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IMPROVING THE ACCURACY OF AM AND PM NOISE MEASUREMENTS

by Perry C. Bates
Techtrol Cyclonetics, Inc.

ABSTRACT

Measurement of low level AM and PM noise is a troublesome and difficult procedure for many engineers. After noise measurements are made, in many cases uncertainty still remains as to whether the data is correct and accurate. Improvements in measurement techniques and calibration have recently demonstrated a method which reduces the frustration and uncertainty of taking these noise measurements AND which provide greater confidence in data results and enhanced accuracy of the data.

Many times, after the tribulations of getting the noise measurement accomplished, something inevitably creeps into the analysis which causes uncertainty as to the accuracy of the data taken during the measurement. Again, as we interrogate the noise measurement and the resulting data, questions begin to arise which cause us to be uncertain of the analysis. As a result, the vision of what we see is never quite as clear as we would wish. Much of the time spent in making noise measurements is therefore spent in re-taking many measurements to prove to ourselves that the measurement data is correct. The issue of accuracy is however often unresolved.

Each noise measurement is slightly different due to frequency, power level of the different devices being measured, and our measurement needs relative to the measurement system setup. These differences, and other factors such as external noise and spurious signal, work against accurate measurement and subsequent analysis of AM and PM noise data. For the skilled, and unskilled alike, the question as to whether or not the data is valid, many times remains a mystery. There have been few improvements to noise measurement technology over the years which offer to enhance our confidence and reduce the mystery as to correctness of noise data. This paper seeks to provide insight into improved noise measurement method and techniques which improve the accuracy and uncertainty of noise measurement to ± 1 dB and which can be used with any noise measurement system.

OPERATOR SKILL

The mathematics relative to the measurement of AM and PM noise, as is the AM and PM noise signature itself, are very complex. The purpose of most noise measurement systems generally is to reduce or eliminate the tedious mathematical manipulation of measurement data required to arrive at the assumingly correct noise results. The more automated the noise measurement system is the less skilled the operator needs to be to operate it; or at least that's the generally the accepted hypothesis. This paper will provide insight into a new method and technique which allows this hypothesis to be more closely realized.

The operator's understanding of the complexity of noise measurement is important however, to allow us to appreciate the many factors which effect measurement accuracy. To that end, and to understand the new methodology and techniques, we will discuss several technical issues relative to noise measurement. It will be shown to the reader that a simple solution to several of these technical issues which affect accurate noise measurement is provided by the new methodology and technique.

METHODS

In general there are two domains or methods associated with noise measurement, each with its associated mathematical definitions, used to describe specific aspects relating to the noise signature of an electronic signal. The Frequency domain method, which is typically referred to as Phase Noise measurement, is the most commonly used measurement domain as shown in Figure 1.

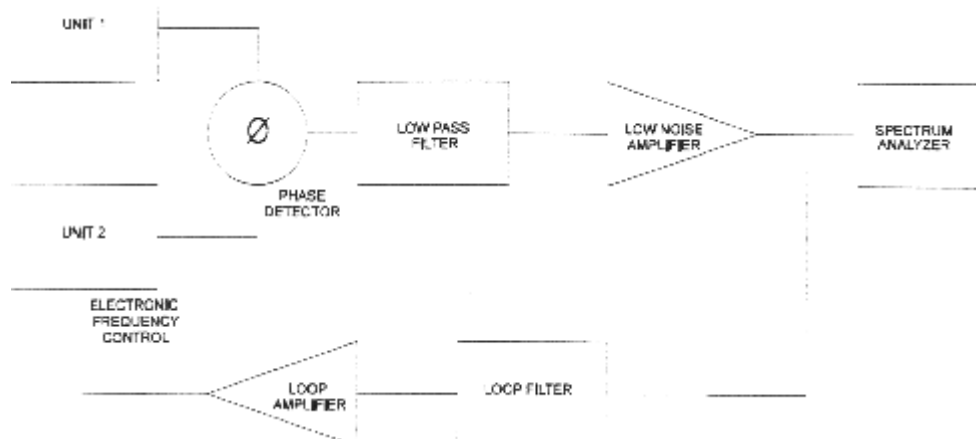


Figure 1

The Time Domain Method is a second method, but does not provide complete analytical data for all applications. Our discussion in this article will be limited to the Frequency domain measurement method. We choose this measurement method because Time domain data can be derived from Frequency domain data. However, the inverse is not necessarily true. The methods and techniques discussed in this paper are adaptable to any measurement method.

TECHNICAL DISCUSSION

Phase noise measurement is generally performed as a statistical measurement to improve accuracy, which relates amplitude to frequency offset (from a carrier). In the method described in this paper, the carrier is removed by beating two signals together, which have been phase locked, thereby producing a baseband or carrier offset frequency interval. This frequency interval is a small percentage of the carrier frequency, typically less than 10 percent at VHF frequencies. The measurement is typically performed with the instrument such as a Fast Fourier Transformer Spectrum Analyzer, along with other associated components as shown in Figure 1. During the measurement process, reduction of the offset frequency interval into smaller measurement intervals or windows is done by the instrument making the measurement. Sampling is used by the measurement instrument to improve its accuracy. The sampling period and the number of samples are additional variables, not typically reported, but which can have a significant effect on measurement results.

Each measurement instrument frequency interval window has a different measurement bandwidth and sampling period associated with it. These are generally chosen by the instrument to optimize the instrument's measurement accuracy. To improve accuracy further, each measurement is made several times and mathematically averaged. All of these factors, associated with making the noise measurement over the offset frequency interval, tend to complicate achieving accurate noise measurement.

As noise levels become lower and lower, the noise measurement becomes more and more difficult to accomplish due to measurement limitations of the measurement instrument. Most Spectrum Analyzers have a minimum sensitivity of -125 dBm. If noise measurements were made with a signal carrier of +20 dBm the noise floor of the Spectrum Analyzer translates to -105 dBc/Hz. In addition to sensitivity, most Spectrum Analyzers do not have more than 90 dB of dynamic range. Error, relative to dynamic range

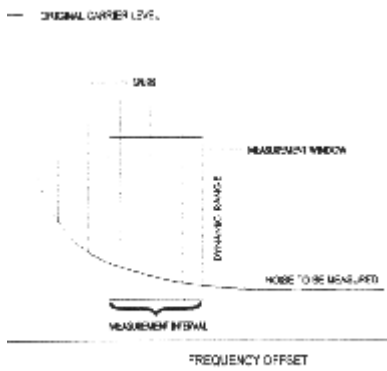


FIGURE 2

limitation, comes into a measurement relative to spurious signals which are greater than 80 dB in amplitude, relative to the measurement window limitations. Figure 2 provides a graphical representation of these issues.

Measurement bandwidth can be used to provide an apparent improvement in Spectrum Analyzer sensitivity. Noise data is generally reported as dBc/Hz; dB level relative to a carrier level, relative to a 1 Hz bandwidth. When the actual measurement is made, the bandwidth which the spectrum analyzer samples is typically much greater than 1 Hz. (See Figure 3) Since the spectrum analyzer will see all of the energy within the measurement bandwidth window, increasing the bandwidth of the window increases the energy measured. A 10 fold increase in bandwidth will produce a 10 dB increase in noise. When the data results are translated to 1 Hz noise, the bandwidth is subtracted out of the instrument's measurement data. Opening the measurement bandwidth to 1 KHz would provide an apparent increase in sensitivity of 30 dB.

A larger measurement bandwidth increases sensitivity, but the increased frequency interval reduces the accuracy of the measured slope segment.

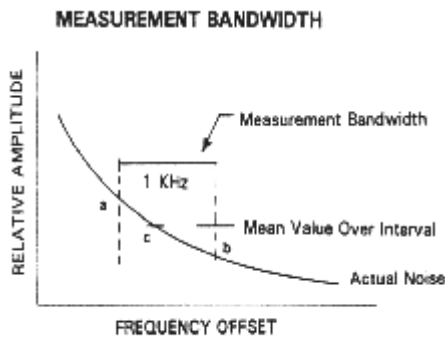


Figure 3

Because noise data reports the integrated noise within the segment, the noise value will be lower than the highest noise and higher than the lowest noise contained within the measured segment. If the slope of the data line passing through the measurement window is straight, the integrated result will be fairly accurate. If, however, the slope of the data line is rapidly changing in one direction, the integrated result will be in error by some amount. The best choice is to keep the measurement bandwidth to a minimum. The trade off is the amount of time allowed to make a measurement. An increase in measurement time introduces other effects into the measurement, such as power line variations. AC power harmonics can be annoying and can affect accuracy relative to dynamic range of the measurement instrument.

THE MEASUREMENT SYSTEM

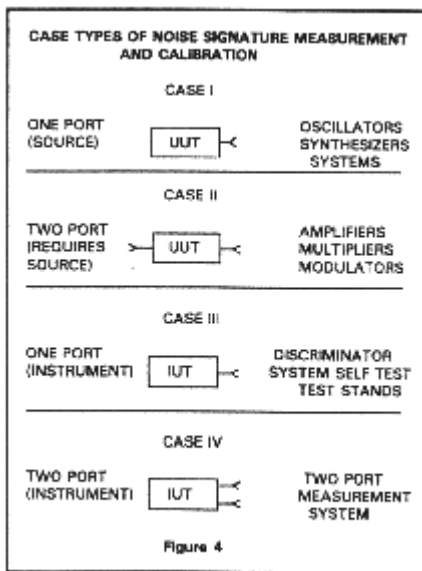
The phase noise of an electronic signal generally exists at very low levels relative to its carrier level. The phase noise level is typically below the measurement range of individual electronic measuring instruments, which normally would be available to make the measurements. This factor requires that a measurement technique incorporate electronic instruments configured into a system which improves the sensitivity of the measuring devices used within it. An analogy of this would be the use of a low noise amplifier ahead of a receiver to improve its sensitivity. In the case of phase noise measurement, the low noise amplifier is at

base band (very low frequency) rather than at the frequency to be measured. Every noise measurement situation requires a decision as to the method used to acquire noise data.

The improvement technique presented here can be used in conjunction with any noise measurement system because it is non-intrusive with regard to the system. The measurement and data improvement technique will work on any other measurement technique with the same improvement capability.

There are four general categories or cases of noise measurement as can be seen in Figure 4.

Cases 1 and 4 are of interest regarding this paper. Special considerations exist in measuring cases 2 and 3 and those measurement improvement conditions are not discussed here. The most sensitive method commonly used to measure phase noise is the two unit method as shown in Figure 1.



The two unit method offers a high degree of measurement sensitivity for the measurement of Phase Modulated noise (PM). The two unit method is used to measure the PM noise of two independent, non-correlated signal sources, one of which provides for phase locking. The signal sources are fed into a mixer, which will be set up as a phase discriminator. A condition of the measurement technique requires that the two signal sources be at precisely the same frequency. A phase locking technique, within the measurement setup, resolves this issue. Another condition is that the two signals be in a carrier phase relationship of 90 degrees; to allow the mixer to function as a phase discriminator. Closing a phase locked loop using the phase discriminator sets the two signal source carriers at precisely 90 degrees, thereby satisfying both conditions. The signal sources deliver to the phase discriminator both AM and PM noise, generally at different levels. The phase discriminator provides AM suppression of greater than 20 dB, if the two source carriers are in 90 degree quadrature. Because the AM is only suppressed by a limited amount, AM remains as part of the measurement results. The AM components are however generally discrete spurs such as AC line frequency and its harmonics, which generally effect the measurement system's dynamic range limitations.

To improve the sensitivity of the instrument making the actual measurement, such as a spectrum analyzer, a low frequency Low Noise Amplifier (LNA) is used to amplify the signal from the phase discriminator. Either the LNA or the spectrum analyzer will determine the measurement frequency range and minimum noise level which can be measured. A portion of the signal from the LNA is coupled through a loop filter to a frequency control port of one of the two signal sources to form a phase locked loop. See Figure 1. The addition of the LNA can provide only limited sensitivity improvement for measurement because of its Noise Figure and gain. The achievable noise floor of the LNA is:

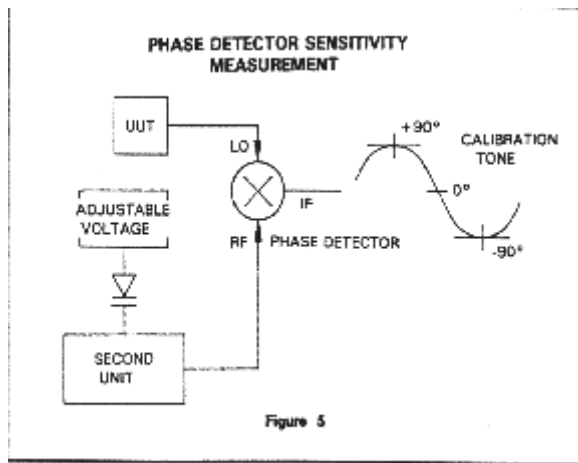
$$-177 \text{ dBm} + \text{LNA NF} + \text{LNA gain} = \text{Noise Floor}$$

Typical results are:

$$-177 \text{ dBm} + 5 \text{ dB} + 40 \text{ dB} = -132 \text{ dBm}$$

The results from this calculation suggest that with an LNA gain of 40 dB and a Spectrum Analyzer sensitivity of -125 dBm, a noise floor of -165 could be achieved. If the noise measurement is accomplished using a carrier level of +20 dBm, the resulting carrier to noise relationship will be -185 dBc.

STANDARD CALIBRATION



To calibrate the phase discriminator sensitivity, a tone is developed in the phase discriminator and its amplitude is then checked by the measurement system as shown in Figure 5. The tone needs to have an identical amplitude level as the RF carriers which are applied to the phase discriminator. This is typically accomplished by tuning one of the oscillators off frequency to develop a beat note from the phase discriminator.

This process simply determines the amplitude of the $\pm 90^\circ$ phase points generated by the signals within the phase discriminator. The sensitivity of the phase discriminator is then calculated.

$$\Delta V_{P-P} / 2\pi = \text{volts per radian sensitivity}$$

The measurement accuracy of this sensitivity factor dictates the overall accuracy of the noise measurement. Even though the individual instruments which make up the noise measurement system are calibrated, the phase discriminator sensitivity factor must be established for each measurement. The accuracy of each measurement is therefore suspect unless a method is used to calibrate it for each frequency and power level over which it operates. A detailed treatment of measurement error can be found in Reference 6.

The low frequency LNA must also be calibrated to become part of the overall noise measurement system. This poses a problem. If the amplifier, which typically has 40 dB of gain, is incorporated during the tone calibration process, it will saturate, as will the instrument measuring the phase discriminator sensitivity. In automated noise measurement systems, the phase discriminator sensitivity and LNA gain must carefully be considered with regard to measurement accuracy. The gain accuracy is generally not calibrated for each measurement, but it's gain and gain flatness is typically held in a memory device which is recalled at each offset and calculated into the results, inducing additional inaccuracies.

NEW TECHNIQUE

Recently a noise measurement system, at X-Band, was implemented incorporating an additional instrument called a Noise Calibration Standard, which is Techrol Cyclonetics, Inc. model NAL2000/LF. Figure 6 provides a block diagram of the instrument. The NAL2000/LF provided an easy solution to the phase discriminator and baseband amplifier being included into the overall calibration of the noise measurement system. The additional instrument can also provide National Institute of Standards and Technology (NIST) traceability. The Noise Calibration Standard provides a noise signature reference to be used to calibrate the noise measurement system and to establish the measurement limitation regarding the system's noise floor.

The NAL2000/LF Noise Calibration Standard provides a noise signature reference at the frequency being measured. The signature reference is a carrier which has Gaussian white noise superimposed onto it.

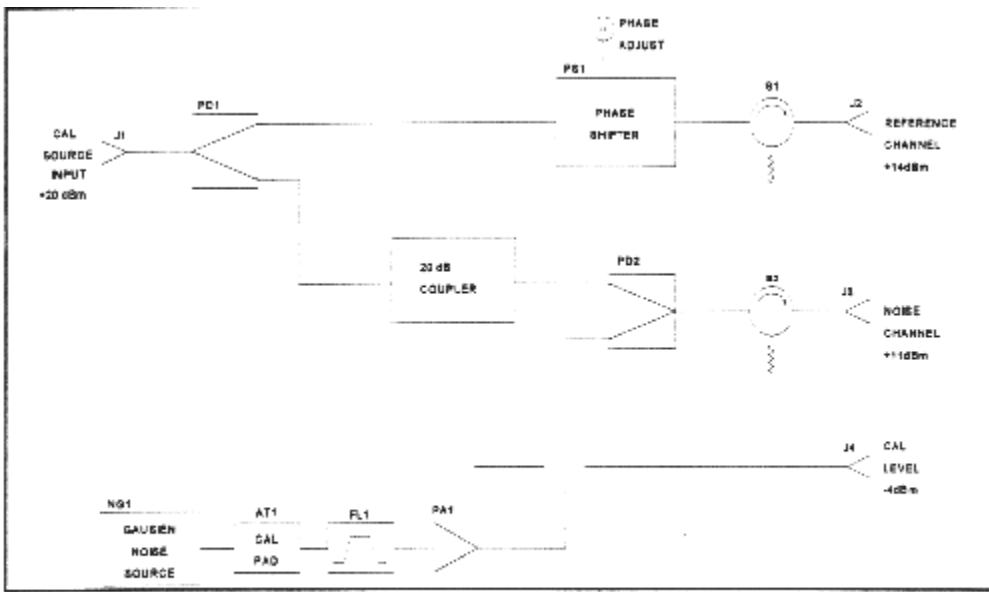


Figure 6

The noise which is superimposed onto the carrier has an extremely flat noise response over a bandwidth which is greater than $\pm 10\%$ of the carrier frequency. The significance of the Gaussian white noise is that the AM and PM components are essentially equal. Two correlated signals are provided. One signal provides a carrier only and is used as a reference signal. The other signal includes the Gaussian white noise which can be turned on and off. With the noise on, a very accurately known noise signature is developed which can be used to verify a noise measurement systems overall accuracy. Figure 7 pictorially shows how the carrier to noise relationship is accomplished.

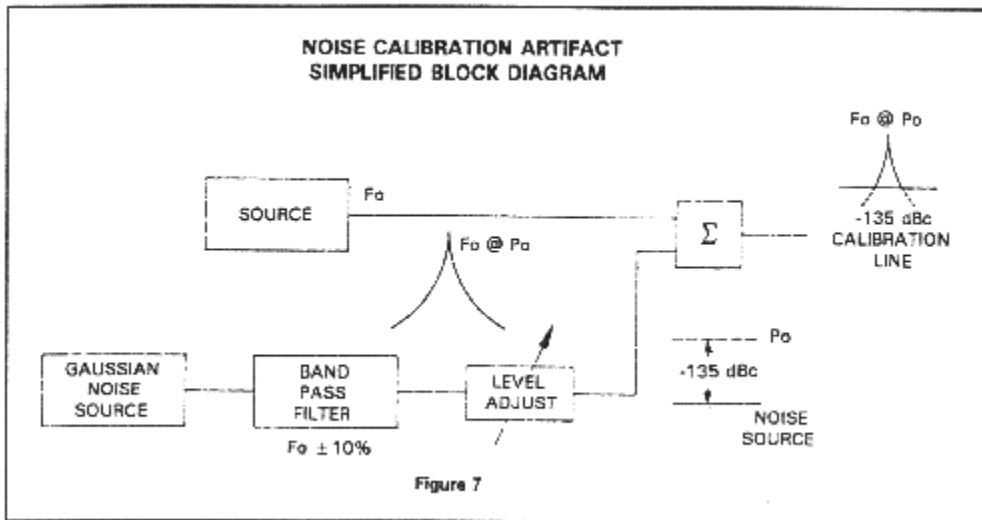
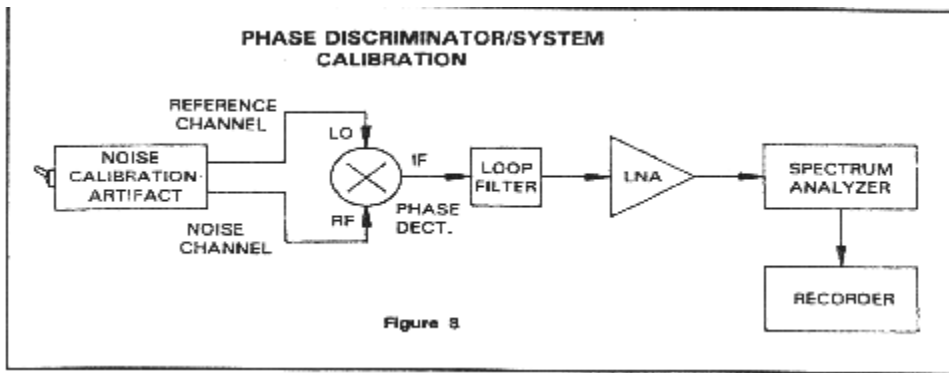


Figure 7

The NAL2000/LF is inserted into the Noise Measurement System in place of the two units to be measured as shown in Figure 8 below.



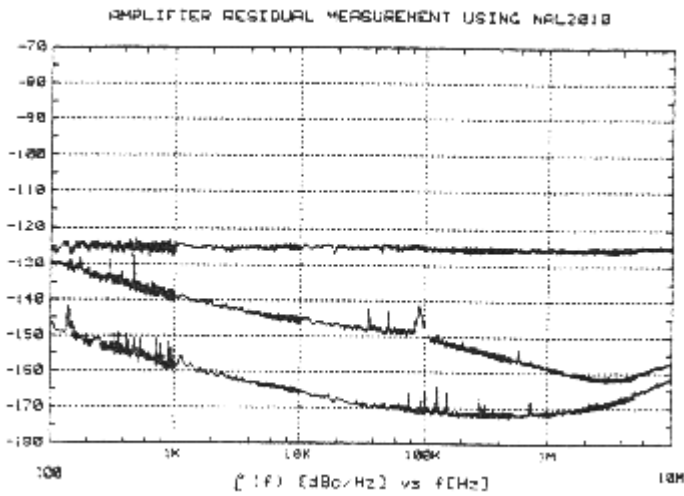
With the noise off, the noise floor of a Noise Measurement System can be verified and recorded, thus establishing the limitation of the system.

The calibration of the Noise Calibration Standard itself is tedious to perform and will not be discussed here. The power of the Gaussian noise over a given bandwidth to an error interval of less than ± 0.5 dB for both PM and AM is measured. To carry out calibration of the Noise Measurement System, the sensitivity of the phase discriminator is conducted as described previously. The carrier level of the Noise Calibration Artifact is adjusted to the same level as the sources under test. See Figure 8. This allows the noise floor of the noise measurement system to be reported accurately relative to the measurement to be made. In turn, the functional limitation of the phase discriminator used to measure the noise is established to be 10 dB above the noise floor of the Measurement System. This 10 dB limitation is created by the action of the phase discriminator upon the two signals being measured. As the noise levels of the two un-correlated carriers approach one another, additional noise is contributed to the resultant noise from the phase discriminator at the amount in the following equation, where N_1 is the lesser noise, N_2 is the greater noise.

$$\text{AddedNoise} = 10 \log \left(1 + 10^{\frac{N_2 - N_1}{10}} \right)$$

If the noise of both correlated signals is equal, 3 dB additional is contributed through this phenomena in the phase discriminator. With the noise applied to one of the two correlated carriers within the Noise Calibration Standard, the calibration of the phase discriminator can be verified. This is achieved through the use of the known Gaussian noise/carrier level which is being measured by the Noise Measurement System supplied by the Noise Calibration Standard. After the calibration process is concluded, measurement of signal sources can be made with NIST traceability and an accuracy of better than ± 1.5 dB for both PM and AM.

If the carrier level of the Noise Standard is adjusted to be the same as the two units under test, the three noise data plots can be plotted together. The noise reference line, the system noise floor and the data taken of the two sources, can be plotted on the same graph for comparison. The plot of the noise data for the two sources under test will be 3 dB higher than the calibration plots, because their noise is un-correlated and therefore algebraically additive as shown in the previous equation. Figure 9 is an example of a tri-noise plot.



AM noise levels are verified in a similar way with the exception that a detector is used instead of a phase discriminator. The carrier is modulated to produce an AM tone, which in turn is used to calibrate the sensitivity of the Measurement System. The AM measurement system noise floor is established by terminating the input of the detector with a precision 50 Ohm termination. The Noise Calibration Artifact is then used to apply a carrier/noise signature to the detector to verify the detector sensitivity. The AM noise component of the carrier/noise from the Noise Calibration Standard is used to verify the AM sensitivity. Again, if the carrier level of the Noise Calibration Standard and the unit under test are the same, the AM signatures can be plotted on the same graph.

The main advantage in using the Noise Calibration Standard to calibrate the noise measurement system is that both AM and PM noise can be measured with ± 1.5 dB accuracy at X-band frequencies. Most AM measurements are typically accurate to within ± 4 dB or worse. The arbitrary selection of a detector for AM measurements can result in inaccuracies as great as 15 dB.

Other advantages of the technique are repeatability of measurement, ease of measurement and confidence in the data. All of these yield a significant cost savings by reducing test time in acquiring valid noise data. The technique builds confidence in the ability to measure noise, whether or not the data is what was expected.

The technology contained in the Noise Calibration Standard is broad based and many other applications relating to electronic signal signature analysis are being found. The carrier to noise relationship can be implemented at any frequency with the same accuracies as discussed above. In the future, accuracies of better than ± 0.5 dB can be achieved. By implementing the technology throughout the electronic industry, it will allow noise signature data to be compared between different measurement sites without the need to defend the data. Additionally, data can be compared when different measurement techniques are used, because the same reference noise is applied to all of the noise data.

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