Transmitter Output Power Measurements in Digital Broadcast Systems

Tim Holt, Director Applications and Systems Engineering
Bird® Technologies Group
Tel: 866.695.4569 / www.bird-technologies.com

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INTRODUCTION

The measurement of transmitter output power has always been an important consideration in the operation of broadcast transmission systems. As broadcast network systems are planned and integrated, coverage predictions, as well as the prediction of the possibility of co-channel interference are based upon several factors, including geographical terrain, antenna gain and directionality, and transmitter output power. The introduction of new digital modulation formats into broadcast settings has necessitated a re-thinking of the methods that are used for the measurement of transmitter power. The accuracy and reliability in which these measurements may be made is related to our understanding of the limitations of conventional power measurement methods, as well as to our understanding of the proven techniques that have been developed for use with digital broadcast systems. In this paper, we will review some of the characteristics of conventional measurement methodologies, as well as to develop a foundation of understanding of newer techniques. We will also discuss “first principle” power measurement methods, and present data as to how various measurement methodologies compare with measurements developed using first principle techniques.

Review of Conventional Transmitter Power Measurement Techniques - Instruments used through the years for the measurement of transmitter output power may be categorized as follows:

- **In-line or Thruline Instruments**
- **Terminating Power Meter / Directional**
- **Coupler Based Instruments**
- **Radio Frequency Calorimeters**

Of the above categories, in-line power meters have been the most popular instruments, owing to their simplicity, ease of use, and their ability to measure both forward and reflected power. First generation instruments of this class were developed in the 1950’s, uses simple point contact diode detectors. Within the past five years, versions of these instruments have been developed using up to date diode devices and low noise amplifiers, more appropriate for the measurement of signals incorporating complex modulation.

Terminating power meters and their associated directional couplers have also been used extensively. Power measurement techniques developed around instruments of this class are adaptations of power meters that were designed for laboratory use, but can provide high quality measurements in broadcast applications when paired with the appropriate directional coupler.

Radio frequency calorimeters provide the advantage of providing measurements that truly represent heating power, as their definition would imply. These devices also provide the advantage of responding to the aggregate power presented to their input, as they are typically broadband devices. One might argue that terminating-type laboratory power meters would also provide this advantage, in that these instruments are also typically broadband in nature, but they are limited to measuring very low power levels, and must be used with a directional coupler. These couplers are useful only over a relatively narrow band.

Following are some additional details regarding these power measurement instruments:

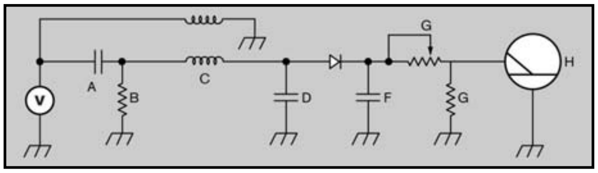


Fig. 1

First Generation In-Line Power Meter - These power meters are comprised of a short length of precision transmission line fitted with either a single or a dual directional coupler. The output of the directional coupler is typically in the range of 40-60 dB below the main transmission line level. The coupler output is connected to a simple diode detector (Fig. 1) and then scaled and displayed on a meter movement. Most of these power meters actually measure the peak power of the signal, while the meter scale is actually calibrated in average power. While this approach has served the broadcast industry for many years, the use of simple in-line power meters in complex modulated signal systems has been questioned due to the inability of simple diode detectors to respond to signals with very high peak to average power characteristics common to digital modulation formats. Diode detectors in conventional in-line power meters are operated largely over the non-linear portion of their dynamic range with their accompanying meter scales calibrated to read average power, even with the diode operating in a nonlinear fashion. This approach works fine, so long as the power meter is used to measure a single defined waveform or a closely related signal, such as CW or FM modulation.

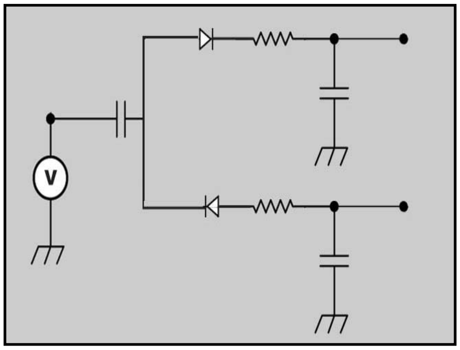


Fig. 2

In-Line Power Meters with Square-Law Detectors (Fig. 2) - This latest generation of in-line power meters is configured in much the same manner as the first generation instruments, with the important difference in the detector technology. An alternative approach using diodes that works well in systems carrying complex modulation is to operate the detector diodes below approximately -20 dBm in an area known as the "square law" region of the diode's dynamic range. In this region, diode detectors behave in much the same manner as thermal detection devices, where at low signal levels; the diode's rectified output is a function of the square of the RMS input voltage. The transfer function for a full-wave square-law diode detector is approximated as follows:

$$\boxed{V_{out} = (V_{in} / 5.77)^2}$$

Where all voltages are in millivolts. This relationship holds as long as the total excursion of the signal is contained within the diode's square law region. The theoretical bounds for this range are from approximately -20dBm on the high side to the noise floor as determined by the bandwidth of the measurement at the lower end. Measurement ranges of 50 dB are possible in most systems.

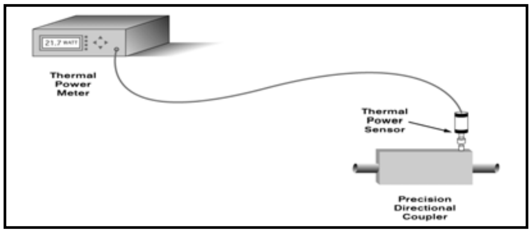
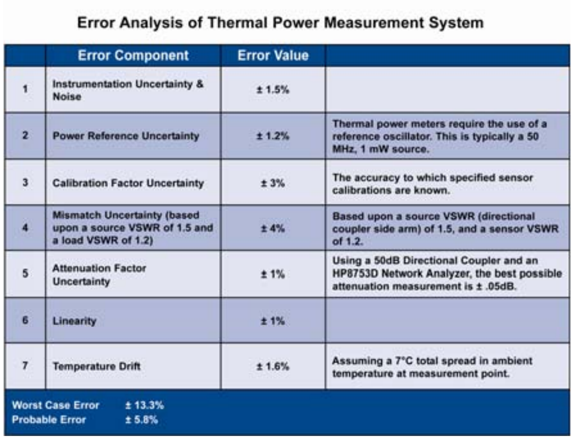


Fig. 3

Terminating Power Meter / Directional Coupler Power Meters - These instruments, generally used for laboratory applications are wide frequency range, wide dynamic range instruments that may be used in conjunction with high power directional couplers for making high power measurements. (Fig. 3)They may use either thermal converter technology, or diode detector measurement approaches to power detection. They are generally more difficult to use, as they require frequent calibration and are more expensive than the above choices. Another issue with these instruments is that the measurement of transmission system VSWR is more difficult, as this measurement requires the use of a dual channel coupler, and a second measurement channel on the power meter. Like the square law based instruments described above, they work well in cases of complex modulation, as they respond to the heating power of the signal.



Error Analysis of Thermal Power Measurement System

	Error Component	Error Value	
1	Instrumentation Uncertainty & Noise	± 1.5%	
2	Power Reference Uncertainty	± 1.2%	Thermal power meters require the use of a reference oscillator. This is typically a 50 MHz, 1 mW source.
3	Calibration Factor Uncertainty	± 3%	The accuracy to which specified sensor calibrations are known.
4	Mismatch Uncertainty (based upon a source VSWR of 1.5 and a load VSWR of 1.2)	± 4%	Based upon a source VSWR (directional coupler side arm) of 1.5, and a sensor VSWR of 1.2.
5	Attenuation Factor Uncertainty	± 1%	Using a 50dB Directional Coupler and an HP8753D Network Analyzer, the best possible attenuation measurement is ± .05dB.
6	Linearity	± 1%	
7	Temperature Drift	± 1.6%	Assuming a 7°C total spread in ambient temperature at measurement point.
Worst Case Error	± 13.3%		
Probable Error	± 5.8%		

Table 1

The error analysis of a typical implementation for this power measurement approach appears in Table 1. While the analysis is fairly self-explanatory, there are a few comments worth making:

1) The accuracy of power meters in this class are dependent upon many factors, one of which is the accuracy of the instrument's internal reference. Also, the internal reference operates at a single frequency and power level.

2) Operation of the power meter at frequencies other than the internal reference frequency

requires the use of calibration offsets. These offsets carry their own uncertainties.

3) The effects of mismatch uncertainty between the input to the power sensor and the output of the directional coupler are significant. Since the VSWR characteristics of the sensor input and the coupler output change with frequency, the magnitude of the mismatch uncertainty will also change with frequency.

Radio Frequency Calorimeters - Have formed the foundation for high power measurements for many years. This power measurement method remains in use today as the means by which NIST establishes primary RF measurement standards. As mentioned above, calorimetric systems measure the true heating power of a signal, including the fundamental frequency, all harmonics and sidebands, and other modulation related contributions. The calorimeter will measure the total aggregate power contained in the signal. The calorimeter is a device that responds to heat and will measure the heating power of a low frequency (50 or 60 Hz), or DC energy in exactly the same manner in which the calorimeter will respond to RF signals. This characteristic enables the calorimetric system to be highly accurate, as the low frequency AC, or DC energy used to calibrate the calorimeter may be known very precisely. This calibrating energy is also very useful in the establishment of a path back to NIST primary standards. Typical field calorimetric system accuracy is +/- 4%, but accuracies of +/- 1% are possible using the substitution calibration methodology outlined above. Although calorimetric power measurement methods yield results with unparalleled accuracy, calorimetric systems have their limitations. These may be characterized as follows:

1) **Calorimeters are generally difficult to use.** This is especially true in field settings, with typically uncontrolled environments.

2) **Best results with calorimetric methods** is obtained with highly trained operators.

3) **Calorimeters are terminating devices**, and are not suitable for directional power measurements, leading to antenna match measurements.

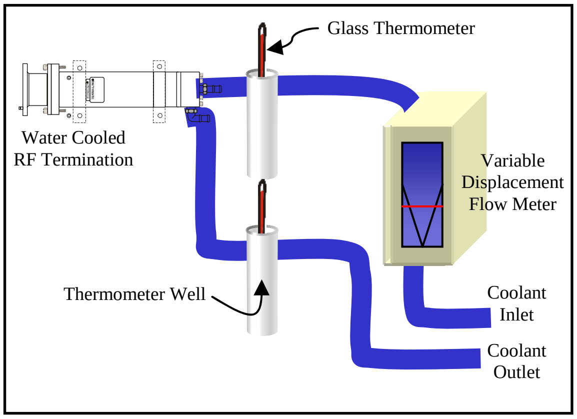


Fig. 4

A pictorial diagram of a typical calorimetric system is described in (Fig 4). In this system, a water-cooled, high power RF termination is used as a means to convert radio frequency energy into heat, with the constraint that this must be done in a highly efficient manner, so as to capture the majority of the energy dissipated in the load. Load efficiency is also important from the perspective of calibration, as the heat flux from the load in areas other than the coolant path cannot be easily captured, and will also behave as a function of the ambient temperature. In other words, if the calorimeter is calibrated at 25° C, and the ambient temperature changes to 15°C, this additional gradient will result in more heat escaping from the load in areas other than the coolant path. This will have the effect of shifting the calibration point of the calorimeter.

Also contained in this system is a means of determining the mass flow rate, in this case a volumetric flow measurement instrument. (Rotameter) While flow meters of this type have been used in field calorimeter instrument through the years, more precise turbine-type instruments are available.

Finally, the system contains two temperature sensing elements, one placed at the input to the RF load, and the other placed at the output. While the picture shows glass thermometers, most modern systems use thermocouples, or thermistors for these components, for their improved accuracy and repeatability.

Calorimetric systems will measure power in accordance with the following equation:

$$\boxed{\mathbf{Power(kW) = 0.263 \; X \; \Delta T \; X \; Flow}}$$

Where, temperature measurements are in degrees centigrade and the flow rate is in gallons per minute. While this formula will provide an indication of the power dissipated in the load, it is necessary in most cases to compensate for the physical changes to the coolant used in the system, both in terms of changes due to temperature, as well as coolant mixtures such as ethylene glycol and water. For example, the specific heat of pure water has a value of 1.0 at a temperature of 15º C, but this value drops to 0.998 at a temperature of 35º C. Modern calorimetric instruments will automatically compensate for these changes.

As mentioned above, one very important attribute of the calorimetric system is that the system will respond essentially the same for DC or low frequency AC energy as for RF energy. This “substitution” calibration procedure may be characterized as follows:

1) **Low Frequency Power Reference -** This reference will be used to measure the actual power used for calibration. Since low frequency energy will be used for calibration, inexpensive, highly accurate instruments are available. Inexpensive digital multimeters, are typically accurate to within +/- 1% for low frequency voltage and current measurements. The best choices are AC power meters such as those made by Yokogawa, which measure voltage, current, as well as the phase angle between these parameters. Using instruments of this type, it is possible to measure the delivered power to the load.

2) **Low Frequency Source -** In many cases, 60 Hz energy may be used. A primary consideration is the stability of the energy source.

3) **Perform Calibration -** The calibration should be performed at or near the power level where the RF measurement will be made, in order to avoid linearity errors. Connect the low frequency source to the calorimeter, along with the reference standard.

4) **Perform Substitution -** Connect the RF source to be measured to the calorimeter in place of the low frequency source, and perform the measurement.

Typical medium term measurement accuracy for the system as calibrated above is quite good, as shown in (Fig. 5).

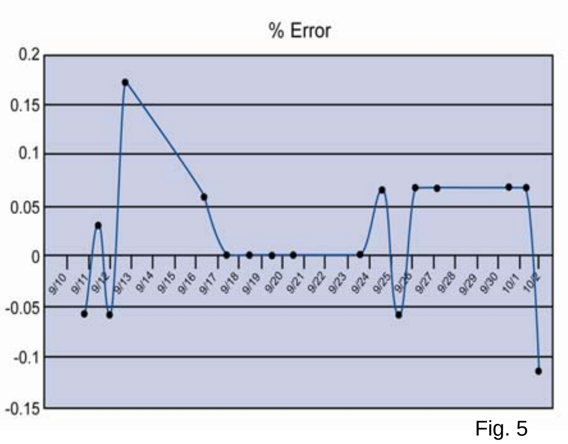


Fig. 5

Traceability to National Standards - As mentioned above, there are two widely used traceability paths from high power RF measurements performed “in the field” back to the low power primary standards maintained by NIST. These two paths are outlined in Fig. 6 and 7.

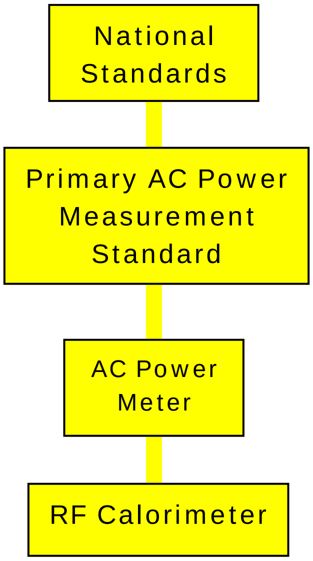


Fig. 6

The first path (Fig. 6) incorporates the concept of DC or low frequency substitution, as we explained above. The path begins with the calorimeter that is used as the “working standard”, and may be used as a reference standard for other power meters. As described above, the calorimeter is calibrated using voltage and current meters, or a low frequency AC power meter. These instruments are easily traceable to primary standards.

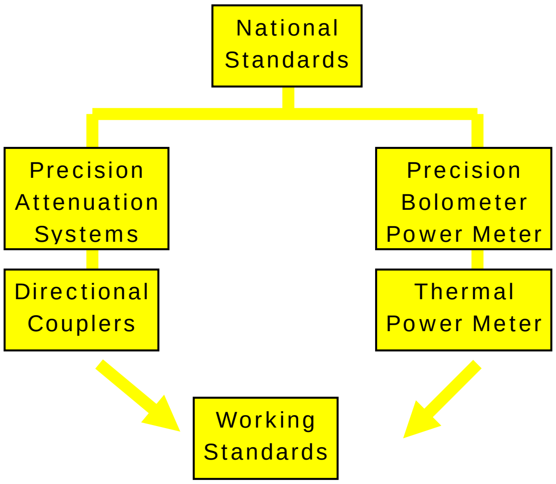


Fig. 7

The second path (Fig. 7) is intended for working standards that are comprised of terminating power meters and directional couplers as described earlier. Traceability for measurement systems of this type requires the use of a dual path, one for the calibration of the directional coupler using precision attenuation standards, and the other for the calibration of the power meter using calibrated thermistor mounts (bolometer).

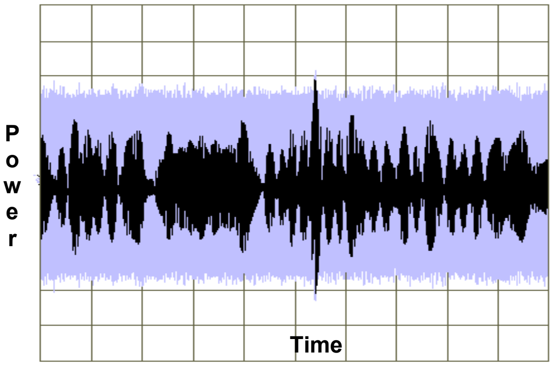


Fig. 8

The Challenge of Digital Modulation (Fig. 8) - The measurement of radio frequency power in digitally modulated signals presents a challenge due to high peak to average power ratios (crest factor) found in 8-VSB, COFDM, and similar signal types. In general, the average power of signals using complex modulation is constant, whereas the peak power is data dependent. In practice, crest factor values of 7 dB are typical for these systems, with crest factor values as high as 12 dB possible, especially in multiple carrier settings. Conventional diode detector power meters, being peak reading instruments tend to follow the envelope established by the peak power value of the signal.

Power Meter Comparative Testing - So far, we have established that calorimeter power meters are able to provide the best accuracy, and provide readings that truly represent heating power values. Since it is not generally practical to use calorimetric methods on a daily basis, it is important to understand how transmitter power measurements made with alternative techniques compare with those obtained with calorimeters. To make this comparison, we chose three different power meter types, along the lines of those described above. These power meters were then used to make transmitter power measurements, while using a high power calorimeter as a reference. In addition, the power measurements were made using signals with no modulation (CW), with COFDM modulation, and with 8-VSB modulation. Each of these formats has different crest factor characteristics.

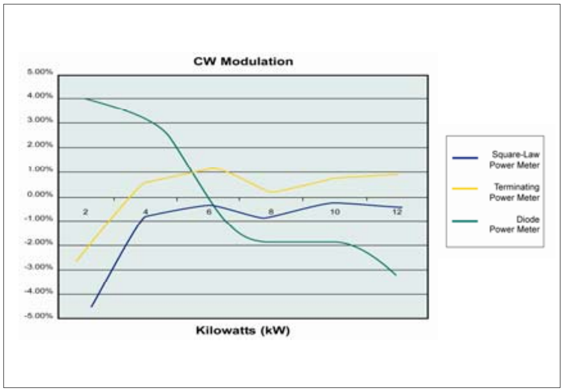
Specifically, power meter types chosen for the testing were:

- **Conventional In-Line Directional Power Meter with Single Diode Detector**
- **Thermal Terminating Power Meter with Directional Coupler**
- **In-Line Power Meter with Square-Law Detector**

Testing Protocol - Each power meter type was tested independently, using the calorimeter as a reference. The testing was performed at power levels from 2 kW to 12 kW, in order to expose issues with dynamic linearity. Test results were as follows:

CW Comparison: The test began by applying power to the systems with **no modulation applied** into a 50-ohm load**.** Under this signal condition, the power meters in the system, including the calorimeter should produce very similar readings. These readings were used as a baseline for the remainder of the tests. Power readings were recorded for various power levels between 2 and 12 kW.

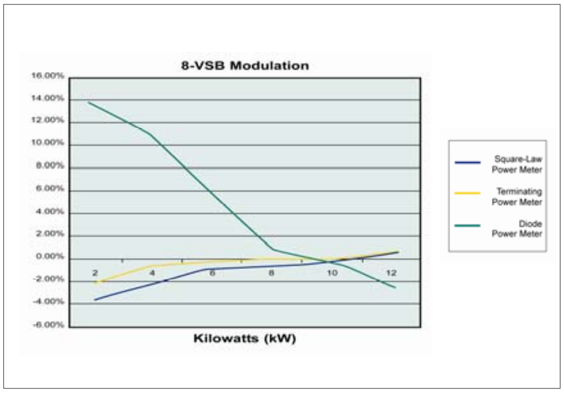
Test Results for CW Test - Within published specifications as illustrated in Graph A. In CW testing, with no modulation applied, the performance of all of the power meters was within published specifications, +/- 5%.



Graph A

8-VSB Comparison: The second phase of the testing required connecting the calorimeter and the in-line power meters to a source of 8-VSB modulated RF power to demonstrate the performance of the various meter types under 8-VSB modulation. The procedure used for the previous CW testing was repeated using the same power levels.

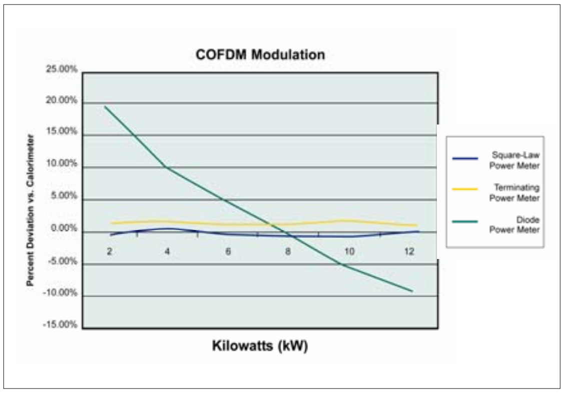
Test Results for 8-VSB Test: The results of the 8-VSB test are shown in Graph B*.* The test data illustrates that the thermal and square–law based diode power meters track the calorimetric system to within 3% across the power ranges tested.



Graph B

COFDM Comparison: In the third phase of testing, the calorimeter and the three in-line power meters were connected to a source of COFDM modulated RF power in order to demonstrate the performance of the various power meter types under COFDM modulation. The test procedure as outlined in the previous steps was followed, again using the same power levels as used during the CW and 8-VSB testing.

COFDM Test Results: The COFDM test results are indicated in Graph C*.* In this phase, the accuracy differences between the thermal and square law diode power meters were even more pronounced than in the previous testing. The results show that the BPM and the thermal power meters were consistently within 2% of the calorimeter.



Graph C

CONCLUSION

In this paper, we have provided information as to various methods for the measurement of transmitter output power, and compared these methods with the “first principle” methodology of radio frequency calorimetry. This information may be used to insure that good choices are made with regard to the measurement of transmitter output power. Finally, we have presented test data illustrating the performance of three types of power meter systems when used with common digital modulation schemes, as well as under conditions where no modulation is present. Based upon the data collected during testing, it is clear that the square-law based diode power meter and the thermal power meter/directional coupler combination are capable of the measurement of signals using complex modulation with accuracy approaching a calorimetric power measurement system.