
Identifying and Avoiding Common Errors in RF Calibration

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There are many potential sources of human and measurement errors in RF calibration. This paper examines five 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.

Introduction

RF and Microwave calibration is one of the most complex fields of metrology, with many potential sources and opportunities for human and measurement errors. While focus is often applied to the technical complexity and ensuring appropriate equipment, procedures and practice are employed, simple basic errors still occur. Common examples are the choice, use and maintenance of cables, connectors and accessories such as adapters, attenuators, splitters and couplers and the application of correction factors and associated uncertainty contributions. This paper examines five common sources of measurement error, how to identify them, and how to avoid them.

The five topics are:

- Choosing and using cables
- Making repeatable connections
- Applying correction factors correctly
- Working with power splitters and dividers
- Minimizing mismatch errors and uncertainties

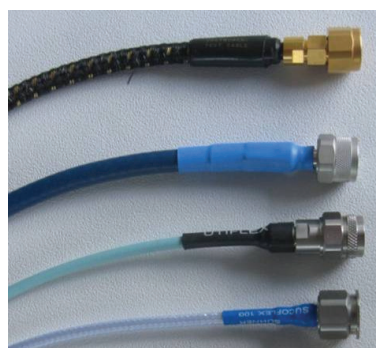
Choosing and Using Cables

Coaxial cables are common throughout RF and Microwave calibration, representing significant investment as precision cables can be very expensive. Choosing an appropriate cable type is often critical to successfully making accurate, repeatable measurements. Characteristics of the cable, the connectors, and the attachment of the connectors to the cable all contribute. The key characteristics are attenuation; phase shift (delay) and match, and their stability with time; temperature; and flexing/movement of the cable and connectors. Maintaining the cable and connectors in good condition is essential to minimizing errors and uncertainties.

For less demanding applications such as distributing reference frequencies, around the laboratory or between individual instruments within a system, typical general purpose RG58 cable using BNC connectors will suffice (Figure 1). However, these types of cables are not appropriate for metrology applications where signal level or phase accuracy and stability or impedance match is critical. Generally the BNC connector is not appropriate for



Figure 1. General purpose coaxial cables.



High-precision flexible, level stable (very expensive).

High-precision flexible, level stable (very expensive).

Precision semi-flexible, clamped connector (moderately expensive).

Precision semi-flexible, crimped connector (moderately expensive).

Figure 2. Precision metrology grade coaxial cables.



Figure 3. Phase and level stable cables used for Vector Network Analyzer (VNA) test port connections. VNA test port cables are extremely flexible, maintaining loss/phase characteristics when moved and flexed (extremely expensive).

calibration applications but there are some higher quality BNC connectors available which are typically used with higher grade cables in oscilloscope calibration. The majority of oscilloscopes appearing in the calibration workload have BNC connectors, so use of a BNC connector is unavoidable.

A few typical examples of metrology grade cables are shown in Figure 2. Unsurprisingly, the improved performance is accompanied by higher costs, typically an order of magnitude more expensive than general purpose cables, with the higher precision cables being even more expensive. These flexible and semi-flexible cables are of the 'level stable' type, where attenuation characteristics are not significantly affected by variations in temperature and flexing. Good practice is to observe a minimum bend radius of around 100mm. Kinked cables will have unpredictable performance and should be discarded to prevent inadvertent use.

Phase stable cable types, as their name implies, also maintain phase (delay) characteristics with time, temperature and flexing. Cable of this type is commonly used as Vector Network Analyzer (VNA) test port cable where good flexibility and immunity to bending and flexing are required (Figure 3).

The manner in which the connector and cable are joined — crimped or clamped — is also important, both electrically and mechanically. Mechanical arrangements differ with connector design, with potential discontinuity of the transmission outer conductor through the termination resulting in variations in transmission line characteristic impedance and therefore contributes to match (mis-match) performance. In a crimped connector, the cable outer conductor is secured by compression between a metal sleeve and the connector body. In a clamped connector, there is a nut and ferrule securing the cable outer conductor to the connector body. Crimping has the potential to add further transmission line discontinuities if the pressure applied to form the crimp distort the cable or connector components. Clamping has the potential for a smoother

transition of the transmission line outer conductor, and therefore better match. However, there is opportunity for loosening of the clamping nut with cable movement, etc, degrading the connection impacting attenuation and match performance, potentially in an intermittent fashion. Crimped and clamped terminations have different attributes and users should choose according to their needs.

It is good practice to consider cables much like any other calibrated item within the laboratory. Cables should be included in routine maintenance and calibration schedules and serialized or provided asset tags as a means of identifying individual items. Many higher grade cables are supplied with measured data for attenuation and match and users may make their own measurements (for example, when using VNAs). Regularly inspect cables and connectors for damage and any other degradation that might affect performance, monitoring characteristics, changes; where appropriate, account for the characteristics during use.

Making Repeatable Connections

RF measurements and the associated uncertainty depend on the integrity of the cables and connectors used to interconnect the various instruments and devices involved. Employing best practice is essential in avoiding and reducing uncertainty contributions. Poor performance of coaxial devices and interconnections can be traced directly to problems with out-of-tolerance dimensions, cleanliness, damage or incorrect tightening of connectors. Furthermore a dirty, damaged or out-of-tolerance connector mated to an otherwise good connector can cause it to become damaged, clearly undesirable if the resulting damage is to a connector on a customer's unit or a laboratory standard. Figure 4 shows a damaged N-type connector on one end of a coaxial attenuator, with arrows indicating cracks in the dielectric disc supporting the center contact. Poor and variable alignment of the center contact arising from this damage was ultimately found to be responsible for bad repeatability in measurements made using this device.

It is essential that connectors are inspected for damage and dirt before they are connected to one another every time a connection is made, or at least daily. Connector threads

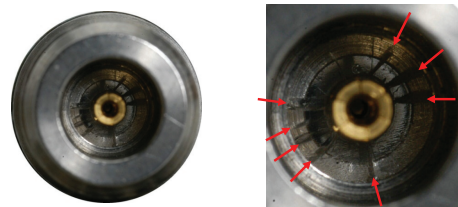


Figure 4. N-type coaxial attenuator connector with cracked center contact supporting disk which caused poor measurement repeatability. The arrows indicate the cracks in the dielectric supporting disc.

and contacts can become dirty from finger oils, airborne contaminants, and from swarf generated in the threads when the connectors are tightened. Dirty or contaminated contacts degrade characteristics of the connector which can cause undesirable effects, particularly poor repeatability and high/variable VSWR (match). Look for dents, raised edges, and scratches on the mating surfaces. Connectors that have dents on the mating surfaces usually also have raised edges around them and will make less than perfect contact. Raised edges on mating interfaces will make dents in other connectors to which they are mated. An illuminated magnifier or eye glass is very useful, and small wooden cocktail sticks can be used to remove small particles. Any loose particles on the connector surfaces, contacts and threads should be removed using low-pressure solvent-free compressed air. Cans of compressed air for this and other equipment cleaning and maintenance purposes are readily available. Never blow into a connector because moist breath will contaminate the connector even further! Once loose particles are removed, cleaning with a small amount of solvent will remove any attached dirt and contamination. Isopropyl alcohol (isopropanol) is the solvent of choice, applied with a cotton swab or lint free cloth. Care is needed to avoid exerting any force on the connector that might damage or bend the connector pins or sockets. Protective end caps should be used to

cover connectors when not in use to prevent contamination or damage by foreign bodies.

Best practice requires that all coaxial connectors fitted on all equipment, cables and terminations should be gauged on a routine basis in order to detect any out-of-tolerance mechanical conditions that may impair the electrical performance or cause connector damage. Coaxial connectors should never be forced together when making a connection, because forcing often indicates incorrectness, damage or incompatibility. Gauge kits for checking the mechanical dimensions for all connector types are available from a variety of manufacturers. Certain dimensions (see Figure 5 for a precision N-type connector) are critical for the mechanical integrity, nondestructive mating and electrical performance of the connector. There are a number of different mechanical specifications for the type N connector and the user should be clear on the mechanical requirement needed for a particular application (precision, general purpose, etc.). Figure 5 shows that the precision Type N connector has the junction mating surface offset from the reference plane to reduce mechanical damage or misalignment when making connections. Also, the inner female pin of the Type N socket connector is of the non-slotted type, to produce characteristic impedance that is independent of the mating pin.

When connecting or disconnecting, avoid misalignment and rotate the

connector nut, not the body. Damage can be caused if the mating surfaces rub against each other or the center contacts are twisted. Correct tightening torque will ensure a good connection and avoid damage. Excessive torque can lead to mechanical damage, deformation of the contacts, and result in degraded VSWR. Connectors should be tightened to the manufacturer's recommended torque using a torque wrench. A gentle smooth pressure should be applied directly through the axis until the wrench "breaks" at the correct torque setting. No further pressure should be applied. With torque wrenches, it is possible to get substantially the wrong applied torque by using a twisting action. It is sometimes useful to use a small flat wrench on a connector body to prevent any rotation when making connection. Always make sure that the torque wrench is at the correct setting before use. The torque wrench used should be routinely checked or calibrated. If it is an adjustable type wrench, it should be adjusted to the correct torque settings for the specific connector and clearly marked. If a connector nut has only a knurl and a torque wrench cannot be used the connector should be finger tight. Be aware, it is possible to over-torque a connector by hand tightening if excessive force is used!

Connector repeatability is typically one of the most significant contributors to measurement uncertainty in RF and Microwave calibrations. Connector repeatability is a type A uncertainty contribution, to be assessed and accounted for within the uncertainty budget, by making repeat measurements. To properly account for connector repeatability, it is necessary to make measurements with several connect/disconnect cycles. Furthermore, best practice is to make each repeat measurement with three to five orientations covering the full 360°. This ensures potential changes in contact conditions of the mated connectors at different axial

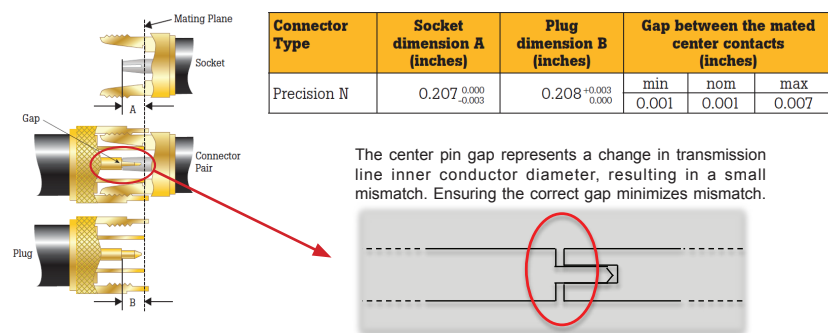


Figure 5. Cross-section of an N-type connector showing the reference (mating) plane and the relevant connector critical dimensions.

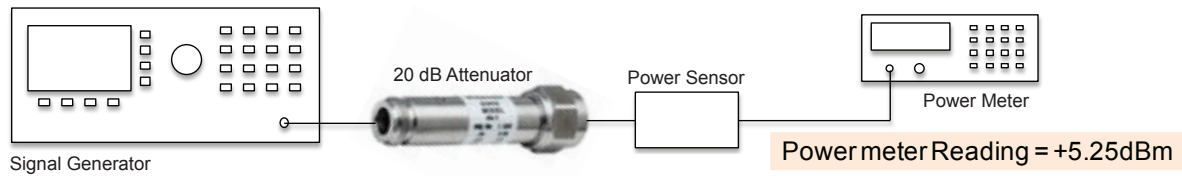


Figure 6. Using a 20 dB attenuator to reduce a signal source output level to within a power sensor range.

orientations and their impact on attenuation, match, etc., are accounted for within the connector repeatability uncertainty contribution.

Applying Correction Factors Correctly

The need to apply correction factors is commonplace in RF and Microwave calibration. Examples would be applying values from a certificate of calibration for standards, or correcting for device/system characteristics derived during measurement, such as adapter insertion loss or splitter tracking error.

Simple human errors may also occur. Incorrect arithmetic and algorithms may be implemented or embedded in automated calculations, such as spreadsheets and software. Mistakes can often go undetected when applied corrections are small. Problems with small values may give apparently believable results, but the results will be in error and any measurement uncertainty estimates will be invalid. Unexpected results are more obvious when large corrections are wrongly applied. It is good practice to test and validate any calculations (including formulae and algorithms in spreadsheets and software) with deliberately large numbers to make the effect of applying correction factors easily observed!

Care is needed to apply 'signed' quantities appropriately and consistently (for example, attenuation values 20 dB or -20 dB). Avoid confusion between 'errors' and 'corrections' usually considered as having opposite signs. The key to avoiding incorrect results is to derive and propagate correction factors consistently. Test algorithms and calculations with values that will clearly demonstrate their correctness or otherwise!

Consider the following simple example of a 20 dB coaxial attenuator, used to reduce the signal level of a source to be calibrated within the range of an available power sensor (Figure 6). Attenuation data from the attenuator's calibration certificate appears in Table 1.

The attenuator could be said to have an attenuation of approximately 19.9 dB, corresponding to an error of -0.1 dB from the nominal 20 dB, which also could be interpreted as requiring a correction of +0.1 dB to be applied to a measurement result (if 'corrections' have opposite signs to 'errors').

In this example, the power meter reads +5.25 dBm, so the signal source power output is nominally $(+5.25 + 20) =$

+25.25 dBm. But the attenuator has an error of -0.1 dB from nominal, so the actual signal source output is $5.25 + (20 - 0.1) = +25.15$ dBm. Simply applying (adding) a correction of +0.1 dB to the nominal +25.25 dBm result would give an incorrect value of +25.35 dBm, demonstrating the caution needed to appropriately and consistently propagate and apply calibrated values, errors, and corrections. Note that the certificate of calibration avoids any ambiguity by stating measured values, not 'errors' or 'corrections.'

Working with Power Splitters and Dividers

The difference between power splitters and power dividers and their applications are often misunderstood, leading to incorrect choice of device and attendant measurement errors. Both devices may be used to split or combine signals, and sometimes the appropriate choice may be unclear.

The power splitter is often referred to as a "2-resistor splitter." As its name suggests, the 2-resistor splitter is constructed in such a manner as to provide two very well matched impedances close to 50 Ω , between the input and each output port. Figure 7 depicts the typical power splitter application of precision leveling, where a power sensor is connected to one splitter output port and the leveled signal appears at the other output port connected to the UUT.

Frequency (MHz)	Attenuation (dB)	Attenuation Uncertainty (\pm dB)
0.10	19.903	0.003
0.30	19.903	0.003
0.34	19.903	0.003
0.50	19.903	0.003
1.00	19.903	0.003
2.00	19.904	0.003
5.00	19.905	0.003
10.00	19.906	0.003
20.00	19.907	0.003
30.00	19.907	0.003
40.00	19.909	0.003
50.00	19.909	0.003

Table 1. Calibration data for the 20 dB attenuator in the example shown in Figure 6

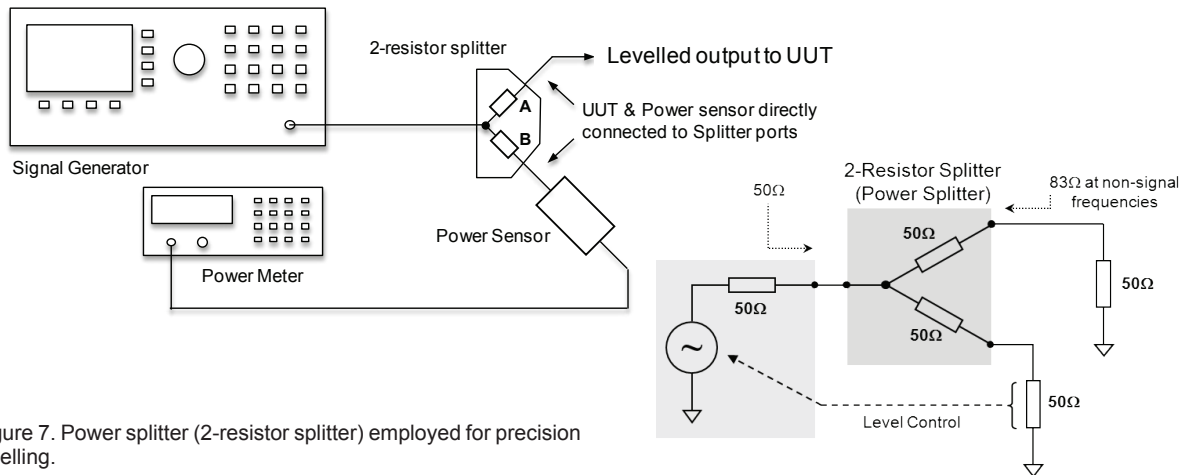


Figure 7. Power splitter (2-resistor splitter) employed for precision levelling.

Feedback from the power meter, either as analog level control feedback, or by computational correction establishes the desired output level at the port connected to the power sensor. As the two splitter resistors are essentially identical, the same level appears at the other port connected to the UUT input. The effect of feedback (analog or computational) is to create a source of precise level from a very good $50\ \Omega$ impedance. However, analysis of the network impedances would suggest the output impedance should be $83\ \Omega$. The $50\ \Omega$ impedance is only presented at the UUT at the signal frequency due to the feedback control loop, and $83\ \Omega$ is presented at all other frequencies. In practice, this is not an issue and power splitters are the appropriate devices when used in this manner for precision leveling applications.

The power divider, often called a “3-resistor divider,” is constructed to be the equivalent of three equal (approximately $16.6\ \Omega$) resistors, as shown in Figure 8. In practice, its construction may not be three individual resistors on a substrate, instead having resistive material deposited on the substrate with three connections providing an equivalent circuit corresponding to three resistors. This power divider device may be used for simple power splitting applications, but should not be used for precision leveling applications commonly encountered in calibration applications. Its use is often more common in signal combining applications, as illustrated in Figure 8. Unlike the power divider, it presents $50\ \Omega$ at all three ports. In calibration application requiring combining of signals and greater

isolation between the sources such as spectrum analyzer intermodulation testing, it is more common to use directional couplers.

In addition to the choice of device, making the connections with the correct physical device orientation is often the cause of errors, for example, when using a power divider. Devices vary in their mechanical layout and packaging, with some having port configuration easier to identify than others. Figure 9 shows one style of power divider device connected for precision leveling where its shape and labeling clearly differentiate the input and output ports.

Figure 10 shows another power divider device connected for this same application of establishing a precision level for spectrum analyzer calibration. However, it is easy to confuse the device port configuration

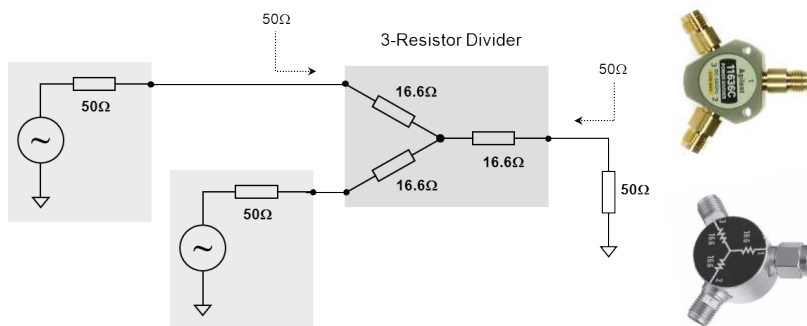


Figure 8. Power divider (3-resistor divider) employed for combining signals from two sources, also showing typical example devices.



Figure 9. An example of a power splitter employed for precision levelling in a spectrum analyzer calibration application where the device shape and labelling help to easily identify its port configuration.



Figure 10. A power splitter correctly configured (left) and incorrectly configured (center) for precision levelling. On the right, a direct connection from the levelling head of an RF Reference Source.

and reverse the source and power sensor connections as shown in the center of Figure 10. This confusion is reportedly a common mistake made with this particular style of splitter device because the incorrect connection appears to offer opportunity to more easily support the power sensor when the setup is made close to the edge of the bench. Mistakes can be avoided and measurement errors reduced by employing an RF Reference Source. The RF Reference Source delivers an accurate input directly to the UUT via a leveling head without need for a power sensor and splitter (the Fluke 9640A), as shown in Figure 10 above.

Minimizing Mismatch Errors and Uncertainties

Along with connector repeatability as discussed previously, mismatch errors are one of the most significant contributions to errors and uncertainties in RF & Microwave calibration. Mismatch error depends on the source and load match:

$$\text{Power Error} = \left\{ 1 - \frac{1}{(1 \pm |\Gamma_s||\Gamma_L|)^2} \right\} \times 100\%$$

where Γ_s is the source reflection coefficient and Γ_L is the load reflection coefficient. The reflection coefficient Γ (gamma) is a vector quantity, however often only its magnitude $|\Gamma|$ is known from a scalar measurement. Reflection coefficient, return loss and voltage standing wave ratio (VSWR) are all related measures of match, with VSWR probably being

the most commonly used, where:

$$\text{Reflection coefficient } \rho = |\Gamma| = \frac{VSWR - 1}{VSWR + 1}$$

$$\text{Return loss} = 20 \log |\Gamma|^{-1}$$

It is evident that the quality of the source and load match both contribute to the mismatch error, and also that if either one is very good (close to the ideal 50 Ω , with VSWR approaching 1.0:1) the impact of the other being relatively poor is reduced. This latter effect can be exploited in practical measurement situations to reduce mismatch errors by deliberately inserting a device with good match characteristics (low VSWR). The device, an attenuator, often referred to as a “masking pad” or “matching pad” is inserted at the point where doing so will bring the greatest benefit—at the point where the match is worst or most variable. In this instance, the purpose of the attenuator is only match improvement and not signals level reduction. (Note that the term matching pad is also used for impedance conversion pads, used to convert between 75 Ω and 50 Ω , and these are different devices.)

An appreciation of the mechanism of mismatch error reduction can be obtained by considering Figures 11 and 12. Figure 11 depicts the reflection of a proportion of the signal at the interconnection of a source and load device where a mismatch occurs. When the masking pad is inserted, as shown in Figure 12, the reflection travels through the masking pad twice. Therefore, the magnitude of the reflection is reduced by twice the pad attenuation value, thus reducing the effect of the otherwise poor match.

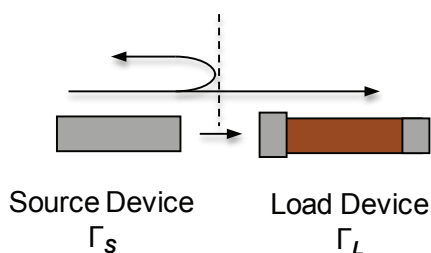


Figure 11. Reflection occurs at the mismatch between source and load.

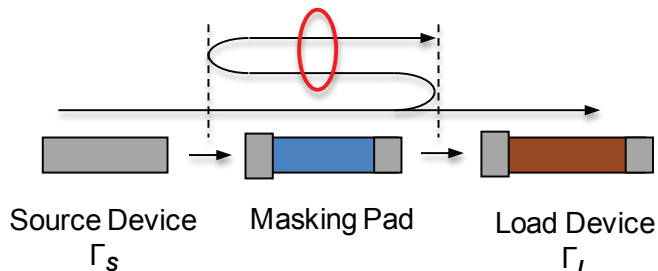


Figure 12. The reflection travels twice through the masking pad inserted between source and load.

Inserting attenuation, thus reducing signal level, can negatively impact measurements. Signal levels move closer to the noise floor or require higher input levels, which place greater demands on signal source output capability. However, relatively small value pads (3 dB or 6 dB) are generally sufficient to significantly improve match conditions and reduce mismatch errors with only moderate and generally tolerable signal level reductions. It is relatively easy to obtain attenuator devices with good match performance. However, there can be a limit where the masking pad match may not be good enough to provide significant improvement over the match provided by the source and load connected directly if they are also well matched devices.

Most commonly, the masking pad technique is used to improve match of active devices such as output match of a signal source or input match of a measuring device. The output or input is directly from/to an active device with no passive circuits or attenuator to better define matching conditions. The masking pad should be placed at the end of any interconnecting cable, furthest away from the signal source, such that it 'masks' the match of both the generator and cable. Another common application is switched step attenuators, which may be permanently fitted with masking pads at their input and output to ensure the various attenuator stages work into a constant well defined match. Frequently, the entire attenuator and masking pad combination is submitted for calibration as a single unit.

Conclusions

Five common sources of error in RF & Microwave calibration have been discussed along with hints and best practice guidance to identify and avoid them. Mistakes, measurement errors, and uncertainties can be eliminated or minimized by following best practice:

- Use appropriate metrology grade cables and connectors.
- Regularly inspect cables connectors and adapters for damage, cleanliness and compliance with mechanical specifications (gauging).
- Ensure connectors are correctly stored, handled, and tightened with correct torque.
- Derive and apply correction factors in a consistent manner.
- Test any and all calculations, algorithms (manual, in paper procedures and embedded in software and spreadsheets) with numeric values that will make obvious any mistakes and incorrect implementations.
- Use power splitters for precision leveling applications. Power dividers may be more appropriate for signal combining applications.
- When using splitters and dividers, pay close attention to device physical input and output configurations.
- Masking pads (attenuators) can significantly reduce the impact if poor match (high VSWR) devices on mismatch errors and uncertainties.

The topics have been treated in a practical back-to-basics manner avoiding, where possible, any detailed mathematics. However, references are provided where further detail may be obtained.

References

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