

High-Power RF Measurement: Techniques and Methods

1050 Watt System												
Slope Errors							Range Errors				Total Error	
Power Level (W)	Coupler Ratio	Cal Factor Unc (% Rdg)	Coupler Monitor Slope Repeatability (% rdg)	Coupler Power Factor Linearity (% rdg)	Coupler Temp Coeff, +/- 3C, % rdg	Uncorrected Port Match, Assumes 1.25 & 1.1, (% rdg)	RSS Slope Errors (% rdg)	Monitor Noise (W)	Monitor Thermistor Drift (5 min)	Noise and Drift Ref'd to Output (W)	Total Error, 95%, (W)	Error, % rdg
1050	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	8.3666322	0.8%
500	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	4.049586762	0.8%
250	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	2.087293381	0.8%
125	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	1.10614669	0.9%
100	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	0.909917352	0.9%
50	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	0.517458676	1.0%
25	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	0.321229338	1.3%
10	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	0.203491735	2.0%
5	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	0.164245868	3.3%
2	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	0.140698347	7.0%
1	50,000.00	0.56062042	0.03	0.1	0.1	0.53	0.7849	5.00E-07	2.00E-06	0.125	0.132849174	13.3%

Table 1: Thermistor-Based Directional Coupler Assembly, Representative Uncertainty Analysis

Demand for high-power RF and microwave device calibration is higher than ever. Technological advances in automation, semiconductor, and communications applications are largely responsible for this increased demand, and have pushed the traditional limits of high power RF metrology to higher frequencies and higher power levels.

Frequency and power are not the only boundaries being challenged however. These new and improved technologies also bring a mandate for lower uncertainties. Low-uncertainty high power RF measurement is especially critical for industries such as semiconductor manufacture, but it's important to all industries involved in high power applications in both commercial and governmental sectors.

Low-uncertainty high-power RF metrology poses unique challenges and requires specialized equipment and measurement techniques to ensure repeatable, accurate measurements. In this

paper, we will provide a broad overview of commonly-used high-power RF measurement techniques, and examine the advantages and disadvantages of each.

We will discuss the equipment required, typical measurement uncertainties, and the power and frequency limits of each. Lastly, we will identify the applications best served by each methodology. See Table 2 for a summary of each of the methods.

For purposes of this paper, measurement uncertainties have been normalized to 2-sigma to facilitate easy comparison between methodologies. However, be aware that uncertainties may be presented at different confidence levels between manufacturers, and sometimes inconsistently between product lines from the same manufacturer. Always carefully read the product datasheets and manuals to properly characterize reported uncertainties.

General Considerations

High-Power Measurement Equipment

High-power RF Test stations typically require specialized, purpose-built equipment. High-quality signal generators, amplifiers, and filters are necessary to supply low-distortion test signals at the measured power and frequency points. Building such a test station can be an expensive proposition, so thoroughly understanding the options available is even more important.

Filters are especially critical as minimal harmonic distortion is required to ensure accurate measurements. Low-uncertainty measurements often require 2nd harmonic distortion to be better than -50 dBc, which can be challenging for amplified CW signals.

Filters must be designed for the particular frequencies and power levels to be tested, with minimal

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VSWR and insertion loss across the specified measurement range. Filters may be stand-alone, or designed into measurement devices. But with either configuration, it's important to verify the system's harmonic suppression characteristics prior to making traceable measurements.

Test stations must also include a load capable of dissipating the expected power levels to be measured.

Measurement Considerations

High-power RF measurement can present challenges more easily handled in lower-power applications. When measuring high-power, measurement errors such as port reflection and mismatch, insertion loss, power linearity, and tolerance to thermal transients become significantly more important.

These topics are beyond the scope of this paper, but will be discussed in detail in upcoming releases from TEGAM. Please visit www.tegam.com, or call us at 440-466-6100 for more information regarding high-power RF measurement instruments, uncertainties, and procedures.

Techniques and Methods

RF Wattmeter

The most straight-forward method for measuring high-power RF is the use of a simple wattmeter. Available in a wide array of designs, wattmeters are a cost-effective method for RF measurement in the 100 mW to 10 kW power range.

Wattmeters typically use a diode-detection circuit to measure RF power across a transmission line. The wattmeter is connected inline with the device under test, and can measure both forward and reflected power. These instruments are often designed to be portable with the indicating meter and measurement elements packaged as a single unit. The portability and versatility of wattmeters make them well-suited for field work.

However, these conveniences come at the expense of accuracy. Wattmeters typically provide measurement uncertainties in the 3% to 10% range. This is often acceptable for field applications such as tuning an antenna for optimal impedance or making a "go, no-go" measurement of a radar station. For metrological measurements however, these high measurement uncertainties are unacceptable.

Directional Power Sensors

Directional power sensors are similar to traditional RF wattmeters. They typically employ a diode-detection circuit that converts RF power to a voltage, and can be used to measure both forward and reflected power. Some models provide the ability to change connector styles, thereby supporting a wider range of test devices. Similar to wattmeters, directional power sensors are designed to cover relatively narrow frequency bands necessitating the purchase of multiple models for broadband applications.

However, there are several key differences as well. First, directional power sensors typically do not include a meter or other indicator on the sensor. Instead, they require an external meter.

Secondly, directional power sensors often provide improved measurement uncertainty over traditional wattmeters. At specific calibrated frequencies and power levels, directional power sensors can be as good as $\pm 2\%$. Uncertainty can be considerably worse at points other than the calibration points though. Users should therefore carefully examine the sensor's measurement uncertainty at all frequencies and power levels of interest before making traceable measurements.

Directional power sensors provide an acceptable bridge between field and laboratory work. However, the requirement of a separate meter / indicator makes them less portable than RF wattmeters, and they have narrower frequency ranges and worse uncertainties than the directional

couple assemblies and calorimeters discussed below.

Directional Coupler Assemblies

Directional coupler assemblies can be used similarly to directional power sensors, but rely on fundamentally different technologies to make power measurements. They utilize a low-power RF sensor paired with a directional coupler to measure RF power levels beyond the usual power range of the sensor.

They also often include a large heat sink to dissipate heat generated at the coupled port of the directional coupler. Dissipated RF power is converted to heat energy inside the coupler, which can induce variability in the coupling coefficient. These variabilities are difficult to predict, and can significantly impact repeatability and absolute measurement accuracy. A heat sink properly positioned and sized to wick away thermal changes within the coupler will mitigate these uncertainties.

Directional coupler assemblies can be configured using either diode- or thermistor-based sensors. The dynamic range of the assembly is primarily determined by the coupler used, and the assembly's overall measurement uncertainty is the combination of the directional coupler power linearity and directivity, and the calibration factor uncertainty of the sensor. In short, the better the sensor and coupler, the better the final measurement uncertainty.

Directional coupler assemblies provide two major advantages over the directional power sensor approach. First, coupler assemblies can cover a much wider frequency bands. Compared to a directional power sensor, coupler assemblies are relatively flat over wide frequency ranges and can be calibrated to provide a reasonably accurate, single-device solution for wideband power measurement.

Second, directional coupler assemblies typically have better measurement uncertainty across their frequency and power ranges

than directional power sensors, with thermistor-based assemblies providing better uncertainties than diode-based assemblies.

Diode sensors typically report power readings relative to a reference, usually 50 MHz. In practical terms this means that before each use, the sensor must be disconnected from the directional coupler assembly, connected to the 50 MHz reference port on the system power meter, standardized, then reconnected to the assembly. This sensor disconnect and reconnect introduces a significant and sometimes difficult-to-calculate uncertainty to the final measurement. Further, the 50 MHz reference itself will contribute a sizable uncertainty to the measurement.

Thermistor-based assemblies however measure absolute power and can therefore be permanently fixed to the coupler assembly, resulting in much-improved measurement uncertainty. This combined with the better uncertainty of thermistor sensors generally, results in a better overall uncertainty compared to diode-based assemblies, and much better than directional power sensors. Uncertainties of better than 1% can be achieved with a properly calibrated thermistor-based coupler assembly.

Linearity is also an important consideration when selecting between diode- or thermistor-based coupler assemblies. Linearity measures the response of a sensor compared to changes to input power. For instance, if input power is doubled, a perfectly linear sensor's measured power will also double.

Diode sensors have a wide dynamic range, with some popular sensors covering ranges as large as -70 to +30 dBm. However, nonlinearity across this range can be as much as 5%, depending on the sensor design. When calculating total system uncertainty, it's important to account for this nonlinearity.

Thermistor sensors on the other hand have a limited dynamic range, but excellent linearity across that range. A typical ther-

Sensor Type	Typical Accuracy (k=2)	Typical Linearity	Typical Frequency Range	Typical Dynamic Range	Portable?	Typical Applications
RF Wattmeter	±5 to 10%	Not specified	2.5 GHz	up to 10 kW, with some high-power models up to 25 kW	Yes	High power measurements in field applications such as communication sites and antenna tuning.
Directional Power Sensor	±1 to 5%	±1.5 to 5%	2.7 GHz	up to 10 kW	Yes, but requires an external meter	Benchtop applications requiring moderate accuracy and speed.
Diode Directional Coupler Assemblies	±1.8 to 5% ¹	±1.5 to 5%	Limited by coupler	Coupler / heat-sink dependent	No – large heat sink and requires an external meter	Applications requiring reasonable accuracy across a wide dynamic range.
Thermistor Directional Coupler Assemblies	< +1% ¹	+0.1%	Limited by coupler	Coupler / heat-sink dependent	No – large heat sink and requires an external meter	RF plasma generator calibration, semiconductor manufacture, RF amplifier testing, and other high-accuracy measurement applications
Calorimeter	<0.5%	0.05%	4.5 GHz	Dynamic range determined by design	No – sensitive to ambient temperature transients	Calibration of sensors, and other laboratory and industrial applications requiring extremely high accuracy.

¹ Accuracy assumes that the coupler and sensor are calibrated as a set

Table 2: Typical Specifications and Characteristics of Commercially Available Measurement Methods

mistor assembly has a dynamic range of -20 to +10 dBm. Nonlinearity however can be as good as 0.1% across that range. This again leads to much better total system uncertainty when using a thermistor sensor.

As mentioned above, directional coupler assemblies are often attached to large heat-sinks and are therefore less portable than wattmeters and directional power sensors. Thermistor sensors also respond marginally slower than their diode-based cousins. However, for applications such as RF plasma generator calibration, semiconductor manufacture, and RF amplifier testing, directional coupler assemblies are ideal. These applications require the low uncertainties provided by coupler assemblies without sacrificing workload throughput.

Table 1 highlights a representative uncertainty analysis for a typical thermistor-based directional coupler assembly. Note that from 10% to 100% of full power, reading error remains relatively flat at less than 1%, while power readings at less than 1% yield higher errors. The data in Table 1 is for a 1050 W assembly, but assemblies designed for lower or higher power will respond similarly.

Calorimeters stand alone among the other methodologies discussed in this paper. They provide the best available measurement uncertainty, but are very slow compared to other techniques. Generally, they are used in the laboratory to calibrate working standards such as directional coupler assemblies, directional power sensors, and wattmeters.

Calorimeters are thermal devices

A source RF signal is applied to a load inside the calorimeter, through which a liquid is circulated at a known flow rate. A thermal transfer occurs between the load and liquid, proportional to the RF signal source. That temperature delta is then measured as a thermocouple voltage from which the applied RF power level can be derived.

To make accurate measurements using this process, calorimeters must carefully monitor and control the flow rate of the liquid through the load, and any potentials for heat loss in the system must be minimized. Calorimeters require the same amplifiers and filters used in the preceding methodologies, but also require a chiller to maintain precise temperature control of the circulated liquid. Because of this, calori-

meters are usually permanently installed in the lab, and often placed in a dedicated area designed to properly handle excess heat and noise from the chiller and other equipment.

As mentioned above, calorimeters are comparatively slow-measuring devices. Precise control of the circulated liquid and stabilization of the RF signal thermal transfer can take a considerable amount of time. Direct-reading systems that utilize high-quality chillers coupled with precision flow-control circuitry can take 10 to 15 minutes per measurement. Other systems use a substitution measurement approach, comparing the thermal delta of an RF source signal to that of an easily-measurable DC signal, and can take several hours per measurement. Another consideration in calorimetry is heat loss within the system. Careful calorimeter design will minimize the poten-

tial for thermal dissipation between the load and measurement circuit. Individual thermocouples are often used to measure the thermal delta, and can provide reasonable measurement uncertainty. But inherent in the design, they introduce opportunity for heat loss. Packaged thermopiles however minimize thermal loss in the system, while still providing very accurate temperature measurements.

Accuracy is the primary advantage of the calorimeter. Direct-reading systems are now availa-

ble with measurement uncertainty better than 0.5% across their frequency and power ranges.

Conclusion

Making high-power RF measurements presents unique challenges, both in terms of equipment requirements and maintaining measurement uncertainties suitable for the application at hand. There are advantages to each of the methods discussed in this paper, and careful consideration and research is necessary

to choose the method that best balances measurement uncertainty, portability, frequency ranges, and dynamic range.

While RF wattmeters or directional sensors are often ideal for field measurements at very particular frequencies, they have larger reading error than other methods. Directional coupler assemblies can measure across a wider frequency range but are not generally suitable for field work. Additionally, thermistor-based directional coupler assemblies provide significantly impro-

ved measurement uncertainties. Lastly, calorimeters will provide the lowest measurement uncertainty, but can only be used in lab environments and are much slower than the other methods discussed.

Table 2 provides a brief summary of the key characteristics of the methods discussed above. This data provides an overview of commercially available instruments, but please refer to manufacturers' published specifications for full performance information. ◀