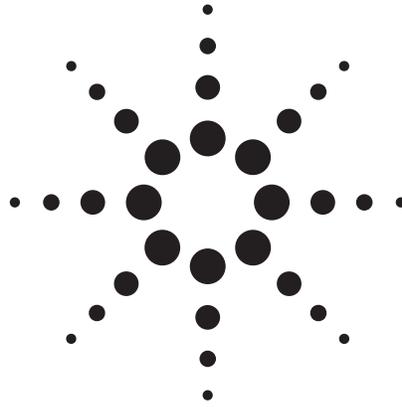


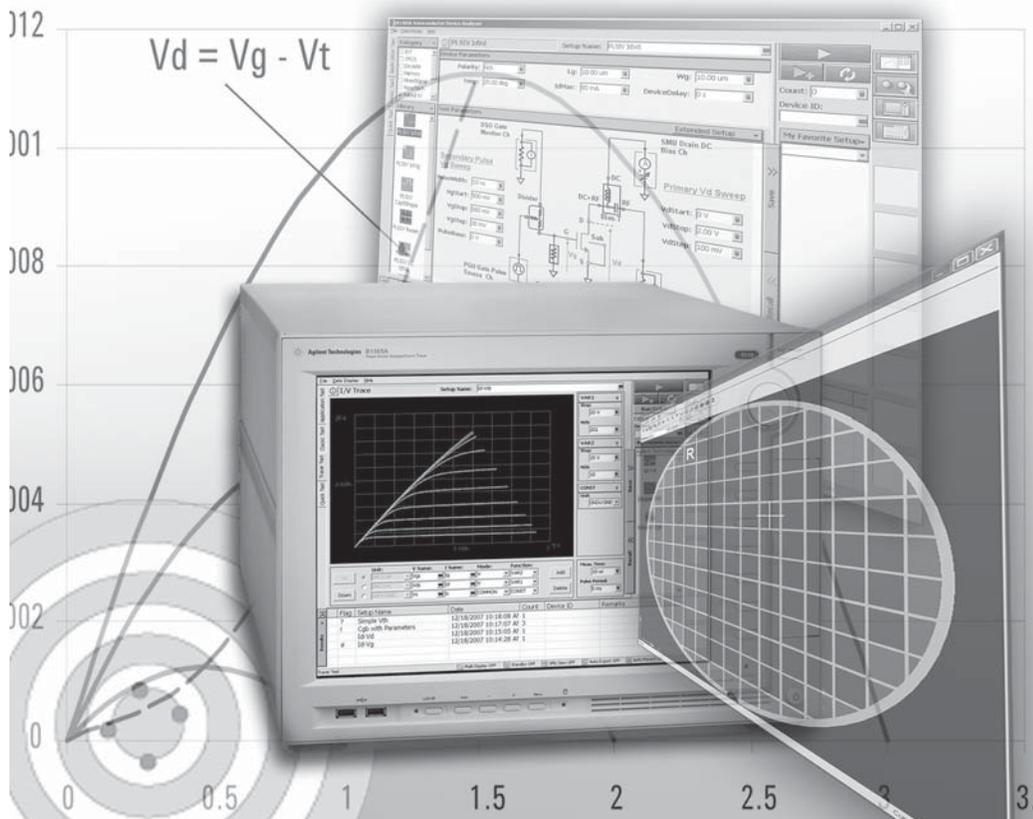
Excerpt Edition

This PDF is an excerpt from Chapter 3
of the Parametric Measurement Handbook.

The Parametric Measurement Handbook



*Third Edition
March 2012*



Agilent Technologies

Chapter 3: Source/Monitor Unit (SMU) Fundamentals

“You do not really understand something unless you can explain it to your grandmother.” — Albert Einstein

SMU overview

Introduction

The primary measurement resource for parametric test is the source/monitor unit or SMU. This is also sometimes also referred to as a source/measurement unit, although the acronym ends up the same. The SMU can force voltage or current and simultaneously measure voltage and/or current. The diagram below shows a simplified SMU equivalent circuit:

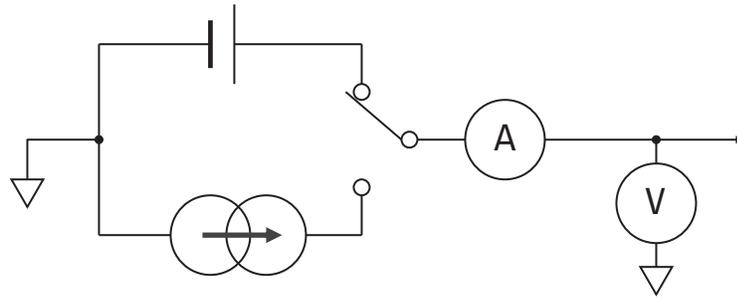


Figure 3.1. Simplified SMU schematic.

Since SMUs must measure very low currents (1 fA or less), they always have triaxial outputs for the reasons discussed in the previous chapter.

There are a variety of different types of SMUs. The most common SMU is the medium-power SMU (MPSMU); as the name implies this SMU can supply moderate levels of voltage and current (± 100 V and ± 100 mA) and current measurement resolution down to 10 fA. For precision measurements there is the high-resolution SMU (HRSMU); this SMU can supply the same current and voltage as the MPSMU, but it provides current measurement resolution of 1 fA or less and voltage measurement resolution of 0.5 μ V. The high-power SMU (HPSMU) is for situations requiring larger currents and voltages than can be supplied by the MPSMU or HRSMU; this SMU can supply current up to ± 1 A and voltages up to ± 200 V, and the measurement resolution capability is similar to that of a MPSMU.

In addition to the basic SMU types just mentioned, some SMUs support an additional module that enables them to achieve current measurement resolutions of 0.1 femtoamps (100 attoamps). In order to achieve this level of current measurement resolution the actual measurement unit has to be placed in close proximity to the device under test (DUT). This means that this module has to be mounted onto the wafer prober and connected back to an SMU installed in the parameter analyzer mainframe via some sort of cabling arrangement. In the case of the Agilent B1500A, this module is called the atto-sense and switch unit (ASU). In addition to providing 0.1 fA current measurement resolution, the ASU also has some switching capabilities that will be discussed further in Chapter 4.

Module	HPSMU	MPSMU	HRSMU	ASU
Maximum Force Voltage	±200 V	±100 V	±100 V	±100 V
Maximum Force Current	±1 A	±100 mA	±100 mA	±100 mA
Voltage Measurement Resolution	2 μV	0.5 μV	0.5 μV	0.5 μV
Current Measurement Resolution	10 fA	10 fA	1 fA	0.1 fA

Figure 3.2. The key specifications of the basic SMU module types.

The B1505A supports two special types of SMUs. The high-current SMU (HCSMU) operates in two modes: DC and pulsed. In DC mode the HCSMU can source up to ±1 A at 40 V; in pulsed mode the HCSMU can source up to ±20 A at 20 V. The HCSMU has a unique output configuration and cabling requirements that will be discussed later in this chapter. The high-voltage SMU (HVSMU) can source up to 3000 V at 4 mA. Due to its high output voltage capability, the HVSMU requires a special high-voltage triaxial cable that has a special screw-on triaxial connector. This insures that a standard triaxial cable cannot accidentally be used with this module.

Module	HCSMU	HVSMU
Maximum force voltage	±40 V (DC) ±20 V (Pulsed)	±3000 V
Maximum force current	±1 A (DC) ±20 A (Pulsed)	±8 mA at ±1500 V ±4 mA at ±3000 V
Voltage measurement resolution	200 nV	200 mV
Current measurement resolution	10 pA	10 fA

Figure 3.3. The key specifications of the HCSMU and HVSMU (B1505A only).

Note: For the HVSMU module the output voltage and current must be the same polarity.

Except for the HCSMU, SMUs are single-ended devices with one end always tied to a common internal reference point. The SMU reference level is normally tied to chassis ground via an external shorting bar, but this shorting bar can be removed and the SMU reference can be tied to an external voltage (up to 42 V maximum) using various types of connectors.

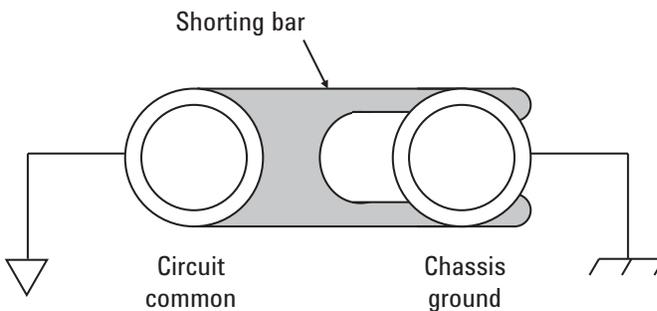


Figure 3.4. You can remove the shorting bar from the chassis ground to float the SMU circuit common.

All SMUs have some pulsing capability during sweep measurements (used to prevent heating on thermally sensitive devices), and SMUs can also make time sampling measurements. However, the pulsing and time sampling capabilities of SMUs are relatively slow (in the microsecond range). It is important to understand when you can use an SMU to make pulsed measurements and when you need the pulsing capabilities of a semiconductor pulse generator unit (SPGU) or waveform generator/fast measurement unit (WGFMU) (which possess nanosecond pulsing capabilities). These different solutions will be covered in detail when we discuss making high-speed measurements in Chapter 5. Because of their relatively slow pulsing capabilities, triaxial cables and DC probes can be used with SMUs when performing pulsed and time sampling measurements. However, as will be discussed in subsequent chapters pulsing and fast measurements made with other types of modules (such as the HV-SPGU and WGFMU modules) require specialized cables and RF probes for optimal measurement results.

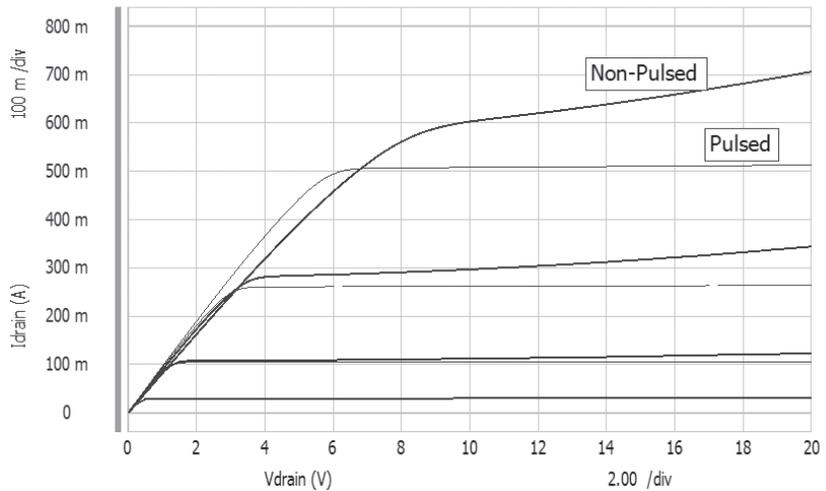


Figure 3.5. SMUs can be pulsed during sweep measurements to eliminate device self-heating effects that can distort measurement results as shown in the above MOSFET I_d versus V_d plots.

SMU operation modes and settings

SMUs have three basic modes of operation: voltage source, current source and common. In common mode the SMU acts as a 0 V voltage source, it cannot perform any measurement, and the current compliance is automatically set to the SMU's maximum value. In addition, for sweep measurements you can have one SMU in voltage pulse or current pulse mode to prevent device self-heating on thermally sensitive devices.

SMUs have the ability to specify a compliance setting. The compliance setting is always opposite to that of the source setting of the SMU (that is, current compliance when the SMU is in voltage source mode and voltage compliance when the SMU is in current source mode). When an SMU reaches compliance, it acts as a constant voltage or current source. The compliance feature prevents inadvertent device damage by not allowing the measured quantity to exceed the specified compliance value. In addition, on swept sources it is also possible to specify power compliance. The power compliance prevents the total power output by the SMU from exceeding the specified power compliance value. If both standard and power compliance are specified, then the SMU will never exceed whatever is the lower of these two settings.

On the "Measurement Setup" tab in Agilent EasyEXPERT software you can specify the various compliance settings for each SMU. In addition, there is a "Sweep status" selection menu that allows you to select either "CONTINUE AT ANY" or "STOP AT ANY ABNORMAL". The "continue at any setting" will continue making measurements regardless of any abnormal conditions that may occur (such as a measurement error, reaching compliance, etc.). Conversely, the "stop at any abnormal" setting will immediately halt testing when any of these conditions occurs. Especially in the case of automated measurements (where you are not monitoring the status of the instrument as it measures) the stop at any abnormal feature can be valuable in reducing needless measurement time. An example of this is shown below.

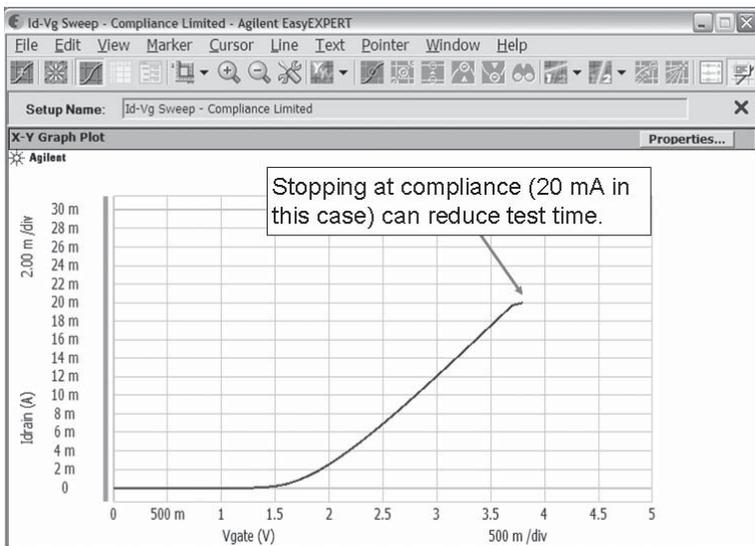


Figure 3.6. By using the stop at any abnormal setting you can automatically halt testing when compliance is reached and avoid needlessly continuing a measurement.

SMU force and sense outputs

The situations requiring Kelvin measurements and the basic theory of Kelvin measurement have already been discussed. By separating the force and sense lines you can eliminate the effect of cable resistance from your parametric measurement. To make this task easier, modern SMUs are designed with both force and sense outputs. The following illustration shows the output configuration of a Kelvin SMU:

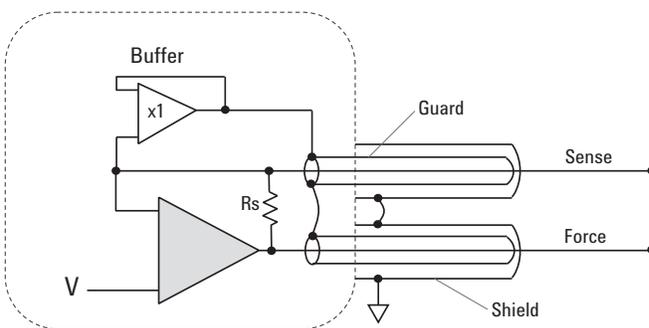


Figure 3.7. Simplified Kelvin SMU output circuit.

The great benefit of a Kelvin SMU configuration is that you only need two SMUs to perform a Kelvin measurement as shown below:

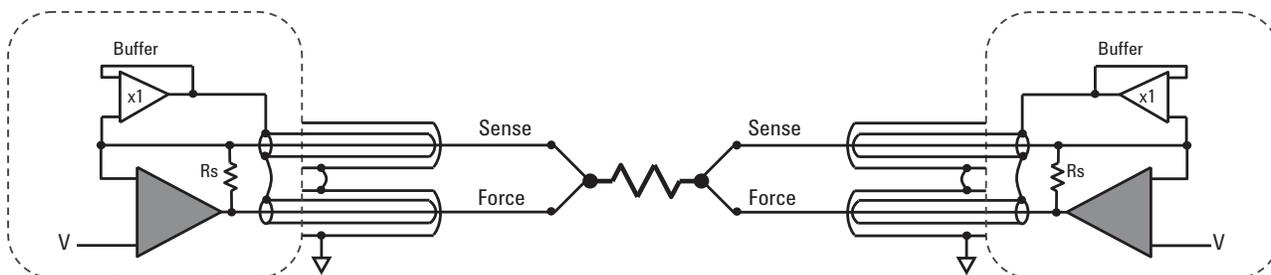


Figure 3.8. Making a Kelvin measurement on a resistor with two Kelvin SMUs.

It is important to point out that the force and sense lines should be shorted together as close to the DUT as possible (for example by using Kelvin triaxial positioners), since the effects of any additional resistance beyond the shorting point will not be eliminated from the measurement.

Many situations do not require Kelvin measurements so it is important to understand which SMU output to use when NOT making Kelvin measurements. If not making Kelvin measurements and using only one output of the SMU then you must always use the force output. The force and sense lines are internally connected via a resistor and this internal sense point is a high-impedance node, so the SMU has no problems with monitoring the current and voltage on the force output when only using the force line. However, consider what happens if you use only the sense line. In this case the entire current flowing out (or in) through the sense output has to pass through the internal resistor as shown below:

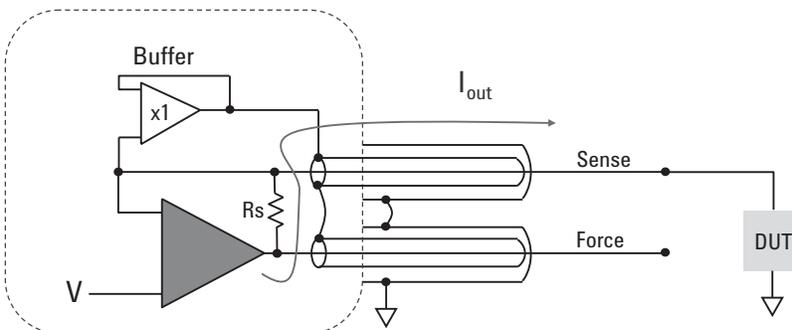


Figure 3.9. The problem with using only the sense line on a Kelvin SMU.

This will distort all of you measurement results and give completely incorrect measurement data! **Never connect only the sense line of a Kelvin SMU to the DUT.**

It is possible to use the SMU sense line as a buffered voltage monitor of the SMU force line in non-Kelvin measurement situations. The most common case is when you are driving the gate of a MOSFET with the force line of an SMU and you want to monitor the gate voltage. Using a triaxial to coaxial adapter (guard floating) you can connect the SMU sense line directly to the oscilloscope input as shown below.

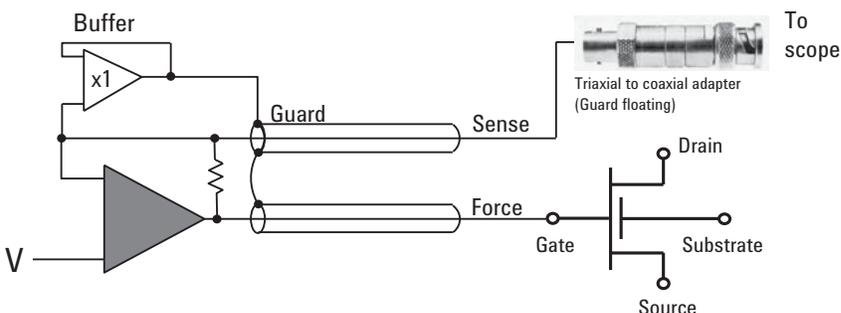


Figure 3.10. If the sense line of the SMU is not used, then you can connect it to an oscilloscope to monitor the SMU output.

Note: When placing any loading onto the output of an SMU you have to be careful, as there is a specified limit on the capacitance. Attaching large capacitive loads to SMU outputs can result in oscillation, so you need to make sure that your oscilloscope input capacitance does not exceed the specified limit of SMU load capacitance.

Understanding the ground unit

The ground unit (GNDU) is a special type of SMU that does not have any measurement capabilities. Its purpose is to provide an active ground to use with the other instrument resources. The ground unit will always maintain a voltage of zero volts as long as you do not exceed the maximum specified value that it can sink or source (for example ± 4.2 Amps in the case of the Agilent B1500A and B1505A). The benefit of using an active ground versus a passive ground should be obvious: you do not need to worry about the Ohmic drop from large currents distorting your measurement results (at least if you maintain a Kelvin environment).

The configuration of the ground unit is a source of confusion for many users. This confusion is understandable given that, while the ground unit looks like a standard triaxial connection, it is not. The ground unit has the configuration that it does for historical reasons; in the past there simply was not enough room on some instruments for a separate force and sense line for the ground unit. Therefore, the force and sense lines were merged into a single connector. A comparison of the connections on a standard triaxial cable and the ground unit is shown below:

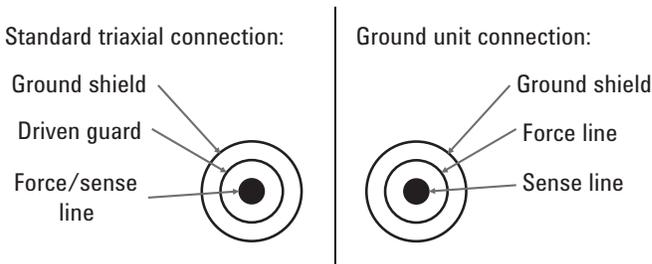


Figure 3.11. Comparison of standard triaxial connection and the ground unit.

The ground unit can have the configuration that it does because the potential of the force and sense lines is always at zero volts, so there is no need to isolate them from the outer ground shield to prevent leakage currents. It should be noted that the ground unit is the only case in which this scheme can work.

The illustration shown below highlights the problem with connecting up the ground unit like a standard triaxial output.

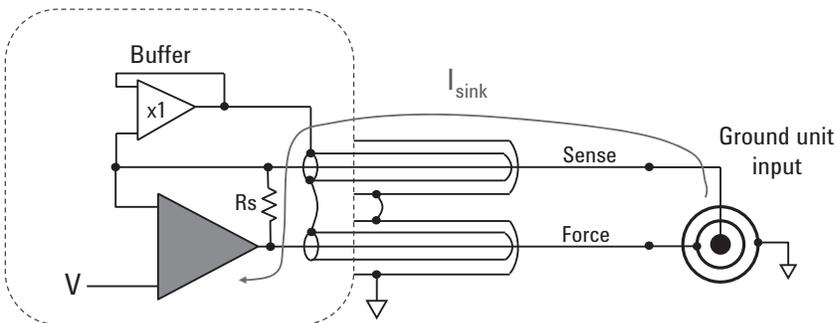


Figure 3.12. The problem with connecting up the ground unit like a standard triaxial connection.

As you can see, connecting up the ground unit like a standard triaxial connection is equivalent to connecting up only to the sense line on a Kelvin SMU. Obviously, this will lead to erroneous measurement results.

The following illustration shows the proper way to connect the ground unit to standard Kelvin SMU connections. Agilent can supply a ground unit to Kelvin adapter, the N1254A-100, which converts the ground unit output into the force and sense outputs as shown below.

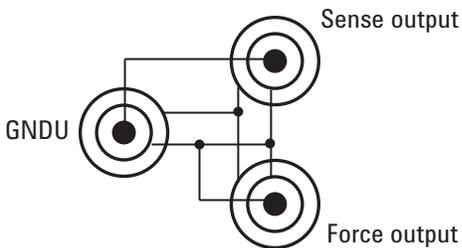
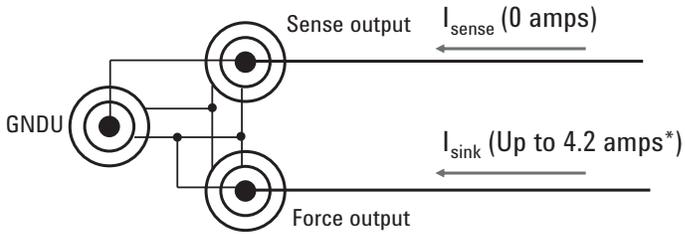


Figure 3.13. The proper way to connect a ground unit to standard triaxial connections.

Of course, the ground unit adapter can be used with only the force output connected just like a standard SMU. However, you need to be careful when doing this. Assumedly one reason that you are using the ground unit is to sink large currents, and large currents innately require a Kelvin connection (using both the force and sense outputs). Therefore, especially if you are using the ground unit to sink current from one or more high-power SMUs, it is highly recommended that you connect the ground unit in a Kelvin configuration as shown below:



*B1500A & B1505A

Figure 3.14. The ground unit should be used in a Kelvin configuration when sinking large currents.

Note: Agilent makes a special triaxial cable designed to be used with the force output of the ground unit. This cable can handle the 4.2 amps maximum current. The part numbers are 16493L-001 (1.5 m), 16493L-002 (3 m) and 16493L-003 (5 m).

High current SMU connections (B1505A)

As was mentioned earlier, the high current SMU (HCSMU) is a special module available only for the B1505A. Its structure is similar to that of an SMU except that it can source up to 20 A of current (pulsed). Because no other module can sink this much current, the HCSMU also has to have the ability to sink its own current. This gives the HCSMU a unique output configuration.

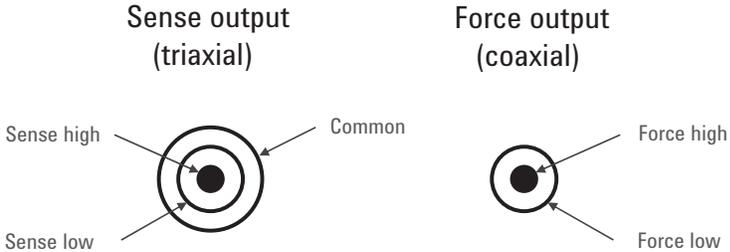


Figure 3.15. The output connections on the HCSMU.

The force lines of the HCSMU do not perform any measurement so they do not require any shielding and they can be coaxial. On the other hand, the sense lines of the HCSMU do perform measurement so they require shielding and they need to be triaxial. Fortunately, this arrangement makes it impossible to confuse the two outputs.

The HCSMU module is floating and is not tied internally to the instrument ground. This means that its low force and sense outputs must be tied to a reference level (normally the ground unit) when making a measurement. An example MOSFET measurement using the HCSMU is shown below.

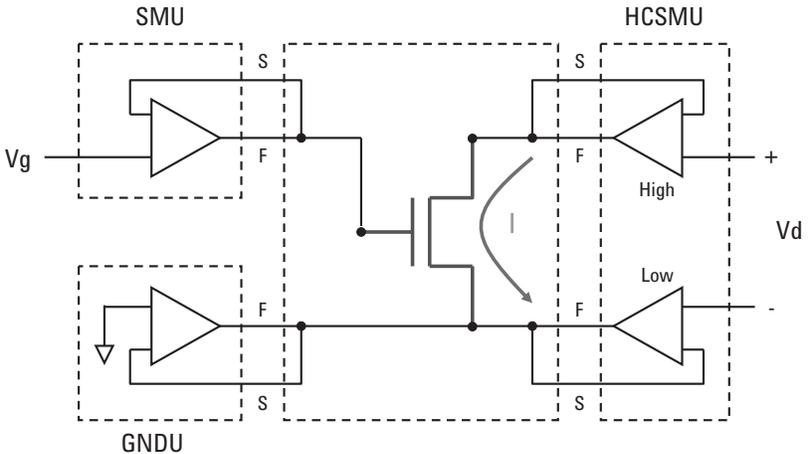


Figure 3.16. The HCSMU needs to have its low outputs (force low and sense low) tied to a known voltage reference when making a measurement.

When you are using the HCSMU with the N1259A high-power test fixture the N1259A takes care of correctly separating out the HCSMU connections. However, you need to make sure that you use the correct cables and adapters when connecting the HCSMU up to a wafer prober. Agilent supplies a variety of adapters and connectors for this purpose. This will be covered in greater detail when we discuss making on-wafer measurements in Chapter 4.

Measurement ranging

Measurement ranging basics

Measurement ranging is intimately interrelated with measurement accuracy and resolution. However, before proceeding it is important to understand why SMUs have a range setting in the first place. The SMU circuitry has to switch in and out (using relays) different resistor values in order to handle the maximum expected current or voltage value based upon the initial compliance setting specified by the user. An example of this circuitry is shown below:

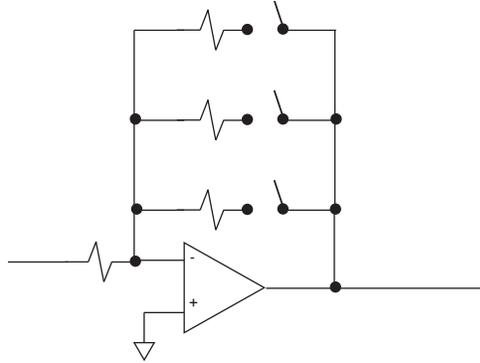


Figure 3.17. SMU ranging requires that resistors of different values be switched in and out of the circuit depending upon which particular range you are in.

Selecting one or more resistors via these relay switches places the SMU into a given measurement range. Obviously, it takes some time to switch these relays and move from one range to the next. While it would be possible to always have the SMU start at the highest possible measurement range and work its way down to the lowest measurement range that contained the quantity being measured, this would result in extremely slow measurements. By allowing flexibility as to how a measurement range is selected, the user gains the ability to trade off measurement speed versus accuracy.

There are typically three types of ranging selectable on an SMU: fixed, limited, and auto. The illustration below shows how each of these choices impacts the measurement range used by the SMU:

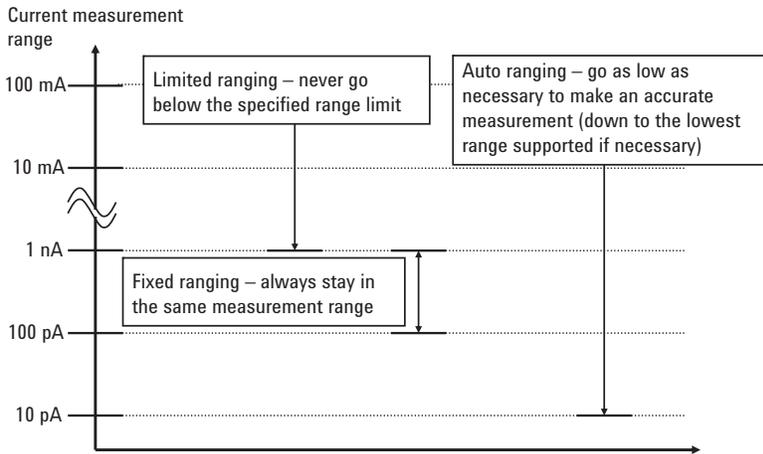


Figure 3.18. An explanation of the three types of measurement ranging: fixed, limited and auto.

Ranking the measurement ranges in terms of fastest to slowest, the order would be: fixed (fastest), limited (next fastest), and auto (slowest). Although fixed measurement ranging yields the fastest measurement results, it has the limitation that the SMU will not go into a lower measurement range to improve measurement accuracy. Also, if you attempt to measure a current or voltage in fixed measurement range that exceeds the maximum value of the fixed measurement range you will get a measurement error. Limited ranging and auto ranging are similar in that they both start in the highest measurement range that contains the user-specified compliance value, and they both work their way down to find the optimal range in which to make the measurement. The difference between the two ranging choices is that limited ranging will never go below the user-specified range limit. Thus, limited ranging is useful when you are uncertain of the value of current or voltage that you will be measuring and you do not care about ultra-precise measurement. However, if you absolutely have to have the best measurement accuracy and measurement time is not a concern then auto ranging is the correct choice.

There is no hard and fast rule to specify the measurement resolution achievable within a given measurement range. The Chapter 2 discussion of measurement resolution pointed out that the primary determining factor is the number of bits in the SMU analog-to-digital converter (ADC). However, the actual measurement resolution achievable has to take into account other factors such as noise, drift, etc. This introduces a stochastic element to the measurement that requires averaging. The net result is that in most cases the minimum measurement resolution is 4-5 decades below the measurement range. Note that on some instruments the SMUs may have more than one ADC available to them; in this case you need to check carefully to make sure that you understand the measurement resolution associated with the ADC that you are using.

There is one important point to understand regarding the use of fixed measurement ranging that was mentioned previously but is worth repeating again here. In fixed measurement ranging you can measure currents or voltages smaller than the measurement range that you have chosen, since as mentioned above the measurement resolution is 4-5 decades below the measurement range. Even if the actual measured value is more than 4-5 decades below the selected measurement range, the instrument will still return a result (albeit with reduced measurement resolution). However, if you try to measure a current or voltage that exceeds the specified fixed measurement range then you will get a measurement error. Therefore, finding the optimal fixed measurement range is always a balancing act between selecting a range low enough to provide sufficient measurement resolution and high enough to always contain the quantity under measurement.

Measurement range management

In order to understand the range management feature and why it is sometimes necessary we must first understand the issue of range compliance. We previously explained that the SMU switches various resistors in its internal circuitry in and out as it moves between different ranges. This process takes some time and it is part of the normal operation of the SMU. However, what was not mentioned was that as the SMU (for example) moves into lower current measurement ranges, its output sourcing capability is also temporarily reduced to the value of the measurement range plus a guardband factor (around 10%). This is called "range compliance" to differentiate it from the SMU compliance that is specified by the user. Obviously, range compliance is only a transient issue in that if the SMU needs to source more current then it will move up into the next measurement range until it either can supply the required current or it reaches the user-specified SMU compliance.

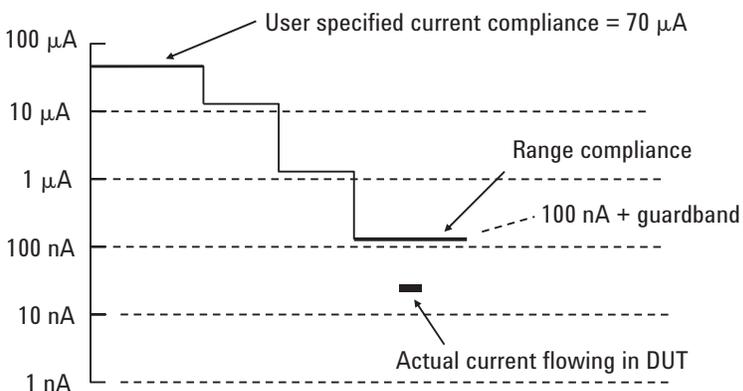


Figure 3.19. Range compliance limits the amount of current that an SMU can supply in a given measurement range.

In order to understand why range compliance can sometimes be an important issue, please refer to the figure shown below.

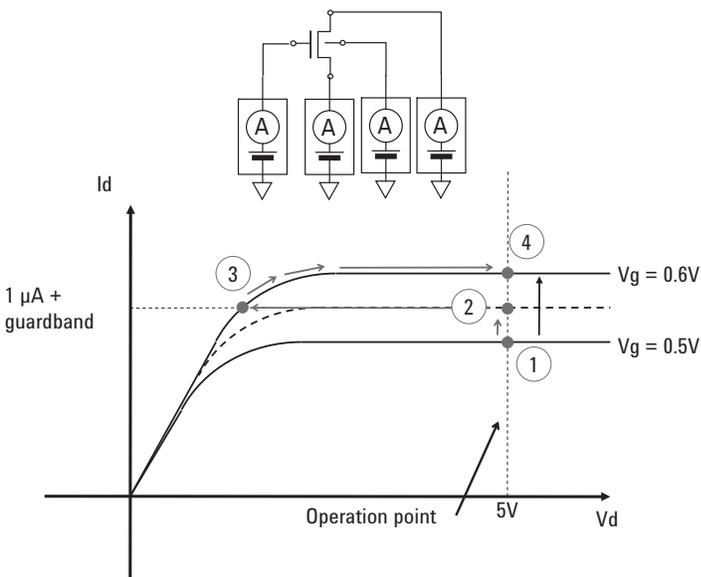


Figure 3.20. The effect of range compliance on SMU voltage output.

Suppose that we are measuring a device with the I_d - V_d characteristic shown in the above figure and that we are starting at the operating point denoted by "1" ($V_g = 0.5$ V). We want to move to the operating point denoted by "4" by changing the applied gate voltage to 0.6 V. However, this action requires us to move up into the next measurement range. Since this measurement range change is not instantaneous, as soon as the operating point moves to the position denoted by "2" the SMU cannot supply all of the current that the DUT wants. This means that the operating point must move to the position denoted by "3". When the SMU finally moves up into the next measurement range it can supply the current requested by the DUT and the operating point moves to position "4". When viewed on an oscilloscope this would give the appearance of an SMU voltage glitch, even though what is really happening is that the DUT is causing the voltage droop because the SMU is starving it for current.

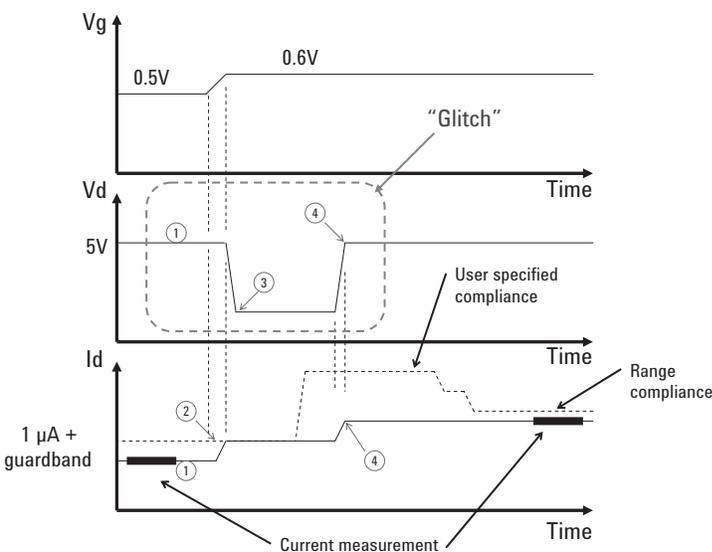


Figure 3.21. Voltage "glitch" on a MOSFET drain caused by temporary range compliance.

For the vast majority of parametric measurements, range compliance never causes any measurement issues. In fact, if we had not just discussed this issue you probably would never have suspected that it existed. However, in a certain small percentage of cases the voltage swings caused by the DUT due to current starvation can impact parametric measurements and even cause device damage (if the voltage swing is on the substrate and it causes the device to latch up). Until the development of the range management feature, the only solution to this issue was to replace the sweep measurement being performed with a series of spot measurements. Replacing the sweep measurement with a series of spot measurements always fixes this issue, since a spot measurement always starts at the measurement range containing the SMU compliance value and works its way down to the correct measurement range (thus avoiding any range compliance issues). However, performing a series of spot measurements in this fashion takes much more measurement time than an equivalent sweep measurement, and this was not acceptable to most users. To solve this issue Agilent Technologies developed (and patented) the range management feature.

Range management can be viewed as a sort of “range look-ahead” feature. The range management feature allows you to set trigger points within a measurement range (from 11% to 99% of the range) that force the SMU to go up (or optionally down) to a new measurement range BEFORE the measurement range limit is reached. The figure shown below helps to illustrate how the range management feature works.

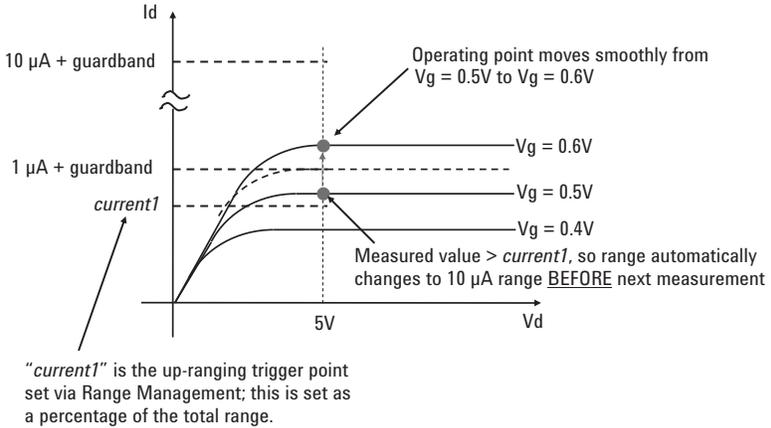


Figure 3.22. Illustration of how the range management feature causes the SMU to move up in range before reaching the range limit.

Applying the range management feature to the case previously discussed, we can see that the voltage droop seen at the MOSFET drain can be eliminated completely.

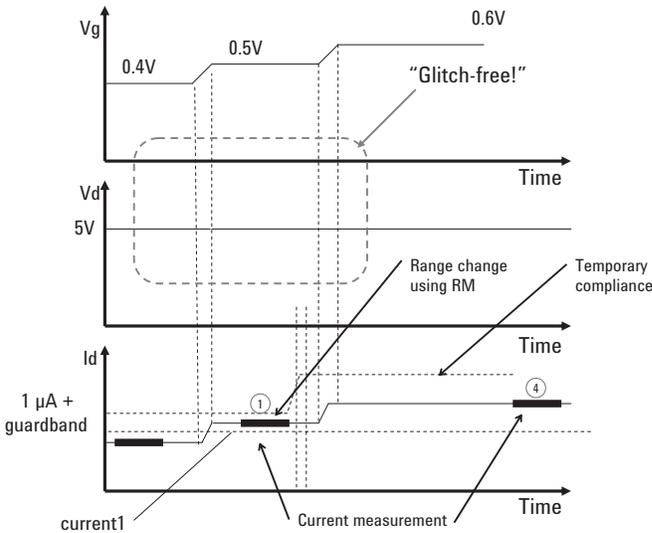


Figure 3.23. Eliminating the effects of range compliance through the use of the range management feature.

It is a worthwhile question to ask if there are any disadvantages to using the range management feature. The answer is “yes” in the sense that if the range limits are set too low then you might uprange unnecessarily and lose some measurement accuracy. However, this is a small potential price to pay if range compliance is causing repeated device damage. It should be obvious that the phenomena of SMU voltage spikes due to DUT current starvation can be

affected by many factors, including the sweep range, the selected sweep step and variations in the DUT characteristics. Therefore, some trial and error is inevitable in order to find the optimal point at which to set the range trigger (“current1”). Finally, it also needs to be pointed out that not all device damage issues and SMU glitching are due to range compliance issues, so you need to be careful and look at all possible causes if you are experiencing these types of problems.

Agilent EasyEXPERT software supports the range management feature for the B1500A and B1505A as part of its built-in GUI. By opening up the range setup window in Classic Test mode you can modify the range change rule as shown below.

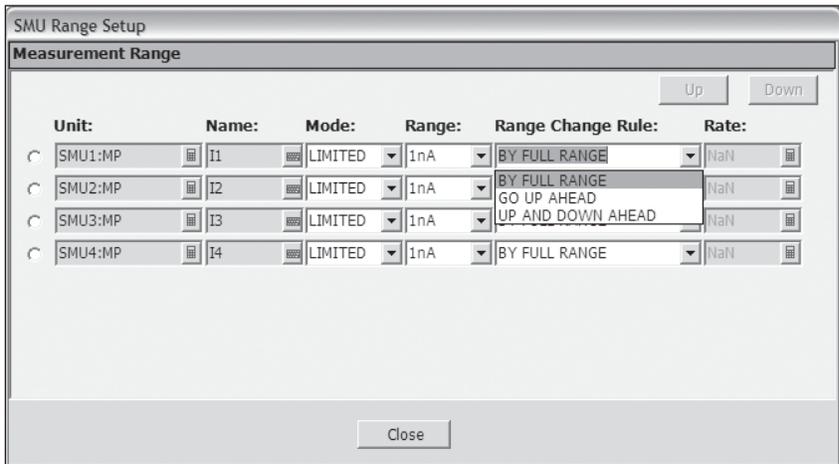


Figure 3.24. Agilent EasyEXPERT software allows you to activate the range management feature using its built-in GUI.

You can select an option to only uprange (“Go Up Ahead”) or both uprange and downrange (“Up And Down Ahead”). Once you have specified a range change rule you can then select the rate or percentage of the total range at which you want to have the SMU uprange (or downrange too if “Up And Down Ahead” is selected).

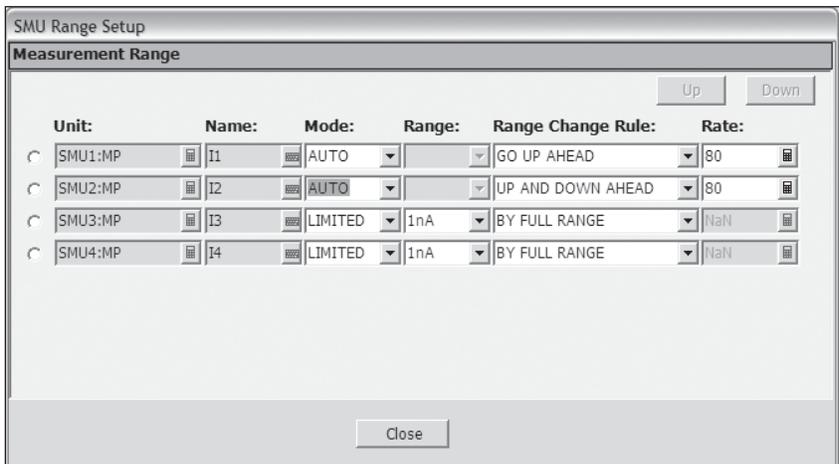


Figure 3.25. The “Rate” parameter sets the percentage of the total range at which the SMU will uprange (or optionally downrange).

Eliminating measurement noise and signal transients

Integration time

Inexperienced users sometimes confuse the purposes of measurement ranging and integration time. It is important to understand that the purpose of integrating a measurement over time is to eliminate noise. Increasing the integration time does not have the same effect as using a lower measurement range. Before increasing integration time to improve your measurement results you should first determine if you have chosen the correct measurement range for the level of current or voltage that you are trying to measure. For example, it makes no sense to try and make a femtoamp current measurement using limited 1 nA ranging on an SMU, since the SMU needs to get down into the 10 pA range in order to make good femtoamp measurements. As a general rule, lower measurement ranges require longer integration times in order to obtain a satisfactory measurement because noise becomes more of an issue as you try to measure small currents and voltages.

The terminology used for integration time is not uniform across all products. In some cases, the term “Short” is used to refer to any integration time that occurs in a time period that is less than one power line cycle (PLC); “Medium” is then used to refer to integration over exactly one PLC, and “Long” is used to refer to integration over multiple PLCs. In other cases, the terms “Auto” and “Manual” are used for integration times of less than one PLC, and “PLC” is simply used to refer to integration over one or more PLCs. The documentation included with your instrument explains the exact terminology used for your equipment. The important point to understand is not the particular terminology used but rather when to use each type of integration time.

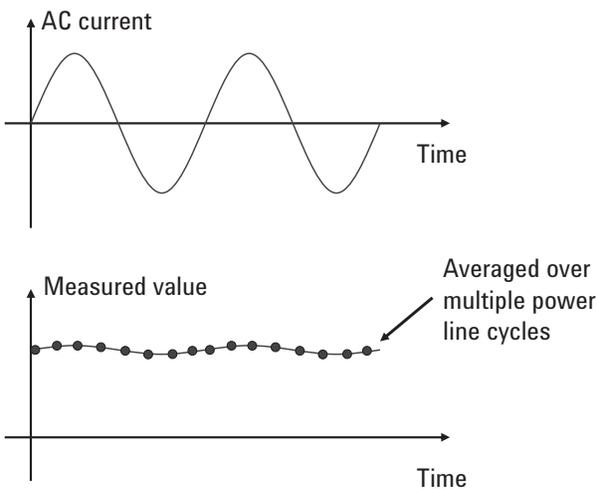


Figure 3.26. Power line cycle (PLC) integration eliminates measurement error caused by noise from the AC supply current by sampling over multiple power line cycles and averaging the samples.

Hold time and delay time

In addition to noise, capacitance on the SMU outputs can cause ringing and other transient phenomena each time the SMU applies a new voltage or current. To insure that the applied voltage or current is stable before making a measurement, you can specify both a measurement hold time and a measurement delay time as shown below.

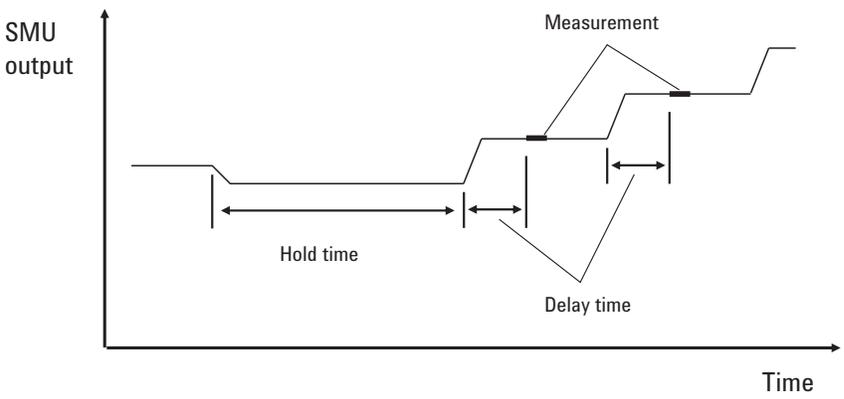


Figure 3.27. The hold time and delay time settings allow you to specify how long to wait before starting a measurement after the SMU applies voltage or current.

The hold time insures that the SMU outputs are stable before the start of a measurement, and the delay time insures that the SMU outputs are stable during a measurement if the value of the SMU output is being changed.

To Get Complete Handbook

If you want to have more information, visit the following URL. You can get the complete "Parametric Measurement Handbook". This total guide contains many valuable information to measure your semiconductor devices accurately, also includes many hints to solve many measurement challenges. Now, English, Japanese, Traditional Chinese, and Simplified Chinese versions are available.

www.agilent.com/find/parametrichandbook

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Appendix A: Agilent Technologies' Parametric Measurement Solutions

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Appendix C: Application Note Reference