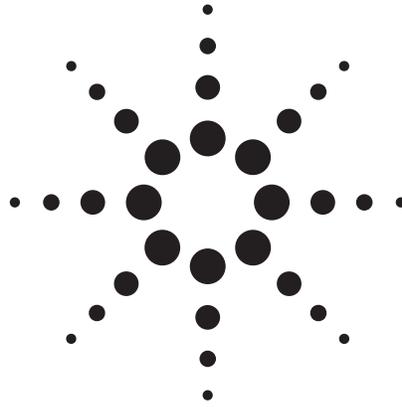


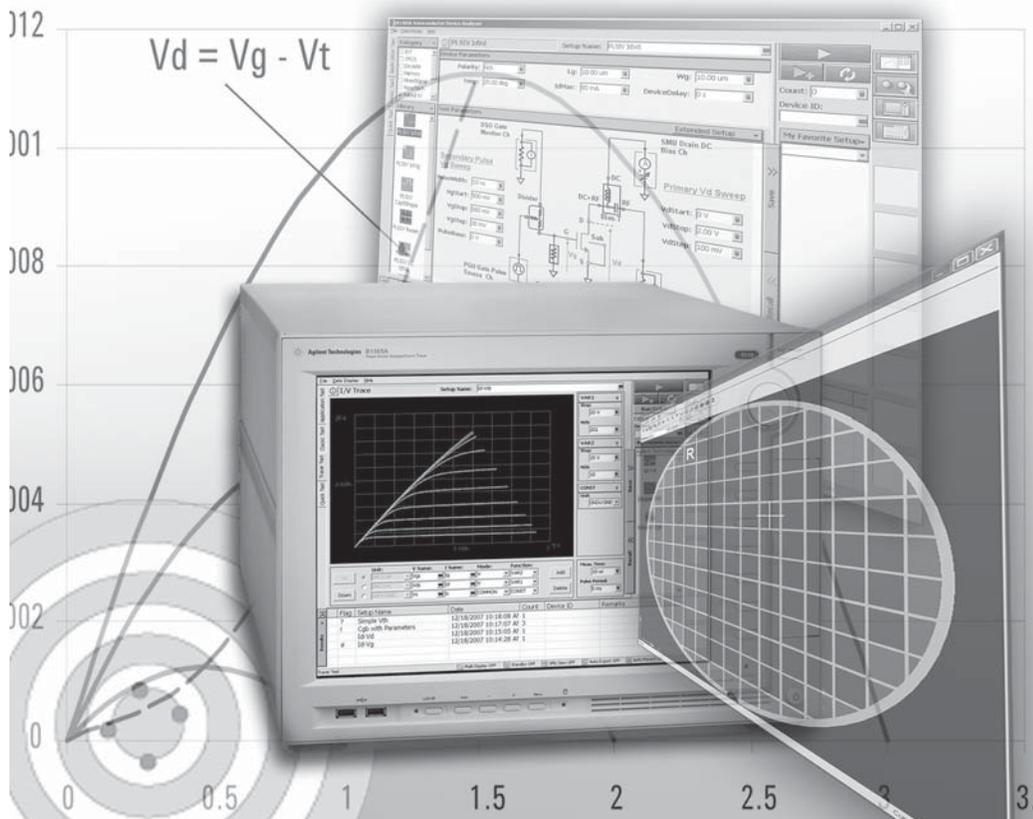
Excerpt Edition

This PDF is an excerpt from Chapter 2
of the Parametric Measurement Handbook.

The Parametric Measurement Handbook



*Third Edition
March 2012*



Agilent Technologies

Chapter 2: Parametric Measurement Basics

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it ..."

"But when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."

— William Thomson (Lord Kelvin)

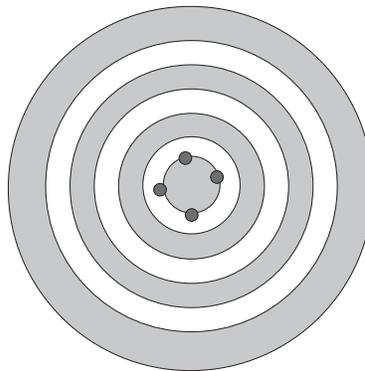
Measurement terminology

Before you can begin to collect measurement data you need to know basic measurement terminology. In particular, understanding the precise meaning of the terms accuracy, repeatability and resolution is essential to understanding parametric test and the measurement capabilities of a parametric measurement resource.

Accuracy and repeatability

Accuracy and repeatability are related but different quantities. Accuracy is the degree of conformity of a measured or calculated quantity to its actual (true) value. Repeatability (also known as precision) is the degree to which repeated measurements or calculations show the same or similar results. Accuracy and repeatability do not have any innate correlation. A measurement can have high accuracy and high repeatability, high accuracy and low repeatability, low accuracy and high repeatability, or both low accuracy and low repeatability.

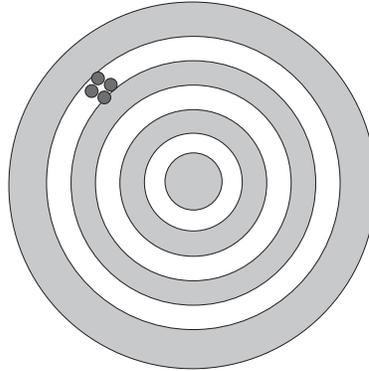
The visual analogy that is often used to explain these terms is a bull's-eye target. A group of points that are close to the center of a target but spaced far apart from one another (as shown below) have high accuracy but low repeatability.



High accuracy, low repeatability

Figure 2.1. High accuracy and low repeatability.

A group of points that are far from the center of a target but spaced close together (as shown below) have low accuracy but high repeatability.



Low accuracy, high repeatability

Figure 2.2. Low accuracy and high repeatability.

The analogies for the two other cases should be fairly obvious. For production parametric test, repeatability is usually more important than absolute accuracy. This is because parametric test is concerned with monitoring trends, which makes having highly repeatable measurements extremely important.

Resolution

For parametric test, resolution is what allows us to gauge accuracy and repeatability. In this sense it is the most important specification for parametric test. Resolution is the lowest resolvable quantity of data that an instrument can accurately measure. The easiest way to think about this is in terms of an analog-to-digital converter (ADC) circuit. The figure below shows a simplified version of an ADC:

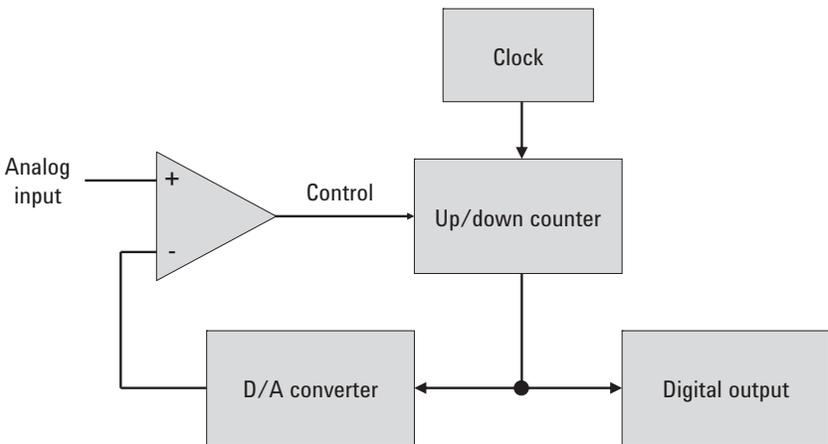


Figure 2.3. Simplified analog-to-digital converter (ADC) circuit.

As this illustrates, the number of bits available to the digital-to-analog converter (DAC) will determine the fineness of the measurement detail that can be distinguished, which is the resolution. For example, a resolution of 20 bits represents the ability to distinguish one part in 2^{20} or 1,048,576 (basically one part in a million).

To express the measurement resolution in terms of current or voltage, you need to know the measurement range in which you are operating. For example, in a 5 V measurement range the ADC measures from -5 V to +5 V, which (assuming a 20 bit ADC) yields a readable or resolvable measurement resolution of:

$$\frac{(5 + 5)}{1,048,576} \approx 10 \mu V$$

However, due to noise and other factors the readable resolution is not the same as the resolution specified in a data sheet. The resolution specified in a data sheet takes into account factors such as thermal noise and amplifier offset and noise, which introduce a stochastic element into the data sheet specification. Typically, the specified resolution is 1 to 2 orders of magnitude larger than the readable resolution.

Measurement traceability

Traceability is defined as the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties. It is important for any company making measurement equipment to establish traceability to national and international standards to provide evidence that measurements are being made correctly.

There are a number of National Metrology Institutes (NMIs) that provide standard reference materials of the highest quality and metrological value. The intent of all NMIs is to realize SI units (such as volts, amperes, ohms, etc.) as closely as possible. A partial list of NMIs is shown below.

Name	Acronym	Country
National Institute of Standards and Technology	NIST	USA
National Metrology Institute of Japan	NMIJ	Japan
National Physical Laboratory	NPL	UK
Physikalisch Technische Bundesanstalt	PTB	Germany

Agilent Technologies obtains standards from these NMIs to use as calibration references. Agilent Technologies' measurement products include a certificate of calibration when they are originally shipped from the factory or after a product calibration has been performed. This document is in compliance with the traceability requirements from these NMIs.

Shielding and guarding

Beginners sometimes confuse shielding and guarding, although they are quite different and have totally different purposes. The purpose of shielding is to prevent electrostatic noise from interfering with a measurement. The purpose of guarding is to prevent leakage currents and enable low-current measurements (in the femtoamp range). A shield does not act as a guard, and a guard does not necessarily provide good shielding. As a general rule of thumb, when making measurements below 1 nanoamp you should use guarding; when making measurements below 1 picoamp you should use both guarding and shielding.

Shielding: Maintaining a low noise floor

Shielding involves surrounding the measurement environment with conductive material so as to eliminate electrostatic noise. Basic electromagnetic field theory shows that surrounding a volume with conductive material creates a barrier across which electromagnetic signals cannot cross. This is also often referred to as creating a "Faraday cage." Typically, for parametric test this is accomplished through the use of some sort of shielding box as shown below:

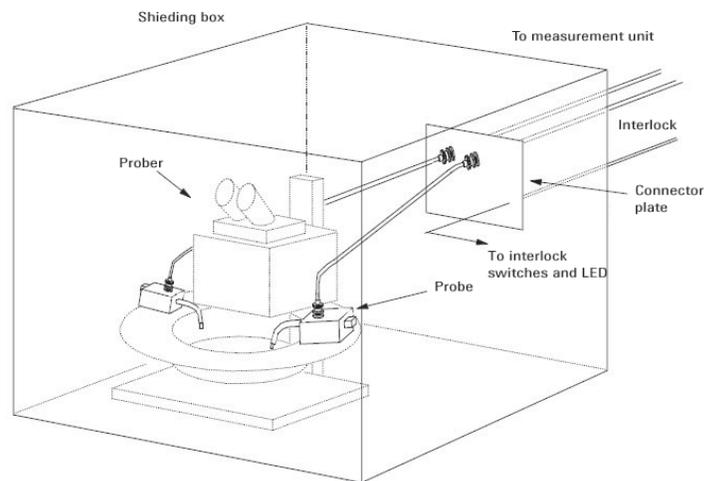


Figure 2.4. A well-shielded parametric measurement environment.

There are a number of best practices that one should keep in mind when trying to create a well-shielded measurement environment:

- Enclose the measurement area with conductive material and measurement cables with a metal shield or braid.
- Electrically connect shielding enclosure and cable shields to the test instrument common (shield) and/or to earth ground.
- To reduce capacitance & vibration effects, keep the shielding and test circuit as far apart as possible.
- Eliminate "light leaks" through gaps around doors and hinges, tubing and cable entry points, connectors and connector panels, and seams/joints between panels.
- Fill seams/gaps/joints with conductive caulking or gaskets.

A reasonable question to ask is: Since a proper shield completely surrounds the measurement environment, how do you connect anything to it? The solution is to use a connector plate that is specifically designed for this purpose.

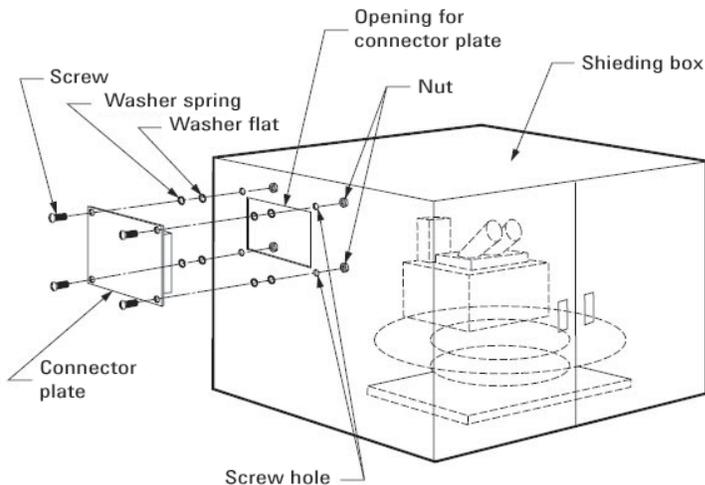


Figure 2.5. Using a connector plate to connect through a shielding box.

Agilent Technologies can supply a variety of connector plates with both triaxial and BNC connectors specifically for this purpose.

In summary, the following are the key points to keep in mind when constructing a well-shielded measurement environment:

- Keep all charged objects (including people) and conductors away from the measurement area.
- Use highly conductive materials instead of insulating materials near the test circuit.
- Avoid movement and vibration near the measurement area (air currents can cause movement and/or vibration).
- When measuring currents $< 1 \text{ pA}$, shield the measurement area with a conductive (metal) enclosure and connect the enclosure to the test instrument common (shield) and/or to earth ground.
- Minimize the capacitance between the shielding enclosure and the test circuit.

Avoiding ground loops

One common problem when using shields that has not yet been mentioned is creating ground loops. While all shields are tied to ground, when you have multiple shielded instruments and cables in a given measurement environment it is almost a certainty that the grounds to which these are tied are not at the same potential. Consider the simple case of two conductive planes both tied to ground:

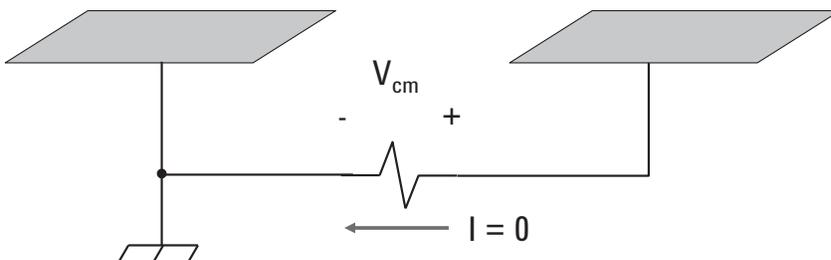


Figure 2.6. Conductive planes connected at only one point cannot have any current flow between them.

As long as these conductive planes are only connected together at one point, any difference in the common mode voltage (V_{cm}) of these planes is not an issue because no current can flow between the planes. However, if the ground planes are strapped together in more than one location then a loop path for current is created that can cause significant current to flow through the conductive planes. This common mode voltage can seriously impact parametric measurement results:

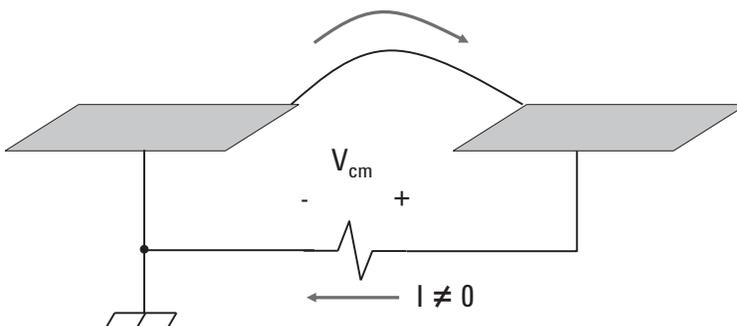


Figure 2.7. Conductive planes connected at multiple points creates a loop for current (a condition to be avoided).

Thus, although it may be counter-intuitive the best strategy when making parametric measurements is to avoid excessive ground connections and instead connect everything together through a single ground point. **Note:** Since instruments almost always have their ground tied to chassis ground, which is in-turn tied to earth ground, this is already taken care of for you. If you suspect that you are having a grounding issue, then the simplest solution is to make sure that the power cords of all of your equipment are tied together to a common power strip.

Guarding: isolation for low-current measurement

Guarding involves surrounding a signal line with an actively driven conductor maintained at the same voltage potential as that of the signal to eliminate leakage currents. Good guarding can only be achieved using triaxial connectors and cabling. In a triaxial cable the signal line is surrounded by the guard line (separated of course by insulating material), which is in-turn surrounded by a grounded shield line (also obviously separated by insulating material). The following illustration shows a cut-away view of a triaxial cable.

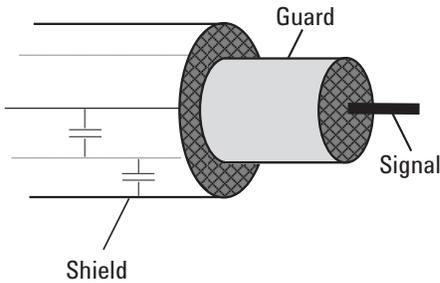


Figure 2.8. Cut-away view of a triaxial cable, showing parasitic capacitance between shield to guard and guard to signal.

Even though there is parasitic capacitance in this cable, the driven guard effectively eliminates the effects of this parasitic capacitance by isolating the signal line from the shield. The diagram below shows the structure of the circuitry driving the guarded (triaxial) output.

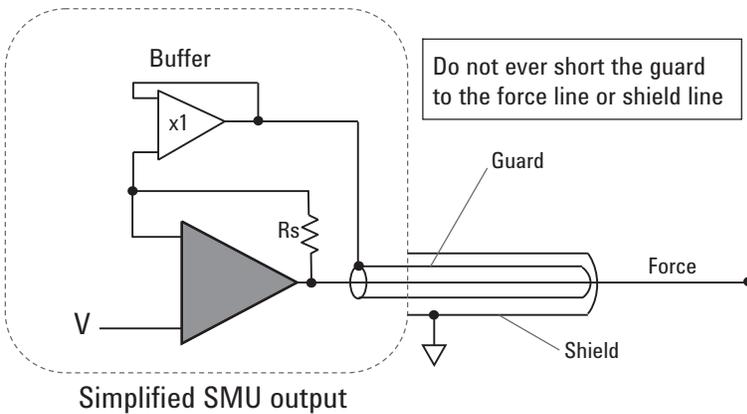


Figure 2.9. Circuitry to provide a guarded (triaxial) output.

The guard line is actively driven by a buffer circuit to maintain the same voltage potential as the center conductor (force) line. Obviously, if you short the guard line to either the force or shield lines then you risk damaging the output circuitry.

Inevitably the question gets asked: Why do we need triaxial cables to measure low current? After all, BNC cables use insulating material, so why should we expect any leakage current? Some simple calculations help to illustrate the need for triaxial cables when measuring ultra-low currents. Assume that the insulation material has a resistance of $1 \text{ G}\Omega$ and that we apply 100 V to the center conductor:

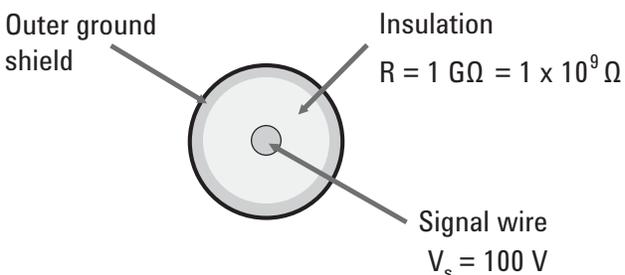


Figure 2.10. Leakage current when using a BNC (coaxial) cable.

A simple calculation shows that the leakage current will be:

$$i_{leak} = \frac{100 \text{ V}}{1 \times 10^9 \Omega} = 1 \times 10^{-7} \text{ A} = 100 \text{ nA}$$

Obviously, if we are trying to measure currents in the femtoamp (10^{-15} A) current range, we cannot use cables with 100 nA of leakage current!

Now let us examine the same case using a triaxial cable. In this case we assume that the driven guard can track the applied (signal) voltage to within one part in a million (which is a reasonable and conservative assumption):

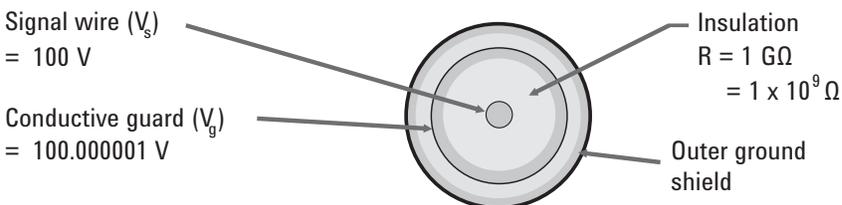


Figure 2.11. Leakage current when using a triaxial cable.

In this case the leakage current will be the difference between the voltages of the signal and guard divided by the effective resistance:

$$i_{leak} = \frac{(100.000001 \text{ V} - 100 \text{ V})}{1 \times 10^9 \Omega} = \frac{1 \times 10^{-6} \text{ V}}{1 \times 10^9 \Omega} = 1 \times 10^{-15} \text{ A} = 1 \text{ fA}$$

By using triaxial cables with a driven guard we have reduced the leakage current to 1 fA , or by a factor of one-hundred million (10^8) as compared to using a BNC cable! It is for this reason that all low-current parametric measurements are made using triaxial cables.

Connecting triaxial and BNC cables

Inevitably you will be faced with the issue of connecting BNC and triaxial cables. The three key questions that require answers are:

1. How do I connect up the driven guard?
2. How does this affect my low-current measurement capability?
3. Where do I get the necessary connectors?

We will address each of these concerns in-turn.

The most important point to understand when connecting up triaxial and BNC connectors is how to connect the driven guard. Remembering that the driven guard exists to allow for sub-nanoamp measurements, we can state as a general rule of thumb that for current measurements above one nanoamp we can simply connect up the force/sense line to the center conductor of the BNC cable and the shield to the outer ground shield of the BNC cable as shown below.

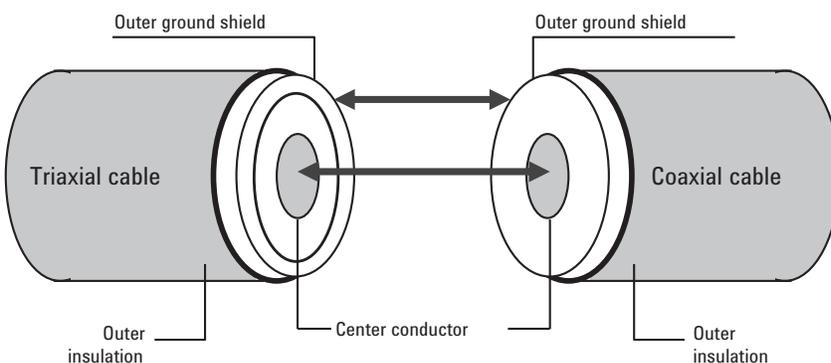


Figure 2.12. Triaxial to BNC connection when not making low-current measurements (1 nA and above).

The advantage of this configuration is its simplicity. We do not need to take any special precautions with the driven guard.

However, the only way that we can make a low-current (below one nanoamp) measurement with a BNC cable is to connect the driven guard to the outer shield of the BNC cable as shown below.

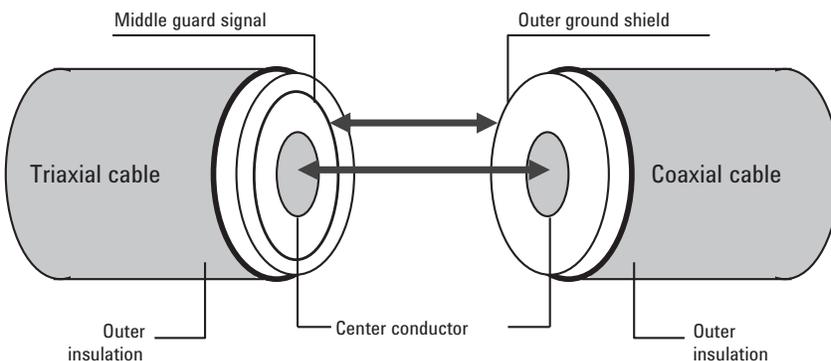


Figure 2.13. Triaxial to BNC connection when making low-current measurements.

This configuration presents a couple of significant challenges:

1. The outer shield of the BNC must be isolated from ground.
2. The outer shield of the BNC can reach dangerous voltages (> 40 V), so precautions must be taken to ensure that the user is properly protected from receiving a fatal electrical shock.

Some analytical wafer prober companies have ready-made solutions to isolate the BNC shield from ground to prevent these types of issues from occurring.

You must be very careful when selecting triaxial to BNC adapters to make sure that you understand which of the above two schemes the adapter is using. If you are uncertain about your connector then it is strongly advised that you use a multi-meter to check the connections. You can purchase triaxial to BNC connectors from Agilent as well as a variety of third-party suppliers.

Agilent part number	Description		
1250-2652	Triaxial (F) - BNC(M)		Safe. Not suitable for low-current measurements
1250-2653	Triaxial (M) - BNC(F)		
Agilent part number	Description		
1250-2650	Triaxial (M) - BNC(F)		WARNING!!!! Shock Hazard!!!! Required for low-current measurements.
1250-2651	Triaxial (F) - BNC(M)		
1250-1830	Triaxial (F) - BNC(F)		

Figure 2.14. Table showing the different types of triaxial to BNC connectors supplied by Agilent Technologies.

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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