Best Practices Using the Guildline 7520 Automated Voltage Divider

The purpose of this paper is to describe how best to use a Guildline 7520 Voltage Divider along with measurement standards' considerations to achieve sub-ppm measurements.

7520 Overview

The 7520 Voltage Divider is the first fully automated Self-Calibrating sub-ppm voltage divider. It provides ratios of 1:1, 10:1, 100:1 and 1000:1 with input voltages to 1100 Vdc. It has three separate 10:1 resistive divider networks which are combined to give 100:1 and 1000:1 divider networks.

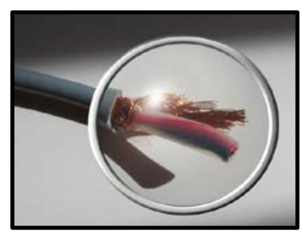
The 7520 automated Self-Calibration System (known as Self-Alignment), described in the 7520 Operator Manual, aligns the ratio values to the factory calibration, or last external calibration. The 7520's built-in Calibration System includes a Wheatstone bridge, Zener voltage reference, and optical Null Detector. The Self-Calibration process can be run once per month, but it is recommended it be run weekly. It is not necessary to disconnect the 7520 during Self-Calibration, however there should be no voltage present on the Reference Standard or Voltage Input terminals. The resistive divider networks and all internal standards used in the Calibration System are placed inside of a temperature regulated and EMI shielded chamber. The 7520 is the only divider that allows complete Self-Calibration requiring only the push of a single button. No external standards are required to perform the self calibration.

The 7520 has two modes of operation, Comparator Mode (i.e. compares two separate sources) and Divider Mode (i.e. divides the output from a voltage reference such as a zener or a calibrator). Each mode is accessed via an on-screen menu or SCPI command. A unique feature of Comparator mode is that the polarity of the reference input (e.g. zener) can be switched automatically thus eliminating the need to move lead connections.

Specifications for the 7520 are an absolute specification and include the Self-Calibration uncertainty. However, they do not include uncertainty contributions from external instruments used with a voltage divider such as a DMM or voltage source (e.g. zener or calibrator). The uncertainty contributions from the measurement setup that uses a 7520 must be quantified by the user.

Measurement Setup (Recommended Practices)

- After a 7520 is powered on, allow approximately six hours for the temperature chamber to thermally stabilize. Once stabilized and the Self-Calibration performed, the 7520 provides sub-ppm uncertainties for 1:1, 10:1, 100:1 and 1000:1 ratios.
- When using a zener voltage reference with a 7520, such as a Fluke 732A/B/C or Guildline 4410, allow at least 10 hours for the reference to stabilize in the measurement environment prior to use. The zener voltage reference should be configured to work off the internal battery with the power cord disconnected from the circuit main when making measurements with the 7520.
- Similarly, any calibrator, like a Fluke 5720A, should be turned on at least 2 hours prior to being used.
- For measuring the output voltage from the 7520 a Null Detector (ND), Voltmeter, or Digital Multi-Meter (DMM) with a nV resolution is typically used.
- When in Comparator Mode, to reduce the effect of lead resistance, equal length leads should be used from the voltage source to the divider and from the divider to the ND/DMM.
- Test leads, especially from the 7520 Voltage Divider to the ND or DMM should have the HI and LO leads twisted.
- Use low thermal EMF leads with clean connections (i.e. non-oxidized copper) or gold flashed connections. Guildline's SCW wire and/or gold plated banana connectors are ideal for low voltage measurements. The length of the leads should be minimized. The resistance of a 1 meter 18 gauge copper wire is about 11 mΩ/m and 1 meter of 22 gauge copper wire is about 14 mΩ/m. Note that if measuring output voltages of 1 V or lower, the resistance of the leads can cause a material offset if a DMM has low input impedance.

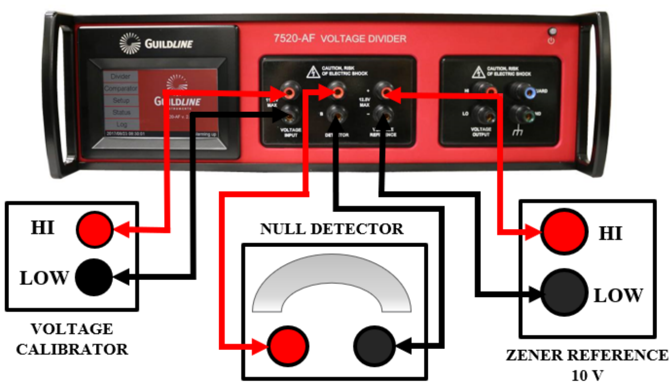


- In Divider Mode, to eliminate errors due to various offset effects, make repeated measurements and reverse the test leads. Lead reversal methods can correct for other errors such as common mode signal errors, etc.
- Any zener voltage reference should be configured to work off the internal battery with the power cord disconnected from the circuit main.

- To avoid noise from the power circuit all equipment should be connected via an isolating Uninterrupted Power Supply (UPS). The Voltage Divider, voltage reference/source and DMM should be connected to the battery side of the UPS.
- When using a UPS, the ‘Ground’ terminals of the equipment in the measurement setup should not be inter-connected to avoid ground loops.
- Ensure that there is no direct airflow or heat/cooling sources near the test setup as these can cause thermal EMF’s and affect the measurement process.
- In case of unstable readings or excessive noise in the measurement, the shields from all equipment used in the test setup should be connected to the 7520 ‘Guard’ terminal. In the absence of excessive noise, the ‘Guard’ terminal should not be connected.

COMPARATOR MODE OF 7520

When a calibrator is used as the voltage reference or voltage source, the Calibrator Sense Line should NOT be connected to 7520 voltage input terminals. This is because of the low input impedance of the 7520 for some ratios. Note that Fluke states in the 5700A Operator Manual that the sense line should not be connected when using a Fluke 752x voltage divider for the same reason.



Before starting a measurement, zero the DMM/ND as per the Operator Manual of the instrument you are using. In case of using a DMM as a ND, set the parameters of the DMM for an optimal measurement.
For example, when using a Fluke 8588A DMM the recommended setup is:

Resolution: 8 Digits (i.e., maximum resolution)
Z in: Auto (i.e. highest input impedance)
Range: 100 mV (i.e. lowest range)
Integration time of the A to D converter: Auto (i.e. 10 Seconds)

A longer integration time eliminates unwanted noise, essentially by filtering via an average over a longer period. If an integration time of 1 second is used the measurement will have more noise.

USE WITH A NULL DETECTOR (ND)

For lowest uncertainty measurements a Null Detector typically works better than a DMM in the comparator mode of the 7520. This is because a ND typically has high input impedance for all ranges (e.g. 10 MΩ to 100 MΩ), excellent sensitivity (e.g. 0.1 µV per division), high isolation (e.g. 10^{12} Ω), can operate off a battery, and sometimes has optical isolation. However, NDs are analogue devices, are susceptible to noise, and require some skill to operate.

The ND should be placed inside of an EMI shielded cage and it is recommended that an operator not be in close physical proximity to the test setup. One method to avoid operator proximity effects is to use a computer controlled camera so that the operator can read the ND analogue dial from at least 3 meters away.

The ND should be fully floating, working off internal batteries with the power cord disconnected, and placed on an isolating plate such as Teflon. Prior to starting a measurement with a ND, set to the lowest range (e.g. 1 µV range) and adjust the zero reading as per the instructions provided by the manufacturer of the ND. It typically takes several minutes for a ND analogue dial to settle so allow sufficient time for the readings to settle.

USE WITH A DIGITAL MULTI-METER (DMM)

Many calibration labs now use a DMM instead of a ND because the Fluke 845A/B ND is no longer available or serviced, and other NDs are manual and have limited application. Fluke recommends the use of an 8508A DMM or 8588A DMM as a replacement for their 845A/B ND.

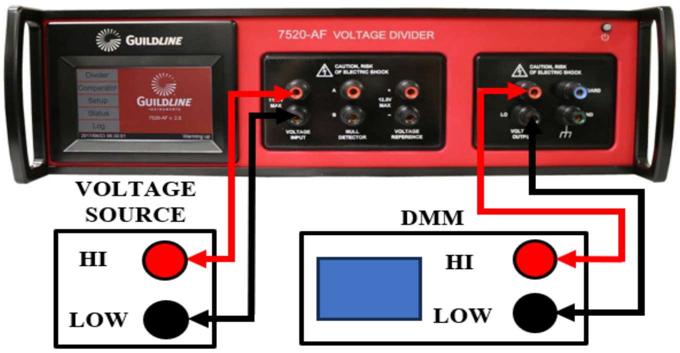
There are three issues with using a DMM: the input bias current of the meter, loading effect of the DMM due to the input impedance of the meter, and a relatively noisy measurement when connected to a device that has more than 100 kΩ output impedance.

The operational amplifiers typically used in a DMM have an input bias current where current flows from the amplifier through the input terminals of the DMM (i.e. between the HI and LO input terminals), typically below 10 picoamps. In contrast a typical 845A/B ND has a bias current of < 1-5 pA.
Due to loading effect, the DMM has an offset that is equal to the input impedance of the DMM placed in parallel with the output impedance of the connected device, such as a voltage divider. The third issue is that all DMMs have a noisier measurement when connected to devices that have an output impedance > 100 kΩ.

Fluke describes the bias current, proper zeroing, and impedance loading in the following Papers:

“Replacing analog null detectors with precision multimeters”,
“Using the Fluke Calibration 8588A in place of analog null detector for self-calibration of the Fluke 720A”, and

"Using digital multimeters in place of analog null detectors for metrological applications".



A. 7520 Ratio Output Impedance

All Voltage Dividers have an output impedance that is seen by the DMM or ND used in the measurement process. It is important to note the divider output impedance for each mode of operation, and the input impedance of the DMM/ND range being used, as these values influence the bias current and loading effect of the DMM or ND. Bias current and loading effects can equal or exceed the 7520 specifications if not accounted for or corrected for.

7520 Comparator Mode Null Detector Terminal Impedances		
7520 Menu Selection	Terminal Impedance (no load on reference or output)	Accuracy of Output Impedance
10 mV (1000:1)	5.8 kΩ	± 0.1%
100 mV (100:1)	43.2 kΩ	± 0.1%
1 V (10:1 V≤100)	43.2 kΩ	± 0.1%
10 V (1:1)	0.0 Ω	± 0.1%
100 V (10:1 V≤100)	43.2 kΩ	± 0.1%
1000 V (100:1)	43.2 kΩ	± 0.1%

7520 Divider Mode Voltage Output Terminal Impedances		
7520 Menu Selection	Terminal Impedance (no load on reference or output)	Accuracy of Output Impedance
1000:1	5.8 kΩ	± 0.1%
100:1	43.2 kΩ	± 0.1%
10:1 V≤1000	270 kΩ	± 0.1%
10:1 V≤100	43.2 kΩ	± 0.1%
10:1 V≤20	5.8 kΩ	± 0.1%
1:1	0.0 Ω	± 0.1%

B. Bias Current Effects and Measurement Contributions

For low uncertainty measurements, accounting for the bias current is necessary to ensure accurate readings, especially for high impedance inputs. If the voltage divider has an output impedance that is in the tens of kΩ or higher the DMM bias current could cause offset errors of several microvolts which is larger than the accuracy specification of the 7520 Voltage Divider. The bias current varies between different DMM models and can vary even within the same DMM model. A DMM that has a low bias current specification should be used, even though the effects of the bias current can be adjusted if the input polarity is reversed.

Determine the input bias current of the DMM, in the Divider Mode of 7520, by connecting the DMM to the voltage output terminals and shorten the voltage input terminals of the 7520 and measure any offsets on the DMM before applying any voltage. The voltage reading on the DMM resulting from the bias current can be determined and if it is stable and not too noisy it can be mathematically removed by applying an offset correction to the measurements being made by the DMM. In the Comparator Mode of the 7520, the input bias current of the DMM can be determined by shortening the voltage input terminals and voltage reference terminals and measuring the offset on the DMM from the null detector terminals of the 7520. If the bias current is too noisy then the DMM cannot be used with a 7520 or any other voltage divider.

In looking at the DMM bias current effect on measurements, it is a simple calculation of Bias Current x Output Impedance which is present at the Detector or Voltage Output Terminals. Listed below are some examples of this effect on the various impedances seen by the 7520 (or other manufactures) Dividers. When comparing a 7520 to a Fluke 752A, consider that the 752A has a terminal output impedance of about 40 kΩ.

Bias Current (A)	Divider Terminal Output Impedance (Ω)	Bias Voltage Produced (V)	Bias Voltage Effect at 10 V (ppm)
1.00 E-12	5.8 E+03	5.8 E-9	0.00058
5.00 E-12	5.8 E+03	29.0 E-9	0.0029
20.00 E-12	5.8 E+03	116.0 E-9	0.0116
50.00 E-12	5.8 E+03	290.00 E-9	0.029
1.00 E-12	43.2 E+03	43.2 E-9	0.00432
5.00 E-12	43.2 E+03	216.0 E-9	0.0216
20.00 E-12	43.2 E+03	864.0 E-9	0.0864
50.00 E-12	43.2 E+03	2.16 E-6	0.216
1.00 E-12	270.0 E+03	270.0 E-9	0.027
5.00 E-12	270.0 E+03	1.4 E-6	0.135
20.00 E-12	270.0 E+03	5.4 E-6	0.54
50.00 E-12	270.0 E+03	13.50 E-6	1.35

Example of How to Measure the DMM for the bias current before measurement.

Prepare the setup: Turn on the power to the DMM and ensure that the DMM is isolated from the rest of the circuit, meaning it's not connected to any other components or loads. Set the DMM to the appropriate voltage range and function.

Connect the resistor: Connect the DMM's positive and negative leads in series with a high-value resistor, usually in the mega-ohm range. Account for the lead resistance to ensure that most of the current flowing through the circuit is due to the input bias current. For example, a 100 MΩ resistance standard will result in approximately 1 mV reading on the DMM if the input bias current is 10 pA. Note that the 100 MΩ resistance standard will not be 100 MΩ due to the loading effect on the DMM. Depending on the DMM input impedance this value could change from less than 0.001% to 10% or more. However, the bias current will be close enough to determine how large this value is (e.g. 10 pA, vs 20 pA or 50 pA).

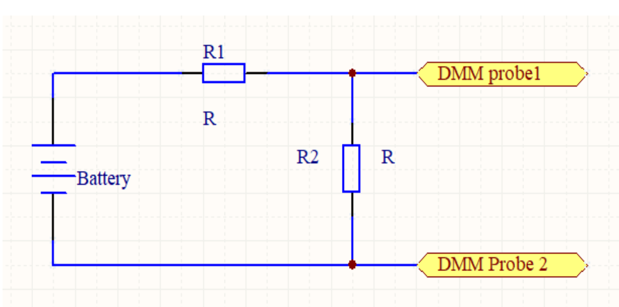
Record the Reading: This voltage reading will indicate the input bias current of the DMM. Repeat this test to observe if the offset is relatively noiseless, stable, and repeatable over time.

C. DMM Loading Effect and Measurement Contributions

All DMMs have a specified input impedance typically defined as Zin. The input impedance of a DMM on ranges typically less than 20 V can vary from 1 TΩ on a Fluke 8588A down to 10 GΩ on a Fluke 8508A; or down to 10 GΩ on a Keysight 3458A or 34420A. In most models of Long Scale DMM's (regardless of manufacturer), when going above the full scale range for measurements typically above 10 V or 20 V the DMM input impedance always changes to 10 MΩ.

How to measure the input impedance of a DMM:

Step 1: Set the DMM on the desired range.
Step 2: If you know the approximate input impedance of the DMM, choose R1 and R2 to be the same. If not then start with 1Mohm.
Step 3: Set the battery/DC voltage so that VR2 is less than the DMM's maximum input voltage. For example, if you want to measure the input impedance of a one-volt range, connect 1V5 to the input - VR2 = 0.75 V.
Step 4: Measure VR2 and Vbattery with the DMM.
Step 5: Calculate the DMM input impedance.
For example, Vbat = 1V, R = 1 MΩ and VR2 = 0.3 V
R||RDMM = 0.3/ 0.7 µA = 428571429 Ω
RDMM = 750013.206 Ω
Step 6: If the input impedance is too high compared to R, change R to a resistor around the measured DMM input impedance and repeat the process.



When a DMM is connected to any voltage divider, it draws some current or affects the voltage in the circuit due to its internal impedance. This loading effect can alter the actual output impedance of the divider terminals. This effect can basically be thought of two resistances (i.e. impedances) in parallel and thus can be calculated by using the parallel resistance Formula (R1*R2)/(R1+R2). The terminal impedance will change based on the DMM input impedance. Again, this effect is present regardless of the DMM used and the Divider being used. You can minimize it, but you cannot eliminate it.

The following is a table that shows the impact of various DMM input impedances on the output impedance of a divider. This is presented in nominal values, but the input impedance also has a specification that can vary from 0.1 % to 10 %. Since every DMM is different, the loading effect is not part of the 7520 specification and must be accounted for by the user depending on measurement standards used.

Nominal DMM Input Impedance (R1) (Ω)	Nominal Divider Output Impedance (R2) (Ω)	R2 Equivalent Impedance (Ω)	Change in R2 Nominal Value (ppm)
1.0 E+12 (1 TΩ)	5.8 E+03	5.799999966 E+3	-0.006
100.0 E+09 (100 GΩ)	5.8 E+03	5.79999966 E+3	-0.058
10.0 E+09 (10 GΩ)	5.8 E+03	5.79999664 E+3	-0.58
10.0 E+06 (10 MΩ)	5.8 E+03	5.79663795 E+3	-580
1.0 E+12 (1 TΩ)	43.2 E+03	43.19999813 E+3	-0.043
100.0 E+09 (100 GΩ)	43.2 E+03	43.19998134 E+3	-0.432
10.0 E+09 (10 GΩ)	43.2 E+03	43.19981338 E+3	-4.32
10.0 E+06 (10 MΩ)	43.2 E+03	43.01417875 E+3	-4301
1.0 E+12 (1 TΩ)	270.0 E+03	269.99992710 E+3	-0.27
100.0 E+09 (100 GΩ)	270.0 E+03	269.99927100 E+3	-2.7
10.0 E+09 (10 GΩ)	270.0 E+03	269.99271020 E+3	-27
10.0 E+06 (10 MΩ)	270.0 E+03	262.90165531 E+3	-26290 (2.63%)

If you examine this loading table and then compare it to the two tables showing the terminal impedance, you will find that in Comparator Mode, if using a DMM with 1 TΩ of input impedance, the maximum error due to loading would be 0.043 ppm. This would also be similar to a Fluke 752A since this terminal impedance is around 40 kΩ.

In the Divider Mode, when using the 10:1 at 1000 V, two things happen. First, the impedance at the 7520 Voltage Output terminals is 270 kΩ. Second, the DMM input resistance will typically change to 10 MΩ for all voltages above 200 V. This is due to the fact you are measuring using the DMM's 100 V

Range input impedance. This will cause around a 2.63 % error, but the reading will be stable. The only way to compensate is to calculate the DMM actual input impedance, and mathematically adjust for the reading.

This large error (e.g. about 2.63 %) is not present on the Fluke 752A, as the 752A only allows for 100 V in the divider mode, putting the impedance on par with the 7520 10:1 at 100 V. Guildline decided to provide 1000 V at 10:1 ratio, however when using the 7520 10:1 ratio with 1000 V input, a customer will need to determine the loading effect.

For the 7520 10:1< 20 V and 10:1< 100 V ratio (i.e. with respective output impedances of 5.8 kΩ and 43.2 kΩ); and for the 100:1 and 1000:1 ratios (i.e. with respective output impedances of 43.2 kΩ and 5.8 kΩ); the DMM noise contribution is not that material with respect to the 7520 uncertainties. However, for the 10:1 ratio for < 1000 V with an output impedance of 270 kΩ, the noise contribution when using a DMM is material.

D. High Impedance Noise

Another consideration when using a DMM is that they are noisier when connected to a higher output impedance, such as > 100 kΩ. This is illustrated by the following table showing the standard deviation when a DMM is used to measure three resistances of similar values to the 7520 output impedances. Although a Fluke 8588A DMM was used for illustrative purposes, noise also increases for a Fluke 8508A or Keysight 3458A when measuring resistances above 100 kΩ.

Measure Decade Resistance Standard Using 8588A DMM

	6 kΩ	40 kΩ	300 kΩ
Standard Deviation (V)	0.000000022	0.000000027	0.000000187
STDEV (µV/V)	**0.022**	**0.027**	**0.187**

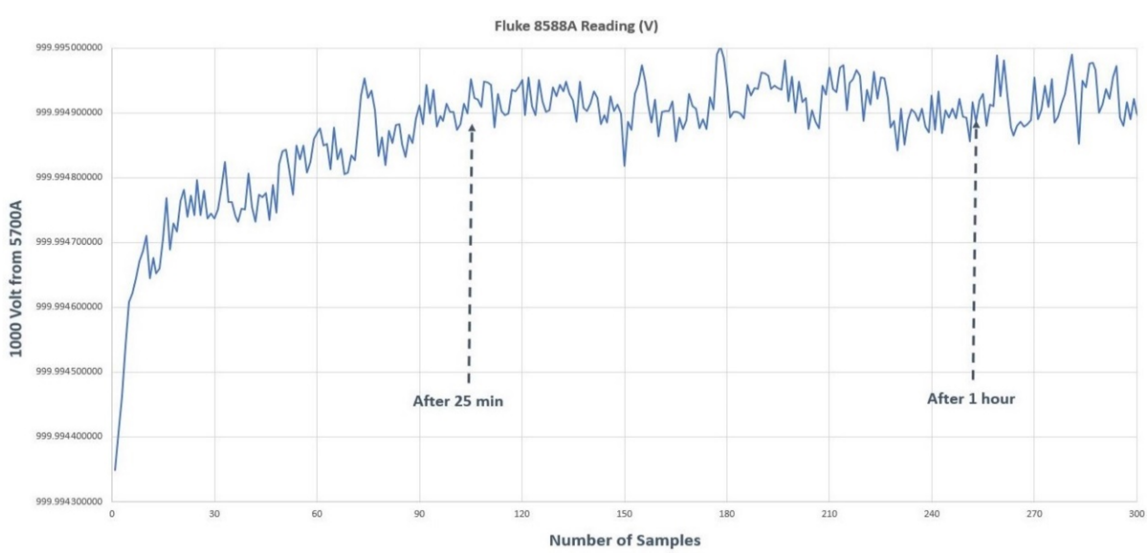
When using the Guildline 7520 10:1 ratios, based on the input voltage, the ratio with the smallest output impedance should be chosen. It is preferrable to use a null detector with any voltage divider to avoid having to address the previously described DMM issues. If comparing the output voltage of a 7520 to a Fluke 752 where possible the 7520 1:10 ratio with output impedance of 43.2 kΩ should be used as the Fluke 752 has an output impedance of approximately 40 kΩ. It is easier to compare different voltage dividers if they have the same output impedance.

USE OF 7520 WITH HIGHER VOLTAGES

It typically takes about 20 to 25 minutes for a calibrator to reach a stable 1000 V output, and this time can vary slightly depending on the calibrator. It is also recommended that a DMM be turned on a half hour before taking a measurement, and a DMM will need about 10 to 20 minutes to stabilize when reading 1000 V. If a 7520, or any other voltage divider, is being used with 1000 V input from a calibrator it is recommended that the test setup be allowed to stabilize for 20 to 25 minutes. The graph below shows a 1000 V output from a Fluke 5700A Calibrator being measured by a Fluke 8588A DMM.

This graph also shows a noisy signal. Consider that the 1000 V stability specification of a Fluke 5700A for 24 hour stability at ± 1 °C from calibration temperature at 95% confidence level is 2 ppm of output voltage plus 400 µV. The specification for a 8588A reading 1000 V is 1 ppm plus 500 µV. The specification of the 7520 10:1, 100:1 and 1000:1 ratios is respectively 0.1, 0.2 and 0.5 µV/V. When using a calibrator and/or DMM, their uncertainty contribution is large in comparison to the uncertainty contribution of 7520 and must be taken into consideration.

When using a 7520 at different voltages it is recommended to start measurements with the lower voltages first. Although the 7520 has a temperature regulated chamber, it takes a few minutes for the self-heating of the resistors in the divider



network to stabilize. For input voltages less than 20 V self-heating is not material. For input voltages between 20 V and 100 V it is recommended that a wait time of 10 minutes be used. For input voltages between 100 V and 1100 V it is recommended that a wait time of 20 minutes be used. However, if using a calibrator to generate the input voltage an equivalent time is required for the calibrator's output voltage to stabilize as illustrated at the bottom of the previous page.

If using a 7520 with 1000 V input and the input voltage is switched to 100 V it is recommended to wait 10 minutes for the resistors in the divider network to stabilize at their new 'self-heating' temperature. If using a 7520 with 1000 V input and the input voltage is switched to ≤ 20 V it is recommended to wait 20 minutes.

Zener Voltage Reference Short Term Stability

When the 7520 is used with a zener voltage reference the short term stability of the zener reference should be taken into account. For example, the 30 day short term stability of a Fluke 732C at ± 1 °C from calibration temperature is "0.3 µV/V", and more importantly the noise specification at k=2 (i.e. 95 % confidence level) is 0.14 µV/V. The zener stability is reflected in the standard deviation of the output voltage and contributes to the measured Type A uncertainty. The uncertainty contribution from a zener voltage reference is typically higher than the uncertainty contribution of a 7520 voltage divider.

Calibrator Voltage Short Term Stability

The stability of the output voltage from a calibrator must be considered. For example, a Fluke 5720A has a short term stability (i.e. relative uncertainty at a 95% confidence level) over a 24 hour period at a temperature range of +/- 1 °C (i.e. from the 5720A calibration temperature) of 1.6 ppm of output + 40 ppm of range at 100 V; and is 2.0 ppm of output + 400 ppm of range at 1000 V. The calibrator stability is reflected in the standard deviation of the output voltage and contributes to the measured Type A uncertainty. The uncertainty contribution from a calibrator being used as a voltage reference is typically higher than the uncertainty contribution of a 7520 voltage divider.

Guildline's Calibrator Setup For A 7520 Voltage Reference

Guildline does not use a DMM for the calibration of 7520 Voltage Dividers to avoid the previously described problems. Guildline uses a Null Detector (ND) in the calibration setup. Guildline's calibration setup is also not dependent on the absolute value of the zener reference or calibrator (i.e. voltage input), nor is it dependent on the short term stability of the voltage input being used. Guildline uses a reference 7520 Voltage Divider, calibrated by a NMI with low uncertainties, as a ratio reference device. The setup is like a Wheatstone Bridge where both the Reference 7520 and the DUT 7520 being calibrated have the same input voltage (i.e. are connected in parallel to the voltage input). Since both the Reference 7520 and DUT 7520 have the same voltage input, the voltage input does not have to be calibrated. Similarly, since both have the same voltage input, the short term drift of the voltage input is not important. In addition, both the Reference 7520 and the DUT 7520 are connected by short low thermal leads of the same length, as are the connections to the ND, so no adjustment is required with respect to the resistance of the leads used in the measurement setup.

Finally, the voltage output is compared via a null detector. The zener reference and null detector are configured to work off a battery, and all other devices are connected to an isolating UPS. All instruments are placed into an EMI shielded cage. The EMI cage is required for best measurements when using a null detector. Finally, the null detector is read by a camera, thus avoiding operator proximity effects.

Once a 7520 Voltage Divider is calibrated by Guildline, or an NMI, the self-calibration process returns it to the original sub-ppm ratio uncertainties with a single touch. There is no need for a customer to re-calibrate their 7520 Voltage Divider using external standards unless required by an Accreditation Body.

In contrast competitors state that their voltage dividers are self-calibrating even though external standards are required. As described in this paper it is not possible to calibrate a voltage divider to sub-ppm uncertainties unless the voltage reference and DMM are calibrated before the voltage divider is calibrated, and the DMM must be characterized for bias current and loading effect. As well, for sub-ppm uncertainties competitive voltage dividers have to be calibrated before use or every few weeks.

GUILDLINE
INSTRUMENTS

For more information about the Automated 7520 Voltage Divider or any of our other primary level instruments contact Guildline Instruments at:

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