RF COMMUNICATION LABORATORY

EE 409/EE691; Fall 2004

Experiment 4

Voltage Controlled Oscillator Measurements

Objective: To introduce the student to the use of the Spectrum Analyzer for the measurement of signal levels, and the characteristics of a Voltage Controlled Oscillator (VCO).

Equipment:
- Spectrum Analyzer (HP 8593E)
- BNC to N cable Assembly (8120-5148)
- Two DC Power supplies (E3630A)

Components:
- Voltage Controlled Oscillator (VTO-8420)
- SMA (M) to N (M) adapter
- SMA (M) to BNC (F) adapter
- BNC (M) to twin-lead adapter
- DC Block Capacitor using Bias-T (ZFBT-6GW-FT)

Pre-Lab:
1. Study the handout “Introduction to Spectrum Analysis”
2. Study the handout “Random Noise Measurement”
3. Study the handout “Carrier-to-Noise Ratio”

Procedure:
I. Getting to know the Spectrum Analyzer:
   Familiarize with the front panel controls of the HP 8593E Spectrum Analyzer. Read the User’s guide (Getting Started) pp. 2-1 to 2-15.

II. Calibration of the Spectrum Analyzer:
   Follow the steps given on page 2-15 of the User’s guide. Use the cable assembly 8120-5148 (N to BNC cable Assembly) for calibration. Capture the spectrum analyzer calibration screen following the printing procedures given below.

   Note: Maximum power that the Spectrum Analyzer can handle is +30dBm (1Watt). No DC must enter the Spectrum Analyzer.

   Printing Procedures: In order to print the spectrum analyzer screen, capture the graph via the computer hooked up to the spectrum analyzer using the software “BenchLink”. To access BenchLink:

   Start>Programs>BenchLink>HP BenchLink Spectrum Analyzer.
To capture the spectrum analyzer screen, click on Image from the tool bar and select New... A window pops up telling you that you are about to capture an image; click OK. You should select New... every time a new image (or set of data) is required.

Save the file(s) obtained with .pcx extension onto a floppy disk. Open the saved .pcx files with any photo editor, and copy/paste them into a word processor like MS word on other computers to get printouts of the obtained results.

III. VCO Measurements:
A. The VCO given to you has two ports, RF OUT and TUNING VOLTAGE, as well as two terminals for DC Bias. It is desired that the VCO be connected to the spectrum analyzer to study its different characteristics. Draw a block diagram of the VCO’s setup to the spectrum analyzer as described in parts a through d that follow; show all components.

a) Block the DC current from entering the port of the spectrum analyzer by using the DC blocking capacitor of the Bias-T provided. The RF port of the Bias-T should be connected to the spectrum analyzer using the SMA to N adapter. The RF&DC port of the Bias-T should be connected to the VCO at its RF OUT port.

b) Connect the first (Bias) DC power supply to the DC bias terminals of the VCO (+15V & GND). Do not apply power (+15V) yet.

c) Connect the second (Tune) DC Power Supply to the tuning voltage port. For this, connect the SMA to BNC adapter to the tuning voltage port then connect the BNC to twin-lead adapter. Do not turn on the power supply yet.

d) Set the frequency range of the spectrum analyzer to 3GHz – 5GHz. Refer to the attached data sheets for VCO specs. Also, turn on both power supplies applying +15V to the VCO bias and 0V to the tuning voltage.

e) Measure and record/print the signal peak power and frequency corresponding to various tuning voltages. The tuning voltage should be varied in steps of 2V, from 0 to 20V. Observe the signal level (dBm) and the frequency of the signal on the spectrum analyzer screen by using the Peak Search option on the front panel. Capture each signal peak obtained and save to a floppy disk; include the tuning voltage value by using the text editor (A button on tool bar). Follow the printing instructions discussed in part II.

Note: Sidebands do exist around the peak signal. But since the bandwidth resolution is large the sidebands can’t be seen.

f) Record the readings in MS Excel spread sheet, and draw graphs using the tools provided in the Excel for:
   i. Frequency of the oscillator output Vs Tuning Voltage
   ii. Power of the output signal Vs Frequency of the signal

B. Observing VCO sidebands:
   a) Set the Tuning Voltage to 10V.
   b) Set the Resolution Bandwidth to 10KHz from the control panel of spectrum analyzer to observe the side bands.
   c) Set the start frequency to 4.3GHz and stop frequency to 4.8GHz.
d) Observe, measure and record/print the side band power levels (close to the desired signal) and the desired signal level. Follow printing instructions discussed in part II.

C. Random Noise Measurement:
Refer to page 9 of the handout “Random Noise Measurement”
a) Using the same signal obtained in part B, change the frequency range to 4.4GHz – 4.6GHz. Observe the sidebands and distortion at the signal. This indicates that the VCO signal is not made of only one frequency. Adjust the reference level so as to see the entire signal.
b) Measure the noise power level in dBm (flat noise floor).
c) Follow the steps and the example in the handout on p.9 to find the random noise power in dBm/Hz.

D. Carrier-to-Noise Ratio Measurement:
Refer to page 12 of the handout “Carrier-to-Noise Ratio”
a) Using the same signal obtained in part B, measure the signal power level in dBm.
b) Measure the noise power level in dBm (noise floor) and apply corrections. Follow only step 1 of example in handout.
c) Then, the carrier-to-noise ratio in dB is the difference of signal power level measured in step (a) to the corrected noise power obtained in step (b).

IV. Observation of Local Radio and TV Stations:
Disconnect the VCO setup from the spectrum analyzer without dismantling the assembly (only if you haven’t drawn the block diagram yet) – keep the SMA to N adapter. Connect the SMA coaxial cable and antenna given to you to the spectrum analyzer. Display and observe the local radio (AM and FM) and TV stations on the spectrum analyzer. Tune the radio and TV in the lab to the stations being inspected and note the variations in the signal and sidebands as you hear or see the stations respectively. To do this, pick the strongest signal and change the resolution bandwidth appropriately to observe the sidebands around the carrier. Note the variations in the side bands with the variations in the sound from the radio when tuned to this station. Interesting frequency bands that can be observed are:

**AM Radio:** stations between 540 KHz to 1600 KHz at Reference Level of –30dBm and resolution bandwidth of 1 KHz. Make your observations for the strongest signal.
Note: The antenna for AM waves must be very long.

**FM Radio:** 89.9MHz and 107MHz at Reference Level –10dBm and Resolution Bandwidth of 10kHz (adjust frequency span as well).

**TV Stations:**
*Channel 31:* 572-578MHz where the video carrier is 573.25MHz and the sound carrier should be about 4.5MHz away. Adjust the frequency span and the other parameters accordingly.
*Channel 47:* 668-674MHz where the video carrier is 669.25MHz and the sound carrier should be about 4.5MHz away. Adjust the frequency span accordingly and the Reference Level to –20dBm and the Resolution Bandwidth to 10kHz or 100kHz.

**Report:**

1. With the help of a block diagram, briefly explain the operation of a Superheterodyne Spectrum Analyzer.
2. What do you understand by the term “resolution bandwidth”? 
3. How does the resolution bandwidth affect:
   a) The signal level?
   b) Noise level?
4. Comment on the linearity of the VCO tuning curve and the output power over the tuning range.
5. Comment on the “quality” of the oscillator output based on measurements in part (III. B).
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CHAPTER 1
INTRODUCTION TO SPECTRUM ANALYSIS

General

The traditional way of observing electrical signals is to view them in the time domain using an oscilloscope. The time domain is used to recover relative timing and phase information which is needed to characterize electric circuit behavior. However, not all circuits can be uniquely characterized from just time domain information. Circuit elements such as amplifiers, oscillators, mixers, modulators, detectors and filters are best characterized by their frequency response information. This frequency information is best obtained by viewing electrical signals in the frequency domain. One instrument which displays the frequency domain is the spectrum analyzer.

What Is the Frequency Domain?

The frequency domain is a graphical representation of signal amplitude as a function of frequency. Figure 1.1 illustrates the relationship between the time domain and the frequency domain. In the time domain, all frequency components of a signal are seen summed together. In the frequency domain, complex signals (i.e., signals composed of more than one frequency) are separated into their frequency components, and the power level at each frequency is displayed.

![Diagram of Frequency Domain](image)

Figure 1.1 Relationship between the time and frequency domains: (a) Three-dimensional coordinates showing time, frequency, and amplitude. The addition of a fundamental and its second harmonic is shown as an example. (b) View seen in the time domain. On an oscilloscope, only the composite \( f + 2f \) would be seen. (c) View seen in the frequency domain. The components of the composite signal are clearly seen here.
What Is a Spectrum Analyzer?

To display the frequency domain requires a device that can discriminate between frequencies while measuring the power level at each. The spectrum analyzer was designed for this purpose. A spectrum analyzer is an instrument which graphically displays voltage or power as a function of frequency on a CRT (cathode ray tube). It can be used to analyze signals in the frequency domain.

![Graph showing frequency domain display of a CW signal.](image)

**Figure 1.2** Frequency domain display of a CW signal.

Spectrum Analyzer Applications

The frequency domain contains information not found in the time domain and therefore, the spectrum analyzer has certain advantages not available with an oscilloscope. Following is an outline of spectrum analyzer applications. These are described in more detail in the following brochures:

- The Spectrum Analyzer for Design Engineers (HP Lit. No. 5952-0932)
- The Spectrum Analyzer Could Be the Most Important Test Instrument On Your Bench (HP Lit. No. 5952-9201)
- AN-150 Series

![Graphs showing waveforms.](image)

**Figure 1.3**

1. The analyzer is more sensitive to low level distortion than a scope. The sine wave in Figure 1.3 looks good in the time domain, but in the frequency domain, harmonic distortion can be seen.
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![Figure 1.3](image)

1. The analyzer is more sensitive to low level distortion than a scope. The sine wave in Figure 1.3 looks good in the time domain, but in the frequency domain, harmonic distortion can be seen.
4. The spectrum analyzer can be used to measure long and short term stability. Parameters such as noise sidebands on an oscillator, residual FM of a source and frequency drift during warm-up can be measured using the spectrum analyzer's calibrated scan times. These parameters are shown in Figure 1.6.

Figure 1.6

Figure 1.7
5. The swept frequency response of a filter or amplifier and the swept distortion measurement of a tuned oscillator are examples of swept frequency measurements possible with a spectrum analyzer, as shown in Figure 1.7. These measurements are simplified by using a variable persistence display or a tracking generator which will be described later.

![Figure 1.8](image)

6. Frequency conversion devices can be easily characterized with a spectrum analyzer. Such parameters as conversion loss, isolation, and distortion are readily determined from the display.

Types of Spectrum Analyzers

There are two basic types of spectrum analyzers, swept-tuned and real-time analyzers. The swept-tuned analyzers are tuned by electrically sweeping them over their frequency range. Therefore, the frequency components of a spectrum are sampled sequentially in time.

This enables periodic and random signals to be displayed, but makes it impossible to display transient responses. Real-time analyzers, on the other hand, simultaneously display the amplitude of all signals in the frequency range of the analyzer; hence the name real-time. This preserves the time dependency between signals which permits phase information to be displayed. Real-time analyzers are capable of displaying transient responses as well as periodic and random signals.
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Figure 1.10 A multichannel and Fourier analyzer are shown on the left and right respectively. Both instruments are real-time spectrum analyzers.

Swept-Tuned Spectrum Analyzers

The swept-tuned analyzers are usually of the trf (tuned radio frequency) or superheterodyne type. A block diagram of a trf analyzer is shown in Figure 1.11. A trf analyzer consists of a bandpass filter whose center frequency is tunable over a desired frequency range, a detector to produce vertical deflection on a CRT, and a horizontal scan generator used to synchronize the tuned frequency to the CRT horizontal deflection. It is a simple, inexpensive analyzer with wide frequency coverage, but lacks resolution and sensitivity. Because trf analyzers have a swept filter they are limited in sweep width depending on the frequency range (usually one decade or less). The resolution is determined by the filter bandwidth, and, since tunable filters don’t usually have constant bandwidth, is dependent on frequency.

The trf analyzer is relatively inexpensive and is often used for microwave applications due to the availability of broadband tuned filters. However, the use of tuned analyzers eliminates the real-time aspect of the display, and sweep rates (MHz/sec) must be consistent with the charge time of the tunable filter.

Figure 1.11 Block diagram of a swept trf spectrum analyzer. The frequency spectrum is sampled using a tuned bandpass filter.

The most common type of spectrum analyzer differs from the trf spectrum analyzers in that the spectrum is swept through a fixed bandpass filter instead of sweeping the filter through the spectrum. The block diagram of a swept superheterodyne spectrum analyzer is shown in Figure 1.12. The analyzer is basically a narrowband receiver
which is electronically tuned in frequency by applying a saw-tooth voltage to the frequency control element of a voltage tuned local oscillator. This saw-tooth voltage is simultaneously applied to the horizontal deflection plates of the CRT. The output from the receiver is synchronously applied to the vertical deflection plates of the CRT and a plot of amplitude versus frequency is displayed.

![Block diagram of a swept superheterodyne spectrum analyzer](image)

Figure 1.12 Block diagram of a swept superheterodyne spectrum analyzer. The input signal is mixed with a tuned LO frequency to produce a fixed IF which can be detected and displayed.

The analyzer is tuned through its frequency range by varying the voltage on the LO (local oscillator). The LO frequency is mixed with the input signal to produce an IF (intermediate frequency). When the frequency difference between the input signal and the LO frequency is equal to the IF frequency, then there is a response on the analyzer. If $f_s < f_{LO}$

then

$$f_s = f_{LO} - f_{IF}$$

where

$f_s$ = input signal frequency

$f_{LO}$ = local oscillator frequency

$f_{IF}$ = intermediate frequency

For example, if the first IF is 200 MHz, and the LO tunes from 200-310 MHz, the analyzer would have a 0-110 MHz tuning range. An input signal at 50 MHz would mix with an LO frequency of 250 MHz to produce the 200 MHz IF, and a response would appear on the display.

This is the basic tuning equation used to determine the frequency range of the analyzer. This frequency range can be extended by mixing the input signal with the harmonics of the LO frequency. Harmonic mixing is discussed in the next chapter.

The advantages of the superheterodyne technique are considerable. It obtains high sensitivity through the use of IF amplifiers, and many decades in frequency can be tuned. Also, the resolution can be varied by changing the bandwidth of the IF filters. However, the superheterodyne analyzer is not real-time, and, once again, sweep rates must be consistent with the IF filter change time.

The superheterodyne approach is the most flexible, and this is what will be discussed in this note.
Figure 1.13 Display of a CW signal

Here is a spectrum analyzer display of a CW signal. The signal can be measured from the display.

The response at the left edge of the CRT is sometimes called the "zero frequency indicator" or local oscillator feedthrough. It occurs when the analyzer is tuned to zero frequency, and the local oscillator passes directly through IF creating a response on the CRT even when no input signal is present. (For zero frequency tuning, \( F_{LO} = F_{IF} \)). This effectively limits the lower tuning limit.

Spectrum Analyzer Requirements

To accurately display the frequency and amplitude of a signal on a spectrum analyzer, the analyzer itself must be properly calibrated. A spectrum analyzer properly designed for accurate frequency and amplitude measurements will satisfy these requirements.

General:
1. Flat frequency response (amplitude is independent of frequency)
2. All functions should be calibrated

Frequency:
1. Wide tuning range
2. Wide frequency display range
3. Stability
4. Resolution
5. Signal identification

Amplitude:
1. High sensitivity
2. Low internal distortion
3. Linear and Logarithmic display modes (voltage and dB)
4. Absolute measurement of amplitude

Frequency Measurements

Modern spectrum analyzers are calibrated in both frequency and amplitude for relative and absolute measurements. The frequency calibration is usually set by the tuning and scale factor controls. The frequency scale can be scanned in three different modes—full, per division, and zero scan. The full scan mode is used to locate signals because the widest frequency ranges are displayed in this mode. Sometimes an inverted marker below the baseline, as shown in Figure 1.14, is used to track the frequency dial on the front panel. When the marker is set under a signal, the frequency dial indicates the signal frequency.
Figure 1.14 An inverted marker is used to indicate the frequency that the analyzer is tuned to. The marker is only present in the full scan mode.

The per division mode is used to zoom-in on a particular signal. In per division, the center frequency of the display is set by the Tuning control and the scale factor is set by the Frequency Span or Scan Width control. The signal in Figure 1.15 was picked out by the inverted marker and zoomed-in on.

Figure 1.15 This signal was picked out with the inverted marker and zoomed-in on using the per-division scan mode.

In the zero scan mode, the analyzer acts as a fixed-tuned receiver with selectable bandwidths for recovering modulating signals or real-time monitoring of a single signal. AM or FM broadcasts can be heard by plugging headphones into the vertical output on the spectrum analyzer since, in this mode, the analyzer displays amplitude variations versus time at a single frequency. There usually is a built-in envelope detector for recovering AM. FM can be recovered by using the slope of the IF filter as a frequency discriminator. A time domain view of a modulating signal using zero scan is shown in Figure 1.16.

Absolute frequency measurements are usually made from the spectrum analyzer tuning dial.

Relative frequency measurements require a linear frequency scan. By measuring the relative separation of two signals on the display, the frequency difference can be
Figure 1.16 This is the modulating wave from an AM signal. The analyzer displays amplitude versus time of the tuned frequency in the zero scan mode.

determined. The linear scan of the spectrum analyzer also means an HP 8406A Frequency Comb Generator can be used to make more accurate absolute frequency measurements. By measuring on the analyzer’s CRT display the frequency separation between a known harmonic from the Frequency Comb Generator and an unknown input signal, the frequency of the input signal can be determined. If the analyzer were not sweeping linearly, this would not be possible.

Stability

It is important that the spectrum analyzer be more stable than the signals being measured. The stability of the analyzer depends on the frequency stability of its local oscillators. Stability is usually characterized as either short term or long term. Residual FM is a measure of the short term stability which is usually specified in Hz peak-to-peak. Short term stability is also characterized by noise sidebands which are a measure of the analyzer’s spectral purity. Noise sidebands are specified in terms of dB down and Hz away from a carrier in a specific bandwidth. An example of noise sidebands and residual FM is shown in Figure 1.17. Long term stability is characterized by the frequency drift of the analyzer’s LO’s. Frequency drift is a measure of how much the frequency changes during a specified time (i.e., Hz/min. or Hz/hr).

Figure 1.17 A signal with noise sidebands indicating poor spectral purity is shown at left. The residual FM of an oscillator is shown at the right.
Both short term and long term stability can be improved by phase locking the tuned LO to a tooth of a crystal generated frequency comb. The stability of the analyzer is then basically that of the reference crystal oscillator.

Phase locking (or stabilization) should occur automatically whenever a narrow frequency scan is selected. When the tuned local oscillator locks to the crystal reference, some display shift may result due to the pulling of the LO to the lock frequency. If there were no compensation for this, the signal could disappear from the display. In HP analyzers, this shift is compensated for, and no jumping in the display results.

![Image](image1.png)

Figure 1.18 As filter is tuned by CW signal, its bandpass shape is traced out on the display.

Resolution

Before the frequency of a signal can be measured on a spectrum analyzer it must first be resolved. Resolving a signal means distinguishing it from its nearest neighbors. The resolution of the spectrum analyzer is limited by its narrowest IF bandwidth. For example, if the narrowest bandwidth is 1 kHz then the nearest any two signals can be and still be resolved is 1 kHz. This is because the analyzer traces out its own IF bandpass shape as it sweeps through a CW signal.

Since the resolution of the analyzer is limited by bandwidth, it seems that by reducing the IF bandwidth indefinitely, infinite resolution will be achieved. The fallacy here is that the usable IF bandwidth is limited by the stability (residual FM) of the analyzer. If the internal frequency deviation of the analyzer is 1 kHz, then the narrowest bandwidth that can be used to distinguish a single input signal is 1 kHz. Any narrower IF filter will result in more than one response or an intermittent response for a single input frequency as shown in Figure 1.19. A practical limitation exists on the IF bandwidth, as well, since narrow filters have long time constants and would require excessive scan time.

![Image](image2.png)

Figure 1.19 Jitter on a signal which is greater than the IF bandwidth.
The resolution of a spectrum analyzer is determined by its IF bandwidth. The IF bandwidth is usually the 3 dB bandwidth of the IF filter. The ratio of the 60 dB bandwidth (in Hz) to the 3 dB bandwidth (in Hz) is known as the shape factor of the filter. The smaller the shape factor, the greater is the analyzer’s capability to resolve closely spaced signals of unequal amplitude. If the shape factor of a filter is 15:1, then two signals whose amplitude’s differ by 60 dB must differ in frequency by 7.5 times the IF bandwidth before they can be distinguished separately. Otherwise, they will appear as one signal on the spectrum analyzer display. Figure 1.20 shows the bandwidth and shape factor of a typical Gaussian filter.

![Figure 1.20 Typical Gaussian filter. Signals of equal amplitudes can just be resolved when they are separated by the 3 dB bandwidth. Unequal signals can be resolved if they are separated by greater than half the bandwidth at the amplitude difference between them.](image)

There is a practical limitation on shape factor. The number of poles used in the IF filters will normally determine the shape factor of a synchronously tuned filter. Synchronously tuned (or Gaussian) filters are normally used because of their phase linearity. Shape factor could be improved through the use of stagger-tuned (or square topped) filters. However, such filters have phase discontinuities at their band edges, and, therefore, a ringing is produced when signals are rapidly swept through them as in a spectrum analyzer.

Sometimes IF filter shape factor is specified as the ratio of the 60 dB bandwidth to the 6 dB bandwidth, or the ratio of the 40 dB bandwidth to the 3 dB bandwidth. This can cause difficulty when comparing filters. For example, a 20:1 shape factor measured 60 dB/3 dB is roughly equivalent to a 10:1 shape factor measured 60 dB/6 dB. Even though the shape factor is smaller when specified as the ratio of 60 dB/6 dB, the resolving capability is the same. Therefore, the shape factor is useful as a means of determining filter sharpness only when the dB bandwidths used to determine shape factor are the same for the filters being compared.

The ability of a spectrum analyzer to resolve closely spaced signals of unequal amplitude is not a function of the IF filter shape factor only. Noise sidebands can also reduce the resolution. They appear above the skirt of the IF filter and reduce the offband rejection of the filter. This limits the resolution when measuring signals of unequal amplitude. Noise sidebands can be seen in Figure 1.21.
Absolute Amplitude Calibration

When a spectrum analyzer can make both absolute and relative power level measurements, it is said to be absolute amplitude calibrated. To be absolute amplitude calibrated, the analyzer must satisfy these requirements:

1. The input attenuator must be flat to maintain the overall frequency response of the system.
2. The input mixer must be flat or gain compensated over the frequency ranges of the input and LO.
3. The IF attenuator must be accurate for proper amplitude display.
4. The log/linear amplifier must be extremely accurate.
5. The sweep times must be slow enough to allow the IF and video filters to respond fully, or an uncalibrated situation will result.
6. Uncalibrated situations should be indicated by an uncal warning light, or avoided by automatic adjustment of the sweep time for any setting of the video or IF bandwidth or frequency sweep width (See Figure 1.22).
7. Must indicate the absolute signal level represented by some point on the CRT for any control settings, and an amplitude internal reference must be supplied.

Figure 1.22 shows the effects of scanning too fast. When the scan time gets too fast for amplitude calibration, the displayed amplitude decreases and the apparent bandwidth increases. Consequently, frequency resolution gets worse.
Sensitivity

Sensitivity is a measure of the analyzer's ability to detect small signals. The maximum sensitivity of an analyzer is limited by its internally generated noise. This noise is basically of two types: thermal (or Johnson) and nonthermal noise. Thermal noise power can be expressed as:

$$P_N = kTB$$

where:
- $P_N$ = Noise power in watts
- $k$ = Boltzmann's Constant ($1.38 \times 10^{-23}$ joule/°K)
- $T$ = absolute temperature, °K
- $B$ = bandwidth of system in hertz

As seen from this equation, the noise level is directly proportional to bandwidth. Therefore, a decade decrease in bandwidth results in a 10 dB decrease in noise level and consequently 10 dB better sensitivity.

Nonthermal noise accounts for all noise produced within the analyzer that is not temperature dependent. Spurious emissions due to nonlinearities of active elements, impedance mismatch, etc. are sources of nonthermal noise. A figure of merit, or noise figure, is usually assigned to this nonthermal noise which when added to the thermal noise gives the total noise of the analyzer system. This system noise which is measured on the CRT, determines the maximum sensitivity of the spectrum analyzer. Because noise level changes with bandwidth, it is important, when comparing the sensitivity of two analyzers, to compare sensitivity specifications for equal bandwidths.

A spectrum analyzer sweeps over a wide frequency range, but is really a narrow band instrument. All of the signals that appear in the frequency range of the analyzer are converted to a single IF frequency which must pass through an IF filter; the detector sees only this noise at any time. Therefore, the noise displayed on the analyzer is only that which is contained in the IF passband. When measuring discrete signals, maximum sensitivity is obtained by using the narrowest IF bandwidth.¹

Video Filtering

Measuring small signals can be difficult when they are approximately the same amplitude as the average internal noise level of the analyzer. To facilitate the measurement, it is best to use some degree of video filtering which is usually adjustable from the front panel of the analyzer. A video filter is a post-detection low pass filter which averages the internal noise of the analyzer. When the noise is averaged, the input signal is easily seen. The effects of video filtering are shown in Figure 1.23.

![Figure 1.23](image_url)

Figure 1.23 How video filter averages noise (right photo) for a better signal-to-noise ratio. No video filtering is used in the left photo.

¹This is not true, however, for impulse signals such as phase coherent noise. The widest bandwidth gives maximum sensitivity for impulse signals. When measuring random signals such as random or white noise, sensitivity is independent of bandwidth because random input noise varies with bandwidth the same as internally generated noise. See AN 1504.
Defining Spectrum Analyzer Sensitivity

Specifying sensitivity on a spectrum analyzer is somewhat arbitrary. One way of specifying sensitivity is to define it as the signal level when:

\[
\text{signal power} = \text{average noise power}
\]

This expression can be rewritten as:

\[
\frac{S + N}{N} = 2
\]

Where:

\[
S = \text{signal power}
\]

\[
N = \text{average noise power}
\]

The analyzer always measures signal plus noise. Therefore, when the input signal is equal to the internal noise level, the signal will appear 3 dB above the noise as in Figure 1.24. When the signal power is added to the average noise power, the power level on the CRT is doubled (increased by 3 dB) because the signal power = average noise power. This is the definition of sensitivity used in describing HP spectrum analyzers. Since a 3 dB difference between the signal level and the average noise level is discernible, it is possible to relate this definition to minimum discernible signal.

![Figure 1.24](image)

Figure 1.24 When signal power equals average noise power, the signal will appear 3 dB above the average noise level.

Input Signal Level

Figure 1.25 illustrates a typical range of signal levels that can be applied to the input of a spectrum analyzer with no input attenuation, and the analyzer's reaction to these signal levels.
Noise figure = 29 dBs

Figure 1.25 Typical spectrum analyzer display range.

The maximum input level to the spectrum analyzer is the damage level or burn-out level of the input circuit. This is typically +13 dBm for the input mixer and +30 dBm for the input attenuator.

Before reaching the damage level of the analyzer, the analyzer will begin to gain compress the input signal. This gain compression is not considered serious until it reaches 1 dB. The maximum input signal level which will always result in less than 1 dB gain compression is called the linear input level. Above 1 dB gain compression the analyzer is considered to be operating nonlinearly because the signal amplitude displayed on the CRT is not an accurate measure of the input signal level.

Whenever a signal is applied to the input of the analyzer, distortion products are produced within the analyzer itself. These distortion products are usually produced by the non-linear behavior of the input mixer. They are typically 70 dB below the input signal level for signal levels not exceeding -40 dBm at the input of the first mixer. To accommodate larger input signal levels, an attenuator is placed in the input circuit before the first mixer. The largest input signal that can be applied, at each setting of the input attenuator, while maintaining the internally generated distortion products below a certain level, is called the optimum input level of the analyzer. For example, a -20 dBm optimum level setting means that all analyzer distortion products are below -90 dBm on the CRT, i.e. down 70 dB. The signal is attenuated 20 dB before the first mixer because the input to the mixer must not exceed -40 dBm, or the analyzer distortion products may exceed the specified 70 dB range. This 70 dB distortion-free range is called the spurious-free dynamic range of the analyzer. The display dynamic range is defined as the ratio of the largest signal to the smallest signal that can be displayed simultaneously with no analyzer distortion products present.

Dynamic range requires several things, then. The display range must be adequate, no spurious or unidentified response can occur, and the sensitivity must be sufficient to eliminate noise from the displayed amplitude range.
The maximum dynamic range for a spectrum analyzer can be easily determined from its specifications. First check the distortion spec. For example, this might be “all spurious products down 70 dB for −40 dBm at the input mixer.” Then, determine that adequate sensitivity exists. For example, 70 dB down from −40 dBm is −110 dBm. This is the level we must be able to detect, and the bandwidth required for this sensitivity must not be too narrow or it will be useless. Last, the display range must be adequate.

Notice that the spurious-free measurement range can be extended by reducing the level at the input mixer. For every 10 dB the signal level is reduced, the spurious products will go down at least 20 dB (a net improvement of 10 dB). The only limitation, then, is sensitivity.

To ensure a maximum dynamic range on the CRT display, check to see that the following requirements are satisfied.

1. The largest input signal does not exceed the optimum input level of the analyzer (typically −40 dBm with 0 dB input attenuation).
2. The peak of the largest input signal rests at the top of the CRT display (reference level).

Frequency Response

The frequency response of an analyzer is the amplitude linearity of the analyzer over its frequency range. If a spectrum analyzer is to display equal amplitudes for input signals of equal amplitude, independent of frequency, then the conversion (power) loss of the input mixer must not depend on frequency. If the voltage from the LO is too large compared to the input signal voltage then the conversion loss of the input mixer is frequency dependent and the frequency response of the system is nonlinear. For accurate amplitude measurements, a spectrum analyzer should be as flat as possible over its frequency range.

Flatness is usually the limiting factor in amplitude accuracy since it’s extremely difficult to calibrate out. And, since the primary function of the spectrum analyzer is to compare signal levels at different frequencies, a lack of flatness can seriously limit its usefulness.
Random noise consists of frequency components which, as the name implies, are random in amplitude and phase. Measurement of random noise, then, depends on some statistical basis. Normally, the process consists of integration or averaging and taking the rms value of this averaged result.

Since the spectral components are random in phase, doubling the measurement bandwidth will not double the measured voltage, but instead doubles the measured power. Therefore, random noise is usually specified as some noise power per unit bandwidth, e.g., dBm/Hz. The normalizing bandwidth is called the random noise bandwidth or noise power bandwidth. For HP analyzers, this is approximately 1.25 times the 3 dB bandwidth.

The definition of the noise power bandwidth is similar to the impulse bandwidth. It is the ideal rectangular filter bandwidth with the same power response as the actual instrument IF filter.

The best way to measure the noise power bandwidth is by the method previously described for the impulse bandwidth, except that all vertical coordinates should be squared to give a power display. This would necessitate graphing the curve by hand to get the desired results or doing a numerical integration.

A simpler method which gives adequate results is to measure the 3 dB bandwidth and multiply by 1.25. To measure the 3 dB bandwidth, use the following procedure:

1. Connect a signal generator to the spectrum analyzer input, and connect the auxiliary output of the generator to a frequency counter.
2. Tune to the signal on the spectrum analyzer, and display the signal generator output in the linear mode.

Figure 8. The noise power bandwidth is defined by an ideal filter with identical power response.
3. Adjust the output of the signal generator for a deflection of 7.1 divisions at the peak of the display.

4. Center the display on the CRT, and switch to zero scan.

5. Carefully tune the signal generator until the vertical deflection is 5 divisions, and record the frequency on the counter.

6. Carefully tune the signal generator through the peak response until the deflection is again 5 divisions. Read and record the counter frequency.

7. Subtract the frequencies in steps 5 and 6 to get the 3 dB bandwidth.

Nominal values for the 3-dB-bandwidth are engraved on the bandwidth knob. This is accurate to ±5% for the 10 kHz bandwidth only. For this reason, the 10 kHz bandwidth can be used without further calibration in a number of cases.

DETECTOR CHARACTERISTICS

Some consideration of detector characteristics is now in order. We noted in our previous discussion that the spectrum analyzer uses an envelope detector. When used with random noise, this creates a reading which is lower than the true rms value of the average noise. This difference is 12.8% or 1.05 dB. (See Appendix A.)

LOGARITHMIC SHAPING

Since log shaping tends to amplify noise peaks less than the rest of the noise signal, the detected signal is smaller than its true rms value. This correction for the log display mode combined with the detector characteristics gives a total correction of 2.5 dB, which should be added to any random noise measured in the log display mode.

AVERAGING

A further consideration is the integration or averaging of the random noise. In the spectrum analyzer, this is accomplished with the video filter. A video bandwidth much narrower than the IF bandwidth should be used. A video filter setting about 100 times narrower than the IF bandwidth will give effective averaging. (See Figure 10.)

The video filter in the spectrum analyzer can be modified for better averaging when narrow IF bandwidths are used. When this is done, the "display uncal" light will not function properly. The proper scan time can be calculated, though, from the following formula:

\[
\frac{BW_{video} \cdot BW_{IF}}{Scan \, Width \, per \, Division} \geq 0.35 \times \frac{Scan \, Time \, per \, Division}{Scan \, Width \, per \, Division}
\]

Note: This is an empirical relationship which is useful for most cases, but it will not provide an exact answer.
CHAPTER 3

CARRIER-TO-NOISE RATIO

Measurement of carrier-to-noise ratio is quite similar to measurement of random noise power density. The measurement basically consists of:

1. Measure the carrier or desired signal level.
2. Measure the random noise and apply corrections.
3. Normalize to the desired bandwidth.

For example, it is desired to measure the video carrier-to-noise ratio of a composite TV signal. The effective bandwidth of the received signal, then, is 6 MHz. So we will normalize to this bandwidth to get the C/N ratio which will be seen by the TV receiver.

So, if the carrier appears at $-25$ dBm, and the noise is measured as $-95$ dBm in a 10 kHz bandwidth, we can make the following calculations:

1. Add 2.5 dB to the noise level.
2. Normalize to 6 MHz bandwidth.

\[
N(6\,\text{MHz}) = N(10\,\text{kHz}) + 2.5 + 20 \log_{10} \left( \frac{6\,\text{MHz}}{10\,\text{kHz}} \right)
\]

\[
N = -92.5 \, \text{dBm/10 kHz} + 27 \, \text{dB} = -65.5 \, \text{dBm/6 MHz}
\]

Then, the carrier-to-noise ratio is $-25$ dBm to $-65.5$ dBm, or 40.5 dB. This method can be applied to any input signal if the bandwidth of the intended receiver is known. That is, if we want to know the signal-to-noise ratio seen by a 0.124 GHz crystal detector, we must normalize to a 12.4 GHz bandwidth, etc.

![Figure 13](image)

Figure 13. In the left photo, we measure the level of an FM broadcast station as received at the spectrum analyzer at $-38$ dBm. In the right photo, we add video filtering to average the noise (the modulation looks like noise, so the carrier level must be measured with the video filter OFF) at $-100$ dBm in a 10 kHz bandwidth. Applying the corrections and normalizing to a 200 kHz transmission bandwidth, we get about a 47 dB signal-to-noise ratio for an FM receiver.
Convert dBm to dB_{µ}V/MHz using the following corrections. (Nominal figures only. Use measured data for greater accuracy.)

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Correction (Add to dBm Reading)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 kHz</td>
<td>116 dB</td>
</tr>
<tr>
<td>100 kHz</td>
<td>124 dB</td>
</tr>
<tr>
<td>30 kHz</td>
<td>134 dB</td>
</tr>
<tr>
<td>10 kHz</td>
<td>144 dB</td>
</tr>
<tr>
<td>3 kHz</td>
<td>154 dB</td>
</tr>
<tr>
<td>1 kHz</td>
<td>164 dB</td>
</tr>
<tr>
<td>300 Hz</td>
<td>174 dB</td>
</tr>
<tr>
<td>100 Hz</td>
<td>184 dB</td>
</tr>
</tbody>
</table>

Correct for random noise.

Convert dBm measurements to dBm/Hz using the following corrections. (Nominal figures only. Use measured data for greater accuracy.)

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Correction (Subtract from dBm Reading)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Hz</td>
<td>8.3 dB</td>
</tr>
<tr>
<td>30 Hz</td>
<td>13.3 dB</td>
</tr>
<tr>
<td>100 Hz</td>
<td>18.3 dB</td>
</tr>
<tr>
<td>300 Hz</td>
<td>23.3 dB</td>
</tr>
<tr>
<td>1 kHz</td>
<td>28.3 dB</td>
</tr>
<tr>
<td>3 kHz</td>
<td>33.3 dB</td>
</tr>
<tr>
<td>10 kHz</td>
<td>38.3 dB</td>
</tr>
<tr>
<td>30 kHz</td>
<td>43.3 dB</td>
</tr>
<tr>
<td>100 kHz</td>
<td>48.3 dB</td>
</tr>
<tr>
<td>300 kHz</td>
<td>53.3 dB</td>
</tr>
</tbody>
</table>