HEWLETT PACKARD

Measurement of White Noise Power Density

application note 63C

An application of Spectrum Analysis

INTRODUCTION

This note describes the use of the HP H10-851B/8551B Spectrum Analyzer to measure white noise power density. Noise power is specified as a power density in microwatts/MHz; therefore, a receiver that can be calibrated in terms of power input and that has a precisely determined bandwidth can make this measurement. The HP broadband spectrum analyzer is well suited for this purpose. Its swept front end and wide dynamic range enable the operator to quickly characterize the output of his noise source over the desired frequency range. Use of the log display mode gives the operator the convenience of a 60-dB dynamic display range. However, since noise is a random phenomenon, some averaging process must be included.

Although the basic operation of the spectrum analyzer is described in detail in the 851B/8551B instruction manual, the specific areas pertaining to the measurement of white noise power density and their effect on the results are described again in this Application Note. The routine procedure for operating the equipment is outlined to assist non-technical personnel with setting up the equipment and easily making accurate noise power density measurements.

USING THE SPECTRUM ANALYZER TO MEASURE WHITE NOISE

GENERAL DESCRIPTION OF THE 851B/8551B SPECTRUM ANALYZER

The 851B/8551B is a triple conversion, narrow band, superheterodyne, swept receiver, that presents output information (signal amplitude versus frequency) on a cathode ray tube. The analyzer operates over a 10.1-MHz to 40-GHz range. The input for 10.1 MHz to 12.4 GHz is a single Type N coaxial connector while external waveguide mixers are used for 12.4 to 40 GHz. Since a thorough discussion of the theory of operation is contained in the operating & service manual, only the function of the specific areas important to the measurement of noise power density are described here. A simplified block diagram is shown in Figure 1. The specific blocks of interest are the input mixer and the local oscillator, the IF bandpass filters, the shaping networks, and the video filter. These are discussed in the following paragraphs.

INPUT MIXER AND LOCAL OSCILLATOR

The input mixer and its local oscillator make possible the exceptional performance of the spectrum analyzer. The input mixer is flat with a wide dynamic range over a broad frequency range (10.1 MHz to 12.4 GHz) and essentially determines the dynamic range of the instrument.

When measuring broadband noise, extra care must be taken to avoid overdriving the mixer, because the power incident on the input is the total power, but only the power in an IF bandwidth is indicated on the CRT. Therefore, gain compression may occur with a low power density, but high total power. Table 1 shows the maximum input power density for noise spread over various spectrum widths.

Table 1

Noise Spectrum Width	Maximum Input Power Density* (Input Atten at 0 dB)
1 MHz	50.0 μW/MHz
10 MHz	5.0 μW/MHz
100 MHz	0.5 μW/MHz
1 GHz	0.05 μW/MHz

*The maximum noise power input is derived in Appendix A.

Since the mixer could be damaged by incident input power greater than +10 dBm (10 mW), the input attenuator should always be set first at maximum attenuation, 60 dB. Then a maximum of +30 dBm, or 1 watt total power, is permissible at the input of the spectrum analyzer.† The user must be sure that the signal to be measured is less than +30 dBm or 1 watt, either by direct measurement with a power meter or by knowledge of the maximum output power of his system.

The use of the HP 8441A Preselector increases the maximum allowable input power density to 10 μW/MHz or 30 dBm/MHz, no matter what the actual noise spectrum width. This is possible since the preselector is a tracking filter with a nominal bandwidth of 50 MHz. For a specific case, the increase in dynamic range to be realized can be calculated from the expression

† This 1-watt maximum is determined by the dissipation capability of the input attenuator.

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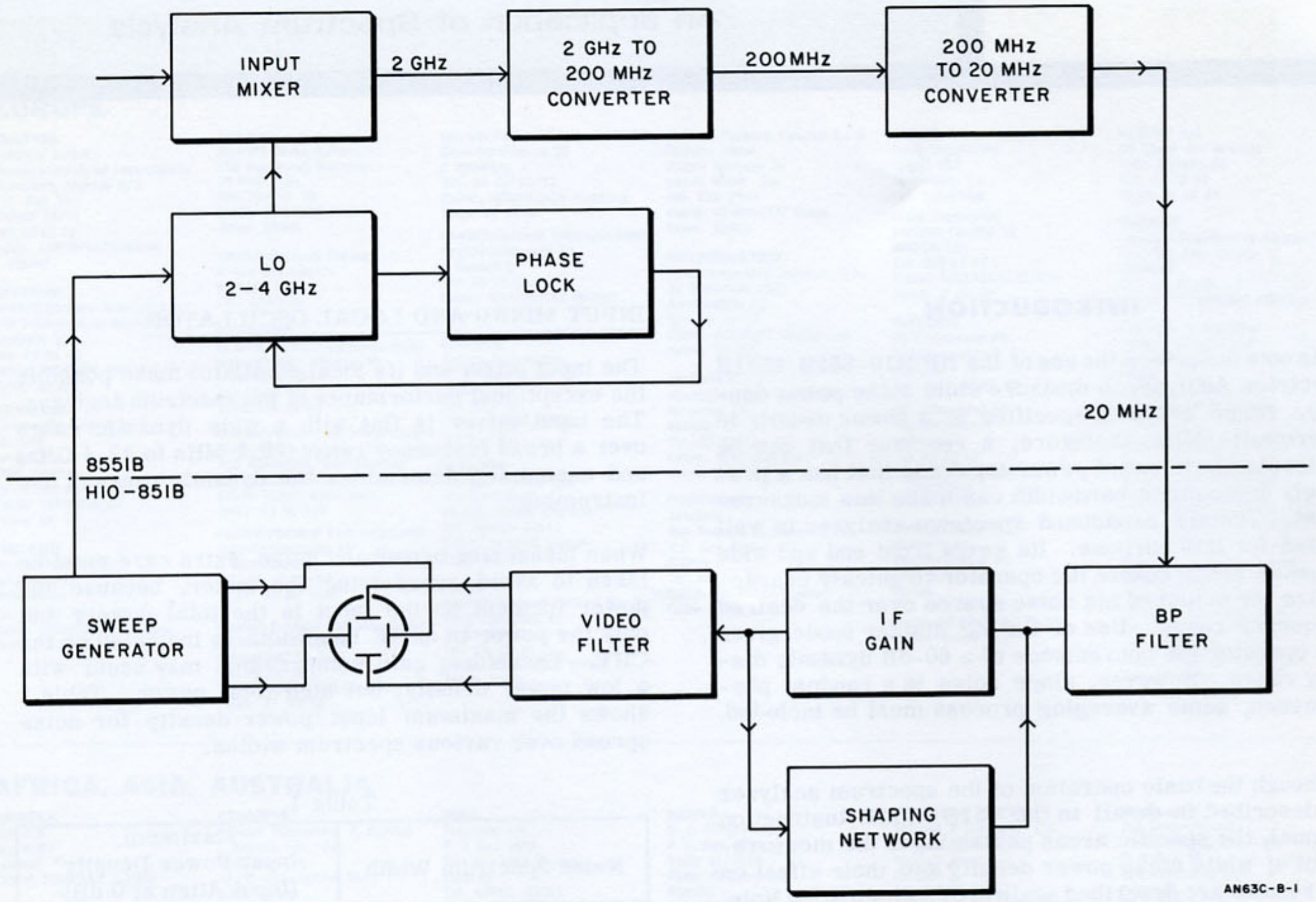


Figure 1. Simplified Block Diagram

$$\mathrm{Log}_{10} \frac{\text{Noise Spectrum Width}}{\text{50 MHz}}$$

The preselector is also useful when noise spectral width is greater than 500 MHz and is located above 4 GHz, since its filtering action prevents possible confusion and overlap due to multiple responses.

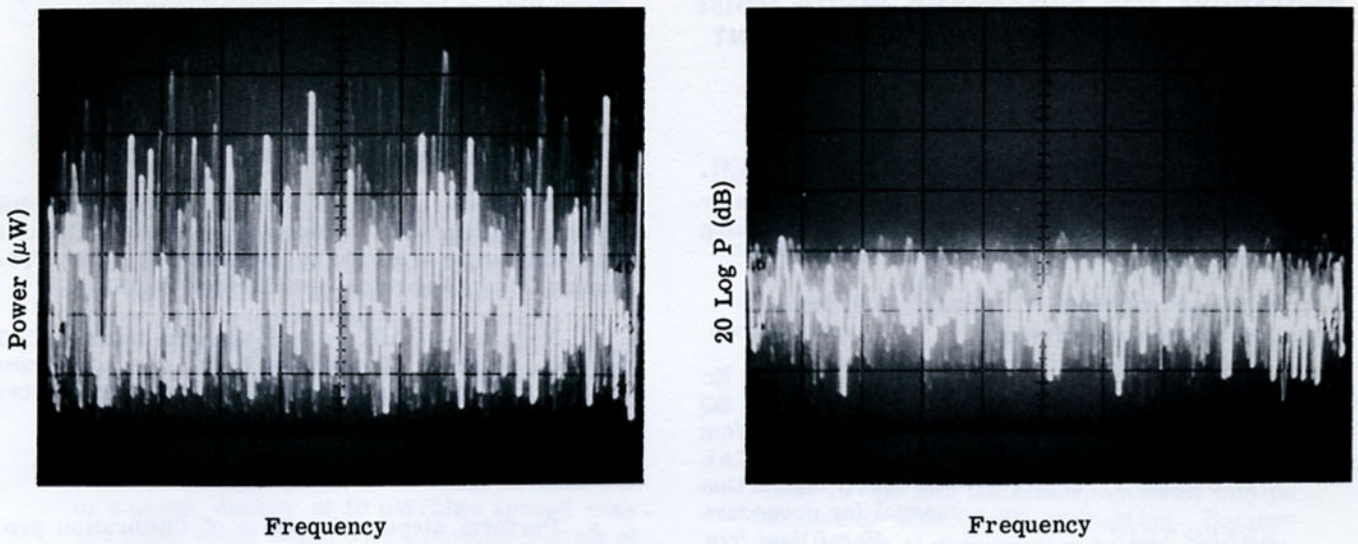
The first local oscillator is a backward-wave oscillator, (BWO), electronically swept from 2 - 4 GHz. The output of the local oscillator or one of its harmonics is mixed with the input signal to produce a difference of 2 GHz, the first IF frequency. When operating with narrow scan widths, the frequency instability of the BWO becomes apparent and the BWO must be phase-locked. The procedure required to phase-lock the BWO is described in the 8551B instruction manual. The steps required should be thoroughly understood before using the 8551B in a narrow scan width (less than 1 MHz/cm).

IF BAND-PASS FILTERS

The 20-MHz IF band-pass filters, located in the H10-851B Display unit, are selected by the IF bandwidth switch on the front panel. The shape of these filters determines the noise bandwidth in which the power is measured. The equivalent noise bandwidth must be determined for the power density measurement to be meaningful. The filters are set up for a 3-dB CW bandwidth, which is different from the noise bandwidth. This difference can be taken into account by calculating the width of a rectangle with a height and area the same as the filter bandwidth. This measurement is made in the SQ or power mode. See Figure 4. Then a scale factor, the ratio of the noise bandwidth to 1 MHz, must be used to get the noise power density in μW/MHz. The 100-kHz bandwidth is optimum for this measurement, since the log shaping network has a bandwidth less than 1 MHz; use of the 10-kHz bandwidth results in a noisier video display, because the noise reduction depends on the ratio of the IF bandwidth to the video bandwidth. The 100-kHz bandwidth is adequate in all respects, giving greater resolution than necessary for the measurement.

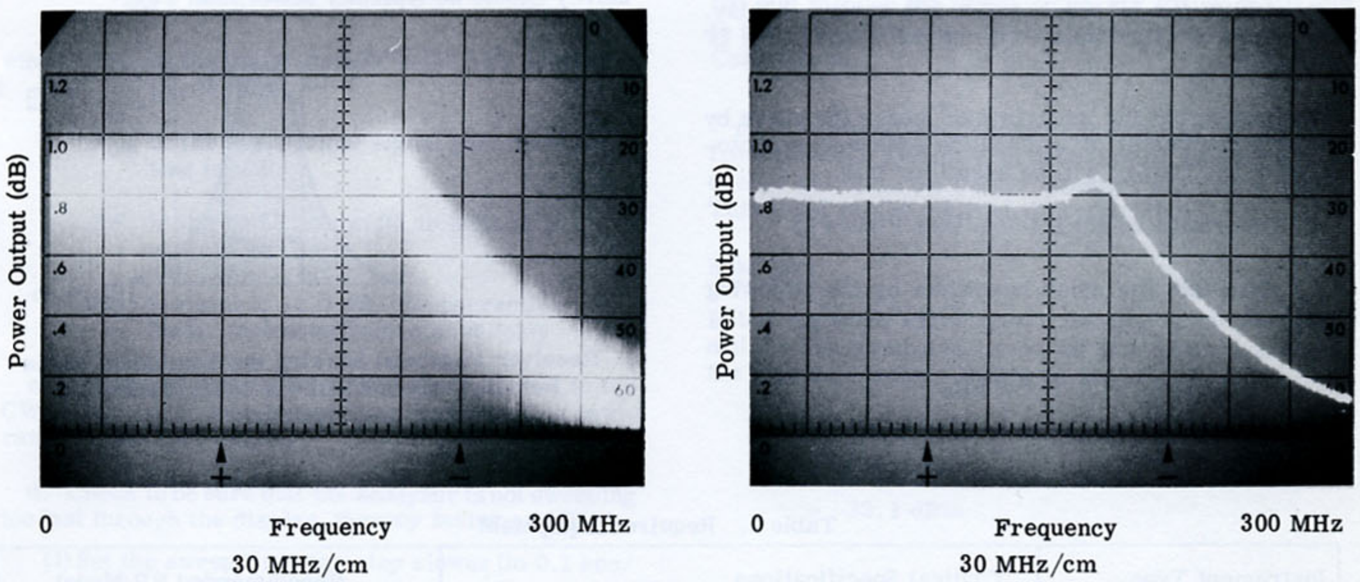
SHAPING NETWORK

The shaping networks involve the linear, square, and log display mode. For power density measurements either the square or log mode could be used. Operation in the square mode is direct and straight forward, but this has a limited dynamic range; however, in the log mode, a constant correction factor must be added to the calibrating signal.



(a) Power Display (b) Log Display

Figure 2. White Noise Displayed in Both the Power Display Mode and in the Log Display Mode. (Video filter out.) Note how the log weighting reduces the effects of the noise peaks. The random nature of the noise is also demonstrated in these photographs by the ghosts of previous sweeps.



(a) Video Filter Out (b) Video Filter In

Figure 3. Noise Output of a Broadband Amplifier Showing the Effect of the Video Filter.

The need for a correction factor arises from the fact that the average of the log of a noise signal is different from the average of the log of the peak of a CW signal. In fact, the noise measurement will read low since the transient spikes of the noise have a lesser effect on average due to the logarithmic weighting, while the CW peak is constant. See Figure 2. Therefore, the CW calibrating signals should be set lower by a constant amount. The value of this correction factor is 2.5 dB and is verified empirically and theoretically. The theoretical derivation can be found in the appendix of this note.

VIDEO FILTERS

The 851B detector output is instantaneous power, observed as peaks on the CRT display; Figure 3 shows how the video filter averages this peak reading. The 175-hertz bandwidth of the video filter allows detail, such as a 0.2-cm wide hole, to be seen at a sweep speed of 30 ms/cm. An 851B with this filter has been renumbered H10-851B.

PROCEDURE FOR BROADBAND WHITE NOISE POWER SPECTRAL DENSITY MEASUREMENT WITH THE H10-851B/8551B

H10-851B NOISE BANDWIDTH CALIBRATION

CALIBRATION PROCEDURE. The bandwidth calibration need be done only once every six months or during regular maintenance. Instruction for checking the IF bandwidth follows this procedure.

a. Set controls as follows:

IF BANDWIDTH . . . . 100 Kc
VERTICAL DISPLAY. . . . . SQ
SPECTRUM WIDTH . 30 Kc/cm or 100 Kc/cm
SPECTRUM WIDTH VERNIER. . . . . . CAL
STABILIZE . . . . . . See 8551B instruction manual for procedure
SWEEP TIME . . . . 10 millisec/cm
VIDEO FILTER . . . . OUT
Other control settings may be set to the user's preference.

b. Feed in a CW signal at a level about -30 dBm. Any frequency can be used. This measurement pertains to the 851 IF bandwidth only and is independent of the input frequency.

c. Adjust the IF GAIN for a full screen display. The shape of this display will be the shape of the IF bandwidth.

d. Determine the area in cm^2 under the curve by use of a planimeter or by counting squares. A photograph of the display will be useful for this.

e. Determine height H in cm (see Figure 4).

f. Calculate the noise bandwidth by the following formula:

$$BW_N = \left(\frac{A}{H} \times SW\right) \text{kHz}$$

where BW_N = the noise bandwidth
A = the area under the curve in cm^2
H = the height in cm
SW = the spectrum width setting used, 30 or 100 kHz/cm.

This measurement will be accurate to within ±5% due to the spectrum width calibration accuracy. Greater accuracy can be achieved by use of an HP 8406A Frequency Comb Generator as described in AN63-D.

g. Reduce IF GAIN by 3 dB and note level on CRT screen. Increase IF GAIN by 3 dB for a full screen display and measure the bandwidth between the two 3-dB points. Record this value.

CHECKING THE IF BANDWIDTH CALIBRATION.

a. Perform steps a, b, and c of Calibration procedure.

b. Reduce the IF GAIN by 3 dB and note this level on the CRT screen.

c. Increase the IF GAIN by 3 dB for a full screen display and measure the bandwidth between the two 3-dB points. This should be the same as that recorded in step g in the paragraph above. The repeatability should be typically better than ±3%.

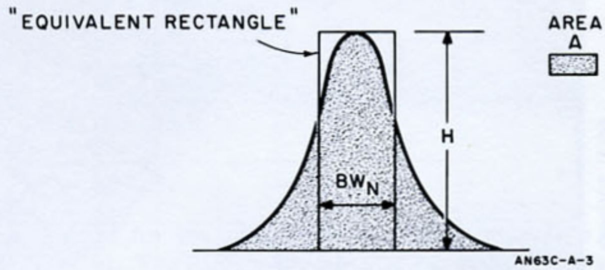


Figure 4
Receiver Passband Showing the Equivalent Noise Rectangle from which the Noise Bandwidth is Calculated.

Table 2. Required Equipment

Instrument Type	Critical Specifications	Recommended HP Model
Broadband Spectrum Analyzer	Video filter to average noise power	H10-851B/8551B
Signal Generator	Frequency Range: 50 kHz - 65 MHz 10 MHz - 480 MHz 450 MHz - 1230 MHz 0.8 GHz - 2.4 GHz 1.8 GHz - 4.5 GHz 3.8 GHz - 7.6 GHz 7 GHz - 11 GHz Output attenuator calibrated in dBm	606B 608E 612A 8614A 8616A 618C 620B
Preselector	Optional -- see text	8441A

POWER DENSITY CALIBRATION

a. Control settings:

IF GAIN. . . . . .60 or 70 dB
VERTICAL DISPLAY. . . . . .LOG
SPECTRUM WIDTH . . . As desired for signal
SWEEP TIME . . . . 30 millisec/cm
VIDEO FILTER . . . . .OUT
INPUT ATTENUATOR . . . The setting of this attenuator depends on the total power incident on the input mixer. This can be measured with a power meter or estimated from the density spectrum width products. Set the attenuator so that the total expected power at the mixer does not exceed -13 dBm. If the preselector is used, the total power in any 50-MHz bandwidth must not exceed -13 dBm. For example, without the preselector, a total power of 0 dBm, or 1000 μW or a power density of 10 μW/MHz spread over 100 MHz, would require an attenuator setting of 20 dB to limit the power to -20 dBm at the mixer input.

b. Apply a CW signal from a signal generator in the frequency range of interest. See Table 2. The magnitude of the CW signal should be determined by the following equation:

$$P_{cw} = PD_n \times BW \times 0.56\ \mu W,$$

where PD_n is the power density reference desired in μW/MHz

P_{cw} is the appropriate signal generator setting in μW

BW is the noise bandwidth in MHz as previously measured

0.56 is equal to -2.5 dB, the correction factor for the log detector display

c. Set the IF attenuator so that the response to the CW power level just touches a reference line mid-range on the CRT display.

d. Check to be sure that the analyzer is not sweeping too fast through the display, thereby losing amplitude.

(1) Set the sweep time one step slower (to 0.1 sec/cm) and see if the display changes. If no change takes place, set the sweep time back to 30 ms/cm. If the display does change, set the sweep time slower still — just short of the speed at which amplitude loss occurs.

(2) If response reduction is taking place and it is impractical to reduce the sweep time, reduce the spectrum width.

POWER DENSITY MEASUREMENT

a. Set the control settings as in Power Density Calibration above.

b. Apply the signal to be measured to the input of the analyzer.

CAUTION

Be careful that the total power does not exceed 10 mW into the mixer, or 1 watt into the attenuator with 60 dB attenuation. Damage will result if this caution is not observed. See Power Density Calibration above. If the input power is not known with full confidence, set the input attenuator at 60 dB.

c. Switch the video filter on.

d. Check to be sure the analyzer is not sweeping too fast through the display, thereby losing detail due to the video filtering. Follow step d Power Density Calibration.

e. The noise power density can now be read directly from the CRT graticule in dB below or above the reference set up in the Power Density Calibration above. This level can be converted to μW/MHz.

Example:

If the expected noise power density is 10 μW/MHz, and the bandwidth was measured at 110 kHz (0.11 MHz), the signal generator should be set at

$$P_{cw} = 10\ \mu W/MHz \times 0.11\ MHz \times 0.56$$
$$= 0.615\ \mu W$$
$$= -32.1\ dBm\ .$$

The analyzer is then calibrated so that the fourth line up from the base line on the log display is 10 μW/MHz. The line below it will be 10 dB below the reference, or 1 μW/MHz, and the line above is 10 dB above the reference, or 100 μW/MHz.

APPENDIX

A. DETERMINATION OF MAXIMUM INPUT NOISE POWER

The maximum input power used to calculate the values in Table 1 was determined as follows. A -10-dBm CW signal will cause 1 dB gain compression in the mixer. This is 70 mV rms or 100 mV peak in a 50-ohm system. With narrow band Gaussian noise such as we are considering, the maximum value of the envelope will be less than $3/\sqrt{2}$ times the rms value of the envelope with a 99% probability or 99% of the time.[1] Thus, the rms value of the noise envelope is

$$\frac{\sqrt{2}}{3}\ (100\ \text{mV}) = 47\ \text{mV or } -13.5\ \text{dBm}$$

Since 99% is quite conservative[2], we can safely say that the maximum input to the mixer is -13 dBm or 50.0 μW. This, then, is the maximum total power allowable at the mixer input.

B. RESPONSE TO NOISE OF THE SPECTRUM ANALYZER IN THE LOG MODE

Narrow band white noise consists of random bursts of energy which have an envelope, R, described adequately by the "Rayleigh distribution."[1] See Figure 5a.

$$P\ (R) = \frac{R}{\sigma^2}\ e^{-R^2/2\sigma^2}\ ,$$

which we normalize, by setting the scale factor $\sigma = 1$, to

$$P\ (R) = R\,e^{-R^2/2}.$$

The rms value of this function is $\sqrt{2}$.

In the spectrum analyzer, this noise is processed by peak detection (envelope detection), logging, and averaging. Thus, with $V(R) = \log_{10} R$, the average of Vn the noise voltage is

$$\overline{V}n = \int_0^\infty [\,V(R)\,]\ [\,P(R)\,]\ dR$$

$$= \int_0^\infty (\log R)\ [\,R\,e^{-R^2/2}\,]\ dR$$

$$= 0.0580$$

by numerical integration.

A sine wave of the same heating power (envelope $=\sqrt{2}$, see Figure 5b) processed in the same way yields

$$\overline{V}s = \log \sqrt{2} = .346$$

Taking the difference and translating it from nepers to dB,

$$\text{Difference} = 8.68\ (.346 - .058) = 2.50\ \text{dB}$$

This is the desired correction factor by which the signal generator power must be reduced to become a reference for noise power density.

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1 Reference Data For Radio Engineers, ITT, 4 Ed., p. 991.

2 If signals causing 1 dB gain compression occur only 1% of the time, they will have only 1% effect.

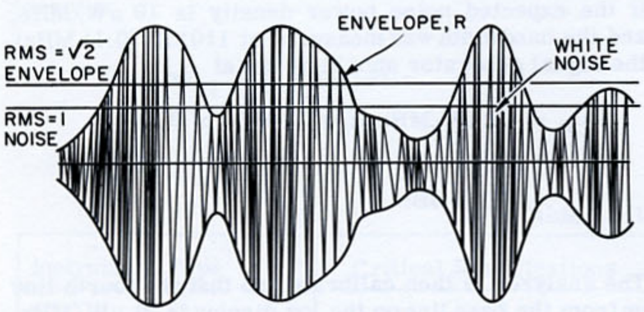

Figure 5a

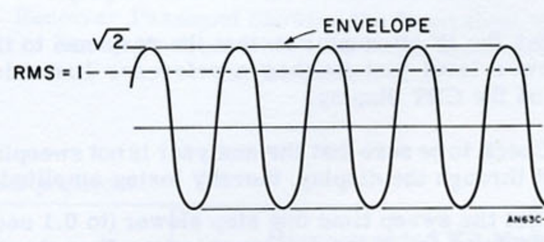

Figure 5b