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Lab Assignment # 1

Spectrum Analysis

(An Introduction to RF Signal, Noise and Distortion Measurements in the Frequency Domain)

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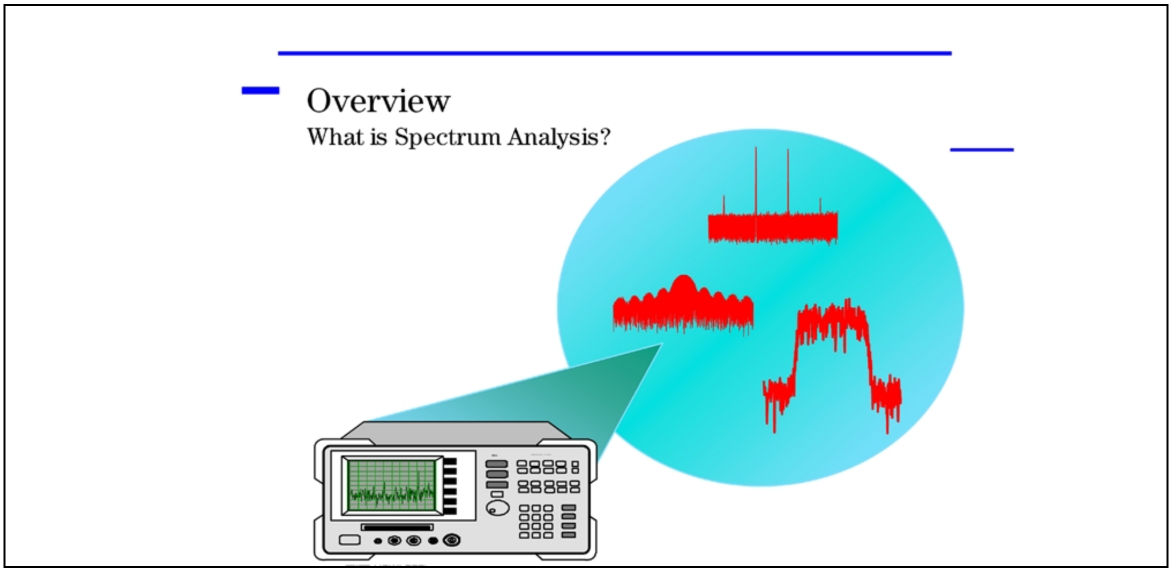
Purpose

This lab is intended to be a beginning tutorial on RF spectrum analysis. It is written for those who are unfamiliar with spectrum analyzers, and would like a basic understanding of how they work, what you need to know to use them to their fullest potential, in signal, noise and distortion measurements. It is written for university level engineering students, therefore a basic understanding of electrical concepts is recommended.

Equipment:

- Agilent ESG-D4000A signal generator
- Agilent ESA-L1500A spectrum analyzer

Pre-Study:



Overview

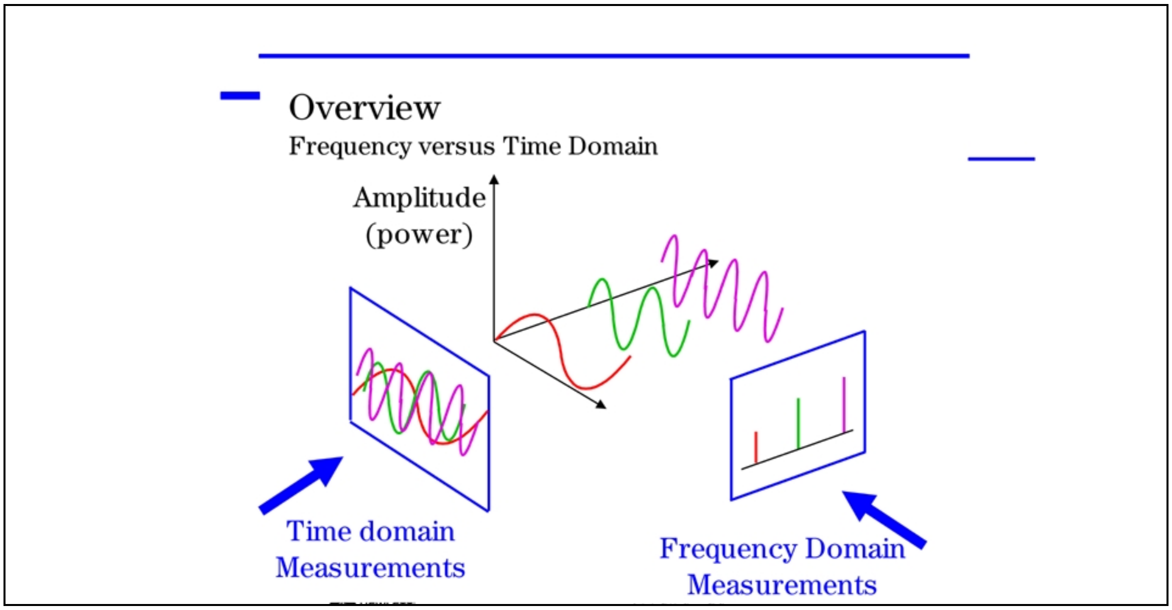
What is Spectrum Analysis?

How can we measure electrical signals in a circuit to help us determine the overall system performance?

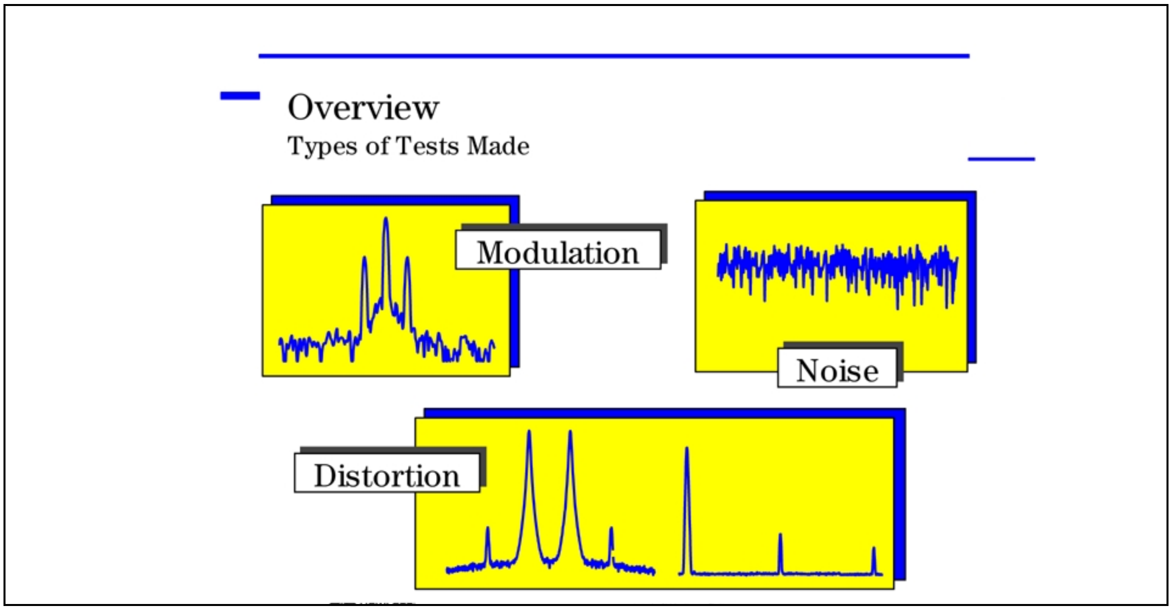
First, we need a “passive” receiver, meaning it doesn’t do anything to the signal under test. I just displays it in a way that makes it easy to analyze the signal, without masking the signals true characteristics. The receiver most often used to measure these signals in the time domain is an oscilloscope. In the frequency domain, the receiver of choice is called a spectrum analyzer.

Spectrum analyzers usually display raw, unprocessed signal information such as voltage, power, period, waveshape, sidebands, and frequency. They can provide you with a clear and precise window into the frequency spectrum.

Depending upon the application, a signal could have several different characteristics. For example, in communications, in order to send information such as your voice or data, it must be modulated onto a higher frequency carrier. A modulated signal will have specific characteristics depending on the type of modulation used. When testing non-linear devices such as amplifiers or mixers, it is important to understand how these create distortion products and what these distortion products look like. Understanding the characteristics of noise and how a noise signal looks compared to other types of signals can also help you in analyzing your device/system. Understanding the important aspects of a spectrum analysis for measuring all of these types of signals will give you greater insight into your circuit or systems true characteristics.



Traditionally, when you want to look at an electrical signal, you use an oscilloscope to see how the signal varies with time. This is very important information; however, it doesn't give you the full picture. To fully understand the performance of your device/system, you will also want to analyze the signal(s) in the frequency-domain. This is a graphical representation of the signal's amplitude as a function of frequency The spectrum analyzer is to the frequency domain as the oscilloscope is to the time domain. (It is important to note that spectrum analyzers can also be used in the fixed-tune mode (zero span) to provide time-domain measurement capability much like that of an oscilloscope.) The figure shows a signal in both the time and the frequency domains. In the time domain, all frequency components of the signal are summed together and displayed. In the frequency domain, complex signals (that is, signals composed of more than one frequency) are separated into their frequency components, and the level at each frequency is displayed. Frequency domain measurements have several distinct advantages. For example, let's say you're looking at a signal on an oscilloscope that appears to be a pure sine wave. A pure sine wave has no harmonic distortion. If you look at the signal on a spectrum analyzer, you may find that your signal is actually made up of several frequencies. What was not discernible on the oscilloscope becomes very apparent on the spectrum analyzer. Some systems are inherently frequency domain oriented. For example, many telecommunications systems use what is called Frequency Division Multiple Access (FDMA) or Frequency Division Multiplexing (FDM). In these systems, different users are assigned different frequencies for transmitting and receiving, such as with a cellular phone. Radio stations also use FDM, with each station in a given geographical area occupying a particular frequency band. These types of systems must be analyzed in the frequency domain in order to make sure that no one is interfering with users/radio stations on neighboring frequencies. We shall also see later how measuring with a frequency domain analyzer can greatly reduce the amount of noise present in the measurement because of its ability to narrow the measurement bandwidth. From this view of the spectrum, measurements of frequency, power, harmonic content, modulation, spurs, and noise can easily be made. Given the capability to measure these quantities, we can determine total harmonic distortion, occupied bandwidth, signal stability, output power, intermodulation distortion, power bandwidth, carrier-to-noise ratio, and a host of other measurements, using just a spectrum analyzer.


Overview

Types of Tests Made

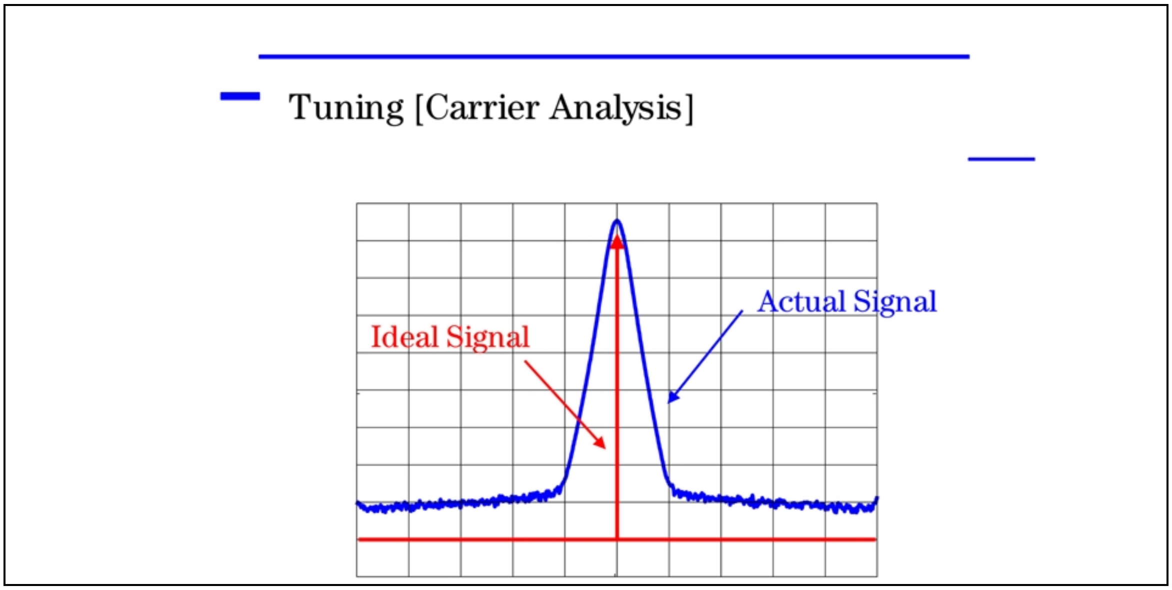
The most common measurements made using a spectrum analyzer are: modulation, distortion, and noise.

Measuring the quality of the modulation is important for making sure your system is working properly and that the information is being transmitted correctly. Understanding the spectral content is important, especially in communications where there is very limited bandwidth. The amount of power being transmitted (for example, to overcome the channel impairments in wireless systems) is another key measurement in communications. Tests such as modulation degree, sideband amplitude, modulation quality, occupied bandwidth are examples of common modulation measurements.

In communications, measuring distortion is critical for both the receiver and transmitter. Excessive harmonic distortion at the output of a transmitter can interfere with other communication bands. The pre-amplification stages in a receiver must be free of intermodulation distortion to prevent signal crosstalk. An example is the intermodulation of cable TV carriers that moves down the trunk of the distribution system and distorts other channels on the same cable. Common distortion measurements include intermodulation, harmonics, and spurious emissions.

Noise is often the signal you want to measure. Any active circuit or device will generate noise. Tests such as noise figure and signal-to-noise ratio (SNR) are important for characterizing the performance of a device and/or its contribution to overall system noise.

For all of these measurements, it is important to understand the capabilities and limitiations of your test equipment for your specific requirements. It is the goal of this lab to familiarize the student with the most important fundamental concepts in spectrum analysis and their applications in circuit design, verification and troubleshooting.



Lab Procedure:

This lab procedure is written around an Agilent ESG-D4000A signal generator and an Agilent ESA-L1500A spectrum analyzer. Lets begin by measuring some simple known signals with the spectrum analyzer. The first step in this process is to set up the signal source. For this lab we will use the ESG-D4000A RF Signal Generator as our source.

Instruction	**Keystroke**
Return the ESG-D4000A to a known state	[Preset]
Select an output frequency	[Frequency][300][MHz]
Select output signal level	[Amplitude][0][dBm]
Enable RF output	[RF On/Off]

Once the signal generator has been configured, set up the spectrum analyzer to display the generated signal, by connecting the RF output of the signal generator to the RF input of the spectrum analyzer and following the instructions below.

Instruction	**Keystroke**
Return the ESA-L1500A to a known state	[Preset]
Select a frequency range to display	[Frequency]
	[Start Freq][250][MHz]
	[Stop Freq][350][MHz]
Adjust the analyzers vertical display resolution to 10 dB per division.	[Amplitude][Scale/Div][10][dB]
For the greatest frequency accuracy use	[Marker][Freq Count]
the spectrum analyzer’s built-in frequency	[Resolution Man][1][Hz]
counter to read out the frequency and	

amplitude of the signal under test __________ MHz __________ dBm

Please take 5 minutes to discuss with your lab group why the frequency and amplitude values for the signal under test that are being displayed by the signal generator and spectrum analyzer are not identical. Write your explanation below.

____

____

____

____

Estimate the cable loss between the signal generator and spectrum analyzer __________ dB

Calculate the frequency error between the signal generator and spectrum analyzer in parts per million (PPM) given our carrier frequency of 300 MHz $\left(\frac{\Delta f}{300\,\mathrm{MHz}} * 10^6\right)$ __________ PPM

Connect the 10 MHz **Reference Output** on the rear panel of the signal generator to the 10 MHz **Reference Input** on the rear panel of the spectrum analyzer and repeat the frequency error calculation.

Repeat the step above, to read out the frequency of the signal under test. __________ MHz

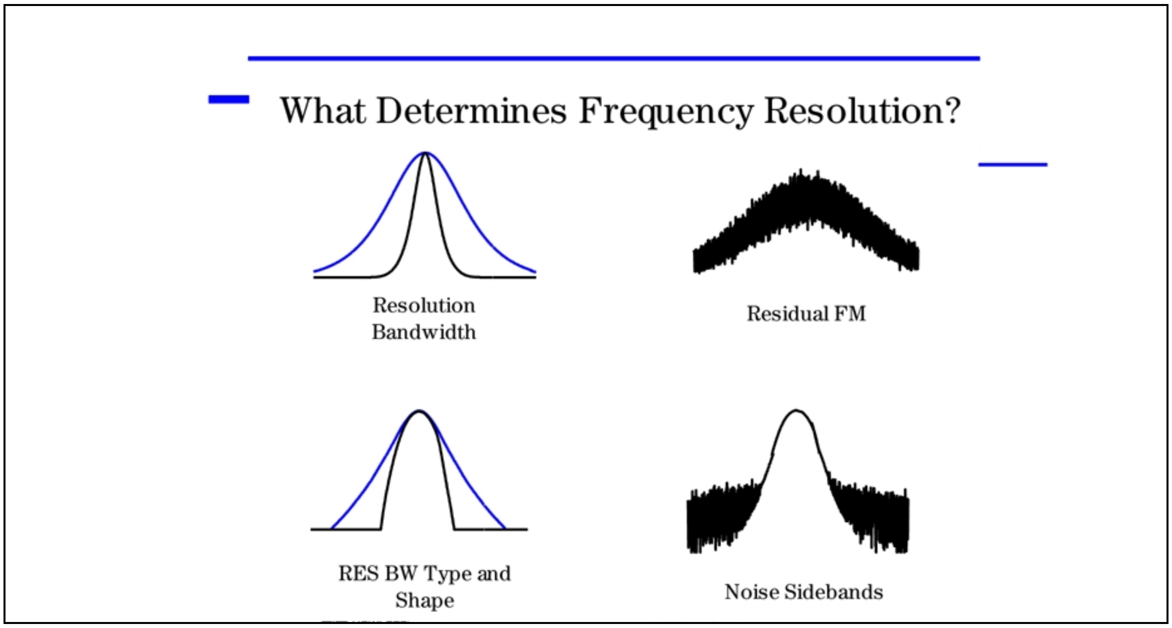
Re-calculate the frequency error between the signal generator and spectrum analyzer in parts per million (PPM) given our carrier frequency of 300 MHz $\left(\frac{\Delta f}{300\,\mathrm{MHz}} * 10^6\right)$ __________ PPM

As you can see, even in the simplest of communications systems, synchronization between transmitter and receiver is essential. Imagine its importance in a complex system like a GSM or CDMA cellular telphone system.

To reduce the spectrum analyzer's sweep time, turn off the frequency counter function.	[Freq Count][Marker Count Off]

Given that the signal generator is outputing a single unmodulated 300 MHz CW signal, why is the spectrum analyzer displaying a response that is something other than a verticle frequency impulse response at 300 MHz? Please take 5 minutes to discuss this questions within your lab group then write your explaination below.

In actuality, both the signal generator and spectrum analyzer are contributing to the “spreading” of the signal under test. Although the signal generator’s absolute frequency accuracy and short and long term stability can cause the energy in the carrier signal to be distributed over some finite band of frequencies centered around the carrier, in most cases it is the spectrum analyzer’s RF characteristics that will be the major contributor to the broad frequency response that you have seen. Let’s briefly review four of the largest contributing factors limiting a spectrum analyzers frequency resolution.



What Determines Frequency Resolution?

Resolution Bandwidth

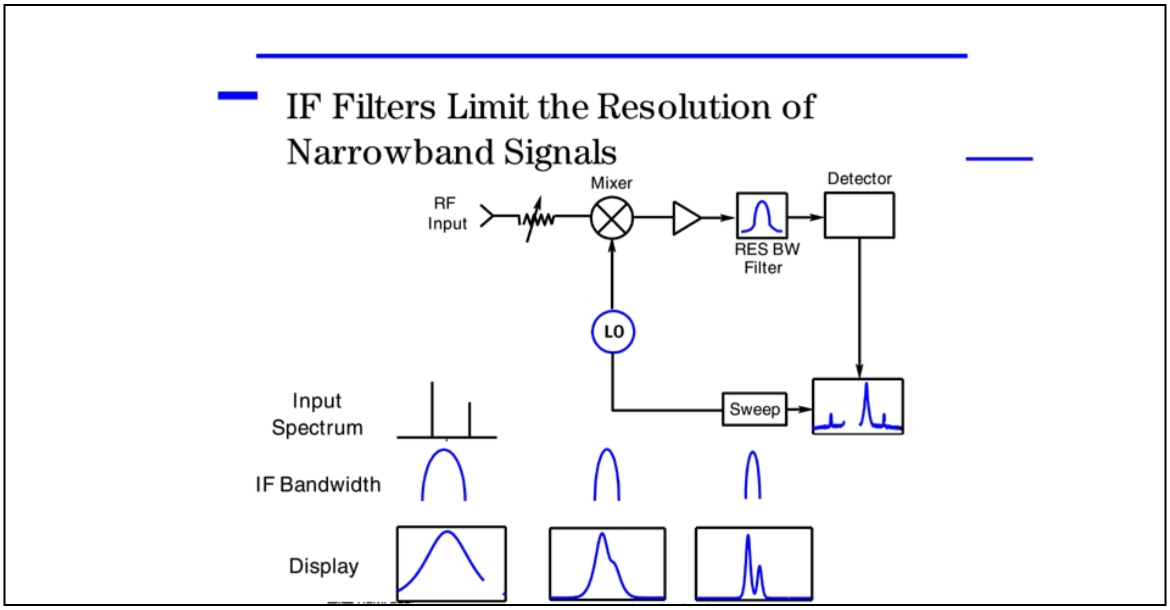
Residual FM

RES BW Type and Shape

Noise Sidebands

These factors are spectrum analyzer resolution filter bandwidth and shape factor, local oscillator residual FM and noise sidebands.

As we discovered earlier, a signal cannot be displayed as an infinitely narrow line. It has some width associated with it. The shape that you see is the spectrum analyzer’s tracing of its own Resolution Bandwidth (IF filter) shape as it tunes past a signal. Thus, if we change the filter bandwidth, we change the width of the displayed response. Most spectrum analyzers specify the 3 dB bandwidth, although a some specify the 6 dB bandwidth.



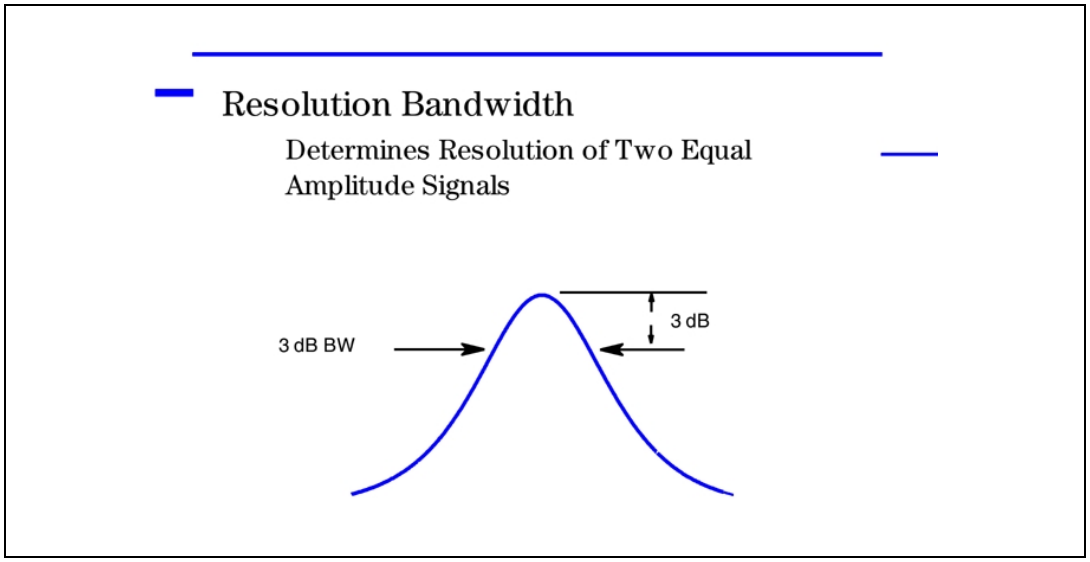
IF Filters Limit the Resolution of Narrowband Signals

Instruction	**Keystroke**
Vary the RBW filter 3 dB BW	[BW/Avg][1][MHz]
and notice the change in the	[100][kHz]
spectrum analyzer's displayed response	[10][kHz]
	[1][kHz]

You may have noticed that as you decreased the RBW the ability of the spectrum analyzer to resolve frequency improved, however at the expense of sweep speed. Repeat the same steps once again, only this time document the sweep time associated with each RBW setting.

Instruction	**Keystroke**		
Vary the RBW filter 3 dB BW	[BW/Avg][1][MHz][Sweep]	_________	ms
and record the change in the	[BW/Avg][100][kHz][Sweep]	_________	ms
spectrum analyzer's displayed response	[BW/Avg][10][kHz][Sweep]	___________	s
and sweept time	[BW/Avg][1][kHz][Sweep]	___________	s

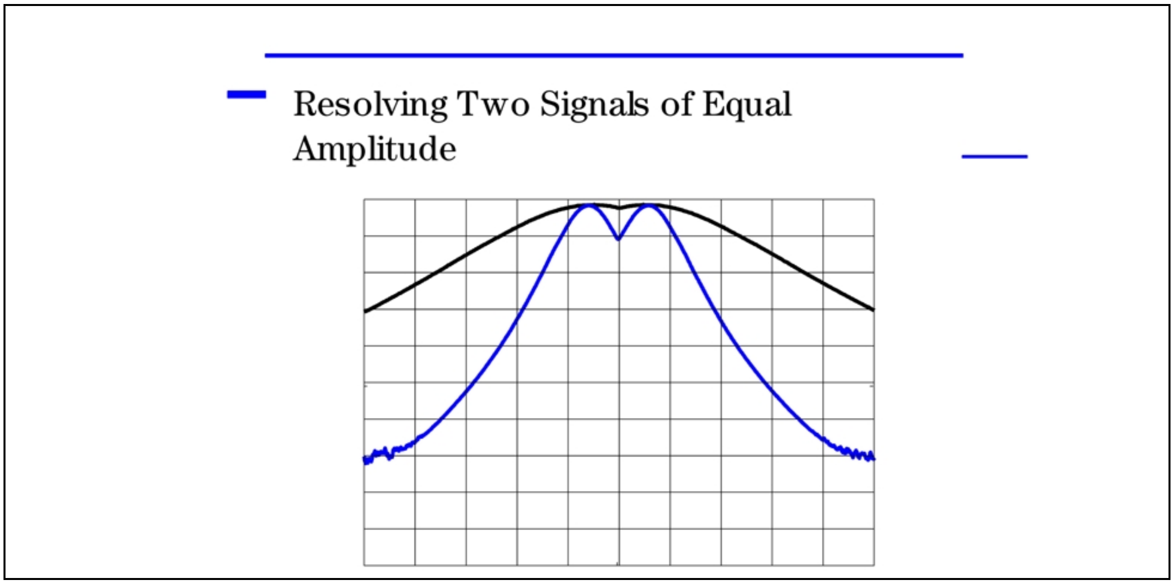
Once you have recorded the sweep times return the spectrum analyzer's RBW to 100KHz	[BW/Avg][100][kHz]



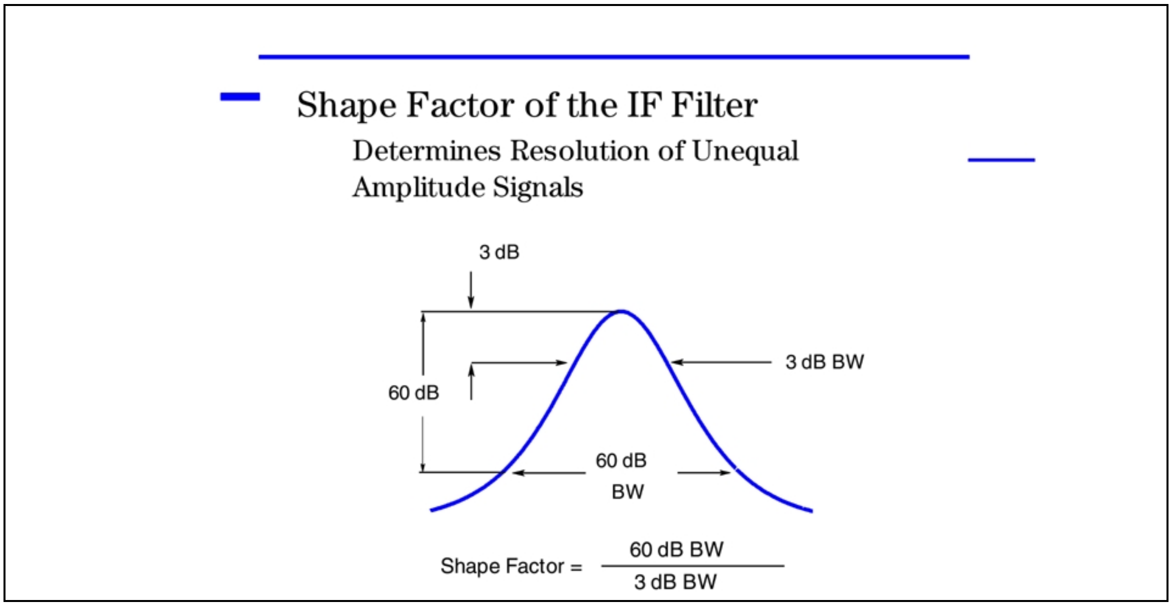
Resolution Bandwidth

Determines Resolution of Two Equal Amplitude Signals

The **3 dB bandwidth** tells us how close together equal-amplitude signals can be and still be distinguishable from one another (by a **3 db “dip”**). In general, two equal-amplitude signals can be resolved if their separation is greater than or equal to the 3 dB bandwidth of the selected resolution bandwidth filter. The two signals shown in the slide below are 10 kHz apart, a 10 kHz Res BW easily separates the responses. However, with wider Res BWs, the two signals appear as one.



Resolving Two Signals of Equal Amplitude

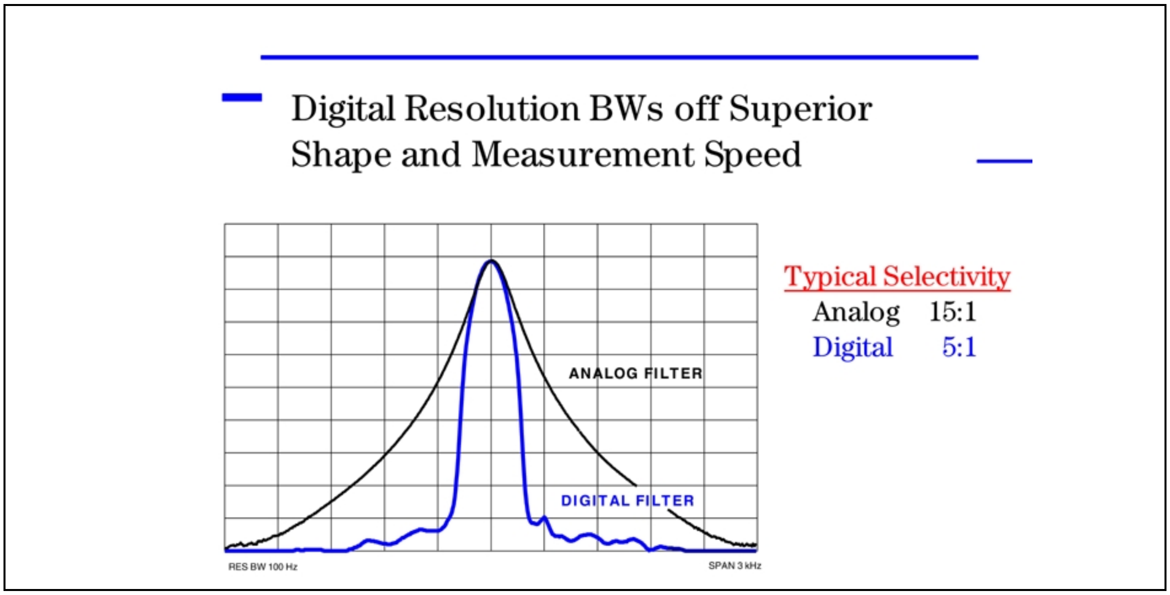


Shape Factor of the IF Filter

Determines Resolution of Unequal
Amplitude Signals

Shape Factor = $\frac{\text{60 dB BW}}{\text{3 dB BW}}$

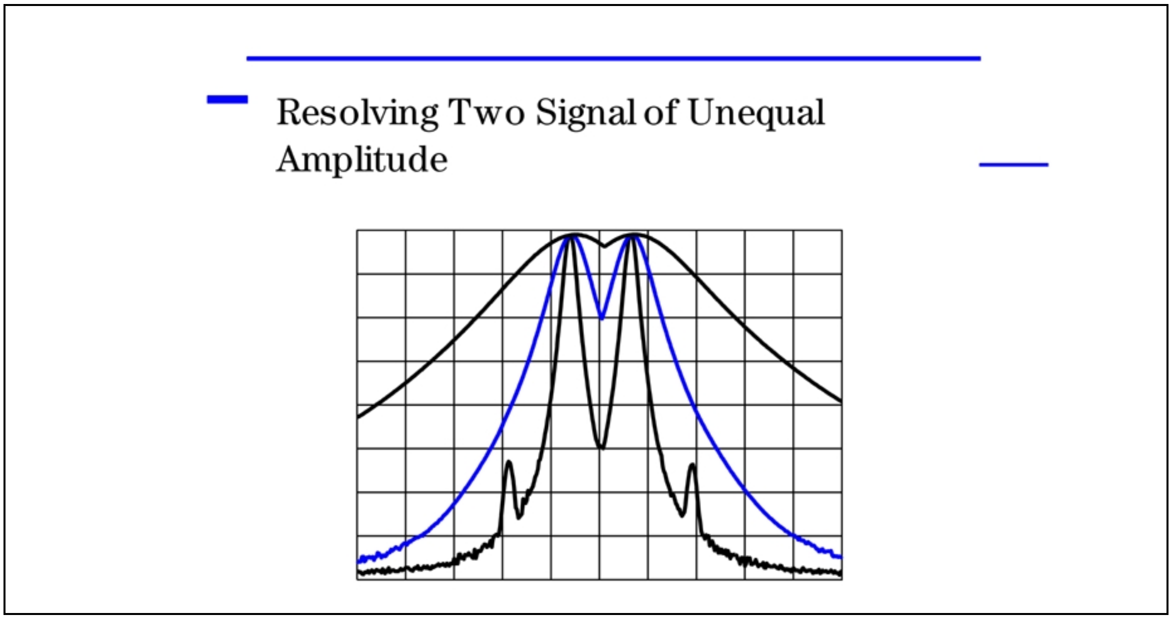
Usually we look at signals of unequal amplitudes. Since both signals in our example trace out the filter shape, it is possible for the smaller signal to be buried in the filter skirt of the larger one. **Two signals unequal in amplitude by 60 dB must be separated by at least one half the 60 dB bandwidth** to resolve the smaller signal (with approximately a 3 db “dip”). Hence, shape factor, the ratio of the 60 dB to 3 dB filter bandwidth, is key in determining the resolution of unequal amplitude signals (shape factor is sometimes referred to as selectivity).



Digital Resolution BWs off Superior Shape and Measurement Speed

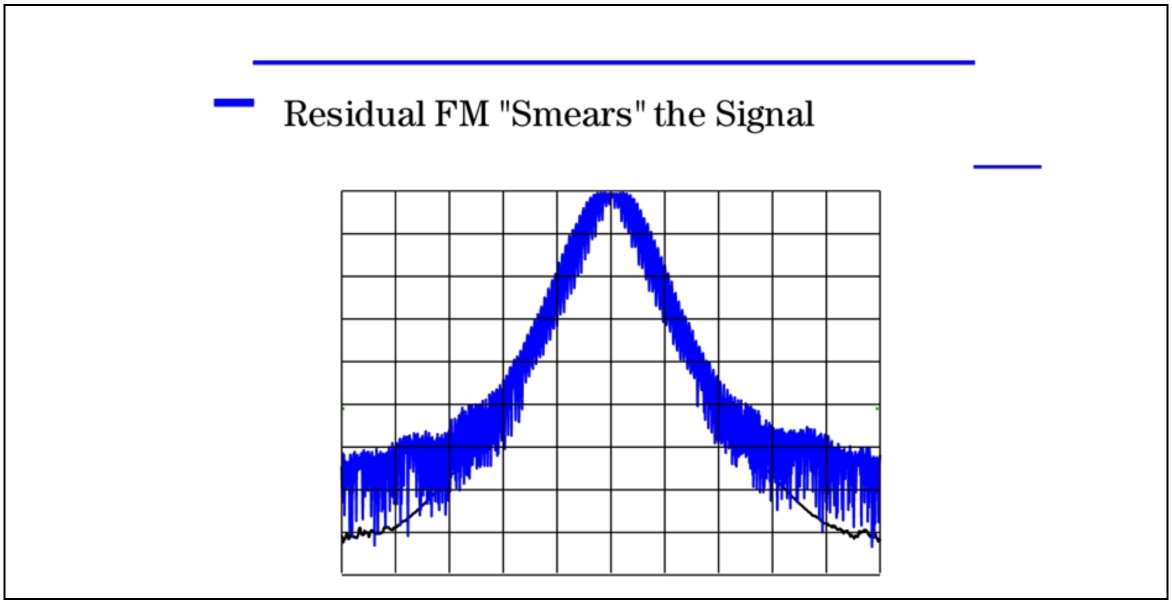
Typical Selectivity

Analog	15:1
Digital	5:1



Resolving Two Signal of Unequal Amplitude

With a 10 kHz filter, resolution of the equal amplitude tones is not a problem, as we have seen. But the distortion products, which can be 50 dB down and 10 kHz away, could be buried. If the shape factor of the 3 kHz filter is 15:1 then the filter width 60 dB down is 45 kHz, and distortion will be hidden under the skirt of the response of the test tone. If we switch to a narrower filter (for example, a 1 kHz filter) the 60 dB bandwidth is 15 kHz and the distortion products are easily visible.

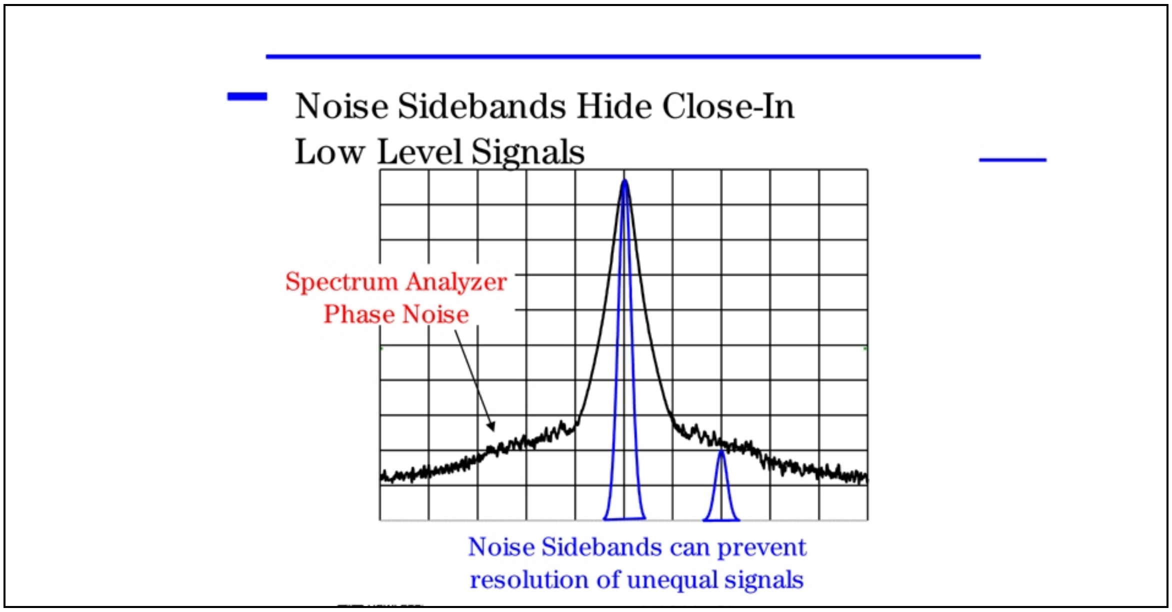


Residual FM "Smears" the Signal

Another factor affecting resolution is the frequency **stability** of the spectrum analyzer’s local oscillator. A spectrum analyzer cannot have a resolution bandwidth so narrow that it allows observation of its own instability. If it did, we could not then distinguish between the analyzer’s residual FM and that of the incoming signal. Also, the residual FM “smears” the signal so that two signals within the specified residual FM cannot be resolved.

This means that the spectrum analyzer's residual FM dictates the **minimum resolution bandwidth** allowable, which in turn determines the minimum spacing of equal amplitude signals. Our required residual FM for this measurement is residual FM 1 kHz.

Phase locking the LOs to a reference reduces the residual FM and reduces the minimum allowable Res BW. Higher performance spectrum analyzers are more expensive because they have better phase locking schemes with lower residual FM and smaller minimum Res BWs.

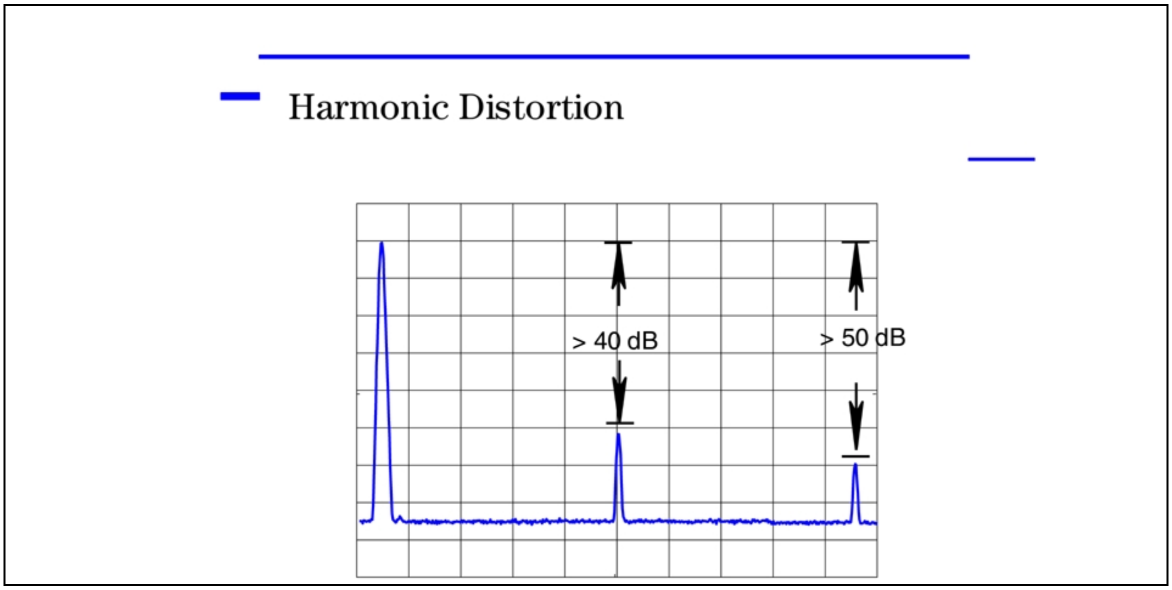


Noise Sidebands Hide Close-In Low Level Signals

Spectrum Analyzer Phase Noise

Noise Sidebands can prevent resolution of unequal signals

The remaining instability appears as **noise sidebands** (also known as phase noise) at the base of the signal response. This noise can mask close-in (to a carrier), low-level signals that we might otherwise be able to see if we were only to consider bandwidth and shape factor. These noise sidebands affect resolution of close-in, low-level signals.



Harmonic Distortion

Now that we have a better practical understanding of the limitations of a spectrum analyzers let's proceed with the laboratory. The next measurement that we will make is second and third order harmonic distortion.

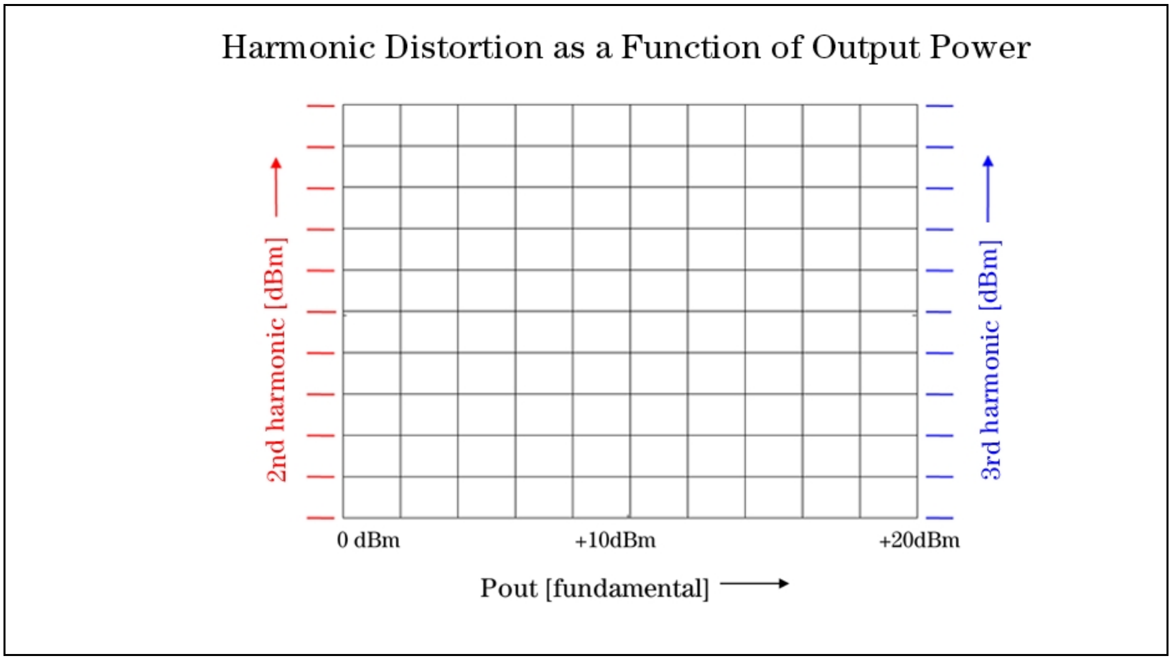
Instruction	**Keystroke**
Increase the spectrum analyzer's stop frequency to allow you to view the 2nd & 3rd harmonics of the signal under test	[Frequency] [Stop Freq][1000][MHz]
Find and record the frequency and amplitude of fundamental signal.	[Marker][Peak Search] __________ MHz __________ dBm
Using the fundamental as a reference, use one of the Marker Next Peak functions to step through the second and third order harmonic distortion products and record their values, in absolute frequency (MHz) and relative amplitude (dBc).	[Marker] [Marker Delta] [Search]
2nd __________ MHz __________ dBc	[Next Pk Right]
3rd__________ MHz __________ dBc	[Next Pk Right]
Once complete turn off all markers.	[Marker] [Marker All Off]

Use the spectrum analyzer to measure the signal under test's fundamental and harmonic (2nd & 3rd order) output power in dBm, as you increase the signal generators output power from 0 dBm to +20 dBm in 2 dB increments. Once you have recorded the results in the table below, plot the data on the blank grid given below.

Pout = 0 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = + 2 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = + 4 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = + 6 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = + 8 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = +10 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = +12 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = +14 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = +16 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = +18 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm
Pout = +20 dBm Fundamental________ dBm 2nd________ dBm 3rd________ dBm

Once you have completed this section of the lab turn off all frequncy and amplitude markers.

Turn off all markers. [Marker] [Marker All Off]

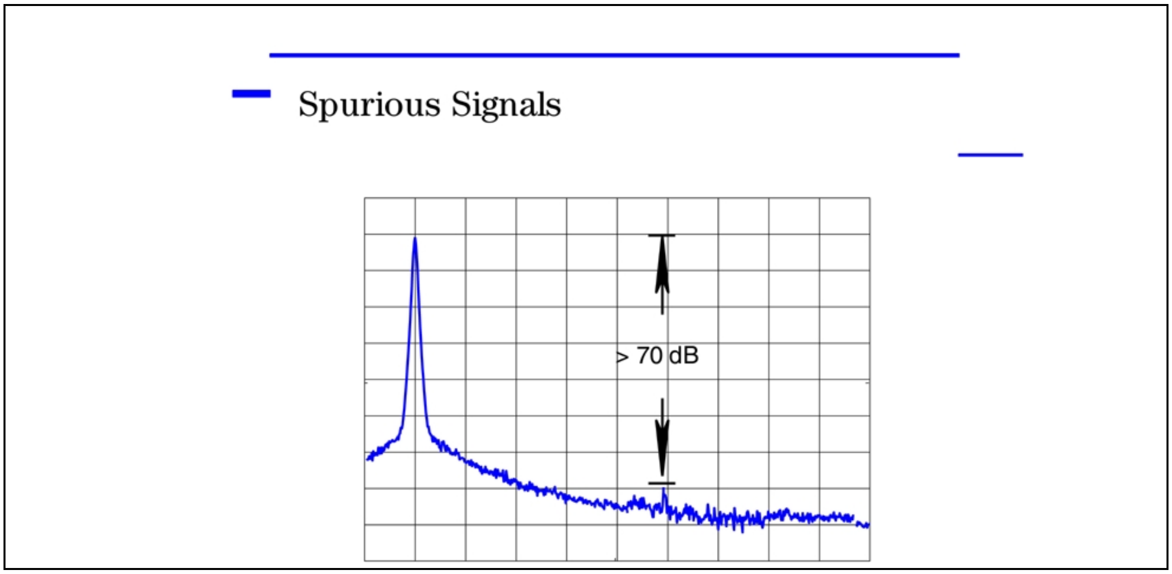


Please explain (quantitatively) the rate of increase in harmonic signal levels.

Once you have completed the harmonic measurements above return the signal generator output power to 0 dBM.

Instruction	**Keystroke**
Reset ESG-D4000A signal generator's output power [Pout]	[Amplitude][0][dBm]

One of the primary uses of a spectrum analyzer is to search out and measure low-level spurious signals. Becasue these spurious signals are small and appear at frequncies that are non-harmonically related to the carrier signal they can be difficult to find and measure accurately. The indication of how well any receiver can detect and measure small signals is its sensitivity. A perfect receiver would add no additional noise to the natural amount of thermal noise present in all electronic systems, represented by kTB (k=Boltzman's constant, T=temperature, and B=bandwidth). In practice, all receivers, including spectrum analyzers, add some amount of internally generated noise.


Spurious Signals

Spectrum analyzers usually characterize this by specifying the displayed average noise level (DANL) in dBm, with the smallest RBW setting. DANL is just another term for the noise floor of the instrument given a particular bandwidth. It represents the best-case sensitivity of the spectrum analyzer, and is the ultimate limitation in making measurements on small signals. An input signal below this noise level cannot be detected. Generally, sensitivity is on the order of -90 dBm to -145 dBm.

It is important to know the sensitivity capability of your analyzer in order to determine if it will adequately measure your low-level signals.

During this section of the lab you will configure the spectrum analyzer to find and measure the value of the largest spurious signal (non-harmonic) in dB relative to the carrier level (dBc) across the operating frequency range of the spectrum analyzer.

Note: The analyzer will display all marker frequencies and amplitude values in absolute terms. Find the largest spur within the bandwidth of interest and calculate its value relative to the fundamental. Be careful that youare measuring a spurious signal and not the peak of the noise floor.

Instruction	**Keystroke**
Set the spectrum analyzer’s frequency range to its maximum span	[Frequency] [Start Freq][9][kHz] [Stop Freq][1500][MHz]
Open the spectrum analyzer’s resolution bandwidth to its maximum value	[BW/Avg][5][MHz]
Find and record the frequency and amplitude of fundamental signal.	[Peak Search]

Fundamental ________ MHz ________ dBm

Is there a spur that is easily detectable above the spectrum analyzers noise floor? _______

If not, why not (please explain)?

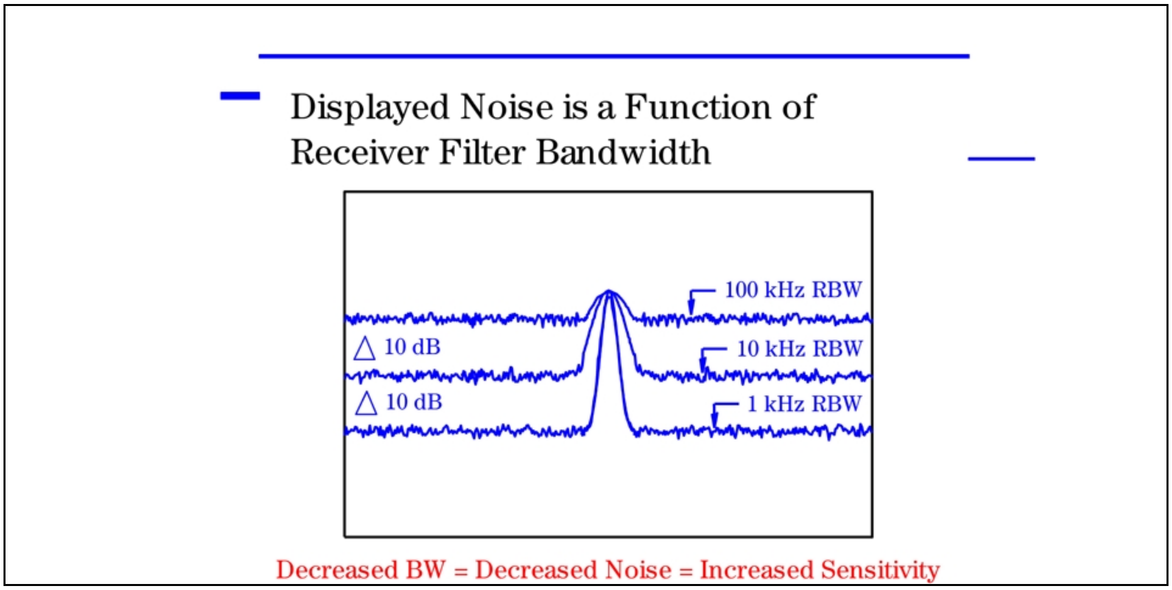
____

____

____

____

Hint: If the signal under test has very good spurious output specifications, you may need to reduce the spectrum analyzer's RBW. Practically, this action reduces the noise power being detected by the spectrum analyzer's signal detection circuitry and enables the receiver to resolve lower level signals that are no longer masked by the noise floor of the analyzer. You can reduce the RBW until you feel you have reached a good compramise between sensitivity and sweep speed (update rate).



Displayed Noise is a Function of Receiver Filter Bandwidth

Decreased BW = Decreased Noise = Increased Sensitivity

Measure and record the value of the largest spur in the bandwidth of interest.

Largest spur ________ MHz _________ dBm

Largest spur ________ MHz _________ dBc

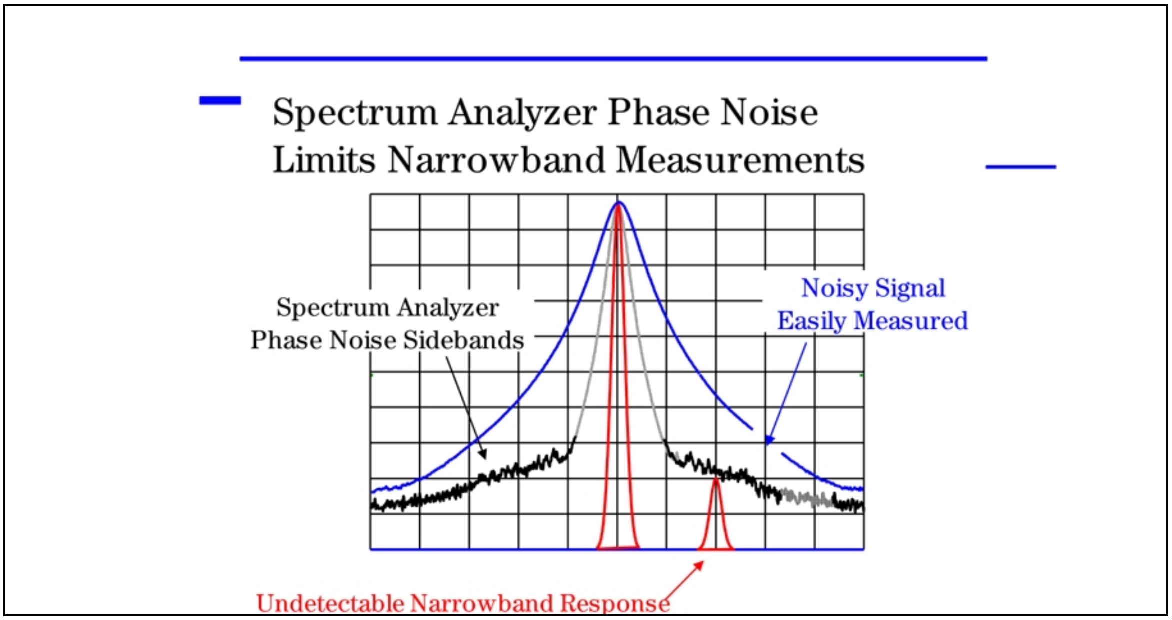
Now use the spectrum analyzers delta marker measurement mode to automatically display the spur value in dBc.

Find and record the frequency and	[Peak Search]
Using the fundamental as a reference	[Marker]
	[Marker Delta]
Record the frequency and amplitude of	
the largest spur (dBc)	[Next Peak]

Largest spur ________ MHz _________ dBc

Configure the spectrum analyzer to measure the phase noise of the signal under test. When measuring signal phase noise characteristics it is important to remember a few key measurement fundamentals.

1. Signals below the noise sidebands of the spectrum analyzer will be undetectable.
2. Phase noise is measured relative the carrier level, at a specific offset and referenced to a specific noise bandwidth (e.g., 1 Hz).
3. Unlike coherent signals, noise is random, and therefore to accurately measure its level, it should be measured using a sampling detection technique rather than the peak detection technique usually used for coherent signal analysis.


Spectrum Analyzer Phase Noise Limits Narrowband Measurements

Configure the spectrum analyzer to measure the phase noise of a 860 MHz carrier in a 1 Hz bandwidth at a 10 kHz offset.

Instruction	**Keystroke**
Return the ESG-D4000A to a known state	[Preset]
Select an output frequency	[Frequency][860][MHz]
Select output signal level	[Amplitude][0][dBm]
Enable RF output	[RF On/Off]

Once the signal generator has been configured, set up the spectrum analyzer to display the generated signal, by connecting the RF output of the signal generator to the RF input of the spectrum analyzer and following the instructions below.

Instruction	Keystroke
Return the ESA-L1500A to a known state	[Preset]
Select a frequency range to display	[Frequency] [Center Freq][860][MHz] [Span][30][kHz]
Adjust the analyzers resolution bandwidth	[BW/Avg][1][kHz]
Use the spectrum analyzer’s built-in noise markers to measure the carrier signal’s phase noise @ a 10 KHz offset.	[Marker] [Peak Search] [Marker Delta]
Rotate the analyzer’s Rotary Pulse Generator (RPG) knob to move the delta marker to a 10 kHz offset from the carrier (860,010,000 Hz).	
Turn on the noise marker function	[Marker Noise On]

Phase Noise @ a 10 KHz Offset ____________ dBc/Hz

Note: Turn off the noise marker and notice the difference in the delta marker’s readout value.