RF RADIATED EMISSIONS MEASUREMENT SYSTEMS TUTORIAL

INTRODUCTION

Measuring radiated electromagnetic emissions first requires a measurement system. A basic measurement system usually contains a minimum of an antenna and a receiver. To measure very small signal levels may require the addition of a pre-amplifier to the receiver system. Figure 1 shows a typical receiver system block diagram *including a pre-amplifier*. Figure 1 will be used for the following discussion.

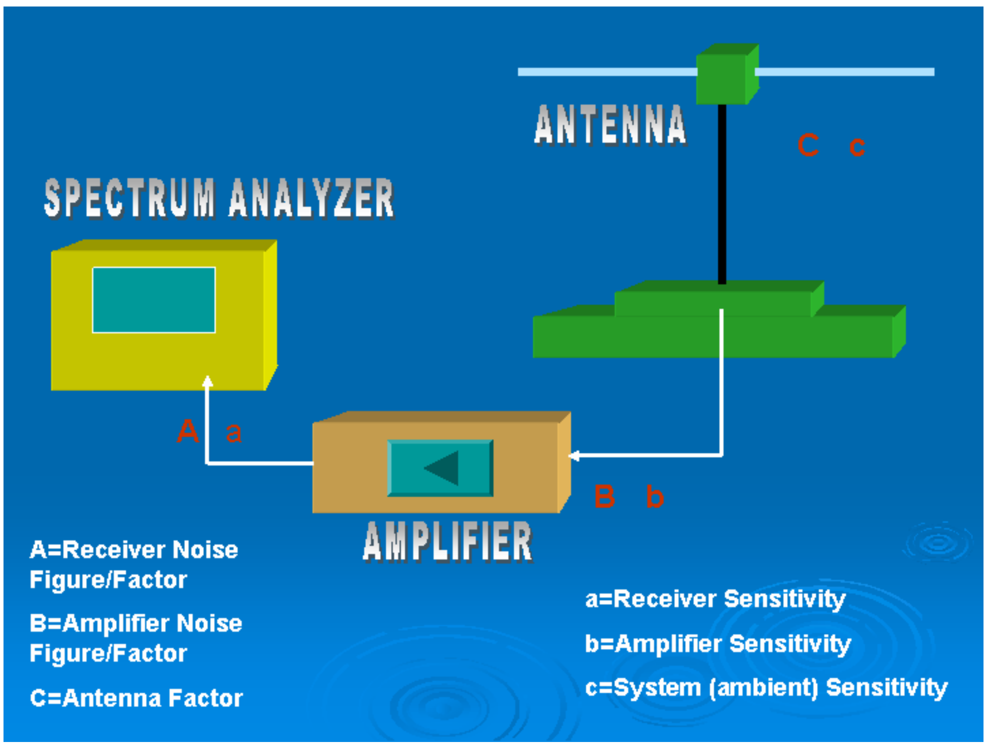

FIGURE 1. RECEIVER SYSTEM BLOCK DIAGRAM

It is beyond the scope of this text to address in detail such measurement errors as receiver detection mode errors, radio frequency pre-selection (RF) filtering, or tuner overload errors. Peak detection of continuous waves (CW) will mainly be discussed.

There are many *terms* currently used to define radiated electromagnetic energy. Some common terms used are non-ionizing radiation (NIR), electromagnetic fields (EMFs), radiated emissions, and broadcast signals. In this paper, "emissions" will be used to describe radiated electromagnetic energy.

Electromagnetic measurement systems are used to measure power densities, or power spectral densities, of electromagnetic fields at a point in space. Power density is defined as the "power per unit area normal to the direction of propagation usually expressed in units of Watts per square meter W/m^2), or for convenience in units such as milliwatts per square meter (mW/m^2), or even in microwatts per square centimeter ($\mu W/cm^2$)." Plane-waves, power densities, electric field strengths (E), and magnetic field strengths (H) are related by *free space* loss, i.e., 377 ohms (Ω). Electric field strengths and magnetic field strengths are expressed in units of Volts per meter (V/m) and Amperes per meter (A/m), respectively. Field strength is therefore defined as:

$$E = \text{Square Root } (120\pi P)$$

where,

E = rms value of field strength in Volts/meter
P = power density in watt/meter^2
120 = impedance of free space in ohms

Power density (P_D) is related to the electric field strength (E) and the magnetic field strength (H) as:

$$P_D = E^2/377\Omega = 377\Omega H^2 \text{ (far field)}$$

Again, the rate at which electromagnetic energy (power) is propagated by a wave -- power density -- is usually specified in Watts per square meter (W/m^2). The power density equation is:

$$P_D = P_T/4\pi r^2$$

where,

P_D = power density in watts/meter^2
P_T = transmitted power in Watts
r = distance in meters

Radiated electromagnetic fields -- radiated emissions -- are produced from many sources. Sources of electromagnetic energy range from manmade sources such as commercial broadcast stations and automobile ignition systems to natural sources such as galactic noise and lightning. To further complicate matters, these emissions can drastically differ in frequencies and in their magnitudes.

Because of the potential wide range of measurement requirements special measurement systems are sometimes necessary. These systems must be well-planned or inaccurate measurements may result. Important design specifications should include *system selectivity* and *system sensitivity*. These terms will be defined and demonstrated in the following sections.

THE ANTENNA

Measuring radiated emissions, or electromagnetic energy, begins with the antenna. Antennas are devices that receive (capture) electromagnetic energy traveling through space. Antennas can also be used for transmitting electromagnetic energy. There are many different types of antennas, some are designed to be "broad-banded," to receive or transmit over a large frequency range, and some are designed to receive or transmit at specific frequencies. In any case, all receive antennas are intended to capture "off-air" electromagnetic energy and to deliver these "signals" to a receiver. For this discussion, electric fields (E) will mainly be addressed.

Because antennas can only capture a small portion of the radiated power, or energy, a correction factor must be added to the detected emission levels to accurately determine the radiated power being measured. The actual power received by an antenna is determined by multiplying the *power density* of the emission by the receiving area of the antenna, A_e. This antenna correction factor is called the "antenna factor."

To further understand antenna factors see Figure 2. Below are the antenna factor derivation equations.

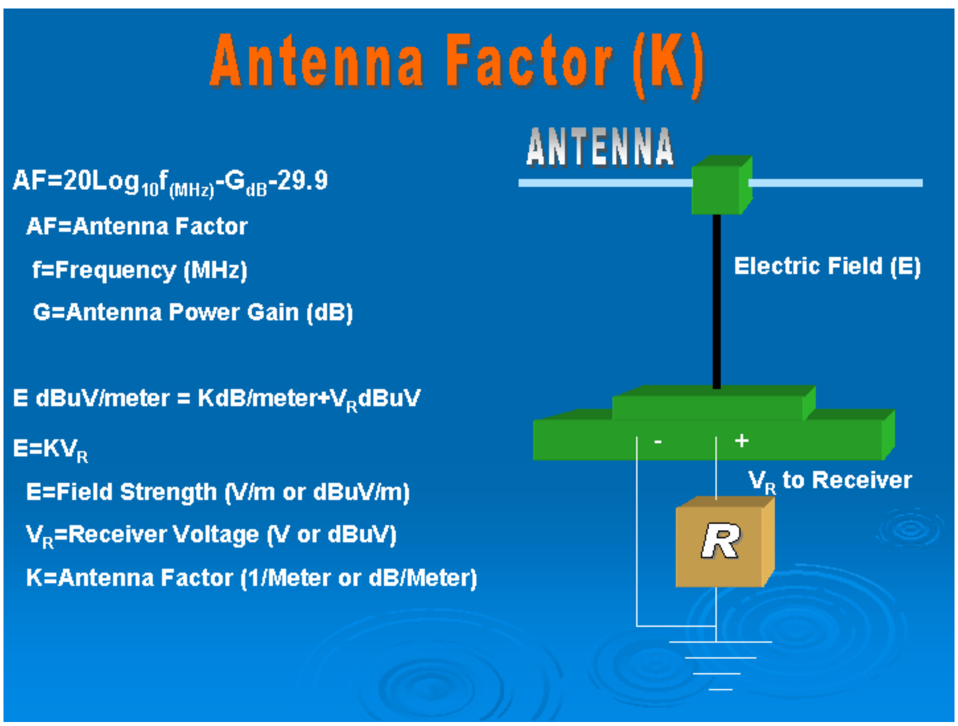

FIGURE 2. ANTENNA FACTOR

$$A_e = \lambda^2/4\pi \text{ (Meters}^2\text{)}$$

The power received by the antenna is then defined by:

$$P_r = PA_e = PG\lambda^2/4\pi \text{ (Watts)}$$

where,

P = power density in Watts/meter^2
G = antenna (power) gain
λ = wavelength in meters

Combining these equations with the field strength equation yields:

$$P_r = E^2G\lambda^2/480\pi^2$$

also,

$$P_r = V_r^2/Z_o$$

where,

V_r = received voltage
Z_o = receiver input impedance

then,

$$V_r^2/Z_o = E^2G\lambda^2/480\pi^2$$

Knowing that:

$$\lambda = 300 \text{ meters/second}/f_{(MHz)}$$

since an antenna factor is defined as:

$$E = (V_r f\pi/50\Omega)(\text{Square Root }(30/Z_0G))$$

we can simplify and rearrange terms to yield:

$$K = E/V_r$$

then,

$$K = (f\pi/50\Omega)(\text{Square Root}(30/Z_0G))$$

or in logarithmic form [*for* Z_o = 50 Ω (ohm) system]:

$$K = 20\log_{10} f_{MHz} - G_{dB} - 29.78 \text{ (dB)}$$

THE RECEIVER AND AMPLIFIER

A receiver is an electro-mechanical device that receives electromagnetic energy captured by the antenna and then processes (extracts) the information, or data, contained in the "signal."

The basic function of all receivers is the same regardless of their specific design intentions, broadcast radio receivers receive and reproduce commercial broadcast programming, and likewise, TV receivers detect and reproduce commercial television broadcasting programming. Special, or unique, receivers are sometimes needed to detect and measure all types of radiated, or transmitted, electromagnetic emissions. These specialized receivers may be called tuned receivers, field intensity meters (FIMs), or spectrum analyzers.

Radiated emissions that receiver systems may be required to measure can be generated from intentional radiators or unintentional radiators. The information contained in intentionally radiated signals may contain analog information, such as audio, or they may contain digital data, such as radio navigation beacon transmissions. Television transmissions, for example, contain both analog and digital information. This information is placed in the transmitted emission, called the "carrier," by a process called "modulation." Again, there are many different types of modulation, the most common being amplitude modulation (AM) and frequency modulation (FM). Receivers detect, or extract, the information/data from radiated emissions by a process called "demodulation", the reverse of modulation.

Many radiated emissions requiring measurements do not contain any useful information or data at all. As an example, radiated emissions from unintentional radiators, such as computer systems, are essentially undesired byproducts of electronic systems and serve no desired or useful purpose. These undesired emissions can, however, cause interference to communications system, and *if strong enough*, they can cause interference to other unintentional radiating devices. Radiated signals (if strong enough) can also present possible health hazards to humans and animals. Because these emissions must be measured to determine any potential interference problems or health hazard risks, specialized receiver systems must be used.

An important parameter for any receiver is its *noise figure*, or *noise factor*. This parameter will basically define the *sensitivity* that can be achieved with a particular receiver.

An amplifier, usually called a pre-amplifier, is sometimes required when attempting to measure very small signals or emission levels. Because these devices amplify signals, they will also amplify ambient electromagnetic noise. If improperly used, amplifiers can detract from the overall system's sensitivity as well as possibly causing overloading to the receiver's tuner input stage. Overloading a tuner's input stage is simply supplying a larger signal amplitude than the receiver's tuner input circuitry is capable of handling, thus, saturating the tuner's input stage.

Just as with the receiver, it is important to know what the *noise figure*, or *noise factor*, of the selected amplifier is when designing or specifying a measurement system containing a pre-amplifier.

The noise figure (N_{fig}) for a device (receiver or amplifier) is defined as:

$$N_{fig}=10\log_{10}N_o-10\log_{10}G_d-(-174\text{ dB}+10\log_{10}B_r)$$

where,

N_o = measured noise in milliWatts
G_d = device power gain - linear ratio
B_R = receiver bandwidth in Hz

The use of these parameters for designing or specifying measurement systems will be explained and demonstrated in the following section.

SPECIFYING OR DESIGNING RADIATED MEASUREMENT SYSTEMS

When specifying or designing any measurement receiver system, one should consider that the "system" will include other devices such as antennas, amplifiers, cabling, and possibly filters.

Because a receiver's selectivity, the ability to select frequencies or frequency bands, is primarily a function of the receiver's tuner design, and will be chiefly dependent on the individual receiver selection, selectivity will not be specifically addressed in this text. Receiver system *sensitivity*, however, presents one of the greatest difficulties, or challenges, when designing or specifying receiver measurement systems. Therefore, the sensitivity of the two basic types of receiver systems, *one with a pre-amplifier* and *one without a pre-amplifier*, will be addressed in some detail.

Because antennas are not perfect devices and have associated "losses," the following examples will include explanations for these error corrections. As mentioned previously, amplifiers will not only amplify the emissions being measured but they will also amplify ambient electromagnetic noise. These ambient conditions can drastically change the overall sensitivity of a measurement system. Another potential problem associated with using amplifiers is that they also generate internal electromagnetic noise. Being active devices they will introduce their own internal electromagnetic noise into the receiver system, again having an influence on the total system's noise level, thus, its sensitivity.

Some corrections for the above mentioned problems are necessary to accurately calculate both the receiver's signal input sensitivity and (more importantly) the total system's *ambient* sensitivity. Without knowing the total measurement system's *ambient sensitivity*, measurements may not be possible down to anticipated emission levels.

In electromagnetic measurement systems terms such as ambient sensitivity, system sensitivity, and receiver sensitivity have been used interchangeably. More confusing expressions commonly used are terms such as "receiver noise floor," or "system noise floor."

In this text, the term "system sensitivity" will be defined as ambient electromagnetic noise level seen by, and at, the antenna for 0 dB *Signal-to-Noise* ratio at the receiver's intermediate-frequency (I-F) stage. System sensitivities defined herein are for *far-field* conditions.

The following are general terms and definitions that will be used in describing and calculating the following receiver/system parameters:

General Definitions:

1. N_{fig} (dB) = Noise Figure = $10\log_{10}$ Noise Factor (NF)
2. A_e (dB) = Effective Capture Area = $10\log_{10}(\lambda^2/4\pi)$ - for *unity gain*
3. T (dB) = Average Room Temperature = $10\log_{10}$ 290°K (K=degrees Kelvin)
4. B_R (dB) = $10\log_{10}$ Receiver Bandwidth (Hertz)
5. K (dB) = Boltzman's Constant = $10\log_{10}$ 1.4×10^{-23} Watts/K/Hz
6. S_e (dBm/m^2) = System Sensitivity = $N_{fig}-174+B_R-A_e$

THE RECEIVER AND ANTENNA SYSTEM SENSITIVITY

Receiver sensitivity is one of the most important design parameters to consider when designing or specifying any measurement system. This parameter will determine the lowest signal level that the receiver will be capable of detecting or measuring. However, when designing a system to measure radiated radio frequency (RF) emissions (signals), it is important to go further in your analysis. The sensitivity level at the receiver may be considerably different than the sensitivity level at the antenna, especially if a pre-amplifier is attached between the antenna and the receiver. If not considered, measuring the "noise floor" of the *receiver system*, itself, instead of the anticipated radiated emissions levels may result. The following measurement system discussion will be as shown in Figure 1, *without the use of a pre-amplifier*.

Receiver sensitivity (S_R) is defined as the RF noise power level generated within the receiver. It may also be defined as the co-channel interference level for 0 dB *signal-to-noise ratio*, defined as:

$$S_R = NF\ K\ T\ B_r\ \text{(Watts)}$$

or in logarithmic form:

$$S_R = 10\log_{10}NF + 10\log_{10}K + 10\log_{10}T + 10\log_{10}B_R\ \text{(dBW)}$$

where,

K = Boltzman's Constant = 1.4×10^{-23} Watts/K/Hz
T = temperature in degrees Kelvin
B_R = receiver I-F bandwidth in Hertz
NF = receiver noise factor

Note: *Noise figures and noise factors are different ways of specifying noise. In this text, noise factors will be used to describe linear ratios, and noise figures will be used to describe logarithmic ratios.*

Again, a receiver's selectivity, the ability to select frequencies or frequency bands, is chiefly dependent on the receiver's tuner design, which is mainly the function of the receiver selection. Because receiver system sensitivity presents one of the greatest challenges, sensitivity will be addressed in detail.

For simplicity, a *spectrum analyzer* will be used as the receiver for this discussion. We will first determine the receiver's sensitivity from its indicated power level. The indicated power level of a spectrum analyzer is essentially the base-line trace observed on its cathode-ray tube (CRT) display, usually expressed in dBm. It may be more useful to convert this unit (dBm) to a more useful unit such as dBV. In a 50Ω system this conversion is done by adding 107 dB to the indicated power level displayed on the analyzers CRT display. As an example, an indicated power level of -90 dBm (on the CRT display) is equivalent to an electric plane-wave of 17µV.

Note: *The 107 dB factor is only applicable in 50Ω systems.*

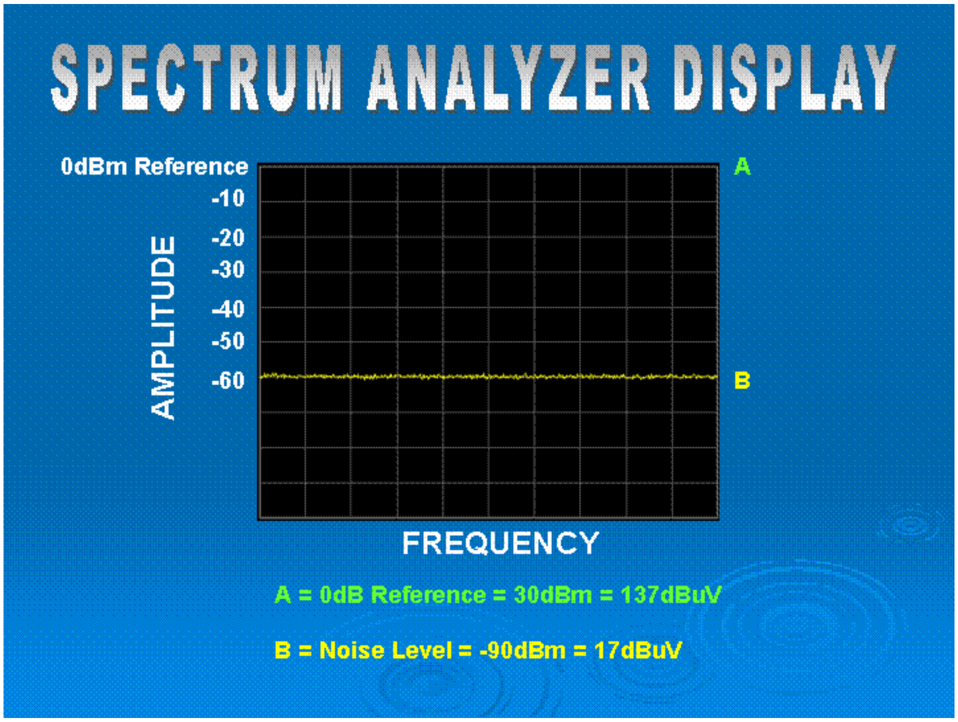

FIGURE 3. SPECTRUM ANALYZER DISPLAY

Converting the *receiver's sensitivity* into a plane-wave field strength equivalency, ambient field strength reference at the antenna, is not difficult but may be confusing at first because of the unit conversions and the concept of equivalent field strengths. As shown above, it may be easier to first convert the receiver's indicated sensitivity power level (dBm), to a plane-wave equivalent voltage (dBµV). After this conversion, the equivalent field strength sensitivities can be easily calculated in units of dBμV/m or V/m. This conversion can be accomplished using "antenna factors."

The antenna factor (dB/m) when added to the indicated sensitivity level (dBμV) of the receiver will produce the equivalent field strength sensitivity referenced at the antenna (dBμV/m), referenced to an isotropic antenna. For example, an indicated field strength of 17 dBμV plus an antenna factor of 25 dB/m is equal to a field strength of 42 dBμV/m.

Because the *antenna factor* does not include any losses such as cable losses and filter losses, these losses will have to be accounted for to accurately calculate equivalent field strengths or field strength sensitivities.

For ease in calculating, these losses (in dB) can be added to the antenna factor. This resultant number, when added to the indicated receiver sensitivity, in dBμV, will yield an equivalent ambient field strength or electric plane-wave sensitivity. **Note:** ***This will only be true for a particular antenna at a specific frequency. Each antenna factor will be different for each measurement frequency.***

Using the following measurement receiver (*spectrum analyzer*) system specifications as an example:

System Specifications:

1. Receiver sensitivity (indicated) = -90dBm
2. The antenna factor at 45.50 MHz = 25 dB
3. The cable loss at 45.50 MHz = 2 dB

By performing the following steps the measurement system's plane-wave equivalent sensitivity, in dBμ V/m, would be:

Step 1. First, converting the indicated receiver sensitivity level from a power (dBm) to an equivalent voltage (dBμV), assume a 50Ω system, would yield:

$$\mathbf{S_R = -90\ dBm + 107\ dB = 17\ dB\mu V}$$

Step 2. Correcting for cable losses and antenna factors, the system sensitivity (S_e) would be:

$$\mathbf{S_e = 17\ dB\mu V + 25\ dB/m + 2\ dB = 44.0\ dB\mu V/m}$$

Step 3. By taking the antilog of the sensitivity level calculated in step 2, the equivalent, or effective, plane-wave electric field strength sensitivity ($S_{e)}$ in μV/m will be:

$$S_e = 44.0\ dB\mu V/m = 10^{((44.0 dB\mu V/m)/20)} = 158.49\ \ \mu V/m$$

THE RECEIVER, PRE-AMPLIFIER, AND ANTENNA SYSTEM SENSITIVITY

Now that the sensitivity of a receiver system with just an antenna has been defined, the sensitivity of a measurement system *including a pre-amplifier* will be explained -- *without the use of antenna factors*. This will be slightly more complicated than a measurement system containing only a receiver and an antenna.

Again, the system's sensitivity will be defined as the minimum ambient signal level, power density, or field strength that the system can detect or measure referenced at the receive antenna.

To determine the overall system sensitivity the total system's noise factor must be calculated using the noise factors of each active device within the system. If the manufacturer of each device has not specified these parameters they can be measured and/or calculated.

To calculate the system noise factor the following equation is used when a preamplifier is included in the measurement system:

$$NF_s = NF_1 + ((NF_2-1)/G))$$

where,

NF_s = noise factor of the system
NF_1 = noise factor of the preamplifier
NF_2 = noise factor of the receiver
G = Gain of the Preamplifier (Power)

Because antenna factors will not be used, there are two other parameters that will be needed to complete the overall system sensitivity calculations, the *measurement frequency* must be defined and the antenna gain must be known. The frequency is important because the *effective capture area* (A_e) of the antenna must be known. This calculation is based on the equation $\lambda^2/4\pi$; Lambda (λ) being the emission wavelength specified in meters. The antenna gain is important because it obviously affects the system's sensitivity.

To make the system sensitivity calculations easier, logarithmic expressions will be used in most cases. Again, noise figures will be used to express noise factors in logarithmic form.

The system sensitivity (S_e) of the measurement system can be calculated using the following:

$$S_e = N_{fig} - 174^{*} + B_r - A_e \quad (dBW/m^2)$$

where,

N_{fig} = system noise figure (dB)
B_R = receiver bandwidth, in Hertz (dB)

A_e = antenna effective capture area (dB)
* = 10 $\log_{10}$ Boltzman's Constant x 290 °K + 30 dB

As an example, the following will demonstrate how to calculate the system's sensitivity (S_e) using the following device parameters:

Device Parameters:

1. Receiver I-F Bandwidth = 9 kHz
2. Receiver Noise Figure = 15 dB
3. RF Preamplifier Power Gain = 26 dB
4. Preamplifier Noise Figure = 4.15 dB
5. Measurement Frequency = 635 MHz

First, the receiver sensitivity (S_R) is equal to:

$$S_R = 15+(-228.5)+24.6+39.5=-149.4 \text{ (dBW)}$$
$$= \mathbf{-119.4 \text{ (dBm)}}$$

(For convenience in later comparisons, *dBW* was converted to *dBm*. You will notice (later) the difference between the *receiver sensitivity* and the ambient *system's sensitivity*.)

Next, we must calculate the system noise figure (N_{fig}). This will be more complicated because we must obtain the answer in *logarithmic form* from calculations performed using a *linear approach*:

1. NF_1 = 4.15 dB=$10^{(4.15/10)}$= **2.6**
2. NF_2 = 15 dB=$10^{(15/10)}$= **31.6**
3. G = 26 dB=$10^{(26/10)}$= **398**
4. NF_3=2.6+((31.6-1)/398)=**2.68**

then,

$$N_{fig} = 10\log_{10} 2.68 = \mathbf{4.3\ dB}$$

The effective capture area of the antenna, A_e, will now be calculated as follows (for unity gain antenna):

1. λ= 300 m/s ÷ frequency (MHz)
   = 300 / 635 = **.47 meters**
2. A_e= $\lambda^2 /4\pi$
   = .472 / (4 x 3.1415)
   = **.0176 meters^2**
   = 10 $\log_{10}$ .0176 = **-17.5 dB**

The receiver bandwidth (B_R) calculation will be:

1. B_R = 10 $\log_{10}$ Frequency (Hz) (power bandwidth)
2. B_R = 10 $\log_{10}$ 9000 Hz = **39.5 dB**

Finally, using equation $S_e = N_{fig} - 174 + B_r - A_e$, we can calculate the total system sensitivity. The system sensitivity (power density) will be:

$$S_e = 4.3-174+39.5-(-17.5) = \mathbf{-112.7\ dBm/m^2}$$

Now that the system sensitivity (S_e) is known, defined in power density units (dBm/m^2), it may be more useful to convert further to more commonly used units such as field strengths. Again, the units of measurement for field strengths are Volts per meter (V/m), or for convenience dBμV/m (decibel ratio of V/m referenced to 1 microvolt).

For ease in understanding, and for simplicity in calculating, it is recommended that unit changes be done by first converting power densities (dBm/m^2) to milliwatts per square centimeter (mW/cm^2), then converting to field strength units such as V/m or dBμV/m. In converting *power densities* to *field strengths* the following conversion factors will be helpful:

1. Units/$\mathbf{cm^2}$ (square centimeters) = units/$\mathbf{m^2}$ - 40 dB
2. Volts/meter (**V/m**) = Square Root (mW/$\mathbf{cm^2}$ x 3763.6Ω)

Using the above conversion factors (1 and 2), the equivalent field strength sensitivity would be:

1. $-112.7\ dBm/m^2 = -152.7\ dBm/cm^2$
2. $-152.7\ dBm/cm^2 = 10^{(-152.7dBm/10)} = 5.4 \times 10^{-16}\ mW/cm^2$
3. Square Root ($5.4 \times 10^{-16} mW/cm^2 \times 3763.6\Omega$) = $1.4 \times 10^{-6} V/m$
4. $20\log_{10} 1.4 \times 10^{-6} V/m$ = **2.9dBμV/m**

Some additional helpful conversion factors for radiated measurement units are:

dBW/m^2 = dBV/m-25.8
dBW/m^2 = dBμV/m-145.8
dBm/m^2 = dBμV/m-115.8
dBm/cm^2 = dBμV/m-155.8
dBm/cm^2 = dBV/m-35.8
dBW/m^2 = dBm/m^2-30.0
dBW/m^2 = dBW/cm^2+40.0
dBW/m^2 = dBm/cm^2+10.0

The measurement system's sensitivity has now been calculated and defined. It is important to note, however, that the system may not be capable of measuring all ambient signal levels down to this level. As mentioned earlier, ambient noise levels may be higher than the measurement system sensitivity. This will result in the ambient noise levels masking potential measurements down to these levels.

These potential problems can be resolved with proper system pre-selection (RF input filtering) and receiver I-F bandwidth adjustments.

SUMMARY

In summary, designing or specifying receiver systems requires that each system be designed or specified for its particular application. Two important design parameters that must be addressed are the system's selectivity and its sensitivity. This can become demanding because measurement systems may be required to detect and measure radiated emissions comprised of narrow-band and/or wide-band signals, they may also be required to measure radiated signal strengths varying from very small to very large amplitude levels.

Selectivity, the ability to tune (select) to a frequency or a band of frequencies, is primarily dependent on the particular tuner (receiver) selection in addition to any radio frequency (RF) input filtering, called pre-selection. By filtering undesired input RF emissions, and with proper receiver intermediate-frequency (I-F) filter adjustments, it is possible to measure very low emission amplitudes present in frequency bands containing much higher amplitude emissions or noise levels. These filter selections will be based on the emission types being measured and on the ambient conditions under which the measurements are made.

Sensitivity, the lowest rf amplitude levels that a receiver system will be capable of measuring, is dependent on several variables. These variables are involved with specific antenna selections, receiver noise figures/factors, pre-amplifier gains and noise figures/factors (if used), and the system's filtering and cabling. If not properly planned, all these devices can detract from the overall system's performance.

The first step in designing or specifying a measurement system is to understand the actual measurement requirements. This should include the emission frequencies, their bandwidth's, and probable emission amplitude levels. This information will determine any required RF and I-F filtering and, in particular, the overall system's sensitivity needs.

The second step should be to calculate the total system parameters to include all the devices selected to be used in the measurement system. Any pre-selection required can usually be accomplished using passive high-pass, low-pass, or band-pass filters. These types of filters can greatly assist in removing any undesired ambient noise or signals removed from the intended measurement frequency or frequency band of interest.

The RF filtering will primarily determine the "*carrier-to-noise ratio*" of the system. RF filtering will also prevent possible overloading to the system's pre-amplifier or to the receiver if a pre-amplifier is not used. Overloading, exceeding the maximum allowed input levels, to the system's pre-amplifier or receiver input levels can result in creating intermodulation products within these devices and may result in inaccurate measurement results.

The I-F filtering selection will primarily determine the "*signal-to-noise ratio*" within the receiver itself.

The overall system sensitivity will thus be dependent on the noise figure of the selected receiver, the noise figure and gain of the preamplifier (if used), the system cabling losses, and the gains of the selected antennas.

For high-gain systems, used for measuring low signal levels, extreme caution should be taken to ensure that the combination of the antenna gains and amplifier gains will not produce signal levels that exceed the maximum input levels allowed for the selected receiver. Again, because of the importance, saturating an amplifier or a receiver's input stage may create intermodulation products and may result in inaccurate measurements.

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Useful example and formulas: