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Spectrum Analysis

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The Spectrum analyser is a measuring instrument used to display many different kinds of signals. To facilitate this overview of spectrum analyzers it is split into four Sections.

Section 1: Introduction

Covers the basics of signal analysis and contrasts the oscilloscope time domain display with the spectrum analyzer frequency domain display. Some basic spectrum analyzer measurements are also reviewed

Section 2: How the spectrum analyzer works and the important controls

An explanation of the basic spectrum analyzer block diagram is given and includes a description of the important controls to understand the significance of the main operator controls in order to reduce or prevent mistakes.

Section 3: Spectrum Analyzer important specification points

This section covers the main specification points that need to be considered by a user in order to select the correct instrument for a particular measurement. Sources of measurement uncertainty and errors are also covered in this section.

Section 4: Spectrum Analyzer measurements

Discusses some of the common measurements that are made using a spectrum analyzer and the measurements reviewed include harmonic and intermodulation measurements as well as the measurement of modulated and pulsed signals.

Introduction

1.1 Signal Analysis using a Spectrum Analyzer

Before making any measurements using a spectrum analyzer the user should prepare the spectrum analyser for use by carrying out any pre-calibration procedure (Auto Cal). Consider the type of input signal that is to applied to the spectrum analyzer and to avoid overloading or damaging the input circuitry. And, finally to interpret and understand the displayed results.

A three-dimensional graph, with three mutually perpendicular axes calibrated in terms of Amplitude, Frequency and Time is shown in figure 1. The signal illustrated consists of a sine wave with a second harmonic. The object of the signal analysis is to display the components of such a signal.

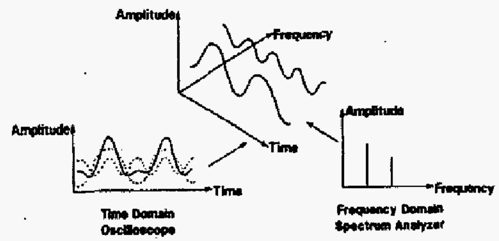


Figure 1 Measurement domains

1.2 The Oscilloscope display

The Oscilloscope display of signal amplitude versus time is shown in figure 1 and is known as a Time Domain display. Only a single waveform is seen when the signal in the illustration is viewed. This is the waveform with the solid line, but there are in fact at least two sinusoids present as shown by the dotted lines. The oscilloscope does not separate out the individual frequency components.

1.3 The Spectrum analyser display

The Spectrum Analyzer display of amplitude versus frequency is also shown in figure 1 and known as a Frequency Domain display. In this case it reveals the two separate frequency components of the applied signal in this case the fundamental and the harmonic. The fundamental frequency is represented on the display by the first single vertical line. A shorter vertical line that can be clearly seen to the right at of the fundamental represents the second harmonic.

1.4 Amplitude Modulation – Oscilloscope

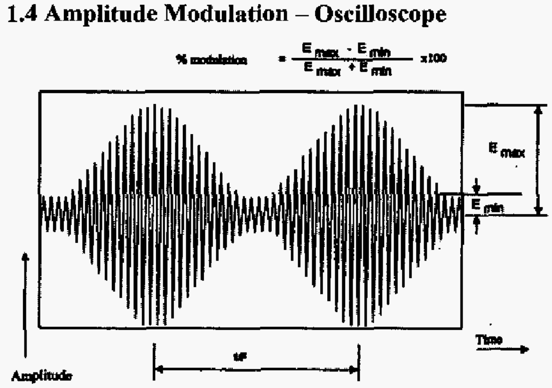


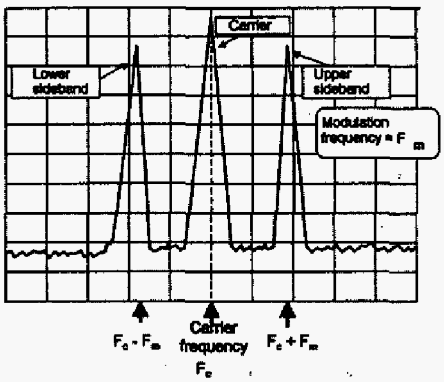
Figure 2 Oscilloscope display

The first analysis example is amplitude modulation.

Fig 2 shows the familiar oscilloscope display of an amplitude modulated signal. The high frequency carrier has a low frequency signal superimposed upon it. The modulation envelope can be seen in the diagram. It is possible to measure the modulation frequency (fmod) and modulation depth from the display but it is difficult to obtain any more information over and above modulation depth and modulation frequency. Consequently the Oscilloscope is not widely used to analyse RF and microwave signals because of the limitations described.

1.5 Amplitude Modulation - Spectrum Analyzer

Fig 3 shows the same amplitude modulated signal is shown as displayed by a Spectrum Analyzer. The carrier, sidebands and noise can all be seen. Many other Spectrum Analyzer measurements can also be made on modulated signals as will be seen later in section four.



Note that the analysis of the amplitude modulated waveform clearly demonstrates the superior analytical powers of the spectrum analyzer.

The Spectrum Analyzer display of amplitude against frequency is more useful because the harmonics, spurious signals, sidebands, and noise can be observed. A further advantage of a Spectrum Analyzer is its high sensitivity; it can measure very low-level signals down to less than 0.1 μV because it is selective rather than broadband. It can also display low-level signals at the same time as high level signals because logarithmic amplitude scales are used. An oscilloscope, which generally has a linear vertical scale, does not have this capability.

2. HOW THE SPECTRUM ANALYZER WORKS

2.1 Basic Spectrum Analyzer Block Diagram

A greatly simplified block diagram of a basic swept-tuned heterodyne spectrum analyzer is shown in Fig 4. In practice the implementation is considerably more complex since there are many more frequency conversion stages.

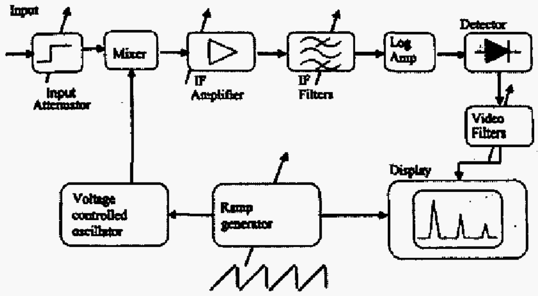


Fig 4 Block diagram of a basic spectrum analyser

The input signal is applied to the input mixer through an input attenuator, which adjusts the sensitivity and optimises the signal level at the mixer to prevent overload or distortion. An input low-pass filter is also included at this stage to avoid intermediate frequency feed-through and to reject the upper image frequency.

The mixer converts the input signal to a fixed intermediate frequency (IF), at which point a range of gaussian band-pass filters or digital filters are switched in to change the selectivity or resolution. To give a vertical scale, calibrated in dB, the signal at the IF stage is passed through a logarithmic amplifier. The signal is then applied to a detector and passes through selected video filters before being applied to the vertical scale of the display.

The horizontal input of the Spectrum Analyzer display (frequency) is achieved by using a variable amplitude ramp generator, or saw-tooth generator that is also applied to a voltage-controlled oscillator that feeds the mixer.

As the ramp voltage is increased, the receiver tunes to a progressively higher frequency and the trace on the display moves from left to right. In this way an amplitude against frequency display is shown on the spectrum analyzer.

2.2 Microwave Spectrum Analyzer Harmonic Mixer

The basic block diagram of figure 4 is generally only used for Spectrum Analyzers covering up to around 4 GHz. For a 4 GHz instrument the first local oscillator would have to cover from approximately 5 to 9 GHz but the local oscillator for a 26.5 GHz Spectrum Analyzer would have to cover approximately 30 to 56.5 GHz. This is a major engineering challenge especially as the oscillator needs to be at a high level and have good voltage frequency linearity, low noise, low-level spurious signals, and an output level, which is adequately independent of frequency. Furthermore, the design has to be implemented at an economical price.

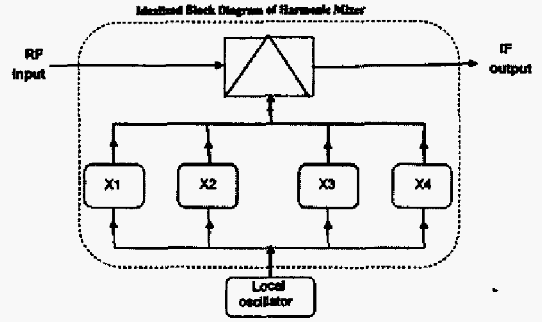
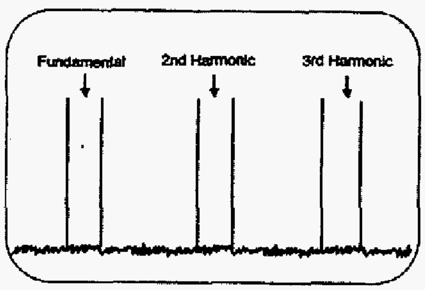


Figure 5 Microwave Spectrum Analyzer Harmonic Mixer

An alternative more practical approach, used in most microwave spectrum analyzers, is to use a harmonic mixer. This concept is shown in figure 5. The fundamental frequency of the local oscillator is used for the lower frequencies and higher harmonics are used to cover the higher frequencies. A separate harmonic multiplier is not actually used in practice; the mixer is designed to mix with harmonics of the local oscillator.

2.3 The Problem of Multiple Responses

The system described in the figure 5 will operate to high microwave frequencies but there is a major limitation. The type of analyzer shown in the previous diagram has a fundamental flaw; one signal at the input generates multiple responses such that one signal has many other signals associated with it, which is obviously incorrect.



Multiple responses are shown for a single input frequency

Figure 6 Multiple Responses

Not only does this one signal mix with each of the harmonics of the local oscillator to produce multiple responses but additional responses are also generated at the image frequencies. Some of the earlier microwave spectrum analyzers used this technique but the limitations are so severe that it is very rarely, if ever, used today.

2.4 Microwave Spectrum Analyzer with a Tracking Preselector.

The diagram shows figure 7 shows how adding a band-pass filter at the input of the spectrum analyzer can refine the harmonic mixer technique.

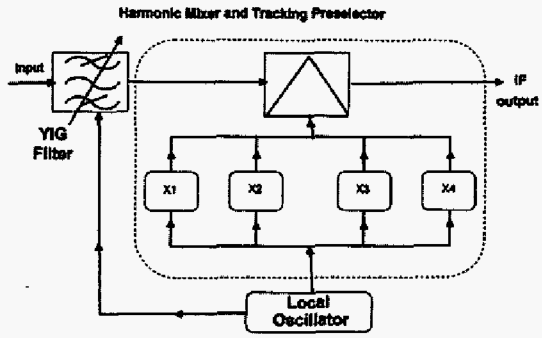
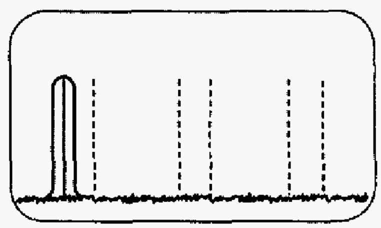


Figure 7 Microwave Spectrum Analyzer with a Tracking Preselector

This is known as a tracking preselector and the microwave spectrum analyzer uses a YIG (Yttrium Iron Garnet) swept band-pass filter for the tracking filter and is referred to as a preselector.

2.5 Effect of the Preselector

The effect of using a preselector is shown in figure 8 the swept band-pass filter selects only the wanted signal so that all the unwanted signals are rejected to make the measurement is valid.
A quality instrument has a preselector with high out of band rejection and the ability to track closely the input tuned frequency.



Preselector selects the wanted signal and eliminates other unwanted responses

Figure 8 effect of the preselector

Certain earlier spectrum analysers required the preselector to be "peaked" before a measurement is made to ensure that the preselector is tuned correctly. this is not necessary with the latest and more complex instruments.

2.6 Microwave Spectrum Analyzer Block Diagram

Modern microwave spectrum analyzers are usually a combination of a fundamental frequency analyzer and a harmonic analyzer. The fundamental frequency method of operation is used at the lower frequencies but at the higher frequencies the multiplication technique, with a preselector, is used.

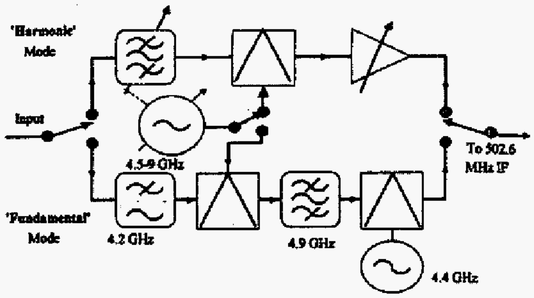


Figure 9 100Hz to 4.2GHz Spectrum Analyzer

Figure 9 shows the architecture of a typical 100 Hz to 4.2 GHz Spectrum Analyzer.

In the fundamental mode the input signal is mixed with a local oscillator covering from 4.5 to 9 GHz. The intermediate frequency is then down-converted to a 502.6 MHz by a fixed 4.4 GHz local oscillator.

To cover the higher frequencies the change over switch operates to bring the swept harmonic mixer into play and the 4.5 to 9 GHz local oscillator is used to down convert the signal to the intermediate frequency of 502.6 MHz.

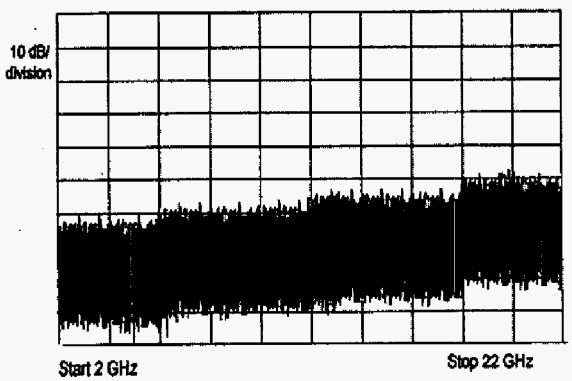


Figure 9a Noise floor display

Microwave spectrum analyzers that use a harmonic mixer have a characteristic "stepped" noise floor as illustrated in the image in figure 9a. The rise in the noise occurs at the frequency break points where the higher harmonics of the local oscillator are used. From figure 9a it can be seen that the instrument is approximately 10 dB or more less sensitive at 22 GHz compared to the sensitivity at 2 GHz.

Spectrum Analyzer with Tracking Generator

Spectrum analyzers are made even more useful by the addition of a tracking generator. A tracking generator is a swept signal whose instantaneous frequency is always the same as the frequency to which the spectrum analyzer is tuned. Many Spectrum Analyzers incorporate tracking generators to increase the applications of the instrument to include wide dynamic range swept frequency response measurements. The use of a tracking generator means that it is not always necessary to have an external signal source when making some measurements

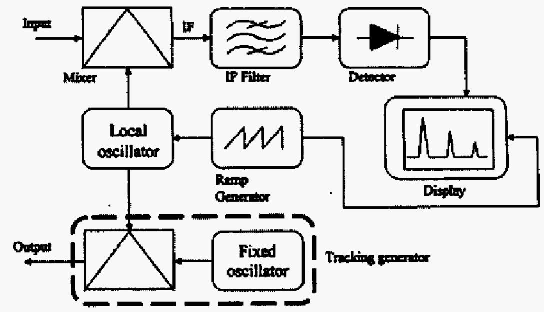


Figure 10 Spectrum Analyzer with Tracking Generator

Figure 10 shows how a tracking generator facility can be added to a spectrum analyzer basic block diagram. The output signal synchronously tracks the input tuned frequency of the instrument with the advantage that the dynamic range is better than would be experienced if a broadband detector were used. A dynamic range of over 110 dB can be achieved with a spectrum analyzer using a tracking generator.

3 SPECTRUM ANALYZER IMPORTANT SPECIFICATION POINTS

Spectrum Analyzers are complex items of test equipment and they can easily be misused. At worst, a wrong result can be obtained; at best, the operator may not be getting the best performance from the instrument.

The latest spectrum analyzers have a many automatic functions, but incorrect results are still possible. When using a spectrum analyzer it is important that the operator understands the function of the basic controls of the instrument in order to be able to use it effectively and to avoid incorrect results.

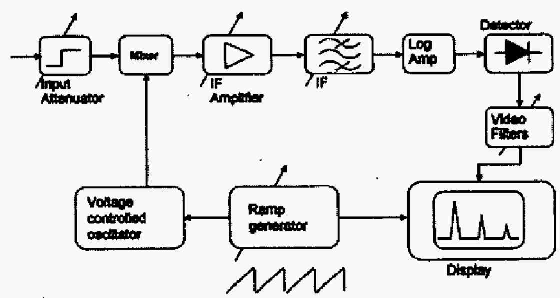


Figure 11 Spectrum Analyzer Controls

The block diagram fig 11 is repeated here to show how the controls change the instrument functions. There are four main controls on a spectrum analyzer that are:

RF Attenuator and the IF gain
Sweep speed
Resolution Bandwidth
Video Bandwidth

The reason for highlighting the four controls listed above is that they are probably the most commonly misunderstood and abused. Incorrect settings of these controls can cause serious measurement errors, so it is important to realise their significance. The frequency and amplitude are also important controls, but they are more easily understood.

3.1 Input Attenuator and IF Gain controls

The block diagram Figure 12 shows how the sensitivity of a Spectrum Analyzer can be changed.

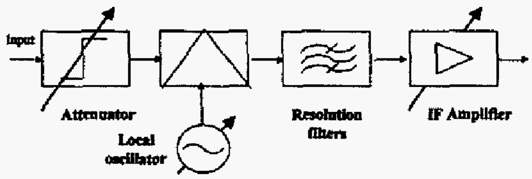


Figure 12 Input attenuator and IF Gain Controls

To increase the sensitivity the operator has two options, either the input attenuation can be reduced or the IF gain can be increased, but if the wrong option is chosen then the measurement may become invalid. It is essential to arrange to have the correct input level to the mixer to ensure correct operation.

If the input attenuation is reduced too much then the input mixer could be overloaded with the result that distortion products are generated within the spectrum analyzer.

If the IF gain is increased then the risk of overloading the input mixer is removed but the noise level could rise to an unacceptable level with the result that some signals of interest could be masked in the noise. A further problem that could arise is the introduction of distortion or intermodulation in the IF stages.

Many Spectrum Analyzers automatically select the optimum RF attenuation ,and IF Gain settings once the reference level at top of display has been selected. Under certain circumstances however it may be an advantage to over-ride the automatic selection to select a mode of operation with either lower noise or lower intermodulation.

3.2 Sweep Speed Control

A spectrum analyzer must be swept sufficiently slowly to allow the signal level in the narrow resolution filters to settle. Figure 13 shows two different responses and the effects produced when sweeping too fast are clearly shown. Firstly the amplitude of the displayed signal is reduced because the filter does not have sufficient timw to respond to the signal and secondly the maximum is moved to the right due to the delay in the response. This effect is sometimes referred to as "ringing".

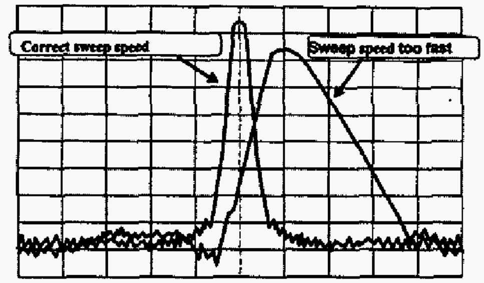


Figure 13 shows the effect of sweeping too fast

Modern instruments incorporate software control to ensure that the correct sweep speed is achieved. But under certain conditions, where high resolution is required, the sweep speed may need to be as slow as 100 seconds and then some form of digital storage is essential to ensure a visible display is achieved.

Manual adjustment of the sweep speed is provided on some instruments to over-ride the automatic selection. Sweeping faster than the optimum value can be useful to carry out a rapid un-calibrated search for spurious signals or to study the effects of rapidly changing transient signals. However, the operator must be aware of the display errors that can be caused. Sweeping slower than the optimum can be used for example when sweeping a filter with very steep skirts when using the Tracking Generator.

3.3 Resolution Bandwidth

Resolution bandwidth is the bandwidth of the IF filter which determines the selectivity of a Spectrum Analyzer. It is basically the ability of the analyzer to separate closely spaced signals.
A wide resolution bandwidth is required for wide sweeps whilst a narrow filter is used for narrow sweeps. Figure 14 shows three superimposed displays of an amplitude modulated signal, they illustrate why it is necessary to be able to change resolution bandwidth.

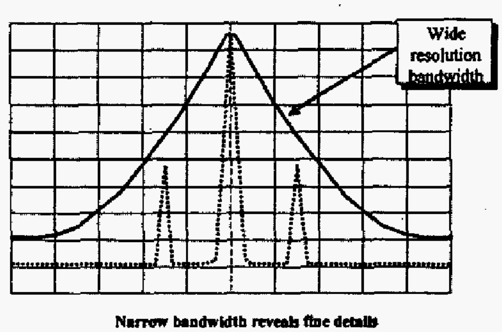


Figure 14 Resolution Bandwidth

The wide resolution bandwidth line is effectively a plot of the resolution filter of the spectrum analyzer; the frequency response of the instrument's filter is swept by the local oscillator and the side frequencies are not seen in this situation.

However, by using progressively narrower resolution bandwidths, the instrument can resolve the side frequencies. However, the penalty for high resolution is a slower sweep speed. Wide filters are thus used when the display needs to be updated rapidly.

3.4 Shape Factor of the Resolution Filter

Figure 15 shows the two types of filters in use as resolution filters in spectrum analysers and they have defined filter shapes. The shape factor is defined as the ratio of the 60db Bandwidth to the 3 db Bandwidth. The first type of filter is the Gaussian filter that has a shape factor of between 15:1 and 12:1 and the second type of resolution filter is a digital filter that has a shape factor of 5:1. The digital filter is particularly useful where a narrow resolution filter is needed say from 1Hz to 30Hz.

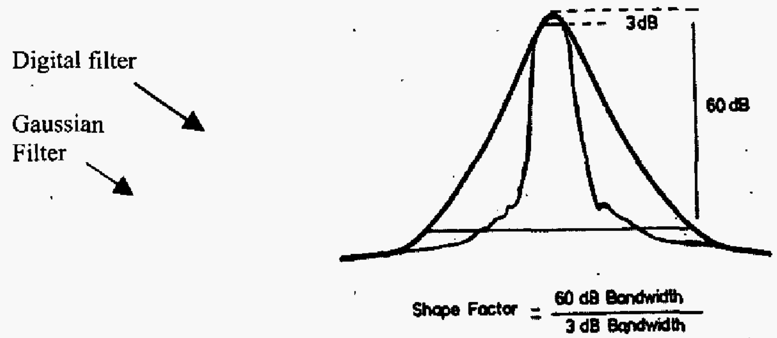


Figure 15 Resolution bandwidth filter shape factor

This means that the minimum resolution bandwidth of a spectrum analyzer is a key measure of the ability to measure low-level signals adjacent to high-level signals.

A measurement that dramatically illustrates the importance of minimum resolution bandwidth is the determination of low-level signal such as a 50 Hz side frequency (hum sidebands) close to a large signal.

For example in Figure 16 the upper trace is using a 10 Hz resolution bandwidth, and only the one signal is discernible. The lower trace, which uses a 3 Hz resolution bandwidth, clearly shows the low-level signals.

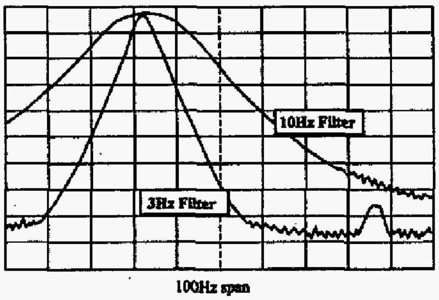


Figure 16 Resolution Bandwidth change

If the sidebands are 70 dB down then a 10 Hz resolution bandwidth filter with a shape factor of 11:1 could not resolve the side frequencies because if the 3 dB bandwidth is 10 Hz then the 60 dB bandwidth is 110 Hz. A signal 60 dB down 55 Hz away could just be discerned but a signal 70 dB down and 50 Hz away would not be resolved.

Using a 3 Hz filter with a shape factor of 11:1 a signal 16.5 Hz away can be resolved if it is less than 60 dB down, it follows that a signal 70 dB down and 50 Hz away can be measured.

Digital filters are now common in spectrum analyzer and they have a shape factor of 5:1 enabling close in signals to be resolved and measured

3.5 Video Bandwidth Controls

The previous section explained that Spectrum Analyzers are often used to measure very low-level signals that may be almost indiscernible from the system noise. Using a narrower resolution bandwidth filter will reduce the average displayed value of the noise. To make signals even easier to view it is often also necessary to smooth out the random fluctuation of noise so that a coherent signal can be more clearly viewed. The traditional way to smooth the noise is to use a low-pass video filter after the detector as shown. In figure 17

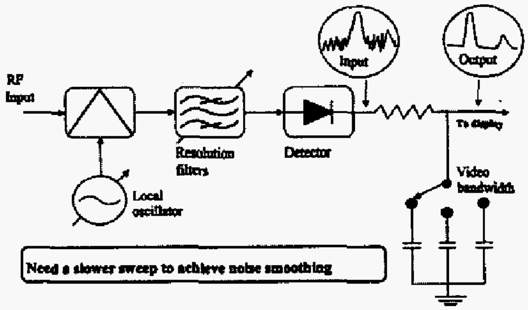


Fig 17 Video Bandwidths

In order to achieve the noise smoothing it is necessary to sweep more slowly because the time constant of the filter is reduced as the bandwidth of the filter is reduced. Modern instruments couple the video bandwidth controls to the sweep speed control so that the instrument automatically selects a slower sweep speed if the video bandwidth is reduced. Conversely, a lower frequency video bandwidth is automatically selected if the sweep speed is increased.

A useful general rule is to set the video bandwidth to be one-tenth off the resolution bandwidth being used.

3.5.1 Video Averaging

An alternative method of noise averaging that has become increasingly popular on software controlled instruments is to use multiple sweep video averaging. Successive sweeps are averaged so that the amplitudes of coherent signals are unchanged whilst the levels of varying noisy signals are averaged out.

The effect of using video averaging is to see the noise level slowly fall. Any low-level coherent signals that have been obscured by noise may become visible.

Clearly it is most important that an operator is aware of the difference between the video bandwidth controls and the resolution bandwidth controls and not to confuse their different functions.

Additional critical aspects of the performance of a spectrum analyzer are noise, dynamic range, accuracy and local oscillator phase noise

3.6 Measuring Low-level Signals -Noise

The problem when measuring low-level signals is that even a component such as passive resistor generates noise due to thermal effects.

The noise voltage is given by the equation:

$V^2 = 4\ KTBR$

where:

K = Boltzmann's constant (1.374 x 10-23 joule/°K)
T = Temperature in °K (absolute temperature)
B = Bandwidth of the system (Hz)
R = Resistor value (generally 50 Ω for most measurements).

This gives a value of V^2 of 8.927 x 10^{-10} V EMF and converting this to dBm gives a value off -174 dBm.

If a spectrum analyzer has a typical noise figure of 20 dB then with a 1 Hz resolution bandwidth, the lowest level signal that could be discerned would be 20 dB higher in amplitude than the noise of -174 dBm of a passive termination.

With a 1 Hz filter a spectrum analyzer with a 20 dB noise floor could thus theoretically measure -174 + 20 = -154 dBm.

An analyzer with the same noise figure but with a minimum resolution bandwidth of 3 Hz could discern a signal at -149 dBm and with a 1 kHz resolution bandwidth could only measure down to -119 dBm, 30 dB worse.

The use of a pre-amplifier at the input of a spectrum analyzer can assist to measure lower amplitude signals.

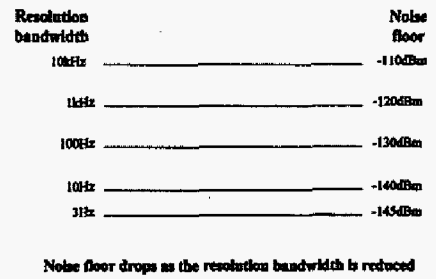


Figure 18 The noise floor drops as the resolution bandwidth is reduced

3.7 Dynamic range

3.7.1 Intermodulation and Distortion

A useful definition of the dynamic range is that it is the ratio of the largest to the smallest signals simultaneously present at the input of the spectrum analyzer that permits the measurement of the smaller signal. The uncertainty of the measurement needs to be taken into account. The dynamic range is quoted in dB.

So, how does the internally generated distortion and noise affect the measurement?

For a constant local oscillator level the mixer output is linearly related to the input signal level and for all practical purposes this is true provided that the input signal is more than 20dB below the local oscillator drive level.

The distortion is normally described by its order and is noted by its relationship to the signal frequency Therefore second harmonic distortion is known as second order and the third harmonic distortion as called the third order.

The input signal at the mixer determines the dynamic range. The level of signal we need for a particular measurement can be calculated using data from the manufacturers specification for the analyser and in some cases the manufacturers data sheets include graphs showing the information otherwise it can be drawn from the data.

A spectrum analyzer can introduce intermodulation and cause distortion on a measurement; certain measurements can not be made if the instrument itself generates excessive distortion.

We will consider the second order distortion first.

Suppose the data sheet gives the second harmonic distortion as 75dB down for a signal level of - 40dbm at the mixer. This means we can measure distortion down to 75dB. The value can be plotted on a graph of

Distortion (dBc) against the Mixer Input Level. Now if the signal level at the mixer changes to – 50dBm then the internal distortion and the measurement range changes from – 75dBc to – 85dBc. The two points are on a line whose slope is 1 so we can draw a line on the graph giving the second order performance for any level at the input to the mixer

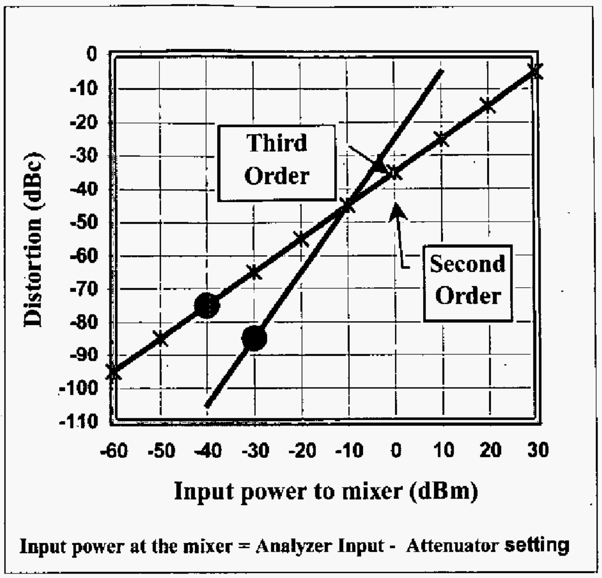


Fig 19 Dynamic range

Similarly we can now construct a line for the third order distortion. The manufacturers data sheet gives -85dBc for a level of -30dBm at the mixer input and this value is plotted on the graph. If the difference between the two values changes by 20dB the internal distortion is changed to -105dBc The two points are on a line of slope 2 giving the third order performance for any level at the input to the mixer.

3.7.2 Noise

There is a further effect on the dynamic range and that is the noise floor of the spectrum analyzer. The definition of the dynamic range is the ratio of the largest to the smallest signal that can be measured. So the noise level places a limit on the smaller signal. The dynamic range is relative to the noise and becomes the signal to noise ratio where the signal is the fundamental we require to measure.

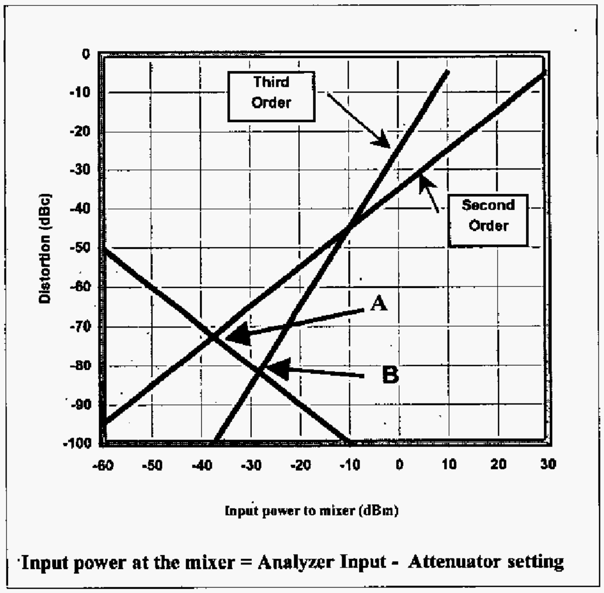


Figure 20 dynamic range versus distortion and noise

To plot the noise on a dynamic range chart we take the data from the manufacturers data sheet at that gives -110 dBm for a 10 kHz resolution bandwidth. If our signal level at the mixer is -40dBm it is 70 db above the average noise. Now for every dB we lose at the mixer input we loose 1dB of signal to noise ratio so the noise curve is a straight line having a slope of –1 and this can be drawn on the graph as in Figure 20.

Figure 20 shows two intercepts marked A and B. And A is the 2nd order maximum dynamic range and B is the 3rd order maximum range.
The best dynamic range for the second order distortion is therefore A= 72.5 dB and for the third order distortion it is B = 81.7dB. Practically, the intersection of the noise and distortion graphs are not sharply defined because the noise adds to the CW like distortion and reduces the dynamic range by a further 2dB.

The plot for other resolution bandwidths can be added the graph as required and by reducing the resolution bandwidth the dynamic range can be improved.

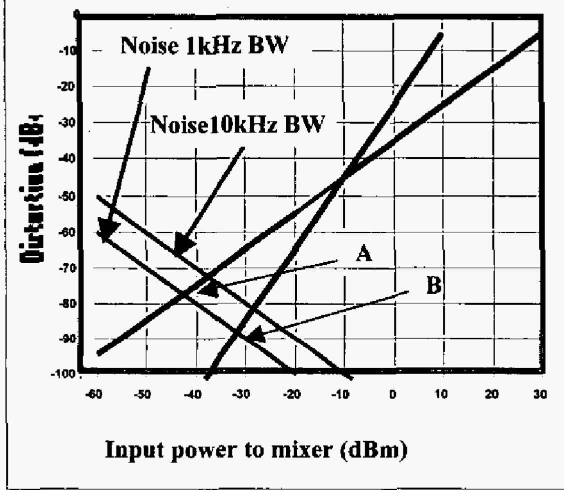


Figure 21. Reducing resolution bandwidth improves dynamic range

The two points A and B in figure 21 show the 2nd and 3rd dynamic range improvement by changing the resolution bandwidth from 10kHz to 1kHz.

Unfortunately there is not a one to one change between the lowered noise floor and the improvement in the dynamic range. And f.or the second order the change is one half of the change in the noise floor and for the third order distortion two-thirds the change in the noise floor.

3.7.3 Spectrum analyzer Local Oscillator phase noise

The final item affecting the dynamic range is the local oscillator phase noise on the spectrum analyser and this affects only the third order distortion measurements.

For example, if a two-tone third order distortion measurement was being made on an amplifier and the test tones were separated by 10kHz. The third order distortion components are also separated by 10kHz. Now, suppose we choose the resolution bandwidth of the spectrum analyser to be 1kHz allowing for a 10 dB decrease in the noise curve then the maximum dynamic range is approximately 88dB. But if the phase noise at a 10kHz offset is only -80dBc then this value becomes the limit of the dynamic range

3.7.4 Selecting the Optimum Conditions

The illustration combines the graphs given in the two previous illustrations. From this combined graph the optimum dynamic range can be determined. The signal-to-noise ratio improves as the input mixer level is increased.

An example illustrates the use of the graph.

To determine the optimum dynamic range available to measure third order intermodulation products the "1 kHz BW" line is followed, at -34 dBm mixer level the signal to noise ratio is almost 90 dB.

No further improvement is possible because as the mixer level is increased further the level of the third order intermodulation products increase. At a mixer level of -30 dBm, the dynamic range is reduced to 80 dB.

Figure 22

As well as the three key aspects highlighted above other points are covered in this section, sideband noise, residual responses, residual FM, and input overload are where experience shows that these areas are also frequently misunderstood

3.7.5 Sideband Noise

Three specification points affect the ability of a Spectrum Analyzer to measure low-level signals close to high level signals. Two of the points have already been described; they are minimum resolution bandwidth and resolution filter shape factor.

The third point is the sideband noise of the local oscillators in the instrument.

The illustration shows the sideband noise of the instrument's local oscillator superimposed on the resolution bandwidth response. Measurement of low-level signals close to a carrier can be impaired if sideband noise is too high.

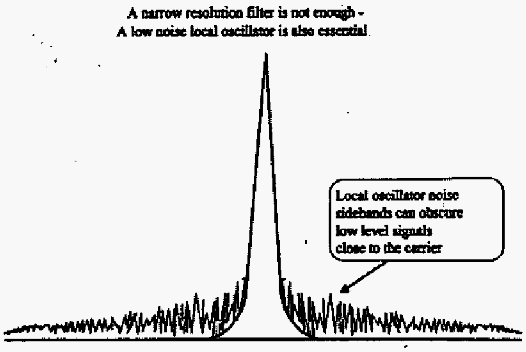


Figure 23 Local oscillator noise sidebands

3.7.6 Checking for Internal Distortion

Some Spectrum Analyzers have an "Intermodulation Identify" key see figure 23 to automate and simplify the self-test procedure. When the key is pressed additional input attenuation is introduced and the IF amplification is simultaneously increased by an equal amount. If signal levels seen on the display do not move then the measurement is valid. This is a useful, quick and effective way to determine a possible mixer overload situation.

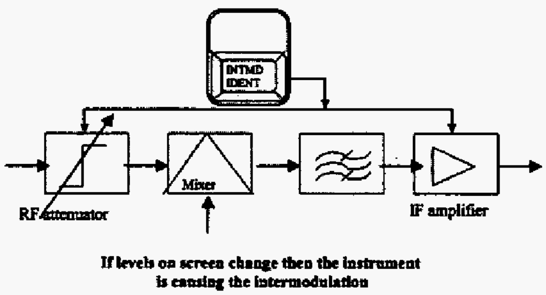


Figure 24 Intermodulation identify

If this feature is not available then a useful way to check for any internal overload is to introduce temporarily additional RF attenuation. If a further 10 dB of attenuation is introduced, for example, then all the signals on the screens should drop by 10 dB. If levels change by a different amount then this indicates that the spectrum analyzer is being overloaded.

3.8 Amplitude Accuracy

A good amplitude accuracy specification is essential for accurate and repeatable measurements, but there can still be considerable measurement uncertainty if the input match is poor.

3.9 Effect of Input VSWR

The Input match, generally expressed as VSWR, reflection coefficient or Return Loss, is a measure of the proportion of the signal incident at the input that is reflected back. Amplitude Measurement uncertainty deteriorates, as the match becomes worse, the effect is aggravated more if the source match is poor.

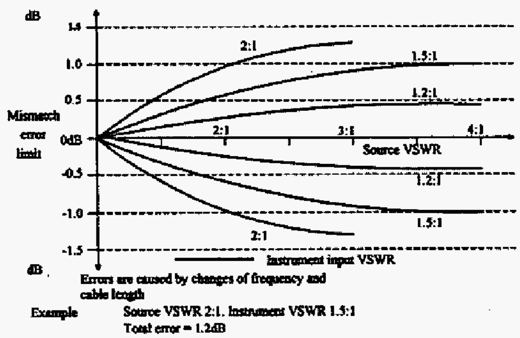


Figure 25 Input Mismatch uncertainty

The graph of figure 25 shows uncertainty limits for a variety of source and load values. Uncertainties rise considerably as the matches become worse.

A Spectrum Analyzer is a very complex device with many elements, which can change with frequency, temperature, and time. Each element contributes towards the inaccuracy or uncertainty of a measurement. The illustration shows a simplified block diagram of a typical instrument with amplitude uncertainty added. These figures are taken from the specification of an instrument in present widespread use. For a given measurement, all the uncertainties may not necessary apply, but the accuracy of such an instrument is poor. The problem can be worse when it is realized that with many instruments it is necessary to adjust front panel presets to obtain such accuracy. This relies on the diligence and skill of the operator and is therefore not reliable.

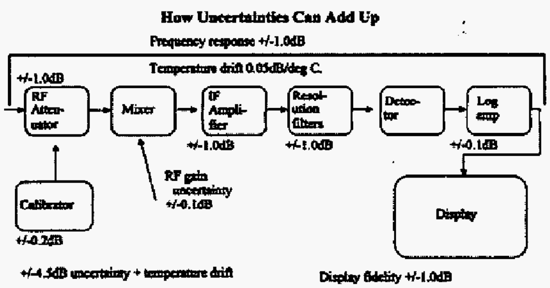


Figure 26 Uncertainty contributions

Some Spectrum Analyzers use an automatic self-calibration process and at the touch of a front panel or soft key the instrument runs through a self-calibration routine. A typical self-calibration routine includes setting up the amplitude and frequency of each of the resolution filters, measuring and correcting for the attenuation of each of the input attenuator steps.

Instruments which have a built-in Tracking Generator can also correct for the frequency response of the system by sweeping through the entire frequency range whilst routing the amplitude levelled tracking generator into the input. The advantage of automatic self-calibration is that total level accuracy is improved dramatically and the specification is valid for all levels and frequencies and for any span or resolution bandwidth.

3.10 Sideband Noise Characteristics

Figure 27 shows the typical sideband noise performance of a quality Spectrum Analyzer. The figure shows how the sideband noise can reduce close-in resolution as well as reducing dynamic range even for measurements 200 kHz away from the carrier.

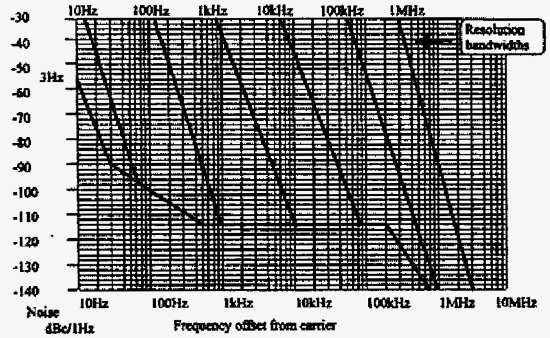


Figure 27 Sideband noise performance

3.11 Residual Responses.

In an earlier section, the problem of spurious responses was highlighted. A Spectrum Analyzer can display a signal on the screen although no signal is present at the input. Instrument designers endeavour to eliminate this undesirable phenomenon but these residual responses as they are known are present in all instruments to a greater or lesser extend. Residual responses occur because within a Spectrum Analyzer there are a number of local oscillator frequencies and their harmonics which can mix with each other to produce signals which can fall within the IF bandwidth and will appear as false signals.

Figure 28 Residual responses

Active RF and microwave systems frequently generate non-harmonically related signals that need to be identified and measured. Tracking down and then reducing the level of unwanted spurious signals is a very common application of a Spectrum Analyzer.

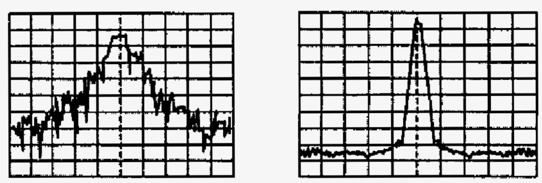
Inexperienced spectrum analyzer users can have problems with such a measurement if they are unaware of the limitations of the instrument. The problem of internally generated harmonically related distortion products has been described but a Spectrum Analyzer itself can have spurious responses. It is essential to ensure that a signal visible on the screen is not generated within the spectrum analyzer. The internally spurious signals generated can either be caused by residual responses that are an inherent limitation of the design or caused inadvertently by the operator if the instrument is overloaded. Image responses and multiple responses are also encountered in microwave spectrum analyzers if a preselector is not used.

Residual responses see figure 28 can create significant measurement problems so it is important to purchase an instrument with a very good specification. Residual responses of a quality instrument are typically less than -120 dBm to -110 dBm. Some instruments can have inferior specifications or in some cases, the residual responses are not even quoted at all.

Spectrum analyzers have a spurious response specification of typically, To be absolutely certain that a signal is not being internally generated it may sometimes be necessary to replace the signal being analysed with a known pure signal and to investigate the difference.

3.12 Residual FM

An important specification point is residual FM. If the local oscillator in the Spectrum Analyzer has appreciable FM on it then close to carrier measurements cannot be made. Residual FM on a quality instrument will vary from around 1 Hz to 10 Hz depending on frequency range. Figure 29 shows how poor residual FM can invalidate close-in measurements.



Poor quality **High quality**

Figure 29 Residual FM

4. SPECTRUM ANALYZER MEASUREMENTS

Spectrum Analyzers are used to make a very wide range of measurements. It is not possible to cover all the possible applications but the more common measurements are included in this section.

4.1 Measurement of Harmonic Distortion

A Spectrum Analyzer can be used to measure the amplitudes of the fundamental and even very low-level harmonics. Sometimes however it is necessary to quote not only the level of the harmonic distortion products but also to give the total harmonic distortion.

Figure 30 Harmonic Distortion

The total harmonic distortion as shown in figure 30 can be calculated by measuring the amplitudes of all the harmonics and then take the square root of the sum of the squares.

4.2 Example of a Tracking Generator Measurement

The display shown in figure 31 is a typical tracking generator measurement, the analysis of a 10.7 MHz band pass-filter over a wide dynamic range. The display shows two different traces simultaneously.

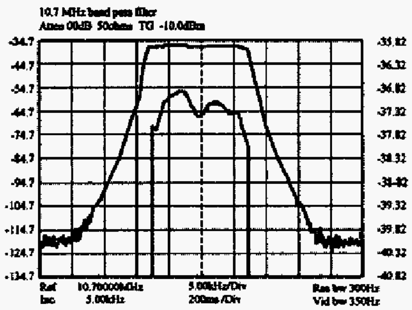


Figure 31 Measurement of a Bandpass filter

The upper trace shows the overall response of the filter over a dynamic range in excess of 80 dB. The other trace shows the ripple on the pass-band of the filter displayed with a resolution of 0.5 dB/division.

4.3 Zero Span

The principal function of a Spectrum Analyzer is to sweep through a selected part of the frequency spectrum. In certain circumstances however it may be necessary to analyze the characteristics of just one fixed portion of the spectrum. The Zero Span mode is used for such applications. In this mode, the local oscillator of the instrument is no longer swept; the oscillator is held at a fixed frequency so that the signal of interest can be studied.

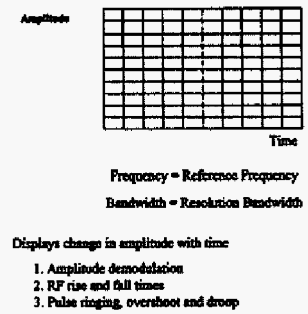


Figure 32 zero span

If sweeping ceases one would expect to merely see a dot or line on the display, which move up and down according to the change in amplitude of the signal to which the instrument is tuned. This would provide a certain amount of information, but much more information is obtained if a time base sweeps the spot horizontally in a similar manner to the technique used in oscilloscopes.

By sweeping the spot horizontally the display will show amplitude versus time variations of the signal to which the instrument is tuned.

4.4 Use of Zero Span

There are many applications of Zero Span mode but one off the most obvious is to demodulate an amplitude-modulated carrier as shown in figure 33. Another common use is to measure response times, one example is the measurement of transmitter decay time at switch off; this can be a critical measurement since it may determine how quickly an adjacent sensitive receiver can be enabled. Synthesizer switching times and overshoots can also be evaluated using the zero span mode.

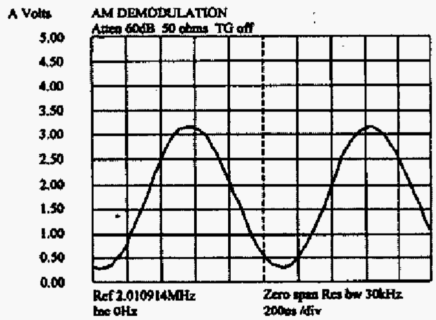


Figure 33 AM Demodulation

The time base of modern sophisticated instruments is derived from the reference oscillator. This ensures the very best accuracy when timing measurements are made. Some instruments only have an inaccurate time-base so it is a wise precaution to check the specification of the instrument before making a measurement.

4.5 Meter Mode

In addition to zero span mode some instruments incorporate a "Meter Mode." This is used for applications where a spectrum display needs to be retained whilst still monitoring the changing amplitude of a part of the spectrum.

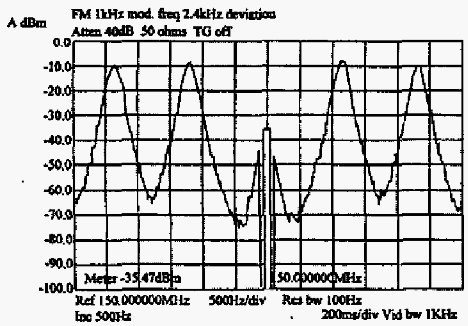


Figure 34 Meter mode

A typical application of "Meter Mode" is shown in figure 34. The amplitude of the FM carrier is continuously up-dated in real time whilst the rest of the display is saved. Any part of the display, selected by the movable marker, can be up-dated and monitored.

4.6 Inter modulation Measurement

Measuring the harmonic distortion caused by a device is not a very discriminating measurement. A more searching method is to use two or more test signals and to measure the intermodulation products that are generated at the output of the device under test. By using more than one test signal the device is receiving signals that are closer to the more complex signals that are generally encountered in practical systems. Two separate signal generators and a combiner are needed as shown.

Great care must be taken when making measurements or they may be invalid. Both signal generators used must have low harmonic content, if this is not possible then a low-pass filter should be inserted at the output of the generator. The combiner used should be a linear device with good matching.

Another problem is that any non-linearity in the output amplifiers of the signal generators can produce intermodulation. Further problems can arise if the ALC detector at the output of one signal generator also detects the signal from the other signal generator. It is for these two reasons that it is good practice to insert an attenuator between the signal generator output and the combiner. This may not be practical in some circumstances, because the signal level may be too low. For higher frequency measurements, an isolator is recommended to improve the measurement integrity.

4.7 Intermodulation Analysis

A typical Spectrum Analyzer display of a two-tone intermodulation test is shown in figure 35. Annotation has been added to explain the origin of the intermodulation products. Signal generator 1 has a fundamental frequency of F1 and signal generator 2 has a fundamental frequency of F2. Non-linearity in the device under test will cause harmonic distortion products of frequency 2F1, 2F2, 3F1, 3F2. . Etc. to be generated

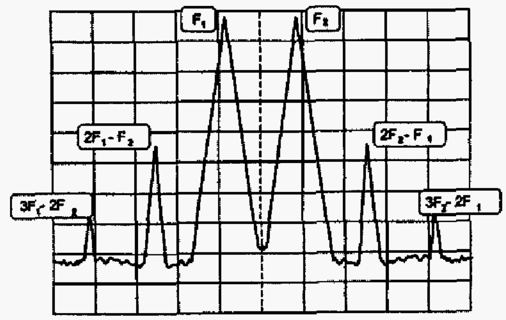


Figure 36 intermodulation

The Spectrum Analyzer will record these harmonic products but the significance of the intermodulation test is that the non-linearity causes the harmonic products to mix together to generate additional signals. Numerous intermodulation products can be generated but the two most commonly encountered ones are known as the third order and fifth other products.

Third order products have frequencies of 2F1 - F2 and 2F2 - F1. Fifth order products have frequencies of 3F1 - 2F2 and 3F2 - 2F1.

Even order products such as F1 + F2 and F2 - F1 are also seen but are less significant since the intermodulation products are widely separated from the two frequencies (F1 and F2) and generally can be readily rejected.

High performance Spectrum Analyzers have an inter modulation distortion of typically -95 dBc or better with a signal level of -30 to -40 dBm at the input mixer to allow for the measurement of low-levels of distortion.

4.8 Intermodulation Intercept Point

The amplitudes of inter modulation products change according to the amplitudes of the test signals applied; it is therefore necessary to specify the level of the test signals. It can be difficult to compare the performance of different devices however if they were measured at different levels. The solution is to use the concept of an inter modulation intercept point.

An intercept point is the theoretical point at which the amplitudes of the inter modulation products equals the amplitudes of the test signals, the illustration shows the concept. There are two lines on the graph in figure 37.

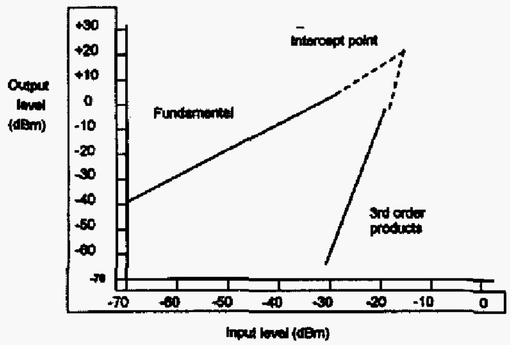


Figure 37 Inter modulation intercept

The fundamental line shows a linear relationship between the input and output signals, the line has been extrapolated beyond the output level of +5 dBm since at such levels the response becomes non-linear. Input and output signal levels have also been plotted for the 3rd order products and the line is extrapolated. The two lines meet at the inter modulation intercept point.

The slope of the inter modulation product lines is equal to their order, that is the 2nd order lines have a slope of 2:1, the 3rd order lines have a slope of 3:1. Practically this means that if the level of the test signal is reduced by 10 dB then the 3rd order product will theoretically drop by 30 dB, provided that the device is operating in a linear mode.

4.9 Nomograph to Determine Intermodulation Products Using Intercept Point Method

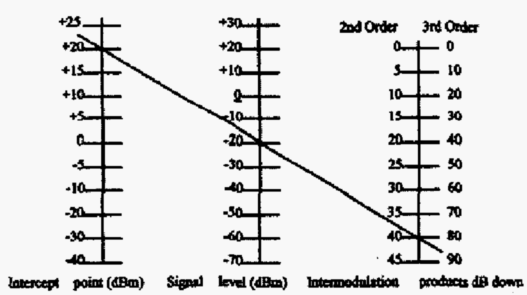


Figure 38 Nomograph to determine intercept

The nomograph in the figure 38 gives a rapid but not very accurate means of determining the intercept point. A straight edge is used to join the two known values so that the unknown can be determined.

4.10 Amplitude Modulation

Figure 38 shows an idealized Spectrum Analyzer display of an amplitude-modulated signal. The carrier frequency is F_c; the frequency of the modulating signal is F_m.

Three separate frequency components are seen

The Carrier frequency	F_cLower
sideband frequency	$F_c - F_m$
Upper sideband frequency	$F_c + F_m$

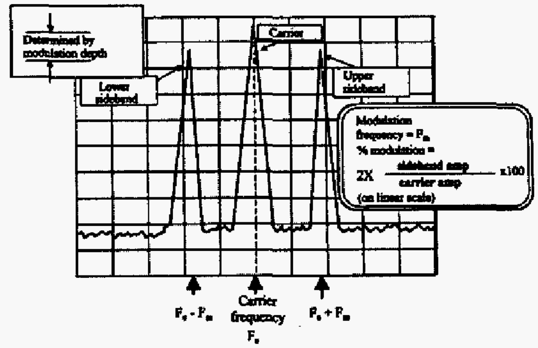


Figure 39 Amplitude modulation measurement

The amplitude of the carrier always remains constant as the modulation depth changes but the sideband amplitudes will change in proportion to the modulation depth. The frequency separation between the carrier and either sideband changes as the modulation frequency changes.

When the modulation depth is 100% half of the power is in the sidebands, so each frequency amplitude will be 6dB less than that of the carrier. For lower modulation depths, the sideband amplitude is proportionately less. To measure modulation depth it is thus necessary to measure the amplitude difference between the carrier and the sidebands.

4.11 AM Spectrum with Modulation Distortion

In practice there will be harmonics of the modulation frequency also present at $F_c \pm nF_m$. Figure 40 shows distortion produced at $F_c \pm 2F_m$.

Figure 40 Modulation distortion

4.12 Frequency Modulation

An FM spectrum theoretically has an infinite number of sidebands, which are symmetrical about the carrier and separated by the modulation frequency.

The FM spectrum display shown in figure 41 is thus considerably more complex than an AM spectrum display. Sideband and carrier amplitudes are determined by the unmodulated carrier amplitude and the modulation index (β) which is expressed as:

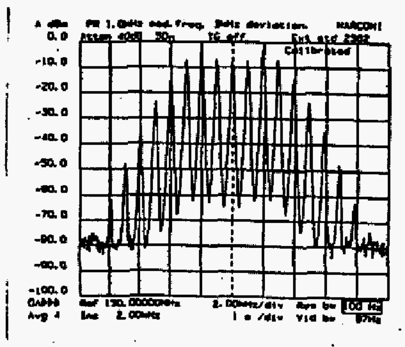


Figure 41 Frequiency modulation spectrum

Modulation index, $\beta = \dfrac{\text{Frequency deviation}}{\text{Modulation Frequency}}$

In practice, although there are an infinite number of sidebands the amplitudes of the higher frequency ones rapidly reduce to near zero and can be neglected. The illustration shows a typical spectrum analyzer display of an FM signal.

4.13 FM measurement using the Bessel Zero method

With frequency modulation the carrier amplitude is thus not constant, it varies according to the modulation index and will become zero at times. Sideband amplitudes also become zero at specific values of modulation index. Modulation indices at which the carrier or sidebands have zero amplitude can be calculated. Tables are available listing the zeros, or Bessel nulls as they are more commonly called. Bessel zeroes see figure 41 are used for accurate calibration of signal generators and modulation meters.

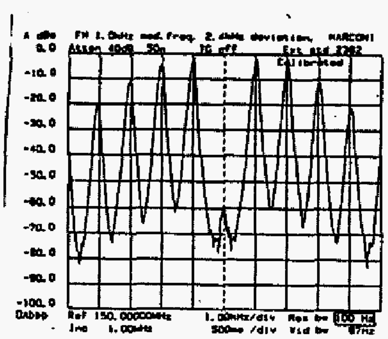


Figure 41 Bessel null

4.14 FM Demodulation

If zero span mode is used on a Spectrum Analyzer no information should be seen if frequency modulation is applied since zero span shows amplitude variation with time. However if the Spectrum Analyzer is de-tuned by a small amount then the demodulated signal will be seen. This occurs because the slope of the resolution filter acts as a slope detector as shown diagrammatically in Figure 42.

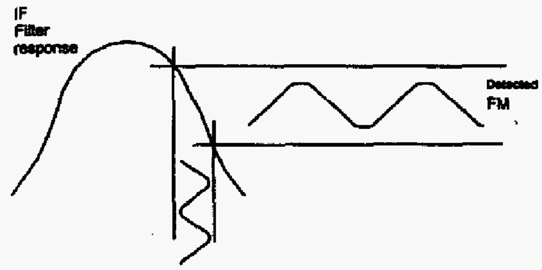


Figure 42 FM Demodulation

Accurate measurements are not possible but this does provide a convenient method to view a demodulated signal. It should be noted that the technique might be invalid if significant spurious AM is present in addition to the FM. Some spectrum analyzers can measure FM directly.

The demodulated FM signal is displayed on a graticule that is vertically calibrated in FM deviation; the horizontal scale is calibrated in time as for zero span. The illustration shows the technique used.

4.15 FM Demodulation Display

Some spectrum analyzers incorporate a function that demodulates the FM signal and displays deviation vertically against time horizontally.

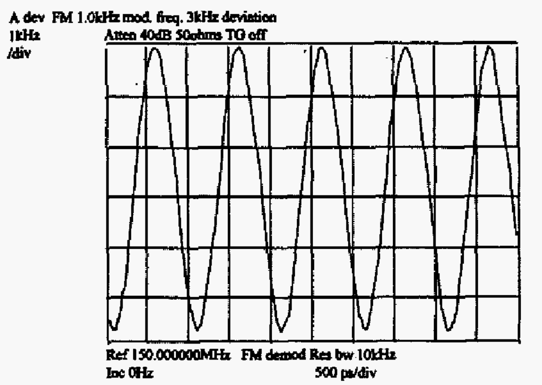


Figure 43 FM demodulation

A typical FM Demodulation screen display from a Spectrum Analyzer is shown in figure 43. The peak-to-peak FM deviation can be readily measured from the vertical scale.

4.16 Modulation Asymmetry

Pure AM and FM signals will have symmetrical spectra thus if a spectrum analyzer display of modulation is asymmetrical this will indicate the presence of unwanted signals.

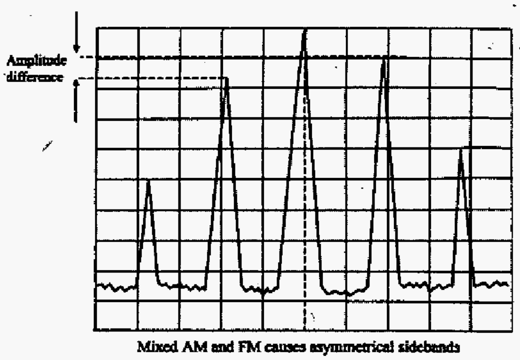


Figure 44 AM and FM Asymmetry

Asymmetry of the Spectrum Analyzer display shown in figure 44 is caused because upper and lower FM sideband pairs are 180° out of phase.

A Spectrum Analyzer does not display this phase difference but since the AM sideband pairs are in phase the incidental FM will increase or decrease sideband power depending on whether the FM and AM sidebands are in or out of phase.

The IF output of the Spectrum Analyzer may be used to further investigate the degree of spurious AM or FM or a modulation meter or oscilloscope could be used.

4.17 Spectrum of a Square Wave

Pulsed RF waveforms are most commonly encountered in radar systems both at IF and at microwave frequencies. To understand the analysis of pulsed RF it is first necessary to study the spectrum of a square wave. Figure 45 shows the idealized oscilloscope display of a train of rectangular pulses of Pulse Repetition Frequency F and pulse width - t.

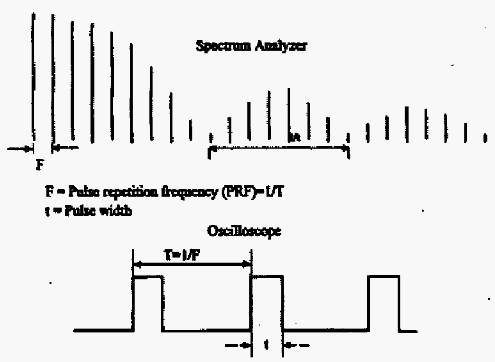


Figure 45 spectrum of a square wave

The corresponding Spectrum Analyzer display in the illustration shows that the individual spectral lines are spaced by the pulse repetition frequency 1/t. The Spectrum Analyzer display also shows that the amplitudes of the individual spectral lines rise and fall in a regular way, the pulse envelope of the spectral lines follows a curve of the form represented by the expression y = sin x/x. The first zero of the sin x/x envelope occurs at a frequency equal to 1/t. Subsequent zeros occur at multiples of 1/t. Each of the rising and falling patterns is referred to as a lobe. In theory, the lobes continue to infinity but in practice the amplitudes of the lobes soon becomes negligible as the frequency rises.

4.18 Pulse Modulation

Figure 46 shows a typical Spectrum Analyzer display of a pulse-modulated carrier. The spectral line, which can be seen at the centre of the display, is the RF carrier.

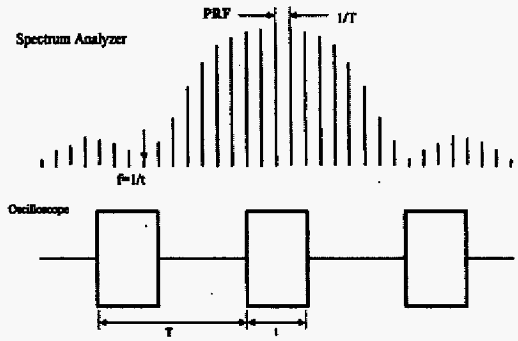


Figure 46 Pulse Modulation

The individual spectral lines, which are symmetrical about the carrier, are separated by a frequency equal to 1/T as for the basic pulse train; refer back to the previous illustration for clarification. The sin x/x zeros again occur at multiples of 1/t. The display is only theoretically symmetrical about the carrier since in some practical radar systems, where there are imperfections, the display may be asymmetrical.

4.19 Varying the Pulse Modulation Conditions

Pulsed RF can be confusing since the Spectrum Analyzer display depends on both the pulse repetition frequency and the period of the modulating signal. The illustration helps to clarify the situation by showing how the characteristics of a pulse modulated spectrum change according to the changes in the pulse width and pulse repetition frequency. The upper portion of each of the four displays shows the oscilloscope representation of the modulating waveform, the lower portion of each of the four displays is the Spectrum Analyzer representation of the pulsed RF signal.

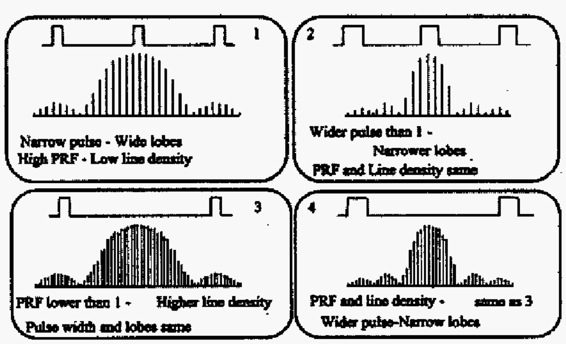


Figure 47 Varying pulse modulation

Display 1 (top left) of Fig 47 is an arbitrary starting point.

Display 2 (top right) of figure 47 the pulse width of the modulating signal is increased whilst the pulse repetition frequency is the same. Increasing the pulse width reduces the value of 1/t so the first zero is at a lower frequency; the lobes are thus narrower.

Display 3 (bottom left) of figure 47 the pulse width is the same as for display 1 but this time the pulse repetition frequency is lower. Spectral lines are spaced according to 1/T so the line density is increased as the pulse repetition frequency is decreased.

Display 4 (bottom right) of figure 47 again shows that a wider pulse causes narrower lobes

4.20 "Line" and "Pulse" Modes

Pulsed RF spectrum analysis is complicated because the display changes according to the resolution bandwidth selected, if it is significantly higher than the pulse repetition frequency then individual spectral lines will not be resolved. Figure 48 shows the frequency response of the resolution filter superimposed over a train of pulses. On the left the resolution bandwidth is shown to be less than the pulse repetition frequency so individual spectral lines are resolved, this is known as "line mode." On the right the resolution bandwidth is greater than the pulse repetition frequency so individual spectral lines are not resolved, this is known as "pulse mode."

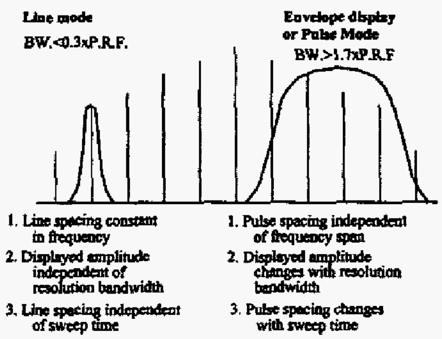


Figure 48 Line and pulse mode

In the pulse mode, the display seen is not a true frequency domain display; it is a combination of a time and frequency display. The lines are displayed when a pulse occurs irrespective of the instantaneous tuned frequency of the instrument. The display is in fact a time domain display of the spectrum envelope. One can rapidly determine that a pulse mode display is occurring by changing the scan time or sweep time; the pulse line spacing will change. The line spacing will not change when the span is changed, as one would expect for a normal Spectrum Analyzer display. A further characteristic of a pulse display is that the displayed amplitude increases as the bandwidth increases. A "rule of thumb" to apply for line mode is to use a resolution bandwidth of less than 0.3 x pulse repetition frequency. For pulse mode, the resolution bandwidth should be greater than 1.7 x pulse repetition frequency.

4.21 Extending the range of microwave spectrum analyzers

Most RF spectrum analyzers have "Local Oscillator Output" and "IF Input" connectors on the front panel to allow the frequency range to be extended higher with the use of external millimetric mixers.

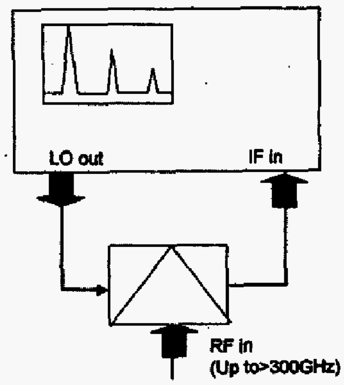


Figure 49 Extending the frequency range

Although this can be useful for a "quick look see" the measurements can be misleading due to poor amplitude accuracy and multiple responses. This feature shown in figure 49 should be used with extreme caution!

4.22 EMC Measurements

The spectrum analyzer can be used make EMC measurements and in some cases additional types of Detectors are included. Peak, Average, RMS and Quasi Peak detectors are often included. The spectrum analyzer is a very useful instrument to use as a diagnostic tool for EMC measurements.

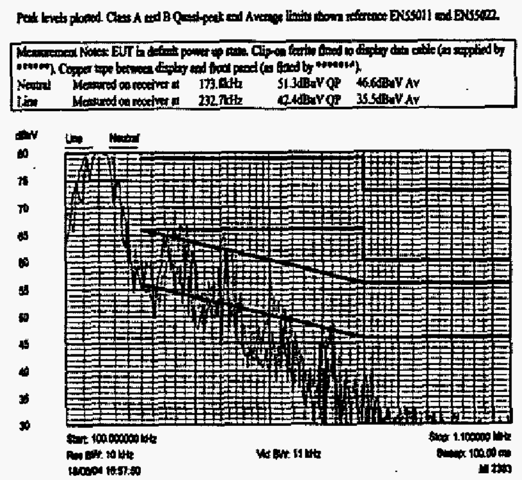


Figure 50 EMC Display

Figure 50 shows a plot from a spectrum analyzer used for a conducted measurement measured in a semi lined screened room. The test was made to En 55011 and EN55022 limits.

4.23 Spectrum Analyser Overloading

Applying AC or DC signals of greater than approximately 0.5 Watts (+27 dBm) can permanently damage the input of a spectrum analyzer. The input attenuator and mixer can be destroyed resulting in costly repair and loss of use of the spectrum analyzer.

Two techniques to protect against overload are incorporated in modern Spectrum Analyzers. In VHF and UHF instruments, a coaxial relay is generally incorporated in the input. Protection to 50 Watts is possible on VHF instruments. Microwave instruments can be switched to AC input so that DC voltages up to 50 V can be safely applied.