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REDUCING ERRORS, COMPLEXITY, AND MEASUREMENT TIME OF PM NOISE MEASUREMENTS

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Abstract

This paper shows that a new measurement technique based on the two-oscillator technique and the addition of a noise source in series with the reference oscillator can significantly reduce calibration time for accurate PM measurements in oscillators and other components as compared to the traditional two-oscillator technique. This technique also significantly reduces the measurement time and improves the accuracy of 3-cornered-hat measurements. Measurement complexity is greatly reduced. The noise source is used to generate a known level of PM noise (PMCAL) for calibrating the product of mixer sensitivity and amplifier gain with Fourier frequency. This can be used to correct for PLL effects when PMCAL is larger than the residual phase noise in the oscillator under test. PMCAL is typically constant to ± 0.1 dB for Fourier frequencies from 0 to 5% of the carrier (maximum width typically less than 500 MHz). When the PMCAL is off, the noise added to the reference signal is typically less than -150 dBc/Hz at 1 Hz and -190 dBc/Hz at 10 kHz for carrier frequencies of 5 to 100 MHz. A similar system also works in the microwave range.

INTRODUCTION

Many applications require repetitive phase modulation (PM) noise measurements at a few standard frequencies. One of the primary factors limiting the accuracy of the traditional two-oscillator technique is the measurement of the mixer sensitivity and the calibration of amplifier gains versus frequency. The phase-locked-loop (PLL) and the mixer-amplifier interaction can also lead to errors. Changing the oscillator's output power, impedance, or length of the cable changes k_d. As a result the k_d requires a new determination. Correction for amplifier or mixer gain with Fourier frequency usually requires a complex computerized measurement system. Overall accuracy is dependent on operator skill for manual systems and ± 2-4 dB in commercial computerized systems [1].

This paper shows that a new measurement technique based on the two-oscillator technique and the addition of a noise source in series with the reference oscillator can significantly reduce calibration time for accurate PM noise measurements in oscillators and other components as compared to the traditional two-oscillator technique [2,3]. This technique greatly reduces the measurement complexity as well. A Gaussian noise source is used to generate a known level of PM noise (PMCAL) for calibrating the product of mixer sensitivity and amplifier gain with Fourier frequency. This can be used to correct for PLL effects when PMCAL is larger than the residual phase noise in the oscillator under test. PMCAL is typically constant to ± 0.1 dB for Fourier frequencies from 0 to 5% of the carrier (maximum width typically less than 500 MHz). When the PMCAL is off, the noise added to the reference signal is typically less than -150 dBc/Hz at 1 Hz and -190 dBc/Hz at 10 kHz. Insertion losses are typically less than 1 dB.

When the noise in available reference sources and measurements is too high to determine the PM noise in a source, two references equipped with calibrated noise sources can be used in a cross-correlation configuration to reduce the noise contribution of the reference and the noise floor of the measurement system by approximately 15-20 dB. Similar cross-correlation techniques can be applied to the measurement of PM noise in other devices [1,4].

CALIBRATION OF PHASE NOISE IN PRODUCTION OSCILLATORS

A. Traditional Approaches

To show the improvements obtained from this new approach, it is necessary to review the traditional

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approach. Figure 1 shows the block diagram of a traditional measurement configuration for measuring PM noise in oscillators when the noise of the reference oscillator and the measurement system can be neglected [1]. The calibration sequence is:

1. Measure the mixer sensitivity k_d, typically by allowing the oscillators to beat and measuring the period and slope of the waveform at the zero crossings.

2. Phase-lock the oscillators together. If measurements close to the carrier are required, determine the action of the PLL on the phase variations.

3. Measure the power spectral density (PSD) of the noise voltage $V_n(f)$. Table 1 gives the 95% confidence intervals versus the number of averages.

4. Compute $\mathcal{L}(f)$ or $S_\phi(f)$ from
$\mathcal{L}(f) = \frac{1}{2}S\phi(f) = \frac{1}{2}\mathrm{PSD}\ V_n(f)/(k_dG(f))^2$.

Step 4 actually measures

$$S_\phi(f) = S_\phi(f)_{DUT} + S_\phi(f)_{REF} + S_\phi(f)_{MS} + \beta\, S_a(f)_{DUT} + \beta\, S_a(f)_{REF}, \qquad (1)$$

where $S_\phi(f)_{DUT}$ is the PM noise of the device under test (DUT), $S_\phi(f)$ is the PM noise of the reference, $S_\phi(f)_{MS}$ is the noise floor of the measurement system (in this configuration), β is the AM to PM conversion factor of the mixer, $S_a(f)$ is the AM noise of the DUT and $S_a(f)$ is the AM noise of the Reference [1]. The complete error model for the measurement is given in Table 2. The various error parameters are in general dependent on f. Overall accuracy is dependent on operator skill for manual systems and approximately ± 2-4 dB in commercial computerized systems. An oscilloscope or other recording device is usually required to determine k_d.

The measurement of $k_d(f)$ typically takes many minutes and can be one of the major factors limiting the accuracy. Changing the oscillator output level, the driving impedance, or length of the cable changes k_d. As a result a new determination of k_d is measured. Correction for amplifier or mixer gain with Fourier frequency usually requires a complex (often computerized) measurement system.

B. Phase Noise Standard Approach

Figure 2 shows an alternate approach that reduces the calibration time and usually improves the accuracy. A calibrated noise source centered about the carrier frequency has been added to the reference signal using a directional coupler. When the calibrated noise source is off the residual PM noise on the reference signal due to the directional coupler and other components is negligible. The phase noise added when PMCAL is on is typically flat to ± 0.1 dB for Fourier frequencies from dc to about 1/4 the bandwidth of the bandpass filter following the noise source. The calibration of the added phase noise is similar to that developed for the NIST phase noise standards [3] and covered by US patent [7]. This calibration only needs to be done occasionally. We have found ours to be stable to ± 0.3 dB for several years. The calibration procedure now becomes:

1. Phase lock the oscillator under test to the reference oscillator.

2. Turn on the calibrated PM noise. Measure PSD of $V_n(f)_{on} = \mathrm{PMCAL}(k_dG(f))^2$. If the mixer sensitivity and amplifier gain are constant with Fourier frequency, PSD $V_n(f)_{on}$ is a constant above the PLL bandwidth. If measurements need to be taken close to the carrier one can measure $\mathrm{PSDV}_n(f)_{on}$ over the same range to account for effect of the PLL.

3. Turn the calibrated PM noise off and measure PSD of $V_n(f)_{off} = \mathrm{PSD}\ \delta\phi(f)(k_dG(f))^2$.

4. Compute $S_\phi(f)$ from
$S_\phi(f) = \mathrm{PMCAL}(\mathrm{PSDV}(f)_{off}/\mathrm{PSDV}(f)_{on})$.

The error model for this approach is shown in Table 3. The accuracy is approximately ± 0.2 dB ± 0.1-0.25 dB $\pm\ 10 \log(1 + 1.9/N^{1/2})$, where the accuracy of the calibration of PMCAL is typically ± 0.2, the uncertainty of the measurement of $\mathrm{PSDV}_n(f)_{on}$ is ±0.1-0.25 dB, and N is the number of measurements of $V_n(f)$. Changes in amplifier or mixer gain with Fourier frequency, even errors in spectrum analyzer voltage reference and noise bandwidth are calibrated by measuring the ratio of PSD $V_n(f)_{on}$ to PMCAL on the spectrum analyzer. The resulting accuracy of approximately 1 dB exceeds the accuracy of most traditional approaches. The skill required to make the measurements is lower than that for most of the computer controlled systems and much lower than that required for the manual systems. Less

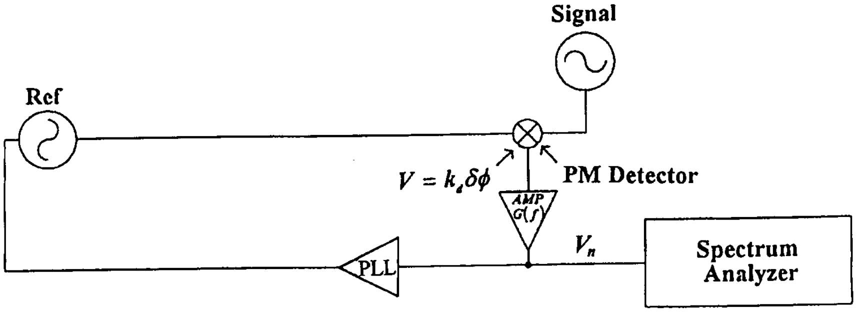

Figure 1. Block diagram of traditional two oscillator measurement system

TABLE 1. STATISTICAL UNCERTAINTY OF SPECTRAL DENSITY MEASUREMENTS

$S_m(f) = S(f)\ [1 \pm k/N^{1/2}]$ for FFT measurements, $S_m(f) = S(f)\ [1 \pm k\ (\mathrm{VIDEO}_{BW}/\mathrm{NRES}_{BW})^{1/2}]$ for swept measurements, k = 1 yields a confidence interval with 68% probability, k = 1.9 yields a confidence interval with 95% probability when the number of samples averaged N is greater than approximately 30, VIDEO_{BW} is the video bandwidth, RES_{BW} is the resolution bandwidth and should be less than f/10. To avoid leakage biases f should be greater than the FFT span/75 for Hanning windows and the FFT span/23 for flat top windows [5].

Number of Samples	k ≃ 1 (approx. 68%)		k ≃ 1.9 (approx. 95%)	
	$S_m = S$ [1±]	$S = S_m$ +dB	$S_m = S$ [1±]	$S = S_m$ +dB
4	0.54	-2 , +3.3	2.5	-3 , +6
6	0.42	-1.5 , +2.3	1.4	-2.5 , +5
10	0.32	-1.2 , +1.7	0.61	-2.1 , +4
30	0.18	-0.72, +.86	0.35	-1.3 , +1.8
100	0.1	-0.41, +0.46	0.19	-0.76, +0.92
200	0.058	-0.24, +0.25	0.14	-0.46, +0.51
1000	0.032	-0.13, +0.13	0.06	-0.26, +0.28
3000	0.018	-0.08, +0.08	0.035	-0.15, +0.15
10000	0.01	-0.04, +0.04	0.019	-0.08, +0.08

TABLE 2. PM ERROR MODEL FOR TRADITIONAL "2 OSCILLATOR" MEASUREMENTS

5 MHz CARRIER, f = 10 Hz to 100 kHz

	TYPICAL (dB)	TIME
1. DETERMINATION OF k_d	0.1	300 s
2. DETERMINATION OF G(f) VERSUS f	0.5-2	--
3. PLL EFFECTS AT LOW f	?	0 - 600 s
4. LINEARITY OF SPECTRUM ANALYZERS	0.1	
5. CONTRIBUTION OF AM	0.05	
6. 95% STAT. CONFIDENCE FOR N = 390	0.4	210 - 780 s
7. ACCURACY OF PSD FUNCTION	0.1	
8. HARMONIC DISTORTION EFFECTS	?	
9. SYSTEM NOISE FLOOR CONTRIBUTION	?	
10. UNFOLDING 3-CORNERED-HAT	?	
TOTAL	1-4 dB	10-30 MIN

TABLE 3. PM ERROR MODEL FOR 2 OSCILLATOR MEASUREMENTS WITH PMCAL

5 MHz, f = 10 Hz to 100 kHz

	TYPICAL (dB)	TIME
1. DETERMINATION OF k_d	0.45	10 s
2. DETERMINATION OF G(f) VERSUS f	INCLUDED	--
3. PLL EFFECTS AT LOW f	?	0 - 230 s
4. LINEARITY OF SPECTRUM ANALYZERS	0.1	
5. CONTRIBUTION OF AM	0.05	
6. 95% STAT. CONFIDENCE FOR N = 390	0.4	210 s
7. ACCURACY OF PSD FUNCTIONS	INCLUDED	
8. HARMONIC DISTORTION	?	
9. SYSTEM NOISE FLOOR CONTRIBUTION	?	
10. UNFOLDING 3-CORNERED-HAT	?	
TOTAL	1 dB	4 - 8 MIN

equipment is also required since one does not need the counter or recording device used to measure k_d in the traditional approach. The measurement of $PSDV_n(f)_{on}$ is typically very fast as well because the noise is approximately white [5,6]. Taking 1000 measurements at 10 kHz using a 100 kHz scan takes an FFT analyzer less than 10 s. This corresponds to a 95% confidence interval of $\pm$ 0.25 dB. This improves to $\pm$0.1 dB by averaging 7 adjacent points [5,6].

C. Cross Correlation Phase Noise Standard Approach

The configuration shown in Figure 3 can be used to improve the noise floor of figures 1 and 2 approximately 20 dB [1,4]. This is useful in cases where the phase noise of the oscillator under test is close to or lower than the reference oscillator or measurement system. Two channels are used to measure the PM noise between the oscillator under test and two independent references, each of which are equipped with the PMCAL technology. Both independent oscillators are phased locked to the oscillator under test. A two channel FFT is used to measure the $PSDV_{n1}$ calibration from channel 1 and the $PSDV_{n2}$ from channel 2. The sensitivity for the cross-spectrum (CS) is the mean of the measured values for channel 1 and 2. The two-channel FFT analyzer measures channel 1, channel 2, and the cross-spectrum simultaneously. The measurement sequence is

1. Phase lock both reference oscillators to the oscillator under test.

2. Turn on the calibrated PM noise in both reference oscillators (PMCAL1 and 2). Measure PSD of $V_n(f)_{on} = PMCAL(k_dG(f))^2$ for both channels at the highest Fourier frequency of interest. If measurements need to be taken close to the carrier one can measure $PSDV_n(f)_{on}$ over the same range to account for effect of the PLL.

3. Turn the calibrated PM noise "off" and measure the $PSDV_n(f)_{off}$ for each channel and the cross spectrum $PSD(V_{n1} \times V_{n2})_{off}$.

4. Compute $S_\phi(f)$ from:

$$S_\phi(f) = PSD(V_{n1} \times V_{n2})_{off}/[k_dG(f)_1(k_dG(f)_2)]$$

$$= PSD(V_{n1} \times V_{n2})/[(PSDV_{n1on}/PMCAL_1)^{1/2} (PSDV_{n2on}/PMCAL_2)^{1/2}].$$

Step 4 actually measures

$$S_\phi(f) = S_\phi(f)_{DUT} + (S_\phi(f)_{REF} + S_\phi(f)_{MS1} + S_\phi(f)_{MS2})/N^{1/2} + \beta S_a(f)_{DUT} + S_a(f)_{REF}. \tag{2}$$

The contributions of the reference and the two measurement systems to the noise floor are reduced by $N^{1/2}$. The accuracy of the measurement is approximately $\pm$ 0.2 dB $\pm$ 0.1-0.25 dB $\pm$ 10 log(1 + {(PSD V_{n1} +PSD V_{n2})/PSD CS}/$N^{1/2}$), where the accuracy of the calibration of PMCAL is typically $\pm$ 0.2, the uncertainty of the measurement of PMCAL for each channel is of order $\pm$ 0.1-0.25 dB.

This accuracy far exceeds the accuracy of traditional three-cornered-hat techniques. First, errors in the calibration of each channel are linear in the resulting estimate of the oscillator phase noise, whereas in a traditional three-cornered-hat the estimate of the oscillator phase noise is derived by subtracting large numbers to obtain a small value. As a result the estimate of the phase noise of the oscillator converges much better (no negative PSDs). Second, the amount of time required for a given accuracy is greatly reduced because only one set of $V_n(f)_{off}$ data is required and the calibration of k_{d1} and k_{d2} is fast. With this approach it is possible to measure an oscillator that is 10 dB better than either reference to a precision of approximately $\pm$ 3 dB with 1500 samples. If the oscillator under test is 17 dB better than the references then 10 000 samples yields a precision of approximately $\pm$ 3 dB. Thirdly, the noise floor of the measurement system is reduced by approximately $N^{1/2}$ as compared to the traditional three-cornered-hat technique.

MEASUREMENT OF PASSIVE COMPONENTS

A. Traditional Approach

Figure 4 shows the block diagram of a traditional setup for measuring the phase noise added by a passive component. The calibration sequence is

1. Adjust the phase shift ϕ so that the dc output voltage of the mixer is nominally 0.

2. Measure the mixer sensitivity k_d, typically by terminating divider B output and substituting another oscillator of equal source impedance and power. The oscillators are allowed to beat and the period and slope of the waveform at the zero crossings measured to determine the slope in volts per radian.

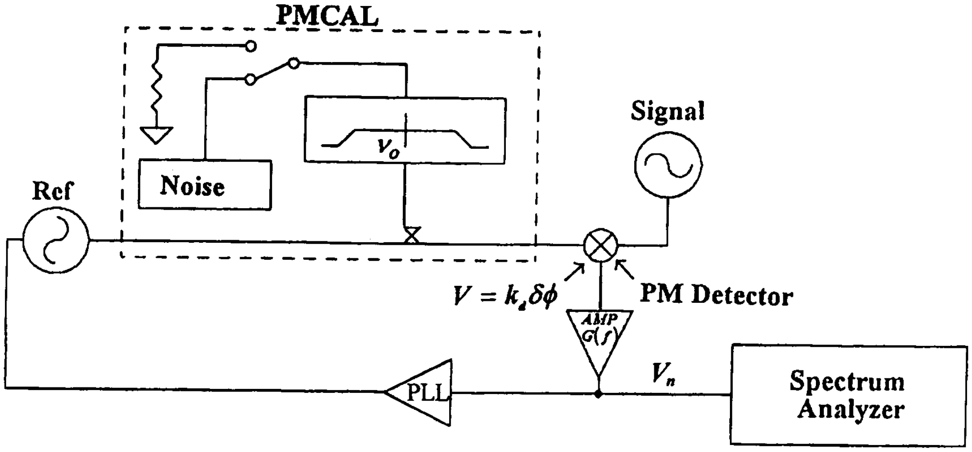

Figure 2. Block diagram of new measurement system using PMCAL to calibrate mixer sensitivity and amplifier gain with Fourier frequency.

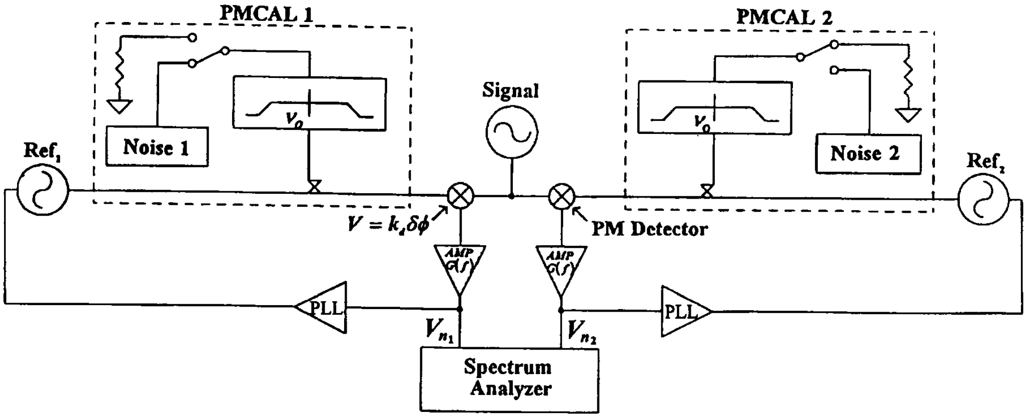

Figure 3. Block diagram of new system for 3-cornered-hat measurements using dual PMCAL noise sources to calibrate mixer sensitivity and amplifier gain with Fourier frequency.

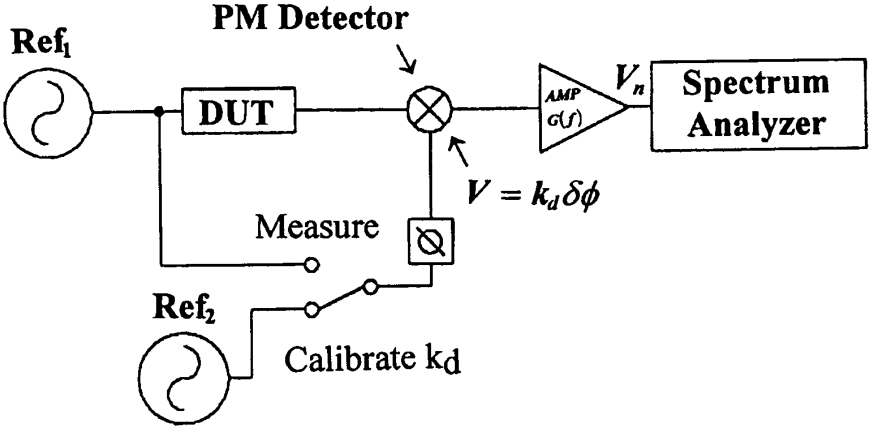

Figure 4. Block diagram of traditional two oscillator measurement system for measuring the phase noise added by a device under test (DUT).

3. Reattach Channel B.

4. Measure the power spectral density (PSD) of the noise voltage V_n.

5. Compute $S_\phi(f) = \text{PSD } V_n/(k_d G(f))^2$.

Step 4 actually measures

$$S_\phi(f) = S_\phi(f)_{DUT} + S_\phi(f)_{MS} + \delta S_\phi(f)_{REF} + \beta\, S_a(f)_{DUT} + \beta S_a(f)_{REF}, \quad (3)$$

where δ takes into account the decorrelation of the PM noise in the reference [1]. The measurement of k_d takes several minutes, and the accuracy depends on the extent that the output level, the driving impedance, or length of the cable used with the substitution oscillator matches the actual drive from divider output B.

B. Phase Noise Standard Approach

Figure 5 shows an alternate approach for this meausrement that reduces the calibration time and usually improves the accuracy. This approach uses the PMCAL technology described above. The added phase noise is typically flat to ± 0.1 dB for Fourier frequencies from dc to about 1/4 the bandwidth of the bandpass filter following the noise source. The calibration procedure now becomes:

1. Turn on the calibrated PM noise. Measure PSD of $V_n(f)_{on} = \text{PMCAL}(k_d G(f))^2$ at the highest Fourier frequency of interest. For 1000 measurements at 10 kHz this typically takes an FFT analyzer less than 10 s. This corresponds to an uncertainty in the measurement of ± 0.25 dB. By averaging 7 adjacent points this improves to ± 0.1 dB. The uncertainty of PMCAL is typically ± 0.25 dB. There are no PLL effects for this measurement.

2. Turn the calibrated PM noise off and remeasure PSD $V_n(f)_{off}$.

3. Compute $S_\phi(f) = \text{PMCAL}(\text{PSD}V_n(f)_{off}/\text{PSD}V_n(f)_{on})$.

The accuracy of this approach is approximately ± 0.2 dB ± 0.1-0.25 dB ± $10 \log(1 + 1/N^{1/2})$, where the accuracy of the calibration of PMCAL is typically ± 0.2, 0.1 is the uncertainty of the measurement of $\text{PSD}V_n(f)_{on}$, and N is the number of averages of V_n. The resulting accuracy summarized in Table 4 of approximately ± 1 dB far exceeds the accuracy of most traditional approaches and it is obtained in a much shorter time.

If the PM noise of the passive component under test is close to or better than the PM noise of the measurement system, cross correlation techniques similar to those described above for oscillators can be used to improve the noise floor by approximately 15-20 dB [1,4].

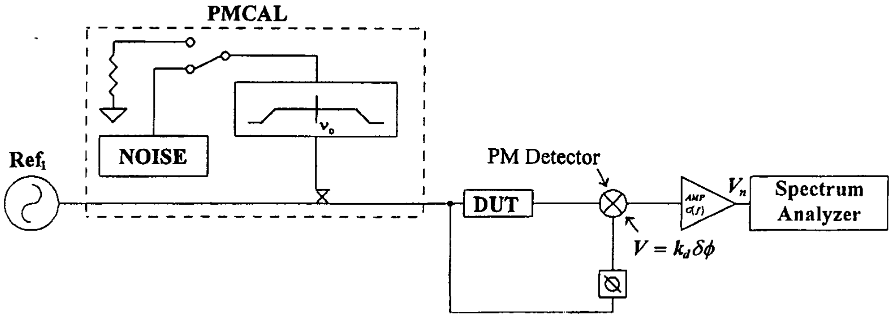

Figure 5. Block diagram of new measurement system for measuring the phase noise added by a device under test (DUT) using PMCAL to calibrate mixer sensitivity and amplifier gain with Fourier frequency.

TABLE 4. PM ERROR MODEL FOR PASSIVE COMPONENTS WITH PMCAL

5 MHz, f = 10 Hz to 100 kHz

	TYPICAL (dB)	TIME
1. DETERMINATION OF k_d	0.45	10 s
2. DETERMINATION OF G(f) VERSUS f	INCLUDED	--
3. PLL EFFECTS AT LOW f	NONE	
4. LINEARITY OF SPECTRUM ANALYZERS	0.1	
5. CONTRIBUTION OF AM	0.05	
6. 95% STAT. CONFIDENCE FOR N = 390	0.4	210 s
7. ACCURACY OF PSD FUNCTION	INCLUDED	
8. HARMONIC DISTORTION	?	
9. SYSTEM NOISE FLOOR CONTRIBUTION	?	
10. UNFOLDING 3-CORNERED-HAT	?	
TOTAL	1 dB	4 MIN

CONCLUSION

Common to all the three new measurement systems discussed is the use of a calibrated noise source to add broadband Gaussian noise to the reference oscillator. By using the existing house standard(s) for the reference(s), we obtain considerable savings over a system that requires new internal references. Significant reduction in the complexity of the measurement process is also obtained. No longer is it necessary to use an elaborate computer program to correct for changes in amplifier gain or PLL effects with Fourier frequency. As a result, measurements can be made much faster than before and will have improved accuracy. Also, both of the oscillator measurements schemes (Figures 2 and 3) can easily be adapted to large scale testing by using a matrix switch to connect the oscillators under test to the measurement system.

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