Fluke Calibration

How to Seminar

Electrical Calibration - Best Practices for Cabling and Test Leads

WELCOME

Broadcasting live from –

Fluke Calibration

Everett, Washington, USA

TODAY'S PRESENTERS

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WEB SEMINAR ETIQUETTE

- This webinar is voice over IP only
- Use Q&A or chat to send me questions or request clarification
- There will be an opportunity throughout the discussion to pause and ask questions.
- Copies of this presentation and a recording of this session will be available to all registered attendees
  - an email will follow with instructions on downloading this material

OVERVIEW

- Cables are not commonly thought of as electrical instruments when they are used in a calibration setup. Leads and cabling are the leading cause of measurement errors in the laboratory.
- This webinar covers practices that mainly apply to precision measurement, but these practices can be used to ensure best results for non-precision measurement as well.
- Cabling and leads must be suitable for the work being performed. Consider the following:
  - Safety and category (CAT) ratings
  - The precision and accuracy required for the measurement (i.e. 3.5 digit DMM vs. an 8.5 digit DMM)
  - The type of measurement being performed (i.e. resistance, voltage…)
  - The environment the leads are going to be used in (controlled vs. not controlled).
- In the world of precision metrology, it is important to make the simplest connection possible with the least amount of adapters.
- An investment in the correct cables and connector will potentially save you many hours troubleshooting measurement errors and give you confidence.

TWO HELPFUL RESOURCES

FLUKE

Calibration

How cables and connectors impact measurement uncertainty

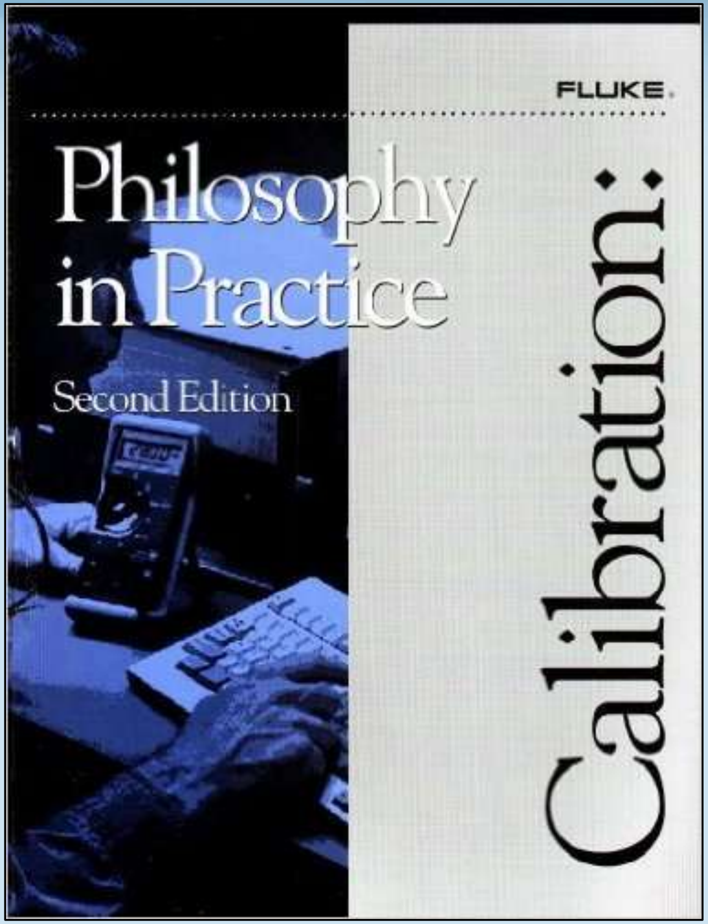
Application Note

More often than perhaps known, the outcome of a calibration procedure can depend on the technician knowing which cables and connectors are appropriate for the calibration setup. Choosing the wrong cables and/or connectors can have a significant impact on the overall uncertainty of the setup or calibration system.

If you're new to dc and low frequency ac calibration, it's important to understand the impact connectors and cables have on overall measurement uncertainty, as well as the importance of cable maintenance.

Cables, connectors, and traceability

Model of a test connection

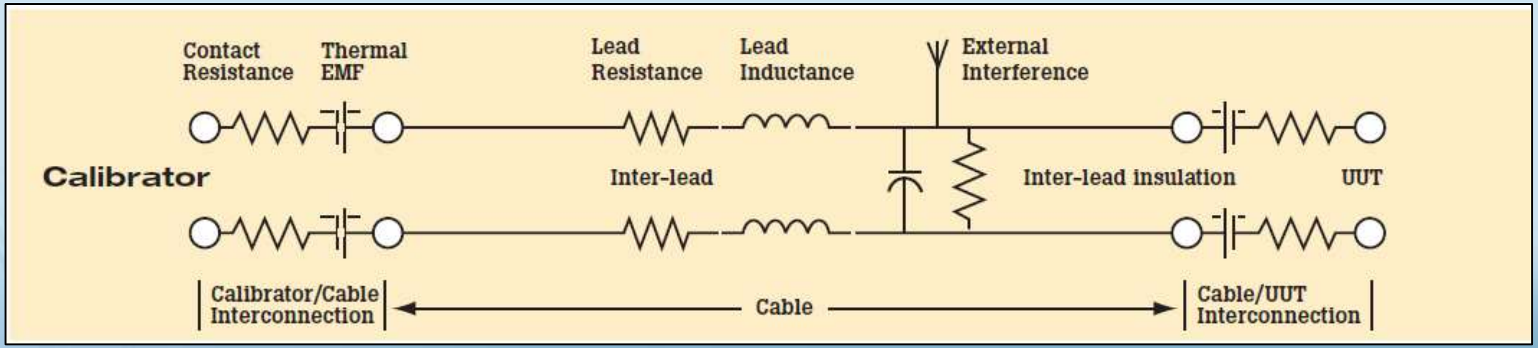


TEST SETUP EVALUATION

Schematic of a complete test setup, including the cables

Potential error sources:

- Contact resistance between the connectors and cable junction at the calibrator.
- Thermal EMFs are generated at the connector and cable junctions at the calibrator.
- Series lead *resistance* in the cable wires.
- Series lead *inductance* in the cable wires.
- Parallel *capacitance* and *dielectric absorption* between the cable wires.
- Susceptibility to external electromagnetic interference (EMI) in the cables.
- Leakage resistance between the cable wires via their insulation resistance or external contamination.
- Thermal EMFs (voltages) generated at the connector/cable junctions at the UUT.
- Contact resistance between the connectors/cable junction at the UUT.



COMMON LEADS AND CABLES USED IN THE INDUSTRY

There are many leads and cables used in the measurement industry – we'll focus on three types commonly used in calibration:

Patch Cords

Test Probes

Coaxial Cables

Coaxial Cables

- These cables are easy to connect and manage (one wire vs. two). They have good characteristics such as shielding that can reduce measurement errors.
- Come with many connector end types:

N-TYPE Straight Plug

BNC

SMA

- Ideal for use when a coaxial connector is available on the device (for example, oscilloscopes and RF applications).
- Typically specified by impedance (usually 50 or 75 Ω).
- These cables are usually shielded to prevent measurement errors from external sources.
- Typically can be adapted to banana jacks with an adapter.
- Coaxial cables can have high capacitance, resulting in *reduced signal at the end of the cable (or increased levels if resonances occur)*. For example, one of the most common types (RG 58U, a 50 Ω RF impedance cable) is around 90pF/m (30pF/ft).

Important considerations:

1. Some cables have a maximum bend radius that if exceeded, will damage the cable.
2. Some high-end calibrators such as the Fluke 5730A have a cable shipped with the unit that is calibrated with it.
3. Most coaxial cables is constructed using fine-wire braid as the outer conductor. Depending on how the wire is woven, there can be small gaps that reduce the effectiveness of rejecting unwanted radiation or coupling. Most on the market varies from 80% to 98% in coverage. A few in the market use a foil shield instead of a braid increasing the coverage to 100%; but these are typically higher priced and are more susceptible to damage.

Test Probes

- Easy to obtain – many vendors with many types of leads but not all are alike and are not designed for precision measurement.
- Typically used by DMMs
- Gives you a way to make direct, touch measurements with ease – typically with many accessories giving more connection options.

Important considerations:

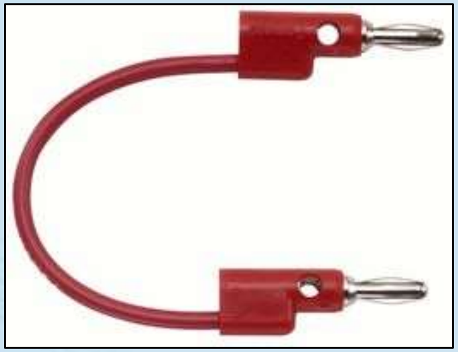
1. Voltage and category ratings are sometimes hard to read.
2. Inexpensive lead sets typically are not shielded and are not suitable for high resistance measurements.

Typical Accessories for DMM Test Leads/Probes

Electrical Patch Cords

- Typically used for Calibrator to UUT connections.
- Easy to obtain – many vendors with many types of leads but not all are alike and not all are designed for precision measurements.
- Many can be stacked easily
- Many different types of lead connectors designed with application and safety in mind:

Stacking Banana Plug Patch Cord



Non-Stacking Banana Plug Patch Cord (with non-retractable sheath)

Version with a spring loaded, retractable sheath

Important considerations:

1. Voltage and category ratings are sometimes hard to read.
2. Inexpensive lead sets typically are not shielded and are not suitable for some measurements.
3. The metal flare that holds the banana plug in can loosen over time causing a loose connection.
4. Potential safety issues with exposed metal and high voltage
5. Dissimilar metals can cause thermal EMFs

Low Voltage Spade Lug, Shielded Cable

Measurement Influences

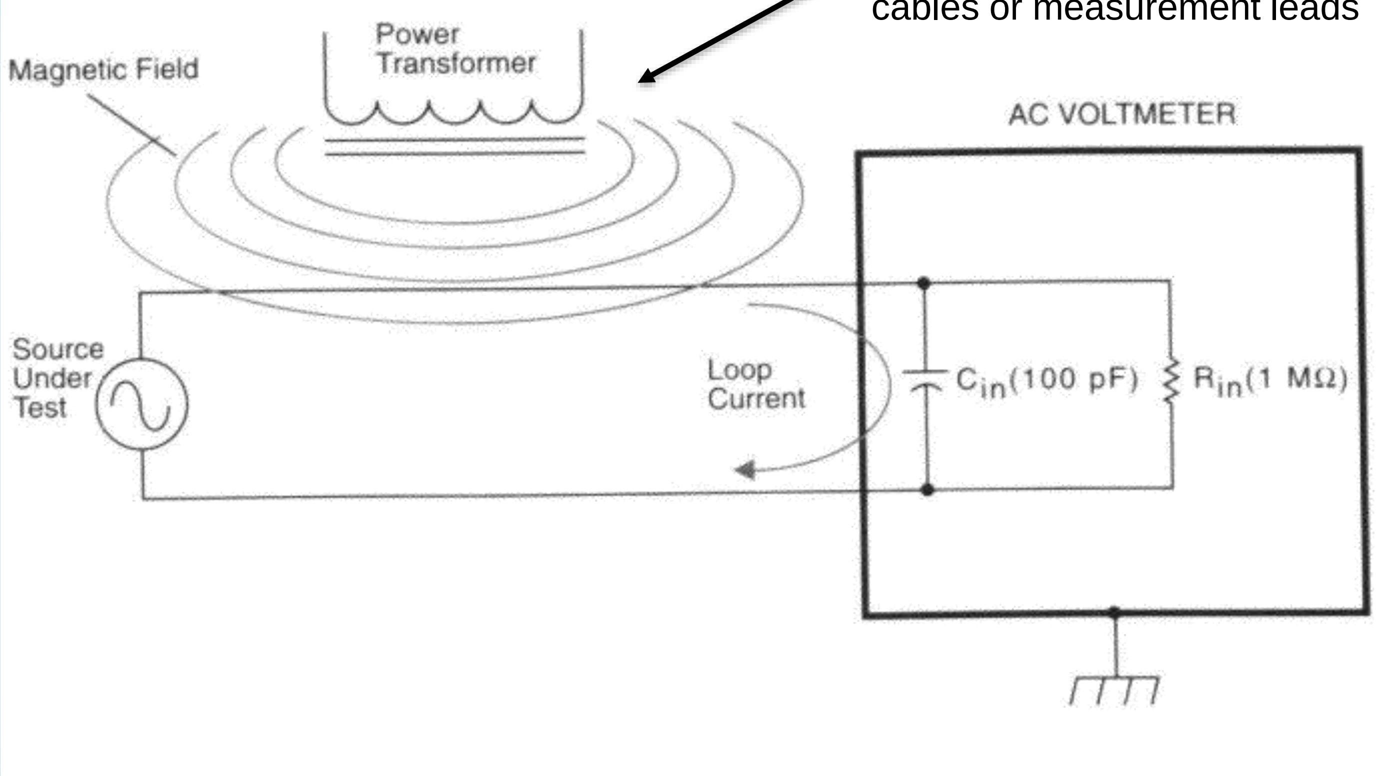
Let's briefly talk about some measurement influences that can be mitigated by using the correct lead or cabling.

Electromagnetic/Static Radiation

- Comes from power transmission lines, florescent lights, electric motors, CRT monitors, communication equipment, cellular phones, transmitters, etc…
- The result of the radiation is noise or pickup in the measurement. Higher voltages tend to radiate electric fields. Higher currents tend to radiate magnetic fields.
- Shielding will mitigate and potentially eliminate the radiation. Use shielded wires for measurements. Fluke provides special shielded low thermal, EMF banana plugs and spade type lead sets.
- While the shielded wire will help with the problem, evaluate the surroundings to see if the root issue can be addressed. Here are a few tips:
  - In the layout of the laboratory, it is common practice to run the power mains wiring through a grounded metal conduit and to use florescent fixtures with grounded metal enclosures.
  - In an instrument such as a precision calibrator or DMM, it is common to shield primary power circuits with chassis (power line) ground, to shield digital circuits with the digital supply common, and to use local shielding (faraday shield) for sensitive analog circuits.
  - Take care with the measurement lead layout, especially with leads carrying high current to avoid unwanted pickup in other sensitive voltage/current measurement leads close by.

Magnetic Field Coupling

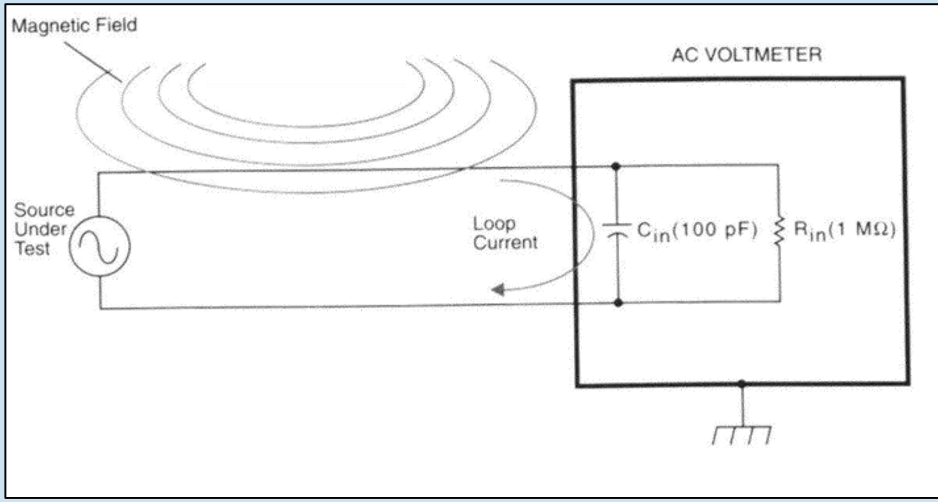
Magnetic fields can also be produced by current carrying cables or measurement leads



Note that maximum pickup is from fields perpendicular to the loop

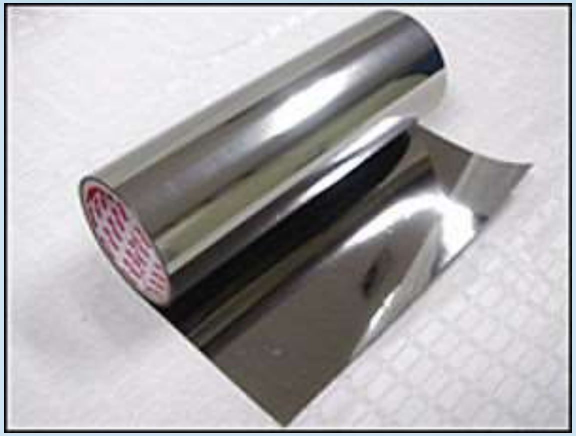
Minimize Magnetic Pickup

- Reduce magnetic field pickup:
  - Reduce the area of the pickup loop
  - Reduce the magnetic field intensity
- Use twisted pairs rather than separate test leads where possible to reduce magnetic pickup and minimize series inductance.
- Use coaxial cables to reduce both magnetic and electrostatic pickup.
- Separate any leads where magnetic pickup may take place. If leads must be close or cross each other, orient them at right angles to minimize magnetic coupling.
- Take care when stacking instruments. Make sure that the magnetic interference in one instrument does not affect the sensitive circuitry in another instrument.
- The best material for magnetic shielding is an alloy of nickel and iron known as *mu-Metal.*



More on Magnetic Pickup…

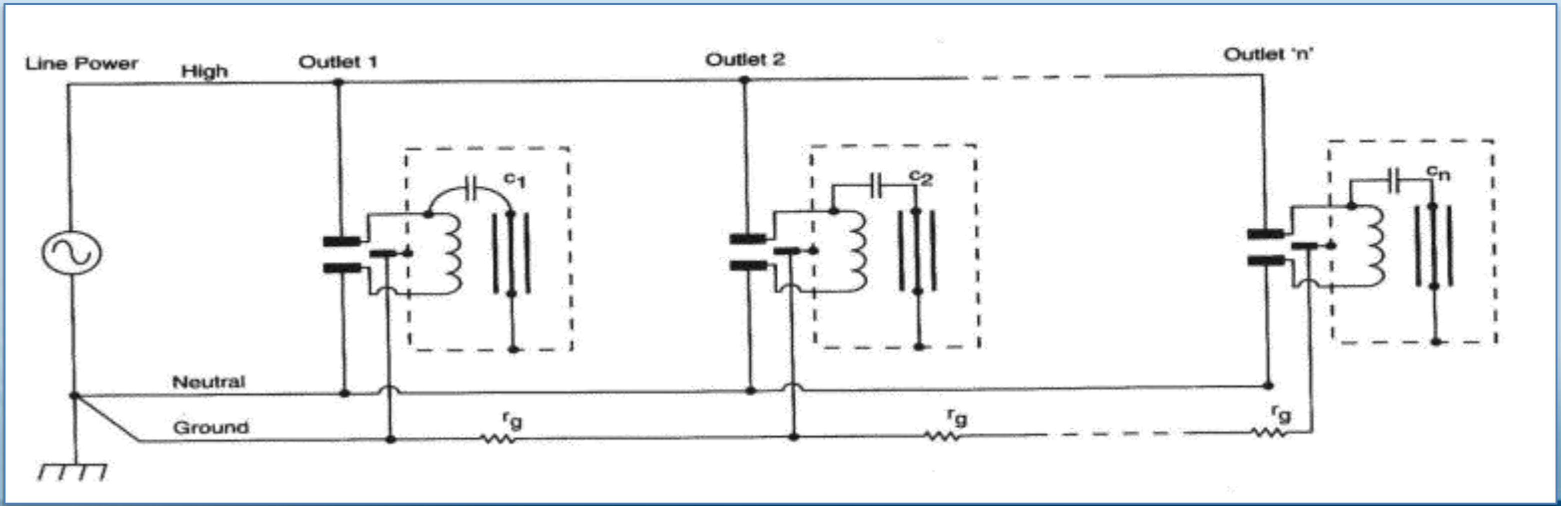
- Magnetic fields can come from many sources on the lab bench; such as a power transformer or a CRT monitor.
- To mitigate or reduce the risk of measurement errors, use shielded twisted pairs rather than a separate test lead.
- Use coaxial cables to reduce electromagnetic pickup and electrostatic pickup.
- The best material for magnetic shielding is an alloy called **Mu-Metal.** It is a nickel–iron soft magnetic alloy with very high permeability suitable for shielding sensitive electronic equipment against static or low-frequency magnetic fields. It has several compositions. One such composition is approximately 77% nickel, 16% iron, 5% copper and 2% chromium or molybdenum.
  - As an example, this is used in our current coils to protect certain parts of the coil from inductive, magnetic fields.
  - The mains transformer in the 5730A is surrounded by a Mu-Metal enclosure.



Example of Mu-Metal as a sheet

Poor or Lack of Proper Grounding

- Ground loops from poor or mismatched grounding can cause measurement errors. It is possible for some of the signal current to flow through the mains safety ground loop.
- In regards to the calibrator, here are a few tips to reduce the risk of ground loops:
  - Plug the mains power of the calibrator and the UUT into the same receptacle.
  - If possible, remove any equipment that is putting large amounts of current into the safety ground plug and connect it to another circuit.
  - Keep system interconnections as short as possible with low resistance cables to reduce resistive and reactive impedances. Coaxial cable is preferred, especially for RF signals.
  - IMPORTANT – Never operate equipment where the safety plug has been bypassed by removal or via a “cheater plug”. This removes protection from electric shock.



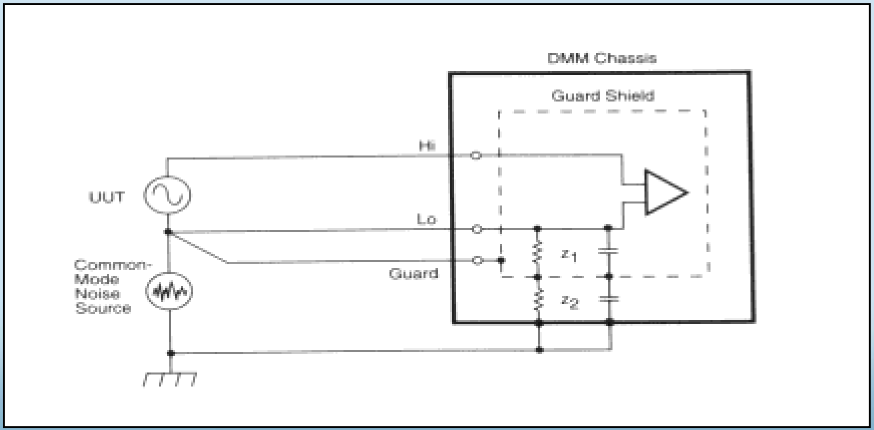
Common Types of Shielding

- There are many shielding techniques used to protect from outside influences. Each type has pros and cons:

	Braided Mesh	Foil	Twisted Pair	Twisted Pair with Foil
Picture				
Pros	Most common and inexpensive	100% coverage (compared to braid)	Reduces EMF and easy to work with or obtain. Doesn’t wear as quickly.	Best for protecting against EMF.
Cons	80% to 98% coverage (compared to foil)	Can wear quickly and breaks are hard to detect	Not good for high-frequency ACV and ACI due to capacitive coupling	Fairly expensive
Shielding Rating	**Good**	**Very Good**	**Good**	**Very Good**

Instrument Guard

- The Guard is a Faraday or electric field shield enclosing the analog circuitry of a meter or source, electrically isolated from the instrument case and ground.
- In addition to shielding, also provides a path to ground for common-mode generated currents so they do not cause errors in the measurement.
- Connection to the Guard is usually made available via a terminal on the front panel.



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Dissimilar Metals

- The connection of leads into binding posts brings two dissimilar metals into contact, creating a thermal junction also known as the "Seebeck" effect.
- When the junctions of two dissimilar metals form a closed circuit and are exposed to different temperatures, a net thermal EMF can be generated (voltage).
- When making precision measurements, it's important to make sure the leads being use match the metal used in the calibrators binding post. Use pure copper when available.
- In Fluke's calibrators, we use tellurium-copper in the binding posts.
- For best results, use low thermal, tellurium-copper or gold plated banana plugs. Avoid nickel plating on banana plugs for precision measurements.

Did you know?

When a wire is soldered to a spade lug, a thermocouple pair is created. Therefore, don't make measurements until the junctions temperature matches the ambient surrounding area. Protect from draughts by covering these joints and terminals with thermal insulating material. Try to not handle the cables close to the joints and terminals when changing connections.

Thermal EMF Comparison Table

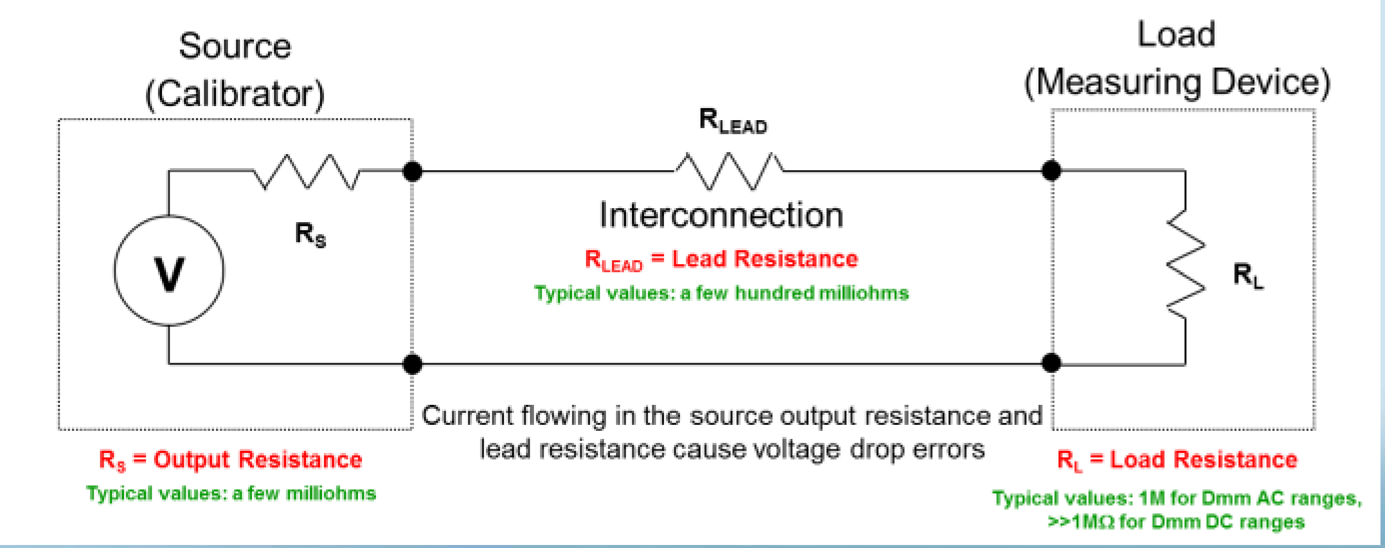
Thermal EMF to Hard-Drawn Copper in Microvolts per Degree Celsius at 23° C	
Metal to Copper	**Microvolts**
Evanohm	+0.20
Electrolytic Silver	+0.03
Gold	+0.01
Electrolytic Copper	–0.18
Annealed Silver	–0.30
Brass	–1.60
Manganin	–1.70
Tin	–2.98
Lead	–3.05
Nickel	-10
Constantan	≈39.7
Copper Oxide	>500

SPECIFIC MEASUREMENTS AND RECOMMENDED CABLING TECHNIQUES

Let's discuss specific measurements and the recommended cabling…

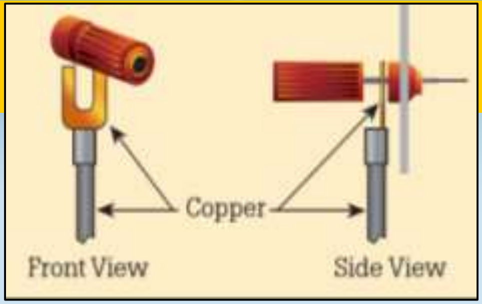
Voltage - DC

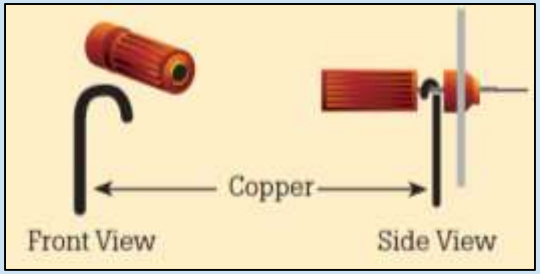
- Use low thermal, low EMF cables for best performance.
- Low voltage DC measurements are more adversely affected by dissimilar metals than AC, simply because thermal EMFs are of no concern in AC.
- With good cables and connections, there are not many error sources from a DC measurement as illustrated:
  - Typically the measuring device has a high impedance input (R_L), usually 1MΩ, 10MΩ or greater for a DMM DCV input).
  - Any DC loading effects will usually be negligible because the lead series resistance (R_{LEAD}) is very low compared to the measuring device input impedance. Typical leads will be around 0.1 or 0.2 Ω.
  - 2 x 0.1 Ω leads with a 1 MΩ input DMM will give 0.2 ppm error.

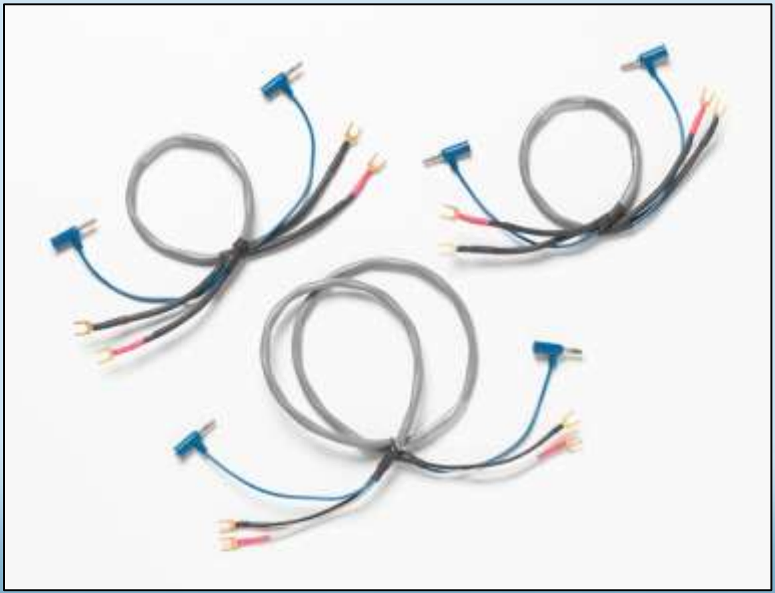


Resistance – Low

- First requirement is for cable/connector resistance to be low and constant.
- Use a copper wire or spade lug securely tightened to the binding post as shown.
- For experiments, consider using a solid wire. For everyday use, a braided wire is recommended.
- Using four-terminal techniques minimizes the effects of cable and connector lead and contact resistance. Most modern calibrators and laboratory DMMs have built-in features that nullify the effects of lead resistance by using remote sensing techniques. More on this later in the presentation.







Resistance – High

- Use of banana jack connections OK – most of the high resistance workload is DMMs with only banana jack connections.
- The key to error free measurements is shielding and insulation. The cable must have very high insulation resistance (polytetrafluoroethylene aka “PTFE” typically used which has $\geq 10^{12}$ ohms or greater insulation resistance).
- Never use low voltage wire coated with other materials for high-resistance applications.
- Keep the environment very controlled and don’t touch the wire during the measurement. Give the measurement time to stabilize.
- Other considerations - dielectric absorption, settling and effects, voltage memory.

5440A-7002 Test Lead Set, Low Thermal

4-Wire Ohms

- 4-wire techniques are used to minimize the effects of cable and connector lead and contact resistance.
- 4-wire measurement works by separating the current “source” and voltage measurement ”sense” paths.
- Adding another set of wires to “sense” the voltage drop across the unknown resistance (in which no current flows) eliminates the effect of cable resistance.
- For highest accuracy, four-wire measurement should be used with lower value resistances when possible. (Some measuring devices only provide 2-wire measurement, usually lower accuracy devices such as handheld DMMs).

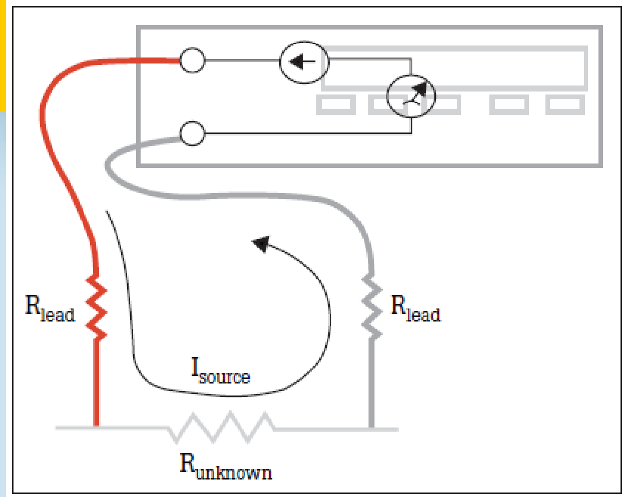


Figure 1: Two-wire resistance measurements introduce error due to voltage drop in the test leads.

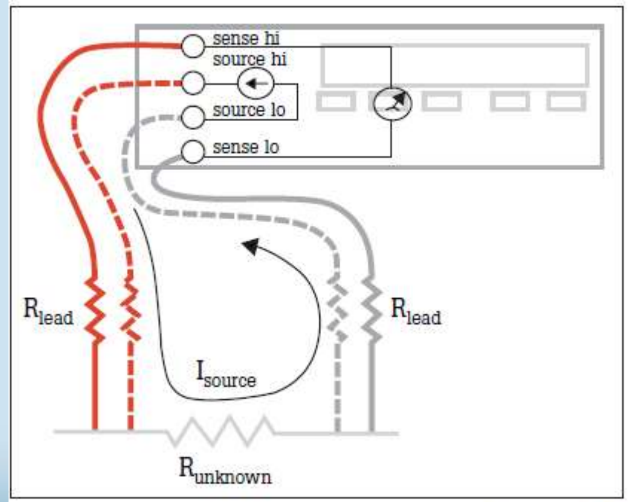
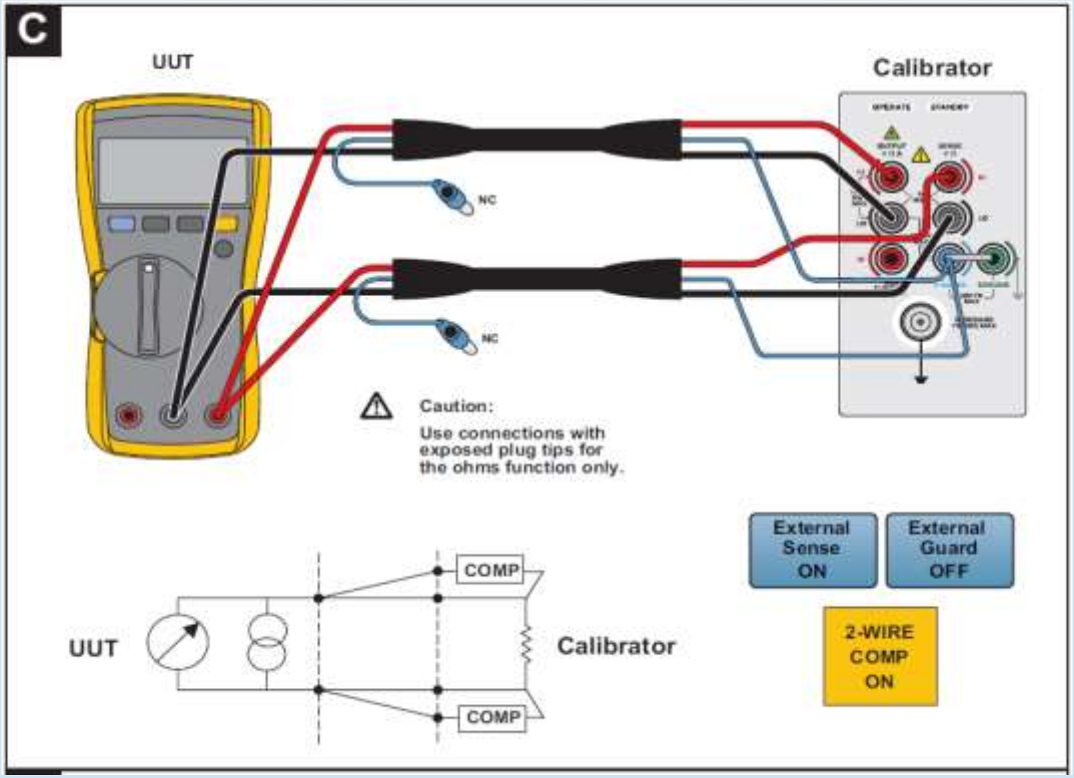


Figure 2: Four-wire resistance measurements eliminate current in the voltage leads and eliminate this source of error.

FLUKE Calibration

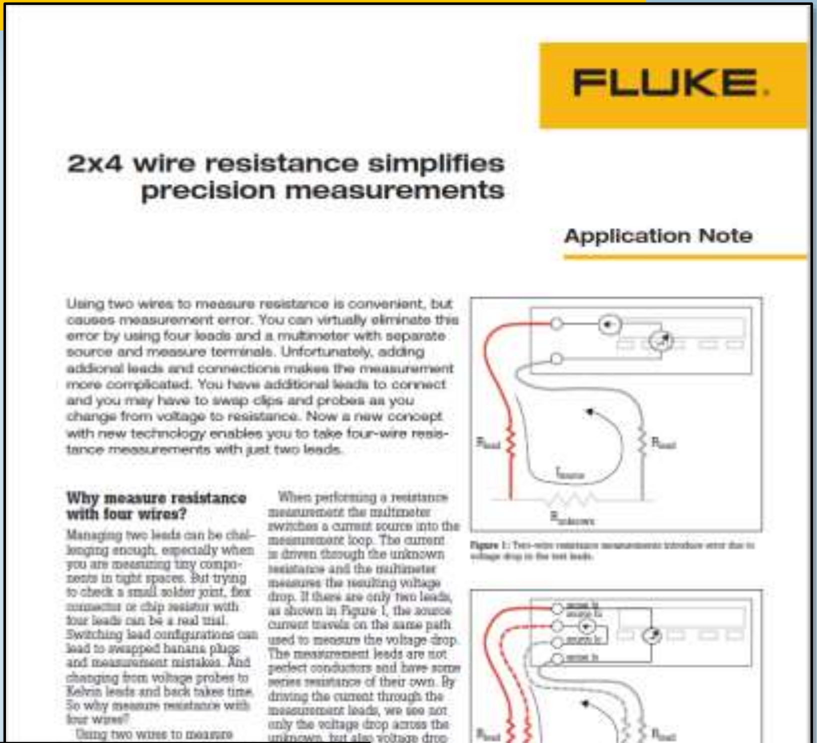
2-Wire Ohms

- The measurement leads are not perfect conductors and have some series resistance of their own. By driving the current through the measurement leads, we see not only the voltage drop across the load, but also voltage drop for each lead. Thus, we end up measuring the combined resistance of the positive lead, the unknown, and the negative lead.
- **The Solution** - If we use four leads, the source current and the measurement can be separated. The meter terminals are called *"Source"* for the current supply and *"Sense"* for the voltage input.



Application Note

- An application note is available with more information on this topic. Download from www.flukecal.com
- The 2x4-wire method is patented technology by Fluke and provides the convenience of using two leads, but delivers the measurement performance of a 4-wire connection.
- 2x4-wire resistance is available on the 8845A and 8846A 6 ½ digit DMMs


FLUKE.

2x4 wire resistance simplifies precision measurements

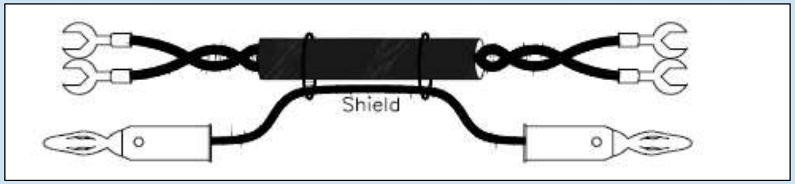
Application Note

Using two wires to measure resistance is convenient, but causes measurement error. You can virtually eliminate this error by using four leads and a multimeter with separate source and measure terminals. Unfortunately, adding addional leads and connections makes the measurement more complicated. You have additional leads to connect and you may have to swap clips and probes as you change from voltage to resistance. Now a new concept with new technology enables you to take four-wire resistance measurements with just two leads.

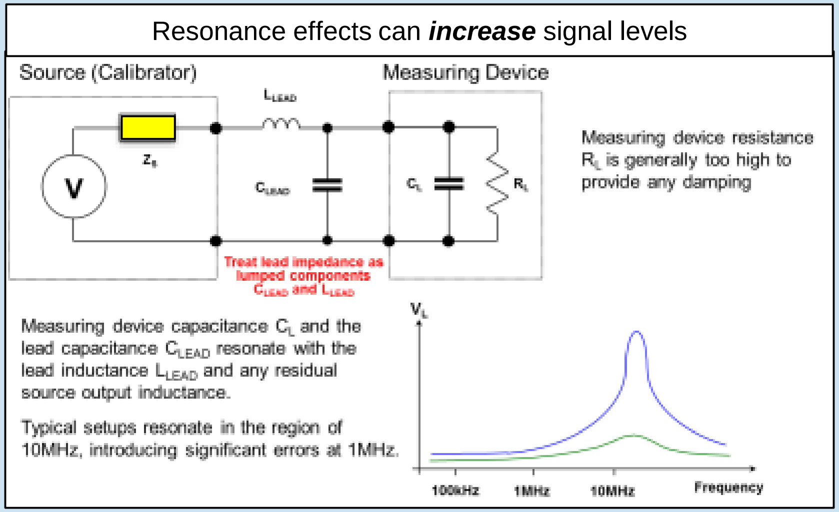
Why measure resistance with four wires?

Voltage - AC

- In general, all the factors applying to the various dc and resistance applications also apply to AC. But, there are a few additional conditions to be considered, as well.
  - The major differing factor to consider for AC is the effect of cable capacitance on the measurement. Keep cable capacitance as low as possible (< 50 pF/m).
  - When sourcing voltages at the millivolt levels into the higher input impedance of electronic voltmeters or DMMs, there may be a problem with excessive noise pickup due to lack of shielding.
  - High frequency AC can present many errors if the wrong cabling is used, due to the additional error sources associated with AC such as inductance, capacitance and resonances
  - These effects become progressively more apparent above 100 kHz and can easily produce unexpected errors of 0.1% to 0.2%.
- Use high quality, shielded, twisted pair or low capacitance coaxial cable.

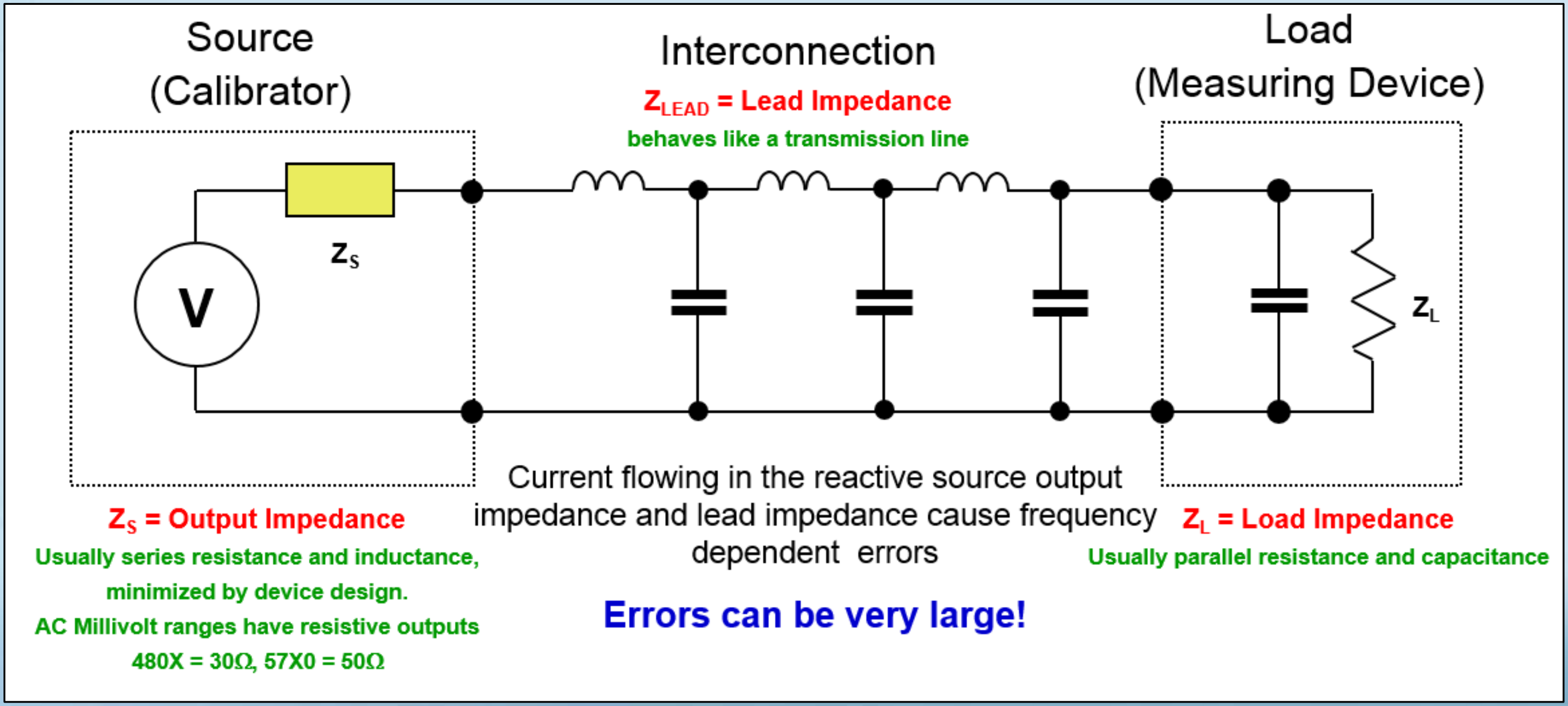


Shielded twisted pair leads



Voltage – AC (High Frequency)

- High frequency AC can present many errors if the wrong cabling is used. This is due to the additional error sources that is associated with AC such as inductance, capacitance and resonances between the load and the lead.
- Become progressively more apparent above 100 kHz and can easily produce unexpected errors of 0.1% - 0.2%
- Best to use a low capacitance coaxial cable.

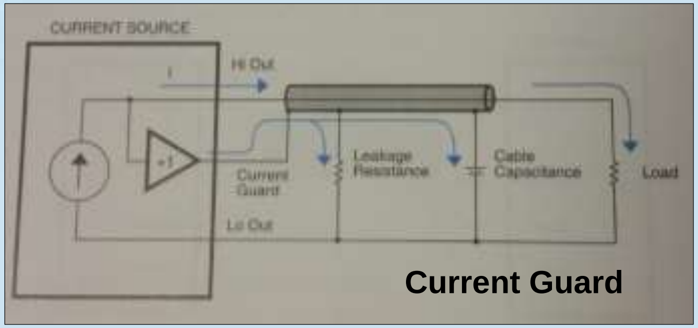


MEASUREMENT GUIDANCE

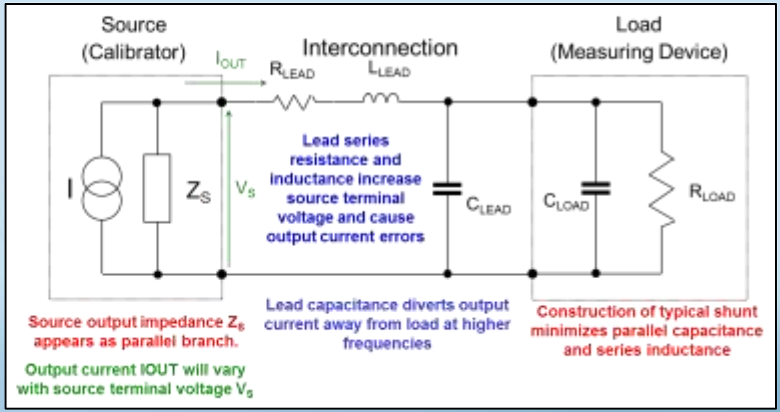
Current – AC

Low Current:

- Low level, high frequency current measurements are subject to large errors caused by leakage impedances.
- These errors can be reduced by the use of an active guard connected by to a shield around the Hi lead as illustrated...



Current Guard

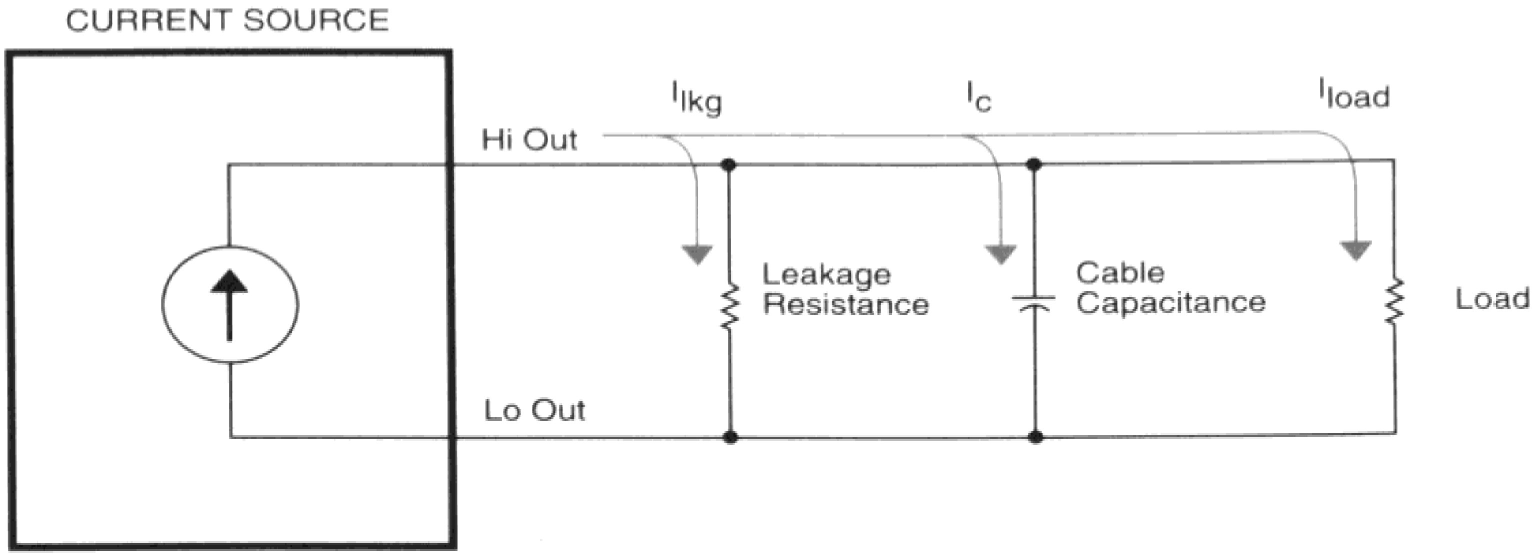


Example High-Current Cables

High Current :

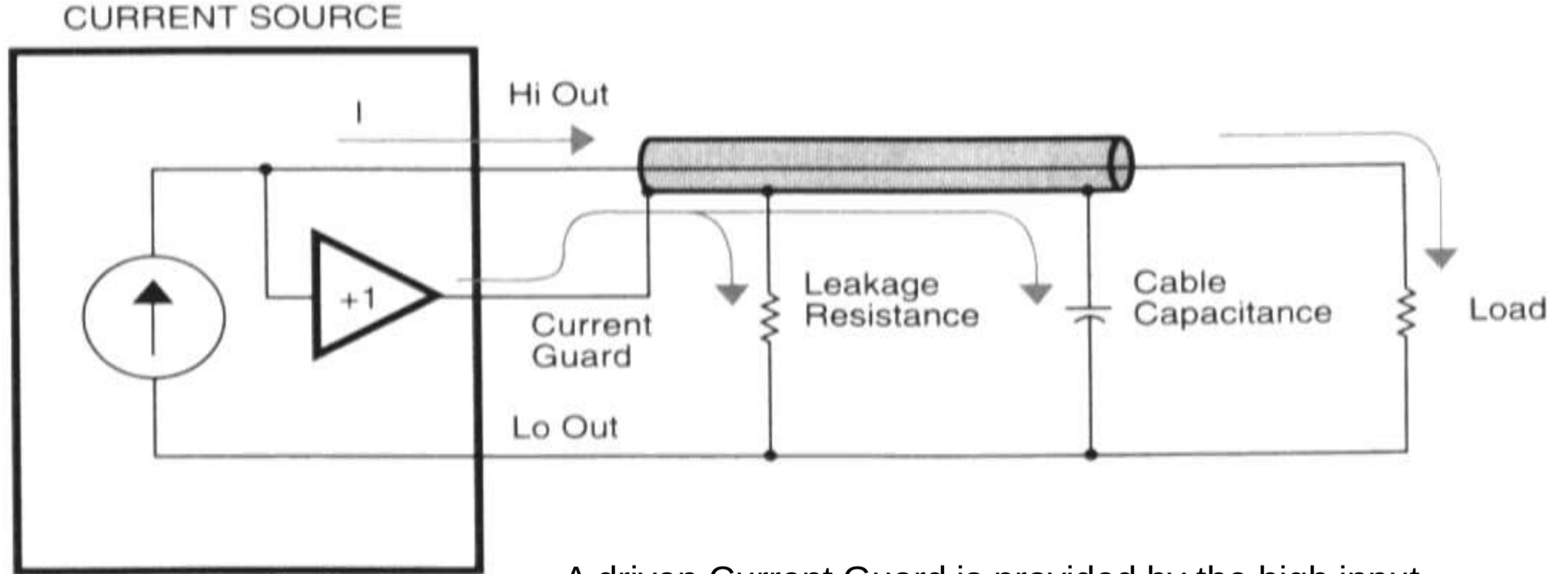
- The cable's ampere rating needs to be considered. (Most cables will easily handle up to 5 A without appreciable self-heating). Make sure to use the correct gauge of wire for the application current.
- Lead series resistance and inductance can increase the voltage seen by the current source, introducing compliance voltage errors.
- Mutual inductance (cross-coupling) can induce unwanted voltage in other measurement leads, for example when using current shunts.
- Keep the current lead loop area as small as possible to minimise series inductance and radiated magnetic fields. Twist together single leads, or use figure-of-eight, twisted pair or coaxial leads.

Guarding Current Sources



Current flowing in the leakage resistance and cable capacitance create a measurement error.

Guarding Current Sources

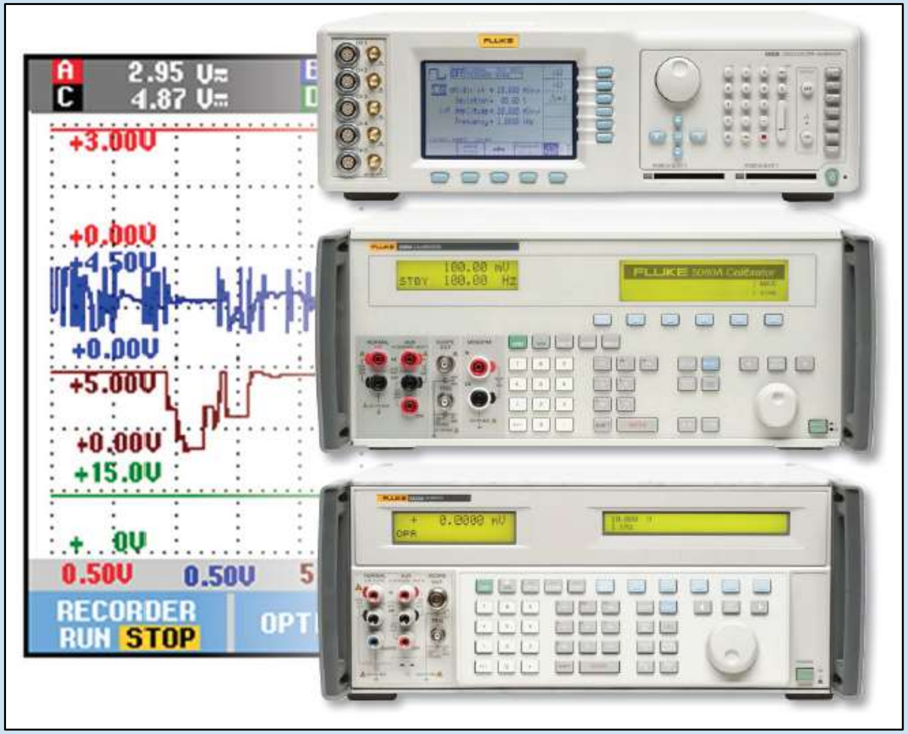


A driven Current Guard is provided by the high input impedance unity gain amplifier.

Leakage resistance and stray capacitance between the Hi conductor and the shield driven by the Current Guard have no voltage difference across them, therefore no current flows in them.

Scope Calibration Considerations

- Oscilloscope calibration can be very tedious and difficult. There are error sources associated with cables and connections, especially when high-frequency signals are involved (for example bandwidth and risetime, etc, calibrations).
- Fluke's dedicated oscilloscope calibrators employ 'active heads' rather than cables, avoiding long cable and RF transmission line lengths and their associated errors.
- Fluke's multi-product calibrators also have oscilloscope calibration options, employing precision high-quality coaxial cable and connectors.
- If other cables are used, make sure any cables have the appropriate electrical and robustness characteristics, including high-quality BNC connectors. Don't substitute low-cost general purpose low frequency coaxial cables that might suffice for LF AC (<1 MHz).
- Please refer to our "*Oscilloscope Calibration Made Easy*" seminar series for more information…



RF Calibration

- Three application notes available to help with RF cables and connections:
  1. *Choosing and Using Cables for RF Calibration*
  2. *Making Repeatable RF Connections during RF Calibration*
  3. *RF Calibration Best Practice Guide: Coaxial Connectors*
- Download from www.flukecal.com
- A few webinars also to help:

RF & Microwave Calibration Fundamentals:

New to RF & Microwave calibration, moving beyond DC & Low Frequency AC , or would a RF & Microwave refresher be interesting and beneficial? This web seminar introduces RF & Microwave basics, discusses how RF & Microwave is different to DC/LFAC calibration and examines common measurement uncertainty contributors and how to minimize them with metrology best-practices. Topics include key RF parameters and units, transmission line basics, cable and connector types, and connector care.

How to identify and avoid common errors in RF calibration:

Five common sources of measurement errors in RF calibration explained - how to identify and avoid them. There are many potential sources of human and measurement errors in RF calibration. This web seminar examines common error sources associated with connectors, cables, and accessories such as adapters, splitters and couplers, their choice, use, maintenance and application of correction factors and uncertainty contributions.

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Fluke Calibration

How to Seminar

Any more questions?

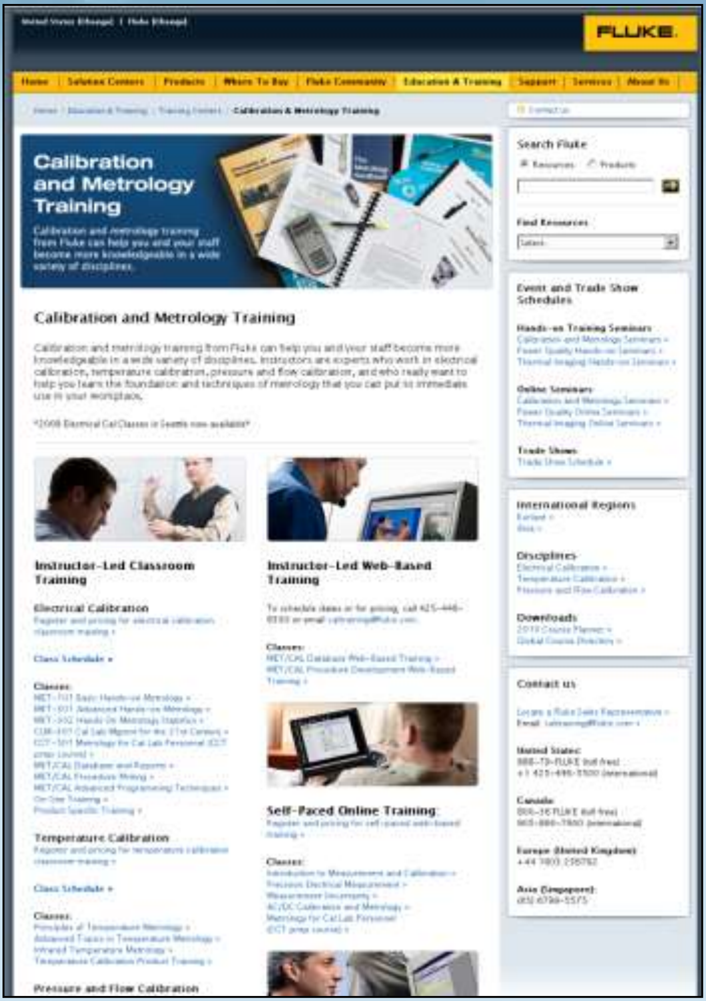
Calibration and metrology training from Fluke

- Fluke calibration and metrology training helps you get the most from your investment in calibration instruments and software
- Multiple ways to learn:
  - Instructor-led classroom sessions
  - Instructor-led web-based courses
  - Self-paced web-based training
  - Self-paced CD-ROM training
- Multiple locations
  - United States and Canada
  - Europe
  - Singapore

Members of the MET/SUPPORT Gold and Priority Gold CarePlan support programs receive a 20 % discount off any Fluke calibration training course

Calibration and metrology training

- **Instructor-Led Classroom Training**
  - MET-101 Basic Hands-on Metrology
  - MET-301 Advanced Hands-on Metrology
  - MET-302 Hands-on Metrology Statistics
  - Cal Lab Management for the 21st Century
  - Metrology for Cal Lab Personnel (A CCT prep course)
  - MET/CAL Database and Reports
  - MET/CAL Procedure Writing
  - MET/CAL Advanced Programming Techniques
  - On-Site Training
  - Product Specific Training
- **Instructor-Led Web-Based Training**
  - MET/CAL Database Web-Based Training
  - MET/CAL Procedure Development Web-Based Training
- **Self-Paced Web-Based Training**
  - Introduction to Measurement and Calibration
  - Precision Electrical Measurement
  - Measurement Uncertainty
  - AC/DC Calibration and Metrology
  - Metrology for Cal Lab Personnel (A CCT prep course)
- **Self-Paced Training Tools**
  - MET/CAL-CBT7 Computer Based Training
  - MET/CAL-CBT/PW Computer-Based Training
  - Cal-Book: Philosophy in Practice textbook



More information:
www.flukecal.com/fluketraining

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