PHASE NOISE CHARACTERISTICS OF FREQUENCY SOURCES

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ABSTRACT

In order to predict the requirements and specifications for a broad category of systems in today's technology, one must take into account the effects which oscillator instabilities produce in those systems.

The purpose of this presentation is to illustrate data plots of phase noise characteristics of various commercial frequency sources, a laser amplifier, Surface Acoustic Wave (SAW) oscillators, and Gunn oscillators. The phase noise characteristics are plotted in the frequency domain as the Normalized Phase Noise Sideband Power Spectral Density in dBc/Hz, which is called Script $\mathcal{L}(f)$. Two automated measurement systems are described with particular emphasis on practical experience in the measurements and assessed limitations and characteristics of each system.

Measurement data is shown for measurements close to the carrier.

INTRODUCTION

Phase Noise is the term most widely used to describe the characteristic randomness of frequency. Practical oscillators demonstrate noise which appears to be a combination of causally generated signals and random, non-deterministic noises. The random noises include thermal noise, shot noise, noises of undetermined origin (such as flicker noise), and integrals of those noises. The end result is time dependent phase and amplitude fluctuations.

Measurements are performed in the frequency domain using a spectrum analyzer which provides a frequency window following the phase or frequency detector. One system measures the combined phase noise characteristics of two sources. The two source signals are applied in quadrature to a phase sensitive detector (double balanced mixer) and the voltage fluctuations analog to the phase fluctuations are measured at the detector output. One measurement system is designed to measure the phase noise characteristics of a single oscillator. The single-oscillator measurement system is designed using the delay line as an FM discriminator. Voltage fluctuations analog to frequency fluctuations are measured at the detector output.

The calibration and measurement steps are controlled by a calculator program. The calibration sequence requires several manual operations. The software program controls frequency selection, bandwidth settings, settling time, amplitude ranging, measurements, calculations, graphics, and data plotting.

A quasi-continuous plot of phase noise is obtained by performing measurements at Fourier frequencies separated by the IF bandwidth of the spectrum analyzer used during the measurement. Plots of other defined parameters can be obtained and plotted as desired. Data plots will be used to show the effects of phase lock loops, inadequate isolation of two sources when using the two-oscillator technique, and the limiting frequency range of measurements performed using the delay line as an FM discriminator.

In this presentation the Greek letter nu (ν) represents frequency for carrier-related measures. Modulation-related frequencies are designated (f). If the carrier is considered as dc, the frequencies measured, with respect to the carrier, are referred to as baseband, offset from the carrier, modulation, noise, or Fourier frequencies.

General Theory and Definitions

A representation of fluctuations in the frequency domain is a graph called spectral density. Spectral density is the distribution of variance versus frequency.

The spectral density $S_y(f)$ of the instantaneous fractional frequency fluctuations $y(t)$ is defined as a measure of frequency stability [1].

$S_y(f)$ is the one-sided spectral density of fractional frequency fluctuations on a "per hertz" basis; the dimensionality is Hz^{-1}.

$$S_y(f) = S_{\delta\nu}(f)/\nu_o^{\,2} \qquad [Hz^{-1}] \qquad (1)$$

$S_{\delta\nu}(f)$, in Hz^2/Hz, is the one-sided spectral density of frequency fluctuations $\delta\nu$. It is calculated as $(\delta\nu_{rms}{}^2/$(Bandwidth used in the measurement of $\delta\nu_{rms}$).

The spectral density of phase fluctuations is a frequency domain measure of phase fluctuations defined as follows:

$S_{\delta\phi}(f)$, in rad^2/Hz, is the one-sided spectral distribution of the <u>phase fluctuations</u> on a "per hertz" basis. It is calculated as

$$S_{\delta\phi}(f) = \frac{(\delta\phi_{rms})^2}{\text{Bandwidth used to meas. } \delta\phi_{rms}} \qquad [rad^2/Hz] \quad (2)$$

The phase and fractional frequency fluctuation spectral densities are related by:

$$S_{\delta\phi}(f) = (\nu_o^2/f^2)\, S_y(f) \qquad [rad^2/Hz] \quad (3)$$

A useful measure of frequency stability relates the sideband power associated with phase fluctuations to the carrier power level. The defined measurand is called Script $\mathcal{L}(f)$. $\mathcal{L}(f)$ is defined as the ratio of the power in one sideband, referred to the input carrier frequency, on a per hertz of bandwidth spectral density basis, to the total signal power, at Fourier frequency f from the carrier, per one device[2]. It is a normalized frequency domain measure of phase fluctuation sideband power.

$$\mathcal{L}(f) \equiv \frac{\text{Power Density (one phase modulation sideband)}}{\text{Carrier Power}} \; [Hz^{-1}] \qquad (4)$$

For the condition that the phase fluctuations occuring at rates f and faster are small compared to one radian, a good approximation is [2]

$$S_{\delta\phi}(f)\Big|_{\text{one device}} = (2\ rad^2)\ \mathcal{L}(f) \qquad [rad^2/Hz] \quad (5)$$

If the small angle condition is not met, Bessel function algebra must be used to relate $S_{\delta\phi}(f)$ to $\mathcal{L}(f)$.

Script $\mathcal{L}(f)$ often is expressed in decibels relative to the carrier per hertz (dBc/Hz) which is calculated as

$$\mathcal{L}(f) = 10 \log \left[\frac{S_{\delta\phi}(f)\big|_{\text{one unit}}}{2\ rad^2} \right] \qquad [dBc/Hz] \quad (6)$$

Basic Two-Oscillator Technique

A block diagram of the measurement system employing two oscillators is shown in Figure 1. NBS has performed phase noise measurements using this basic type system since 1967.

The double balanced mixer acts as a phase-sensitive detector so that when two signals are identical in frequency and nominally are in phase quadrature, the mixer output is a small fluctuating voltage δv, centered on approximately zero volts. This small fluctuating voltage represents the phase modulation PM sideband components of the signal.

If the two oscillator signals applied to the mixer of Figure 1 are slightly out of zero beat, a slow sinusoidal voltage with a peak-to-peak voltage of V_{ptp} can be measured at the mixer output. Under the conditions for which Equation (5) is valid, the relationship between mean-square fluctuations of phase $\delta\phi$ and voltage δv interpreted in a spectral density fashion has been shown to be [1]

$$S_{\delta\phi}(f) = S_{\delta v}(f)/2(V_{rms})^2 \qquad [rad^2/Hz] \quad (7)$$

Here, $S_{\delta v}$, in volts squared per hertz, is the spectral density of the voltage fluctuations at the mixer output. Since the spectrum analyzer measures rms voltage in a bandwidth B, the analyzer reading is in units of volts per $\sqrt{\text{Bandwidth}}$. Therefore,

$$S_{\delta v}(f) = [\delta v_{rms}/\sqrt{B}]^2 = \frac{(\delta v_{rms})^2}{B} \qquad [V^2/Hz] \quad (8)$$

where B is the noise power bandwidth used in the measurement.

If it is assumed that the reference oscillator did not contribute any phase noise, the voltage fluctuations $(\delta v)_{rms}$ represents the oscillator under test and the spectral density of the phase fluctuations in terms of the voltage measurements performed with the spectrum analyzer is

$$S_{\delta\phi}(f) = \frac{1}{2}\frac{(\delta v_{rms})^2}{B(V_{rms})^2} \qquad [rad^2/Hz] \quad (9)$$

The measurement system of Figure 1 yields the output noise from both oscillators. If the reference and test oscillators are the same type, a useful approximation is to assume that the measured noise power is twice that which is associated with one noisy oscillator. This approximation is in error by no more than 3 dB for the noiser oscillator even if one oscillator is the major source of noise. The equation for the spectral density of measured phase fluctuations is

$$S_{\delta\phi}(f)\Big|_{\#1} + S_{\delta\phi}(f)\Big|_{\#2} = \frac{S_{\delta V}(f)\Big|_{\text{two devices}}}{2(V_{rms})^2}$$

$$\doteq 2\, S_{\delta\phi}(f)\Big|_{\text{one device}} \qquad [\text{rad}^2/\text{Hz}] \quad (10)$$

A determination of the noise of each oscillator can be made if one has three oscillators that can be measured in all pair combinations.

Automated Phase Noise Measurement System

The TRW Metrology Automated Phase Noise Measurement System is program controlled by the Hewlett-Packard 9830 Programmable Calculator. Each step of the calibration and measurement sequence is included in the program. The system is used to obtain a direct plot of Script $\mathcal{L}(f)$. The direct measurement of $\mathcal{L}(f)$ is represented by the following equation.

$$\mathcal{L}(f) \text{ in decibels relative to } 1\ \text{Hz}^{-1} = \frac{(\text{Noise Power Level})}{(\text{Carrier Power Level})} \text{ in dB}$$

$$-6\ \text{dB} + 2.5\ \text{dB} - 10\log(B) - 3\ \text{dB} \qquad [\text{dBc/Hz}] \quad (11)$$

The noise power is measured relative to the carrier power level and the remaining terms of the equation represent corrections that must be applied due to the type measurement and the characteristics of the measurement equipment as follows.

- o The basic measurement of noise sidebands with the signals in phase quadrature requires the -6 dB correction due to the linear addition of the two phase sidebands at the mixer output [3,4].
- o The non-linearity of the spectrum analyzer logarithmic IF amplifier results in compression of the noise peaks which, when average detected, require the +2.5 dB correction for the HP 3571A Tracking Spectrum Analyzer.
- o The bandwidth correction is required because the spectrum analyzer measurements of random noise are a function of the particular bandwidth used in the measurement.

- o The -3 dB correction is required since this is a measurement of $\mathcal{L}(f)$ using two oscillators, assuming that the oscillators are of a similar type and that the noise contribution is the same for each oscillator. If one oscillator is sufficiently superior to the other, this correction is not used.

The Calibration and Measurement Sequence

1. Automated Measurement of the noise power bandwidth of each IF bandwidth setting on the Tracking Spectrum Analyzer.

2. Obtain a carrier power reference level (referenced to the output of the mixer).

   a) The precision IF step attenuator is set to a high value to prevent overloading the spectrum analyzer.

   b) Normally, we drive the mixer with a 10 to 13 dBm signal from the reference then increase the signal arm input to obtain operation at a 50 ohm output impedance of the mixer (in the range of 1-3 milliwatts). If minimum noise floor is required, then approximately equal power is applied to the inputs of the mixer as required to obtain the 50 ohm output impedance of the mixer in our 50 ohm system. Special techniques are required to obtain the correct impedance when lower impedance is involved.

   c) If the frequency of one of the oscillators can be adjusted, adjust its frequency for an IF output frequency in the range of 10 to 20 kHz.

   d) The resulting IF power level is measured by the spectrum analyzer and the measured value is corrected for the attenuator setting. The correction is necessary since this attenuator will be set to its zero dB indication during the measurements of noise power.

3. Adjust for quadrature of the two signals applied to the mixer. After the carrier power reference has been established, the oscillator under test and the reference oscillator are tuned to the same frequency and the original reference levels that were used during calibration are re-established. The quadrature adjustment depends upon the type of system used. Three possibilities are illustrated in Figure 1.

   a) If the oscillators are very stable, have high resolution tuning, and are not phase-locked, the frequency of one oscillator is adjusted for zero dc voltage output of the mixer as indicated by the sensitive oscilloscope.

b) If the common reference frequency is used, as illustrated in Figure 1, then it is necessary to include a phase shifter in the line between one of the oscillators and the mixer (preferably between the attenuator and mixer). The phase shifter is adjusted to obtain zero dc output of the mixer.

c) If one oscillator is phase-locked using a phase-lock loop, as shown dotted-in on Figure 1, the frequency of the unit under test is adjusted for zero dc output of the mixer as indicated on the oscilloscope.

NOTE: Throughout the measurement process one should check and maintain phase quadrature.

4. Noise power is measured at the selected Fourier frequencies, the calculations are performed, and the data is plotted (or stored) using calculator and program control (fully automated).

5. Measure and plot the system noise floor characteristics if desired.

A plot of the noise floor characteristics is obtained by repeating the measurements with the unit under test disconnected and and the input to the mixer terminated in a matched load.

With the previous indicated offset power level at the mixer input, it is not necessary to change the power level into the mixer. However, if equal power levels are used, then the mixer input level from the reference must be increased to return the mixer output impedance to 50 ohms when the signal is disconnected for a measurement of the noise floor.

Basics of the TRW Metrology Automated System

1. The HP 3330B Synthesizer serves as the local oscillator for the HP 3571A Tracking Spectrum Analyzer. The calculator program controls the switching of the synthesizer to the desired Fourier frequencies.

2. The Fourier frequency increments are chosen to be equal to the selected IF noise bandwidth in order to obtain a continuous spectrum plot.

3. The minimum delay time for a measurement is determined by the IF filter build-up in the spectrum analyzer. The range is from 2.5 seconds for the 3 Hz bandwidth, decreasing to 70 milliseconds for the 10 kHz bandwidth setting.

4. Video smoothing is used in order to obtain a better approximation of the mean. The program can be designed so that a large number of measurements can be taken for better estimation of the mean value. From statistical theory the confidence in an average is improved by the square root of the number of samples.

5. The IF bandwidth settings for the Fourier (offset) frequency range selections are as follows:

IF Bandwidth (Hz)	Fourier Frequency	IF Bandwidth (kHz)	Fourier Frequency (kHz)
3	10 - 400 Hz	1	40 - 100
10	400 Hz - 1 kHz	3	100 - 400
30	1 - 4 kHz	10	400 - 1300
100	4 - 10 kHz		
200	10 - 40 kHz		

Program running time is 27 minutes when using 100 measurements at each Fourier measurement frequency out to 200 Hz.

6. The 60 Hz line frequency interference appears smaller than the actual amplitude if the noise corrections are applied as set forth in the noise measurement program. The corrections for the log amplifier and detection, bandwidth, and equal oscillator contribution should be removed for a plot of discrete frequencies.

7. Amplitude auto-ranging is used in the program to select the most sensitive range that does not result in overload conditions.

The low-pass filter prevents local oscillator leakage power from overloading the spectrum analyzer when baseband measurements are performed at the Fourier (offset) frequencies of interest. Leakage signals will interfere with autoranging and the dynamic range of the spectrum analyzer.

The low-noise, high-gain preamplifier provides additional system sensitivity by amplifying the noise signals to be measured.

Figure 2a illustrates phase-lock characteristics. The generator employs indirect synthesis, whereby, the output frequency is phase-locked to a reference oscillator. Line harmonics were plotted with noise corrections and, therefore, have higher amplitudes than shown.

Figure 2b illustrates a roll-off characteristic near the carrier. This is the effective loop bandwidth of the phase-locking between two similar oscillators which were not adequately isolated from each other. Radio station interference is observed since the measurements were not performed in a screen room.

Figure 3a is a plot of the phase noise of the Hewlett-Packard 5061A Cesium Beam Standard, with the "super tube". Figure 3b is the 5061A with the original tube. The Austron 5 MHz Oscillator (see Fig. 4a) was used as the reference when performing these measurements.

Figure 3c measurements of the Hewlett-Packard 8672A Microwave Synthesizer were performed at 18 GHz. Measurements were performed using two similar units.

Figure 3d is included to illustrate the effects of a phase-lock loop. Two Hewlett-Packard 8640B Signal Generators were measured using a phase-lock loop as illustrated in Figure 1.

Therefore, the oscillator phase noise characteristics are measured only beyond the phase lock-loop.

Figure 4a shows a comparison of measurements performed using the automated Hewlett-Packard 3045 System and the Rockland 512 Fourier Analyzer. The Fourier analyzer measurements were performed from one hertz to 100 kHz.

Figure 4b shows the phase noise characteristics of the Oscilloquartz High Stability Quartz Oscillator.

Figure 4c shows the phase noise characteristics of a frequency stabilized laser amplifier. One phase noise plot was obtained with the laser amplifier on and one plot was obtained when the amplifier was turned off. Two noise floor plots were obtained. One represents the noise floor of the complete system including the laser detector. One noise floor plot was obtained without the laser detector signal.

PHASE NOISE MEASUREMENTS USING DELAY LINE FM DISCRIMINATORS

Frequency fluctuations are measured directly using FM discriminator techniques [5,6,7,8]. One of the important advantages of this type system is that the phase noise characteristics of a single oscillator can be measured without the requirement of a similar or better source as a reference.

The delay line yields a phase shift by the time the signal arrives at the balanced mixer. The phase shift depends upon the instantaneous frequency of the signal. The presence of frequency modulation (FM) on a signal gives rise to differential phase modulation (PM) at the output of the differential delay and its associated (non-delay) reference line. This is the property which allows the delay line to be used as an FM discriminator. In general, the conversion factors are a function of the delay (τ_d) and the Fourier frequency (f), but not the carrier frequency.

The phase variation at the output of the two-channel system represents the same phase variation as if it consists of a noiseless reference signal and another noisy signal which has an equivalent noise at the output of [5]

$$\delta\nu = a[\mathrm{Cos}\ 2\pi f(t - \tau_d) - \mathrm{Cos}\ 2\pi ft] \tag{12}$$

where, in general, (a) is a function of f. The plot of the spectral density of frequency fluctuations is, therefore, periodic in $2\pi f$ and this will be noted in the data plots as a limitation of the range of valid measurement at Fourier frequencies determined by the time delay of the delay line.

The maximum sensitivity of the transmission line discriminator depends upon the attenuation value of the delay line at the carrier frequency [5,7]. Analysis of the basic delay line system indicates that the length of the delay line is chosen so that the total attenuation is one neper (8.686 dB). This optimum value represented the point where the increase in delay was cancelled due to the increase in attenuation of the delay line, i.e., the basic system was power limited [4,6,7]. In our system this limitation does not occur, since we can maintain the mixer input at the desired operating level and provided that there is adequate source output power. The power input to the delay line can be increased to offset the delay line loss.

Figure 6. illustrates the relative sensitivity (noise floor) of phase noise measurement systems. The delay line system sensitivity differs from the two-oscillator system by $(2\pi f\tau_d)^2$ [5]. The power levels at the mixer were the same for each of these plots.

Discriminator Calibrations

The measurement system is shown in Figure 5. The calculator program performs the same functions as outlined for the measurement system of Figure 1. The automated program is used to measure the IF noise power bandwidths of the spectrum analyzer.

The oscillator under test is connected and the signal levels are established for 50 ohm mixer output impedance, as discussed, for the two oscillator technique. The phase shifter is adjusted to obtain phase quadrature of the input to the mixer (i.e., zero volts dc at the mixer output).

In this system Attenuator No. 4 is used to avoid overloading the spectrum analyzer during calibration. Calibration usually requires replacing the oscillator under test with a signal generator or oscillator that can be frequency modulated.

The power output and operating frequency of the generator must be set to the same precise frequency and amplitude values as the oscillator under test.

The source is modulated to produce a known modulation index (m) and the spectrum anlayzer displays a power reading corresponding to the selected modulation frequency. This power reading is corrected for the dB setting of Attenuator No. 4 and the resulting P(dBm) is used to calculate the discriminator calibration factor.

We use a modulation frequency of 20 kHz and adjust the modulation until the carrier is reduced to the first Bessel null of the carrier as indicated on a spectrum analyzer connected to Coupler No. 1.

The calibration factor is defined as:

$$CF = \Delta\nu_{rms}/V_{rms} \qquad [Hz/V] \qquad (13)$$

Where $\Delta\nu_{rms}$ is the rms frequency deviation of the carrier due to the intentional modulation and V_{rms} is the spectrum analyzer voltage measurement of the modulation sideband.

$$\Delta\nu_{rms} = \Delta\nu_{peak}/\sqrt{2} = m(fm)/\sqrt{2} \qquad [Hz] \qquad (14)$$

The calibration factor of the discriminator is calculated as:

$$CF = m\ (f_m)/\sqrt{2}\ V_{rms} \qquad [Hz/V] \qquad (14)$$

The discriminator calibration factor can now be calculated, since this power in dBm can be converted to the corresponding rms voltage using the following equation.

$$V_{rms} = \sqrt{\frac{10^{P(dBm)/10}}{1000} \times R} \qquad [V] \qquad (15)$$

where R is 50 ohms in this system.

The discriminator calibration factor is calculated as,

$$CF = m \cdot f_m/\sqrt{2}\, V_{rms} = 2.405 \cdot f_m/\sqrt{2}\, V_{rms} \qquad [Hz/V] \qquad (16)$$

since 2.405 is the modulation index (m) for the first Bessel carrier null as used in this technique. The modulation frequency is f_m.

Measurement and Data Plotting

After replacing the modulatable source with the unit under test, Attenuator No. 4 is set to zero dB indication and measurements and data plotting are completely automated.

Each Fourier frequency noise power reading P_n (dBm) is converted to the corresponding rms voltage designated as δv_{1rms}.

$$\delta v_{1rms} = \sqrt{\frac{10^{(P_n(dBm) + 2.5)/10}}{1000} \times R} \qquad [V] \qquad (17)$$

the rms frequency fluctuations are calculated as,

$$\delta\nu_{rms} = \delta\nu_{1rms} \times CF \qquad [Hz] \qquad (18)$$

The spectral density of frequency fluctuations is calculated as,

$$S_{\delta\nu}(f) = (\delta\nu_{rms})^2/B \qquad [Hz^2/Hz] \qquad (19)$$

where B is the measured IF noise power bandwidth of the spectrum analyzer.

The spectral density of phase fluctuations is calculated as,

$$S_{\delta\phi}(f) = S_{\delta\nu}(f)/f^2 \qquad [\mathrm{rad}^2/\mathrm{Hz}] \quad (21)$$

The normalized phase noise sideband power spectral density is calculated as,

$$\mathcal{L}(f) = \frac{S_{\delta\phi}(f)}{2\ \mathrm{rad}^2} \qquad [\mathrm{Hz}^{-1}] \quad (22)$$

Script $\mathcal{L}(f)$, expressed in decibels relative to 1 Hz^{-1}, is plotted in real time in our program.

Noise Floor Measurements

The system noise floor can be plotted by setting Attenuator No. 3 to maximum and repeating the automated measurements. We increase the LO power to obtain essentially the same mixer output impedance which exists when both signals are applied. In systems which require different impedance levels, it is necessary that the total input power (Signal and LO) be adjusted to produce the required mixer output impedance. This will require a method of measuring the mixer output impedance and re-estabilishing the particular value when measuring the noise floor.

Noise floor corrections can be performed as previously set forth.

Figure 7a illustrates measurements performed on a fundamental oscillator at 600 MHz multiplied up to 2.4 GHz. Two different delay lines were used. Note that the first null in the periodic plot, beyond the calibrated area, occurs at 2 MHz for the phase noise plot of the 600 MHz fundamental. Therefore, the line has approximately 500 nanoseconds delay. The null on the plot for the 2.4 GHz output is at 4 MHz and thus indicates that this delay line was shorter (approximately 250 ns) than the one used for the 600 MHz measurements.

Figure 7b is a plot of a cavity stabilized Gunn oscillator with an internal crystal oscillator reference. The phase noise plot shows the improvement in characteristics obtained using this phase-locking technique.

Figure 7c shows measurements from within one hertz of the carrier to 25 kHz as measured using the Hewlett-Packard 5420 Digital Signal Analyzer. The measurements agree closely with the continuous plot that was obtained using the automated Hewlett-Packard 3045 System.

Figure 7d is a plot of the AM and PM noise of a Gunn oscillator. The measurements were performed using the single oscillator delay line system described in the paper. The two Gunn oscillators were offset in frequency (37 - 36.2) = 800 MHz and the measurements were, therefore, performed at 800 MHz. This illustrates that the technique can be extended through the millimeter bands.

Measurement Uncertainty

There are many sources of uncertainties associated with phase noise measurement systems and the techniques used in the measurement process. Minimum uncertainty requires precise calibration of the measurement equipment and proper application of that equipment in the measurement process. Analysis of our specific system follows.

		Unc.(±dB)
1.	Power Level Measurements - (Relative to the unit under test when an additional source is used for calibration of the phase/frequency discriminator).	0.05
2.	Hewlett-Packard 3571 Spectrum Analyzer Attenuator - (Reduced from manufacturer's specifications by special calibration).	Range - 0.03 to 0.12 Linearity - 0.01 to 0.25
3.	Hewlett-Packard 355D Step Attenuator - Used in the calibration of the system.	0.06
4.	Mismatch Uncertainty - (associated with setting CW reference level).	0.15
5.	Uncertainty in ±2.5 dB Log/Det Amp. Correction - (This estimation is based on the ability to verify, with traceability, the calibration of the ±2.5 dB stated correction).	0.20
6.	IF Noise Power Bandwidth - (Based on measurements of actual noise power bandwidth).	0.20
7.	Relative IF Bandwidth Gain - (Relative gain between the different IF bandwidths in 3571A).	0.05
8.	Analyzer Frequency Response, 10 Hz to 13 MHz, Referenced to 250 kHz - (Impractical to calibrate out).	0.25
9.	Phase Discriminator Response - (Two-oscillator technique).	0.20
	Frequency Discriminator Response - (Single-oscillator technique).	0.30
10.	Random Error Due to Randomness of Noise - (Can be reduced to this value by averaging).	0.50

11. Setting Modulation Index of the Calibration Source When Calibrating the FM Delay Line Discriminator. 0.10

12. Noise Floor Contribution - (Can be essentially calculated out). 0.2

The uncertainty that can result when performing measurements using the two-oscillator technique has been discussed and must be taken into account in the overall error analysis.

The following calculations are for minimum and maximum uncertainties in measurement of relative measurements. The data represents these considerations, (1) linear summation of all uncertainties, (2) root-sum-square (RSS) of the errors that are small and independent, plus the linear summation of the mismatch uncertainty and the random errors, and (3) RSS of all uncertainties.

	UNCERTAINTY (±dB)			
	Two-Oscillator Technique		Single-Oscillator Technique	
	Min.	Max.	Min.	Max.
Linear Summation	2.01	2.33	2.11	2.43
RRSS (Systematic) + Mismatch + Random	1.14	1.21	1.17	1.26
RSS - All Uncertainties	.72	.77	.75	.80

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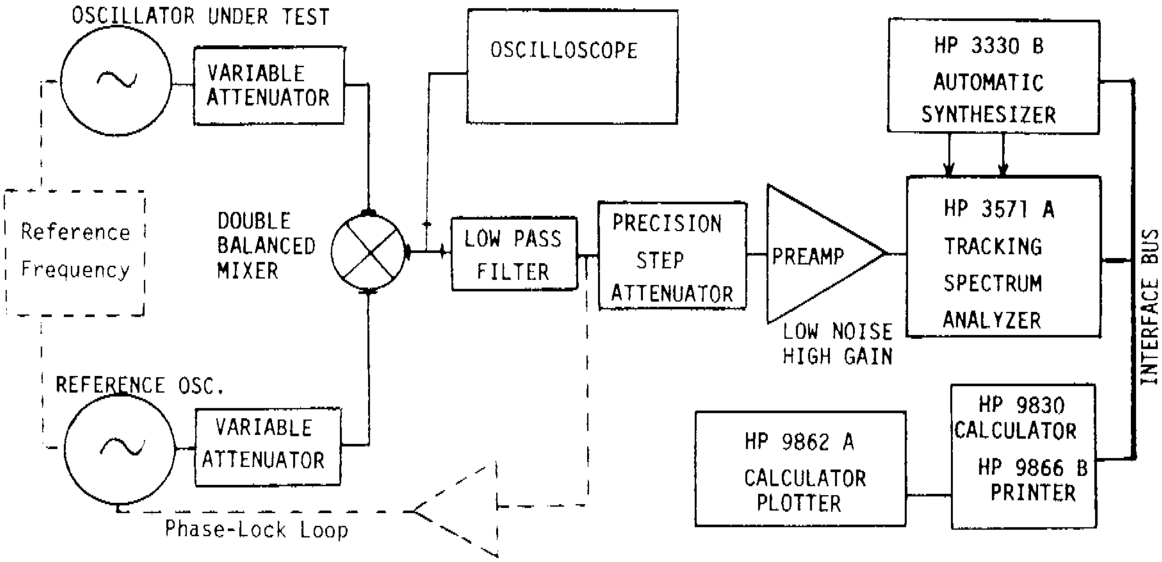
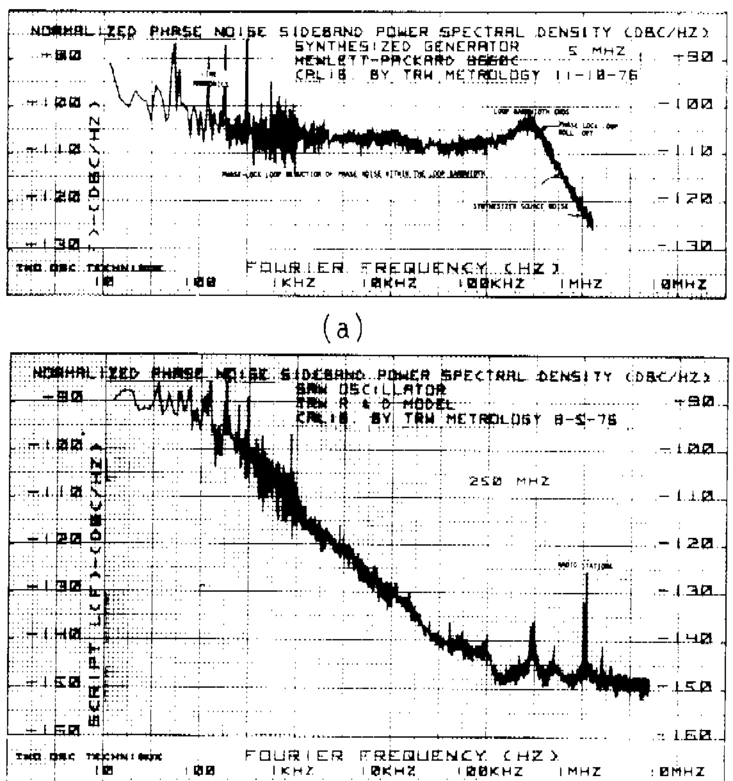
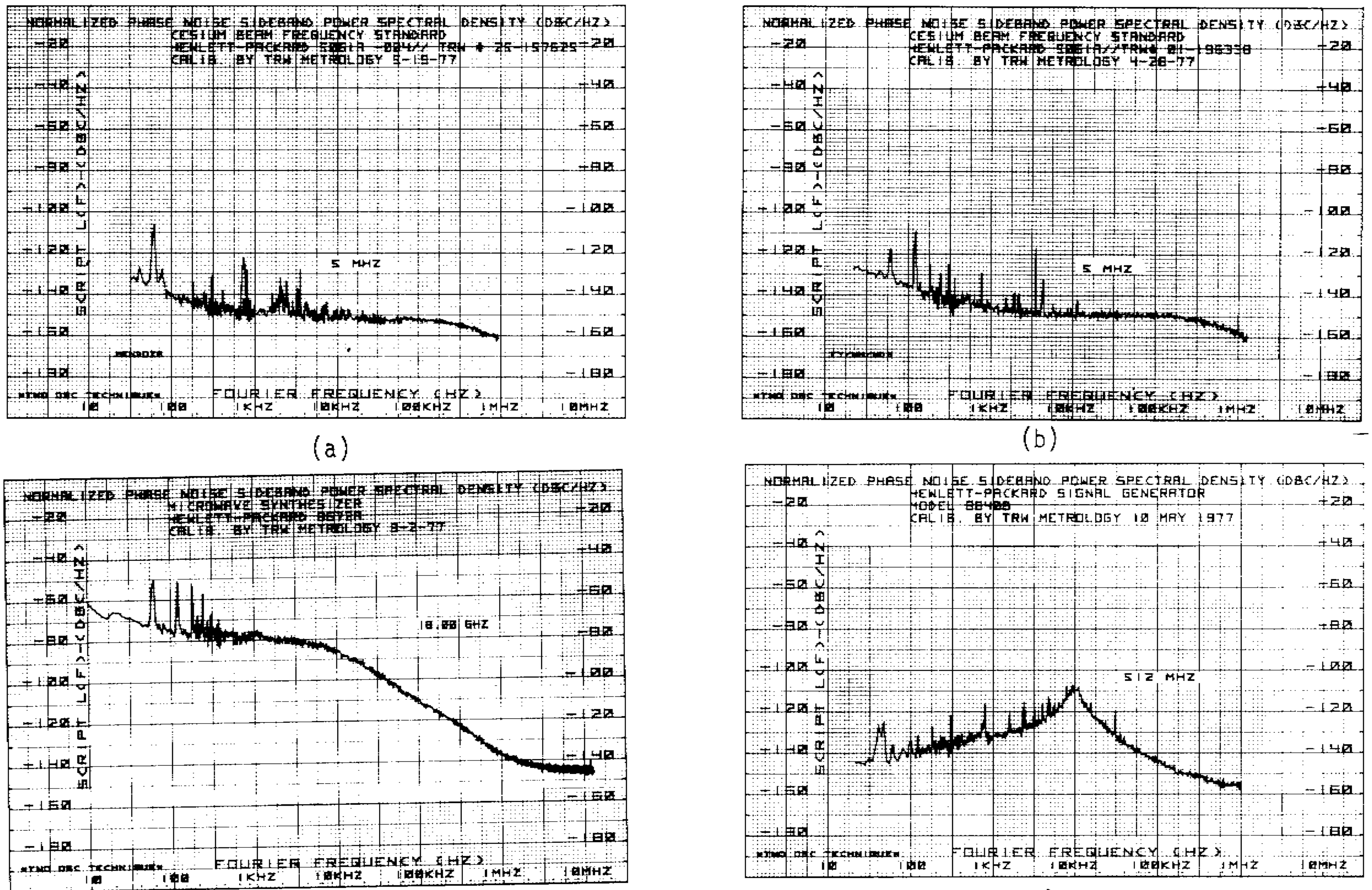


FIGURE 1. PHASE NOISE MEASUREMENT SYSTEM USING THE TWO - OSCILLATOR TECHNIQUE.



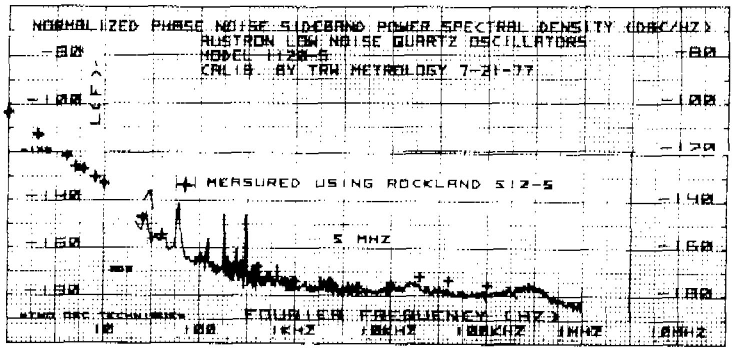
(b)

Figure 2. Phase noise plots. (a) Hewlett-Packard 8660C Synthesized Generator. (b) Surface Acoustic Wave Oscillator.

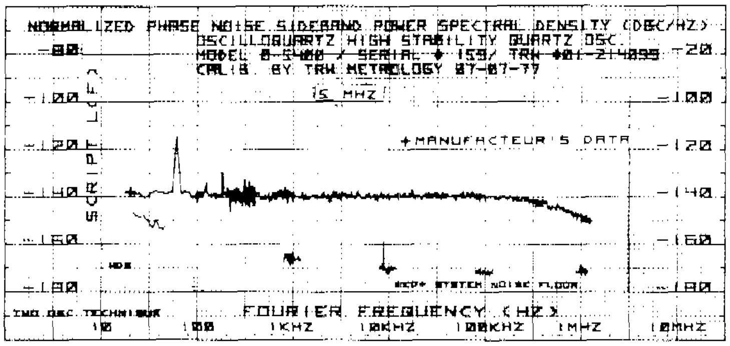


(a) (b) (c) (d)

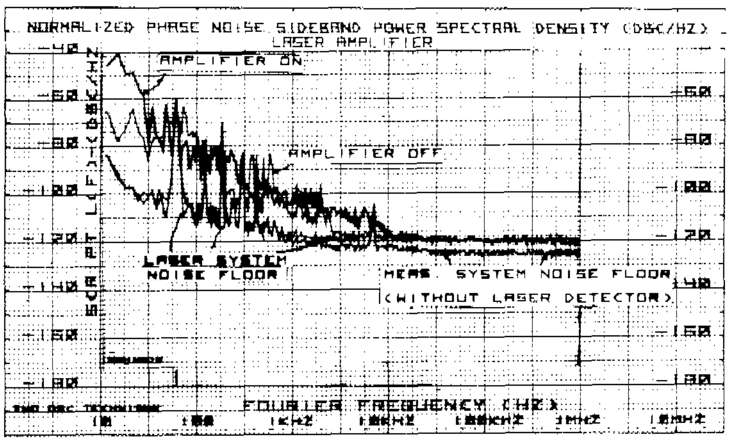
FIGURE 3. Phase noise plots. (a) HP 5061A Cesium Beam Frequency Standard with "Super Tube". (b) HP 5061A (original tube). (c) HP 8672A Synthesizer. (d) HP 8640B Generator.



(a)



(b)



(c)

FIGURE 4. Phase noise plots using the Two-Oscillator technique. (a) Measurements within one hertz of the carrier using the Rockland 512 FFT Analyzer. (b) The Oscilloquartz 3200 High Stability Quartz Oscillator. (c) Laser Amplifier phase noise characteristics.

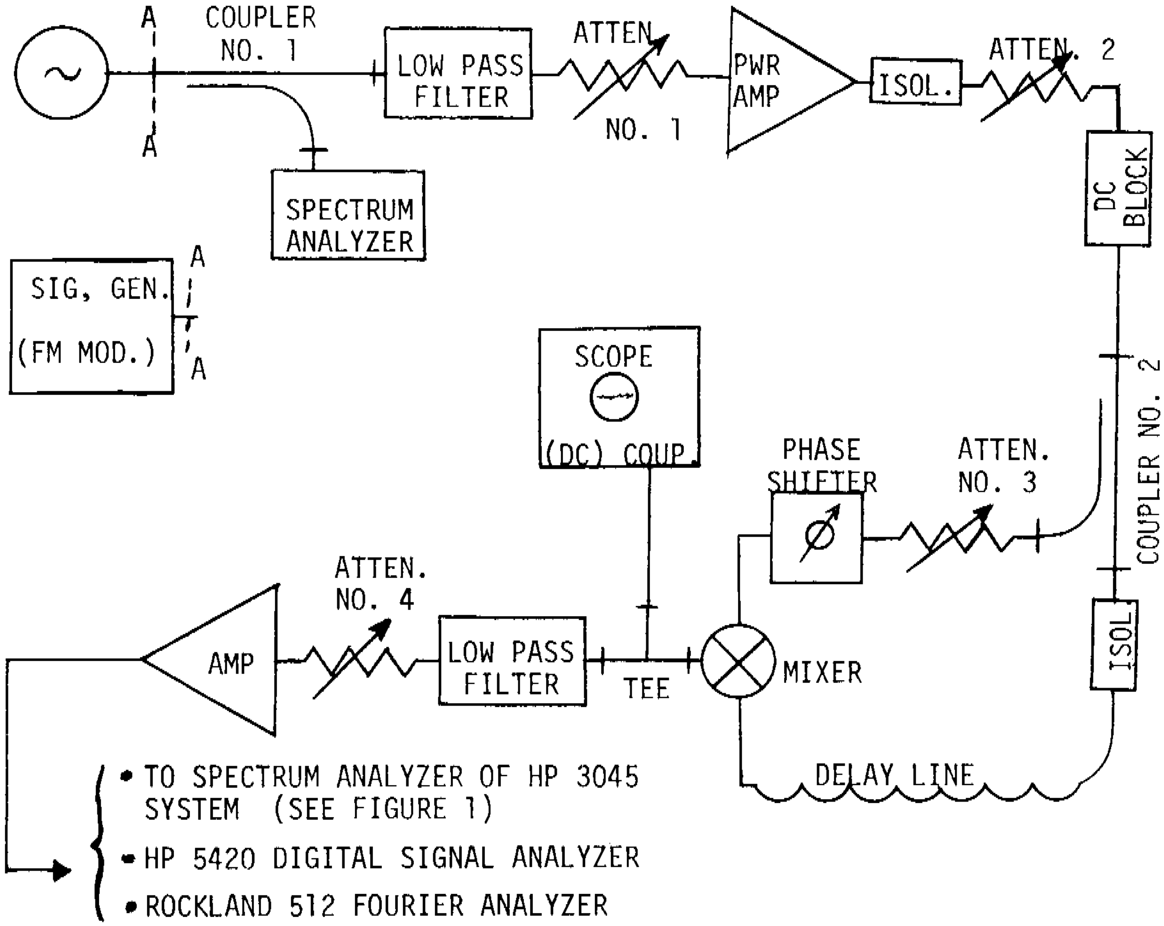


FIGURE 5. SINGLE-OSCILLATOR PHASE NOISE MEASUREMENT SYSTEM USING A DELAY LINE AS AN FM DISCRIMINATOR.

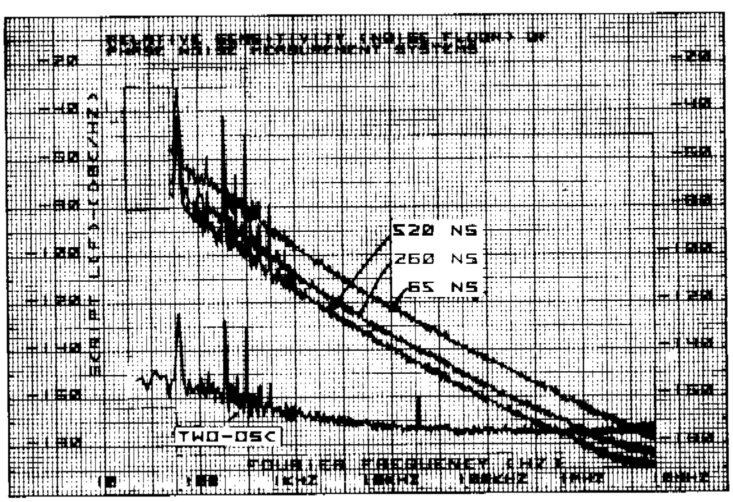


FIGURE 6. Relative sensitivity (noise floor) of phase noise measurement systems.

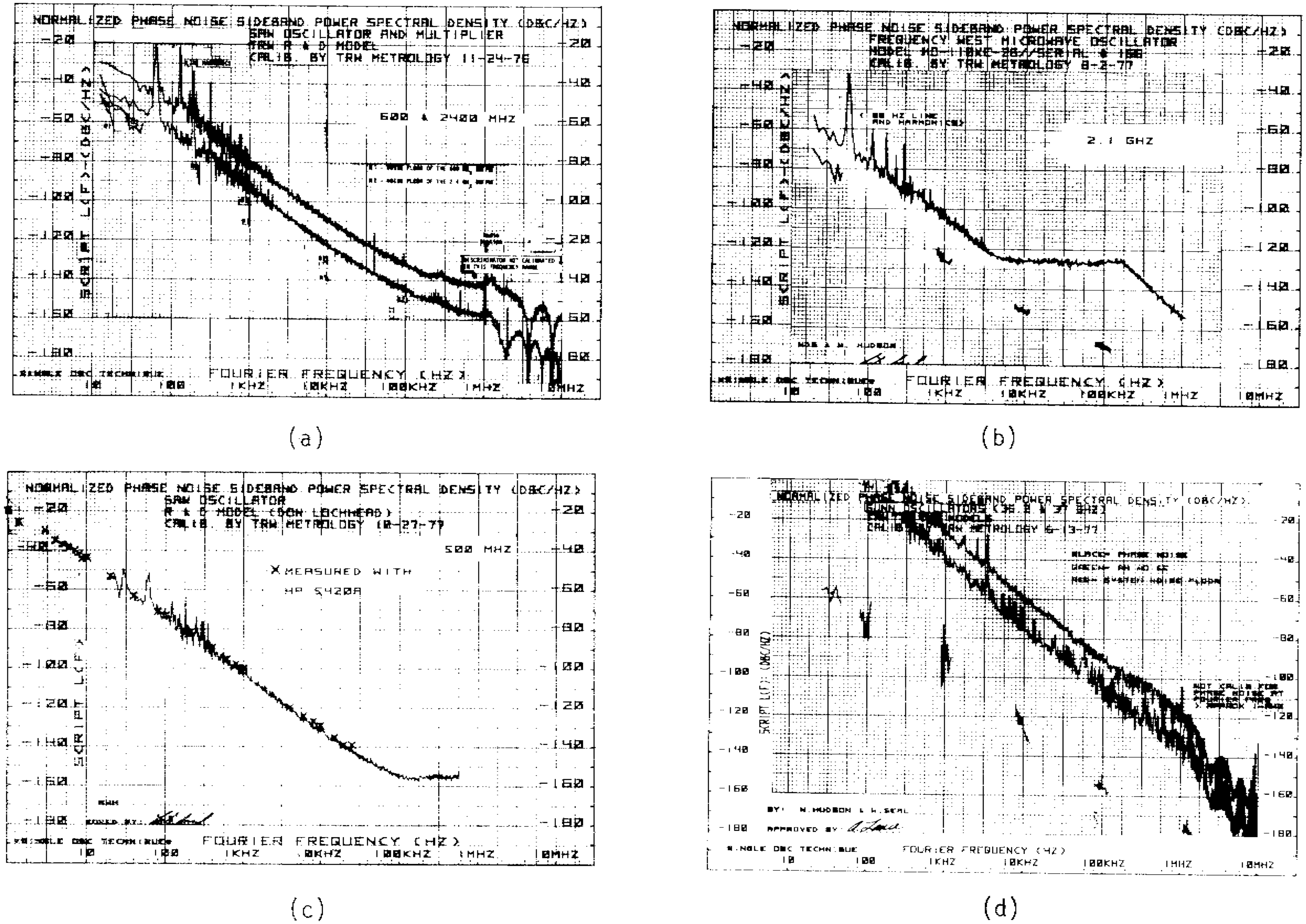


Figure 7. Phase noise characteristics obtained using the single-oscillator measurement technique.