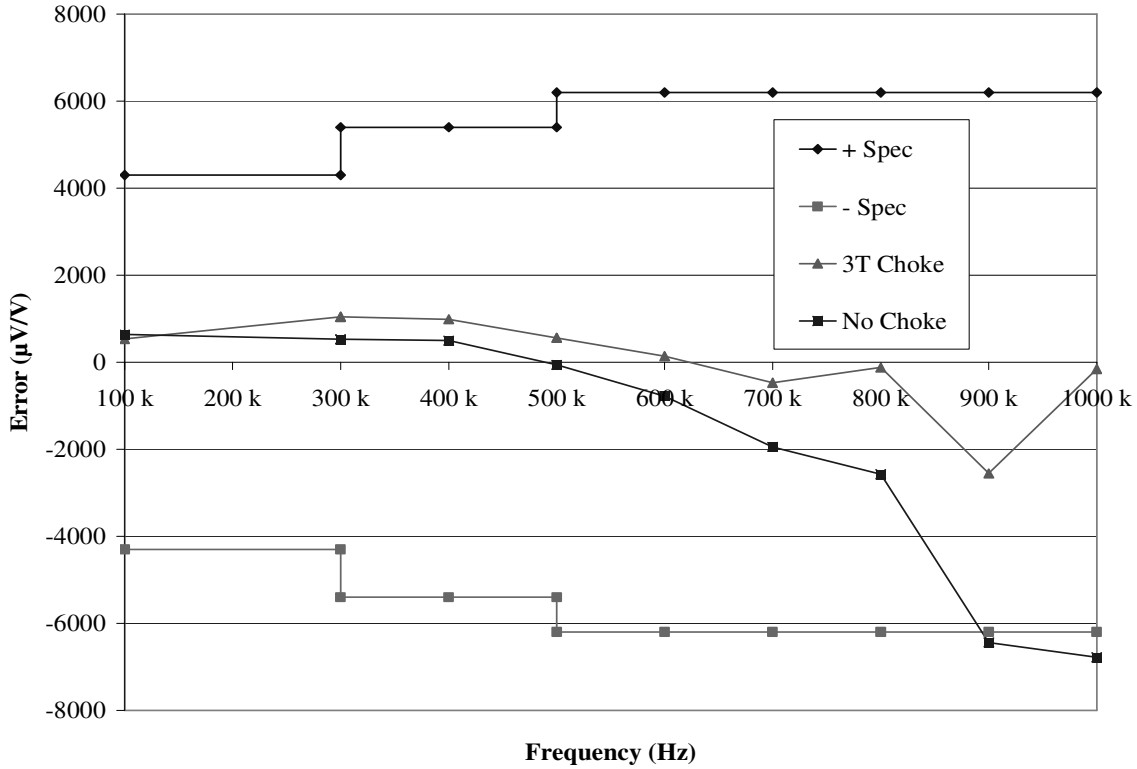

Figure 4. Effect at 2 mV of using a common mode choke on the output of the divider

An important consideration in designing the CM choke is dealing with the series resonant effect it has with the capacitance in the UUT. As mentioned earlie,r a low Q core can be used and/or a resistor placed across the LO side winding. Figure 5 shows the effect such a resistor has on a high Q core. Shown is the division ratio of the divider as a function of frequency from 10 kHz to 1 MHz. The line labeled "No R" is the choke without any means of reducing the series resonant effect. As can be seen there is a substantial variation in the ratio around 100 kHz that would cause a problem when using the divider at 100 kHz. The line marked "75 Ohms" shows the effect of putting a resistor across the LO side winding. Only a small dip remains which does not cause an error when using the divider because it is accounted for when the divider is calibrated. The line marked "ISO" for isolation shows the complete lack of any resonant effect when the UUT is isolated from ground.

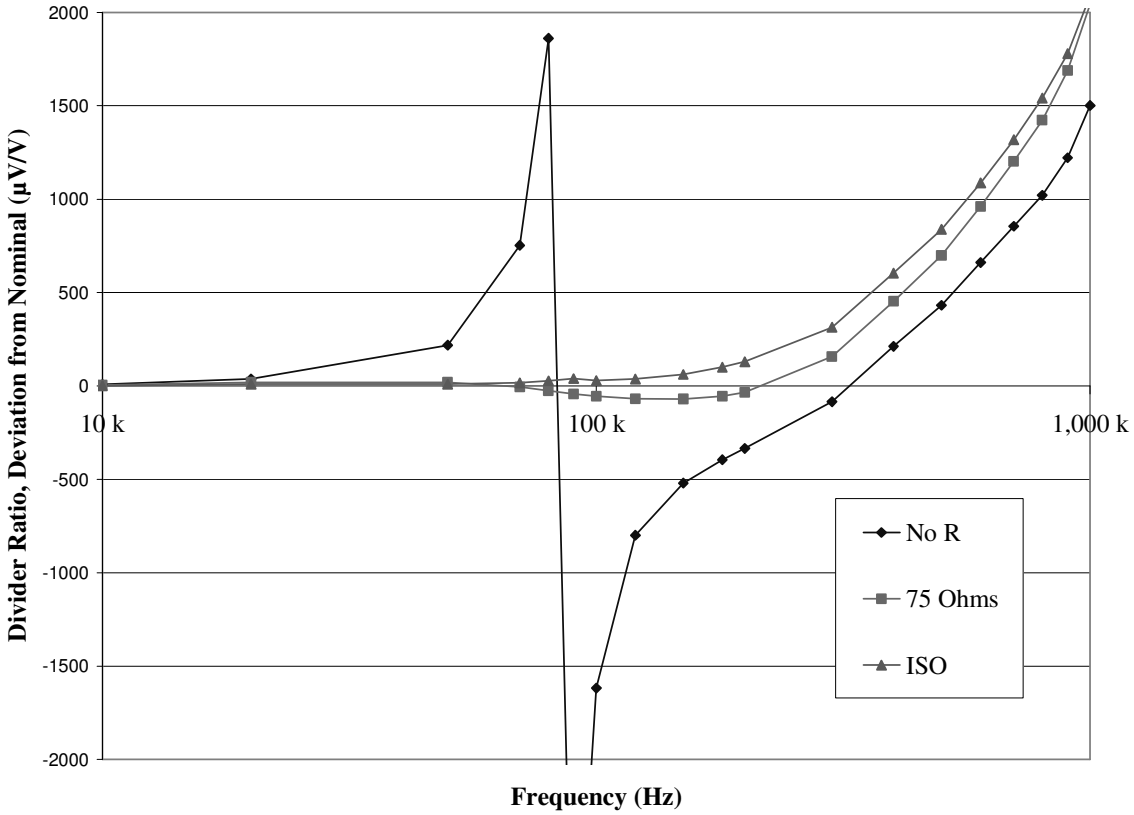

Figure 5. Affect of series resonance on the divider ratio.

Another consideration in the design of the divider is the effect that the change in loading of the UUT under test has on the divider ratio as the range is changed during the tests. As described earlier, the lower the output resistance of the divide,r the less the effect the UUT loading has on the division ratio. Tables 1 shows the results of loading measurements on sixteen different UUTs. These units had date codes from early production to current production. The table shows the average error that the change in loading would have when using a divider with a 50 Ohm output resistance. Also shown is one standard deviation of the distribution of the measurements. Table 1 is for a divider that is calibrated at 10 V in and 100 mV out but it can also be used for a divider that is calibrated at 6 V in and 60 mV out as the differences in loading errors and

standard deviations is insignificant. It can be seen from the table that the loading error is only significant at 1 MHz when compared to the 5790A Specifications. So a good option is to not measure the loading change of each UUT but instead use the values in the table as a correction at 1 MHz and use the standard deviation in the uncertainty analysis. In the Table 1, a negative sign indicates that there is more loading on the range given in the table than there is at 100 mV. So the value in table can be applied as a correction to the divider ratio for that range. It should be noted that this table is for a 50 Ohm divider only and can not be scaled for use with dividers of other output resistances. This is because there is a non linear relationship between the divider output resistance and the error due to the change in loading. In other words, a 25 Ohm divider would have less than half the loading error shown and a 100 Ohm divider would have more than twice the error.

Table 1. Error from change in loading as it affects a 50 Ohm divider.

5790A Range	Test Freq Hz	Average Loading Error µV/V	Standard Deviation µV/V	5790A 90 d Spec µV/V
22 mV	300 k	25	10	1010
22 mV	500 k	60	20	1160
22 mV	1 M	85	110	1700
7 mV	300 k	20	20	1867
7 mV	500 k	20	30	2300
7 mV	1 M	65	190	3000
2.2 mV	300 k	15	45	4300
2.2 mV	500 k	-70	75	5400
2.2 mV	1 M	-285	525	6200

It was mentioned earlier that the change in loading of the UUT from range to range also affects the results of the measurements made with the bootstrap method. Table 2 shows the errors and standard deviations of the sixteen units tested as they apply to the bootstrap method. These too can be used as corrections and uncertainties but only apply for a source with a 50 Ohm output Z.

Table 2. Error from change in loading as it affects the bootstrap method

5790A Range	Test Freq Hz	Average Loading Error µV/V	Standard Deviation µV/V	5790A 90 d Spec µV/V
22 mV	300 k	25	10	1010
22 mV	500 k	60	20	1160
22 mV	1 M	110	100	1700
7 mV	300 k	-5	15	1867
7 mV	500 k	-35	20	2300
7 mV	1 M	-25	90	3000
2.2 mV	300 k	0	40	4300
2.2 mV	500 k	-90	55	5400
2.2 mV	1 M	-315	350	6200

7. Test results – measurements on UUTs

Several UUTs were measured using all the methods to see how well they agree. All test points were measured using the divider method, the bootstrap method and the enhanced bootstrap method. For the enhanced bootstrap method measurements were taken with DC voltage to correct for the range linearity error. Also the actual change in loading of each unit was measured and applied as a correction to the divider method and enhanced bootstrap method. Measurements with the 792A were made at 20 mV and 6 mV at all frequencies but at 2 mV the uncertainty on our 792A was only low enough for four frequencies to be measured.

Figure 6 shows the measured errors at 20 mV for a UUT that had the largest linearity error found amount several units tested. As shown in the figure there is good agreement between the measurements done with the 792A and using the divider method. The difference between these measurements and the bootstrap method is about 35% to 40% of the 5790A Specification. This difference was reduced to about 15% with the enhanced bootstrap method. For most units tested it was reduced to less than 10%. Figure 7 shows the measurements on this same 5790A from 100 kHz to 1 MHz. The maximum difference between the four methods, including the bootstrap method which isn't shown, was 10% or less with most points at 6% or less of the 5790A Specification.

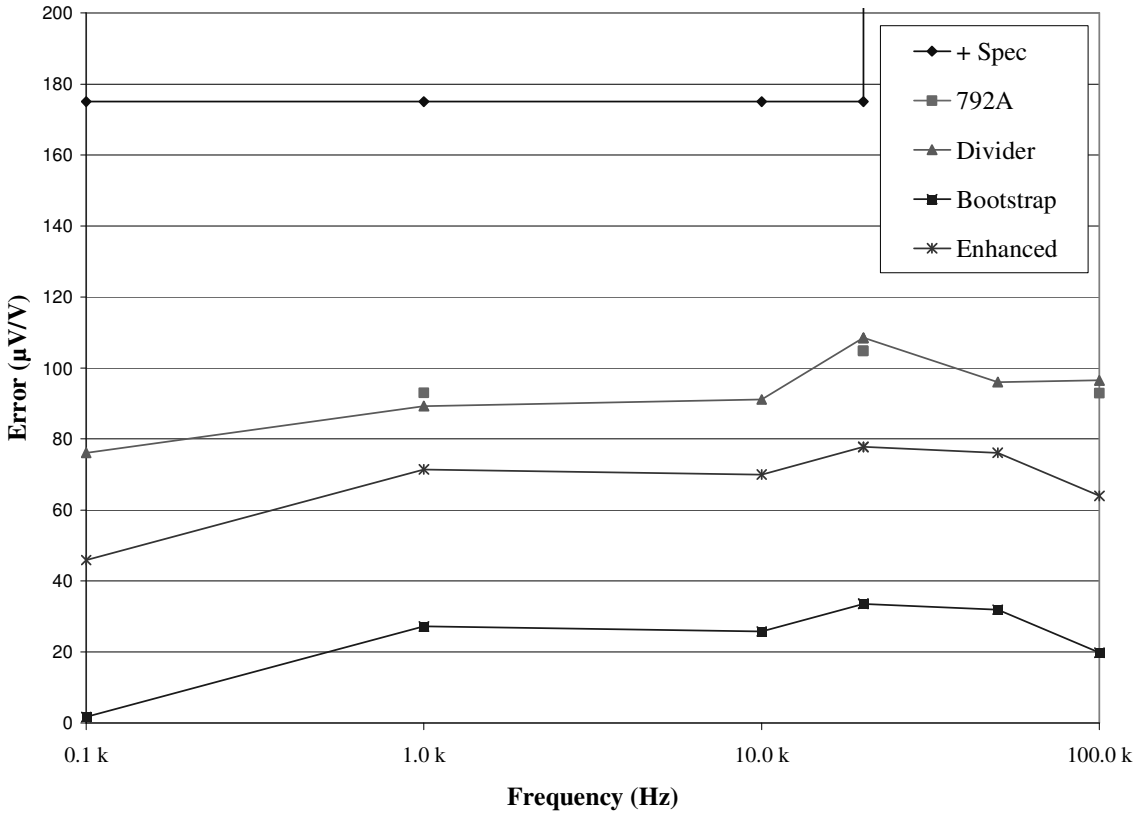

Figure 6. Test results at 20 mV, 100 Hz to 100 kHz, for the four methods.

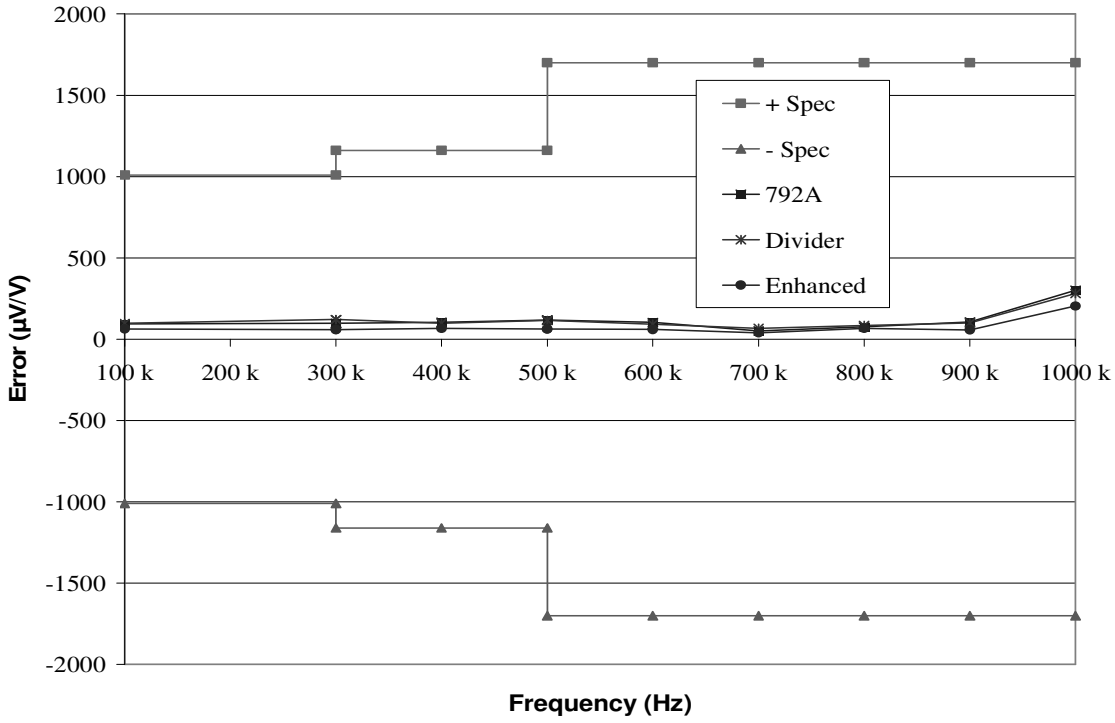

Figure 7. Test results at 20 mV, 100 kHz to 1 MHz, using 792A, divider and enhanced methods

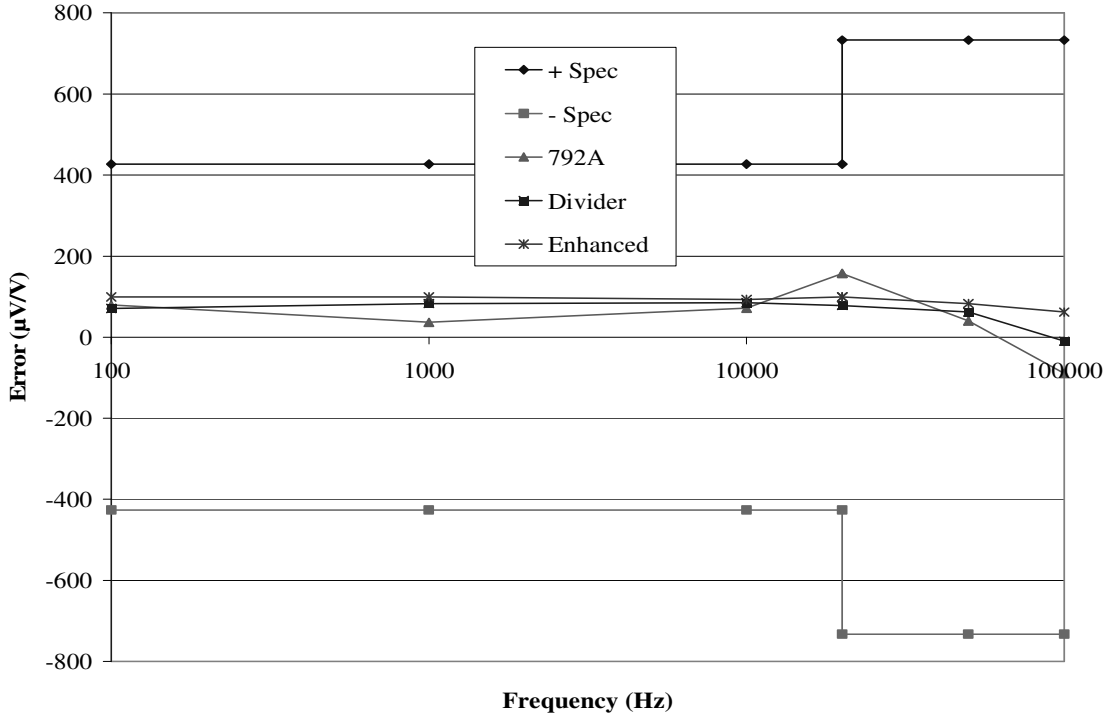

Figure 8. Test results at 6 mV, 100 Hz to 100 kHz, using 792A, divider and enhanced methods

Figure 8 shows the measurement results on a different UUT at 6 mV, 100 Hz to 100 kHz, using the 792A, divider method and enhanced bootstrap method. The bootstrap method was not shown because the linearity error on this unit was small. The maximum difference between the divider and enhanced methods was 9% of the 5790A Specifications. The maximum difference between the 792A measurements and the other two methods was 19%. Figure 9 shows the measurements results for 100 kHz to 1 MHz. The largest difference between the three methods was about 10% of the 5790A Specification. Maximum difference for the bootstrap method, which isn't shown, was 15%.

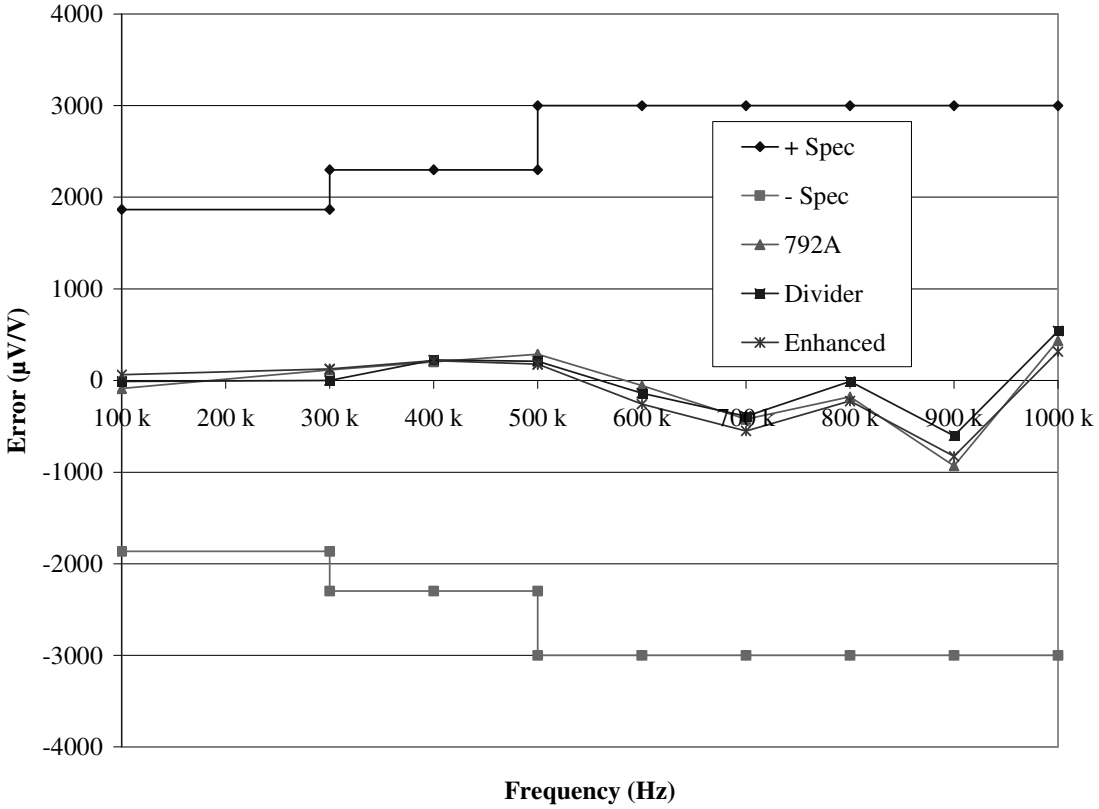

Figure 9. Test results at 6 mV, 100 kHz to 1 MHz, using 792A, divider and enhanced method.

Figure 10 shows the measurement results at 2 mV from 100 Hz to 100 kHz on another UUT. Here again the advantage of using the enhanced bootstrap method over the bootstrap method can be seen. There is good agreement between the two measurements taken by the 792A, at 1 kHz and 50 kHz, and the enhanced bootstrap method while the difference for the bootstrap method is 21% and 16% of the 5790A specification respectively. The maximum difference between the divider method and the enhanced bootstrap method is 12% of the 5790A specification. Figure 11 shows the measurement results at 2 mV from 100 kHz to 1 MHz. The maximum difference between the divider method and the 792A, which is at 1 MHz, is 11% of the 5790A specifications while the maximum for the enhanced method is 6%. For the bootstrap method, which is not shown, it was 20%.

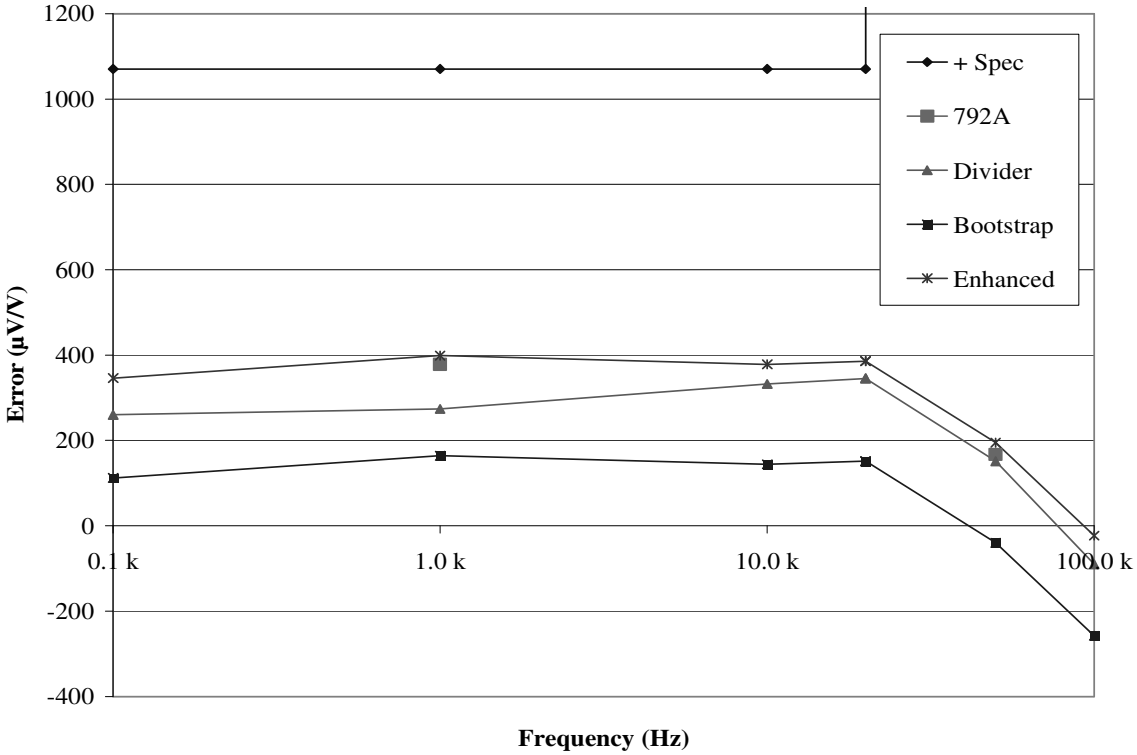

Figure 10. Test results at 2 mV, 100 Hz to 100 kHz, using the four methods.

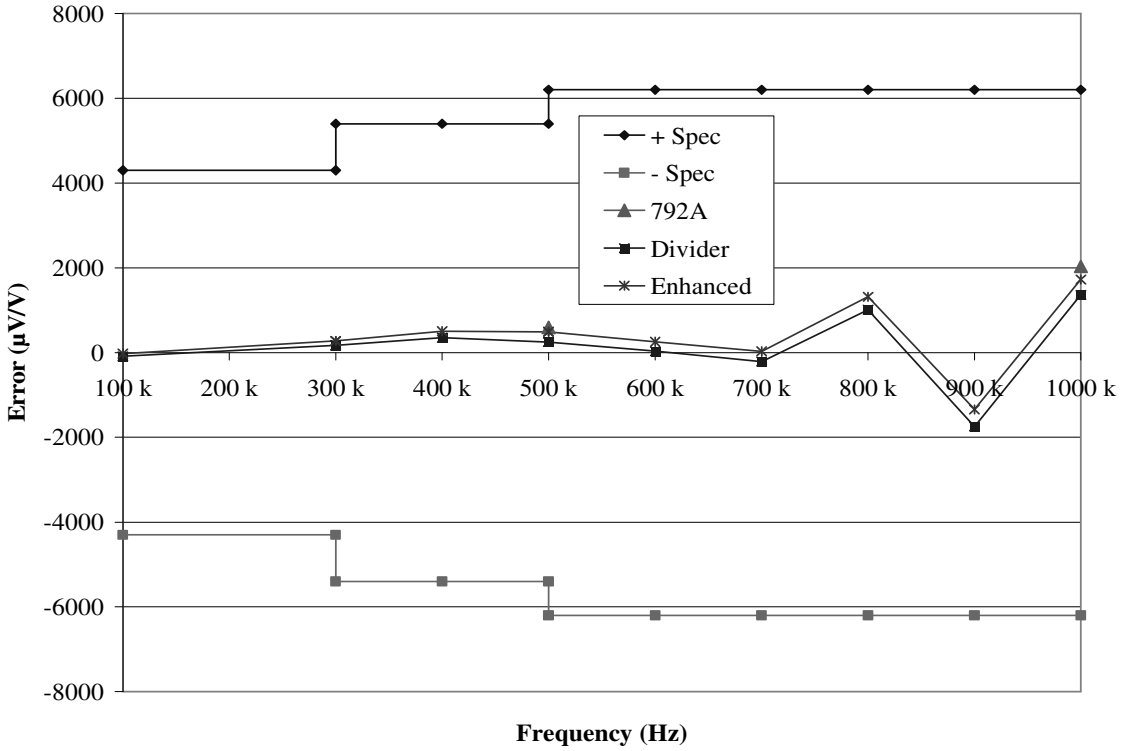

Figure 11. Test results at 2 mV, 100 kHz to 1 MHz, using 792A, divider and enhanced.

8. Conclusion

The uncertainty analysis for the divider method shows that it has a TUR of about 4:1 at 20 mV and 5:1 or better at 6 mV and 2 mV. The comparison data to the 792A given in this paper substantiates this analysis. This comparison data also shows that the bootstrap and particularly the enhanced bootstrap probably have good TURs also but further work is in progress to determine their level of performance. The results of this work will be published when complete.

References

1. Some of the material in this paper was presented in the two page abstract: N. Faulkner, "Comparing Different Methods for the Calibration on the mV Ranges of an AC Measurement Standard", Conference on Precision Electromagnetic Measurements, Conference Digest, London, UK, June 2004.
2. D. Deaver, "Calibration and Traceability of a Fully Automatic AC Measurement Standard", NCSL Workshop & Symposium, Albuquerque, NM, USA, Aug 1991. Available on the Fluke web site: www.fluke.com.
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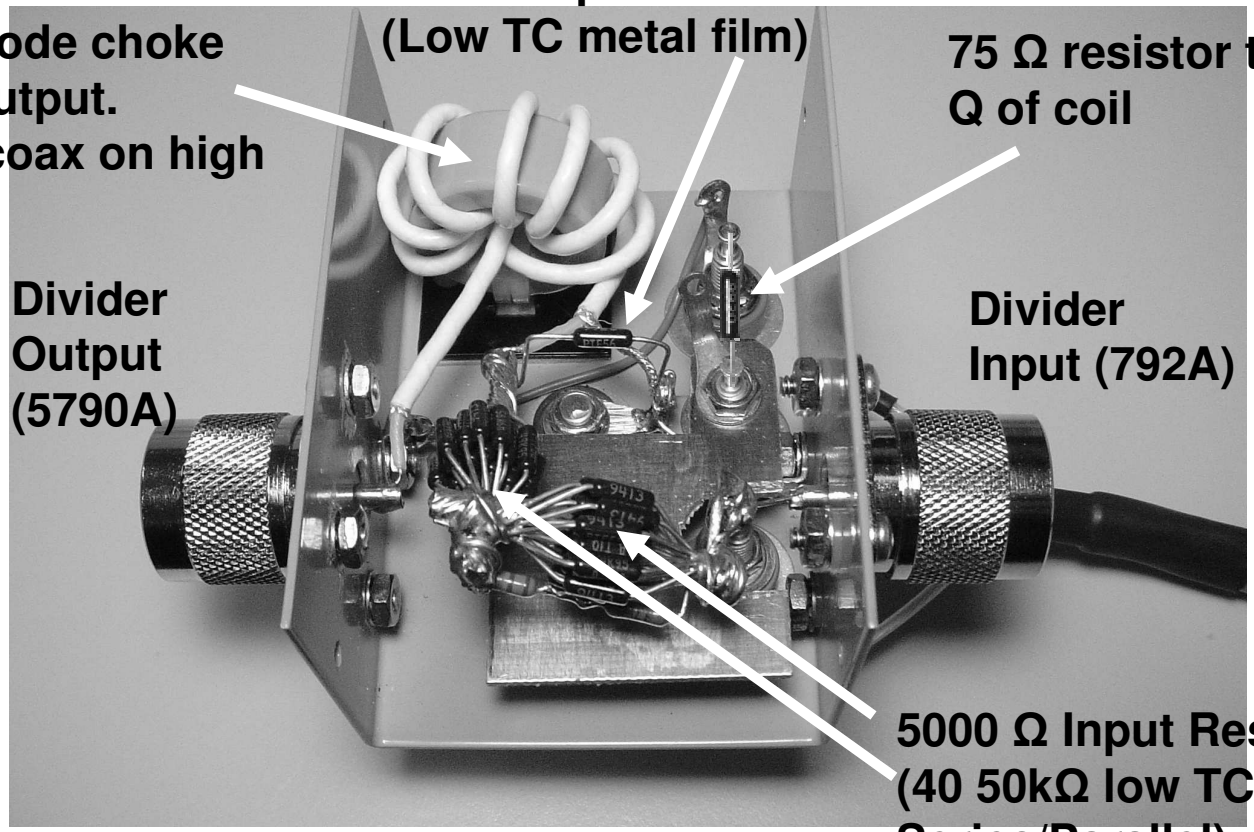
4. N. Faulkner, "How the Loading of an AC/DC Transfer Standard can Effect your Measurement of AC Voltage and Current" 1999 NCSL Workshop and Symposium, July 1999. Available on the Fluke web site: www.fluke.com.

100:1 Divider Construction



50 Ω Output Resistor
(Low TC metal film)

Common Mode choke
at divider output.
(miniature coax on high
Q core)

75 Ω resistor to lower
Q of coil

Divider
Output
(5790A)

Divider
Input (792A)

Cable to Source
(5700A)

5000 Ω Input Resistor
(40 50kΩ low TC metal film
Series/Parallel)