INTERNATIONAL COMPARISON OF PHASE NOISE

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ABSTRACT

During March of 1993 six different laboratories in three countries participated in phase modulation (PM) noise measurements of the PM noise standard that was developed at the National Institute of Standards and Technology (NIST). Measurements were made at 5 MHz, 10 MHz, and 100 MHz. The four different measurement systems that were used at the six laboratories differed widely in their approach to the measurements and in the degree of automation. The agreement of the PM noise at 5 and 10 MHz were typically better than ±1 dB. The difference between the PM noise at the beginning and end of the trip was 0.2 dB at 5 and 10 MHz and 0.5 dB at 100 MHz. The results at 100 MHz were substantially worse, up to 3 dB, depending on details of the measurements. The source of the error was traced to an interference between harmonics of the 100 MHz with the reference signal. When the harmonic distortion was eliminated, the measurement error dropped to approximately 0.2 ± 0.5 dB. The initial error at 100 MHz was much larger than anticipated, indicating that the sensitivity in some measurement systems to harmonic distortion is substantially larger than previously documented. Based on the intercomparisons and earlier work at NIST, a detailed error model for PM noise measurements is presented.

1. NIST, Boulder, USA
2. LHA-CNRS, Orsay, France
3. ENSMM-LCEP,Besancon, France
4. LPMO-CNRS, Besancon, France
5. Observatoire de Neuchatel, Switzerland
6. Swiss Telecom PTT Research and Development, Bern, Switzerland

1. INTRODUCTION

In the past it has been difficult to evaluate the accuracy and noise floor of phase modulation (PM) noise measurement equipment because no artifact standards were available. Comparisons of measurement systems in different laboratories using commercially available oscillators as transfer standards were typically limited to a repeatability of roughly ±3 dB due to the temporal variability of the oscillator noise. Recently a new portable secondary standard and associated measurement techniques for evaluating the noise floor and accuracy versus Fourier frequency of PM and amplitude modulation (AM) noise measurement systems were developed at NIST [1,2]. Evaluations of these new PM/AM noise standards at 5, 10, and 100 MHz yield an accuracy of better than 0.2 dB, a temperature coefficient of less than 0.02 dB/K, and a stability of better than 0.4 dB over 1 y. One of these new PM noise standards was used to compare the accuracy and noise floor of PM noise measurements at six different laboratories in three countries at the time of the 1993 European Frequency and Time Forum (EFTF). This paper reports on the results of these measurements and the insight into possible errors in PM noise measurements. We present an error model which describes all of the commonly encountered errors in such measurements. These measurements in the six laboratories, which used the two-oscillator technique for measuring PM noise, demonstrate that by taking all of these possible error parameters into account, it is possible to make reliable accurate measurements to better than 1 dB.

2. NIST AM/PM NOISE STANDARD

The design of the new NIST AM/PM noise standard is described in detail in reference [1]. Figure 1 shows a simplified block diagram of the PM/AM noise standard model PMAM 115 used for these PM noise comparisons. A frequency source with very low PM and AM noise is regulated in amplitude and divided into the reference and signal outputs using a reactive power splitter. The amplitude and phase of these outputs track one another with great fidelity. The residual differential PM noise between the two outputs, when the noise source is off, is much smaller than the PM noise of the source. The ratio of the differential PM noise to the source PM noise can approach -100 dB at low Fourier frequencies, degrading to approximately -16 dB at $f = \nu/10$ [3], where ν is the carrier frequency. At 10 MHz, for example, the differential phase noise between the two channels, $S_\phi(10\text{ kHz}) = -194$ dB relative to 1 rad^2/Hz. This feature is used to measure the noise floor of PM noise measurement systems.

A broad band power combiner can be used to add passband-limited Gaussian noise to a carrier. The added noise is roughly 40 dB above the noise floor of most measurement systems and 60 dB above the residual noise between the two signals. A switch can be used to change the noise power by 19.8 dB. This results in a spectral density of PM noise $S_\phi(f)$ given by

$$S_\phi(f) = \frac{PSDV_n(f)}{2V_0^2} \qquad (1)$$

where V_0 is the amplitude of the carrier, and $PSDV_n(f)$ is the power spectral density of voltage noise at Fourier frequency $\pm f$ from the carrier. $S_\phi(f)$ is constant from dc to approximately 10% of the carrier frequency. Within 100 kHz of the carrier $S_\phi(f)$ is flat to ± 0.05 dB. Since there is no phase coherence between the signal and the noise, the resulting modulated output has precisely equal AM and PM noise. These noise spectra can be made very nearly constant over a very wide temperature range by stabilizing the carrier and the noise separately using traditional approaches. If necessary, a phase shifter can be used to provide a 90° phase shift between the reference and modulated output. Measuring $PSDV_n(f)$ and V_0^2 separately provides, by Eq. (1), a primary calibration of $S_\phi(f)$. The accuracy of this calibration process is 0.2 dB [2]. This feature is used to evaluate the accuracy of PM/AM noise-measuring equipment as a function of Fourier frequency. The nominal PM noise of the source, the residual PM noise between the two outputs, and the calibrated PM levels versus Fourier frequency at 5, 10, and 100 MHz are listed in Table 1.

Implicit in these discussions is the assumption that the phase detector in the PM noise measurement system under test has sufficient discrimination against AM noise that the AM noise does not bias the PM noise measurements. These assumptions are not excessively restrictive since many devices to be calibrated also have similar PM and AM noise [3,4]. Discrimination of 15 dB reduces the unwanted effects below 0.14 dB. This discrimination level is easily met by virtually all AM and PM noise measurement techniques in use today [3,4] (typical levels of discrimination are 25 dB for PM and even higher for AM measurement systems.)

3. PM NOISE MEASUREMENTS AT 6 DIFFERENT LABORATORIES

The NIST PM/AM noise standard was evaluated using the method described above at NIST on 11 March, 1993 prior to the trip to Europe and on 1 April upon return. Several additional calibrations were made during the trip. The standard was delivered to each of the laboratories for determination of the PM noise for Fourier frequencies from roughly 10 Hz to 100 kHz. None of the laboratories participating in these measurements knew the expected PM noise within ±5 dB until after they had completed their measurements. They were free to measure the PM noise at roughly -110 or -130 dBc/Hz. Each laboratory used their own set of parameters to evaluate possible bias terms.

3.1 PM NOISE MEASUREMENTS AT LABORATOIRE DE L'HORLOGE ATOMIQUE, ORSAY

The PM noise standard was delivered to the Laboratoire de l'Horloge Atomique-CNRS on 13 March and allowed to warm up for about 2 h. Measurements of noise floor and calibrated PM noise were made at 5, 10, and 100 MHz using their custom PM noise measurement system and a Scientific Atlanta 380 Fast Fourier Transform (FFT) spectrum analyzer.[1] A simplified block diagram of the measurement configuration is shown in Figure 2. All control of this system is manual. An external substitution source at approximately the same level as the reference frequency output was used to obtain a beat frequency to calibrate the mixer sensitivity k_d multiplied by the post amplifier gain $G(f)$ at the zero crossing [3,4]. Figure 3 shows a typical wave form and the method of calculating $k_dG(f)$ using an oscilloscope or other recording device. The conversion from radians to volts at the output of the amplifier was about 650 V/rad at 5 and 10 MHz and about 250 V/rad at 100 MHz. Generally 800 averages were taken for the PM noise data at all three carrier frequencies.

The results obtained for the calibrated PM noise and the noise floor are summarized in Tables 2 to 4. Figure 4 shows the raw data for the measurement of the NIST PM noise standard at 5 MHz versus Fourier frequency. At Fourier frequencies of less than 20 kHz, the difference between the measured PM noise and the NIST PM standard is under 1 dB at carrier frequencies of 5 and 10 MHz. The 3 dB differences at 100 MHz is unexpectedly high. See section 3.5 for a

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[1] Certain measurement equipment is identified to properly document the measurement configuration and does not imply endorsement by any author or laboratory.

discussion. The 95% confidence interval for 800 averages is approximately ± 0.26 dB. The noise floor of the measurement system is low enough that it does not bias these results.

3.2 MEASUREMENTS AT ECOLE NATIONALE SUPERIEURE DE MECANIQUE ET DES MICROTECHNIQUES, BESANCON

The PM noise standard was delivered to the ENSMM-LCEP and allowed to warm up for about 1 h. Measurements of both noise floor and the calibrated PM noise level were made at 5, and 10 MHz using a FemtoSecond FSS600 PM noise measurement system and an HP3561A FFT spectrum analyzer. All control of this system is manual. The measurement configuration was similar to that shown in Figure 2. An external substitution source at approximately the same level as the reference frequency output was used to obtain a beat frequency to calibrate $k_dG(f)$ at the zero crossing. An oscilloscope was used to measure the phase slope. The results for the calibrated PM noise and the noise floor are summarized in Table 2. The IF response of this system is extremely flat with Fourier frequency. The 95% statistical confidence interval for the 5000 averages recorded for $f = 1$ kHz, 10 kHz, and 100 kHz is approximately ± 0.12 dB. The 95% statistical confidence interval for the 1000 averages recorded for $f = 10$ and 100 Hz is approximately 0.27 dB. The difference between these PM measurements at 5 and 10 MHz and the NIST PM standard are less than 0.5 dB. The noise floor of the measurement system is low enough that it does not bias these results. No measurements were taken at 100 MHz.

3.3 MEASUREMENTS AT THE OBSERVATOIRE DE NEUCHATEL, NEUCHATEL

The PM noise standard was delivered to the Observatoire de Neuchatel and allowed to warm up for about 1 h. Measurements were made at 5, 10, and 100 MHz using a HP3048A PM noise measurement system. The measurement configuration was similar to that shown in Figure 2. All measurements on this system are controlled by a computer once the initial setup is completed. The maximum number of averages possible with the software was 200. The 95% confidence interval for 200 averages is approximately ± 0.5 dB. An external substitution source at approximately the same level as the reference frequency output was used to obtain a beat frequency to calibrate $k_dG(f)$ at the zero crossing. The rf power was adjusted so that the beat signal was a sine wave. The peak value of the sine wave is then equal to k_d. The phase noise data were then taken with this reduced power for the mixer. The disadvantage of using this simple method for determining $k_dG(f)$ is that the noise floor is somewhat higher than can be obtained by driving the mixer closer to its maximum ratings. This can be seen by comparing the noise floor of this configuration with that obtained in the next two tests. The results for the calibrated PM noise and the noise floor are given in Tables 2 and 3. Figure 5 shows the measurement of the calibrated PM noise at 10 MHz. The effect of a small number of averages on the measurement uncertainty is clearly visible. The IF response of this and the other two HP3048A systems was very nearly flat with Fourier frequency. The small number of averages that was possible with the automated system precluded looking at this effect with high resolution. A modified software package is now available for these systems that greatly increases the number of averages that can be taken [5]. The difference between these measurements and the calibrated PM noise of the NIST standard at 5 and 10 MHz are less than 1 dB. Measurements made at 100 MHz as described above for 5 and 10 MHz, yielded values that were about 3 dB low. The probable cause of this error at 100 MHz is discussed in Section 3.5. The noise floor of the measurement system is low enough that it does not bias these results.

3.4 MEASUREMENTS AT LABORATOIRE DE PHYSIQUE ET METROLOGIE DES OSCILLATEURS, BESANCON

The PM noise standard was delivered to the LPMO-CNRS and allowed to warm up for about 1 h. Measurements were made at 5, 10, and 100 MHz using a HP3048A PM noise measurement system. The measurement configuration was similar to that shown in Fig. 2. All measurements on this system were controlled by a computer once the initial setup was completed. The maximum number of averages possible with the software was 200 [5]. This results in a 95% confidence interval of approximately ± 0.5 dB. A substitution source at the same level of the reference frequency output was used to obtain a beat frequency to calibrate $k_dG(f)$ at the zero crossing. The measurement of the PM of the NIST standard at 10 MHz is shown in Fig. 6. The results for the calibrated PM and the noise floor are given in Tables 2 and 3. The difference between these measurements at 5, 10, and 100 MHz and the calibrated PM noise of the NIST standard are 1 dB or less. The large biases seen at LHA and Observatoire de Neuchatel are absent; see Section 3.5 for a discussion. The noise floor of the measurement system is low enough that it does not bias these results.

3.5 MEASUREMENTS AT SWISS TELECOM PTT, BERN

The PM noise standard was delivered to the laboratory of the Swiss PTT Telecom and allowed to warm up for about 1 h. Measurements were made at 5, 10, and 100 MHz using a HP3048A PM noise measurement system. The measurement configuration was similar to that shown in Figure 2. All measurements on this system were controlled by a computer once the initial setup was completed. The maximum number of averages possible with the software was 200 [5]. This results in an approximate 95% confidence interval of ± 0.5 dB. As with the other HP3048A systems, a substitution source at approximately the same level of the reference frequency output was used to obtain a beat frequency to calibrate $k_dG(f)$ at the zero crossing. The results for the calibrated PM level and the noise floor are given in Tables 2-4. The results at 100 MHz are shown in Fig. 7. The difference between the measurements at 5, 10, and 100 MHz are less than 1 dB when measuring a PM noise at about -128 dBc/Hz. Measurements at a level 20 dB higher indicated significant errors similar to those seen at LHA and Observatoire de Neuchatel. The noise floor of the measurement system is low enough that it does not bias these results.

The occasional errors for the PM noise measurements at 100 MHz of approximately 0-4 dB were quite perplexing. Figure 8 shows the spectrum analysis of the 100 MHz signal. The distortion at 200 and 300 MHz, while relatively large, seemed too small to explain the discrepancies. To explore the cause of the 100 MHz errors, the 100 MHz carrier was reduced 7 dB prior to the power amplifier, which reduced the harmonic content by more than 10 dB. The PM noise standard was recalibrated using the technique of [2] and the PM noise remeasured with the HP3048A. These measurements are shown in Table 4. The agreement with the primary calibration is excellent. To further test the role of the harmonics, a 135 MHz low-pass filter was used to eliminate the higher harmonics. A new primary calibration was carried out and the measurements with the HP3048A repeated. The results are given in Table 4. Again with the harmonics removed, the agreement with the primary calibration is excellent.

The errors in the 100 MHz PM noise calibrations was explored by Bob Temple of HP. He noted that the spectrum in Fig. 8 showed the PM noise on only the 100 MHz signal and not on the higher harmonics. If the higher harmonics were phased just right they could increase the value of k_d leading to an underestimation of the PM noise because the high harmonics contributed to k_d but not to the measured PM noise. He was able to show qualitatively that the presence of the second, third, and higher harmonics could cause the problem and that the error was to indicate a smaller PM noise than was actually present. If the second and third harmonics are more than 35 dB below the fundamental, this effect is negligible. This effect is about an order of magnitude higher than previously reported [3] and changes from one phase detector family to another and as a function of input drive. It may also depend on the IF termination. It is quite likely that this effect has caused errors in many previous measurements.

4. ERROR MODEL

Table 5 shows the various parameters which appear to be the most important contributors to errors and uncertainties in the measurement of PM noise. The first term is the bias and uncertainty in the determination of k_d. Errors in this parameter originate from errors in measuring the slope of the zero crossing (see Fig.3). It is most important that both the positive and negative going slopes be measured. It they differ by more than about 10% it indicates excessive injection locking between the two sources or possibly a damaged phase detector. Another bias occurs when a substitution oscillator is used, as in the measurements described here, which has an output power level and/or impedance that is different from the original source. Another common error is the use of a different length of coaxial cable, when determining k_d, than is used to take PM noise data. The cable transforms the apparent impedance of the mixer as seen by the source. If the voltage reference of the oscilloscope or other recording device used to determine k_d does not agree with the spectrum analyzer to measure $PSDV_n$, there will be additional errors. k_d may depend on frequency if the IF port is not terminated in 50 Ω for the rf signals [4].

The second term comes from the bias and uncertainty in measuring the amplifier gain G(f) versus Fourier frequency. The mixer output impedance is a function of frequency and power [4] making it difficult to always achieve a good match to the low-pass filter and the post-amplifier. As f increases, G(f) may depend on the cable and the impedance of the spectrum analyzer.

The third term comes from the bias and uncertainty in determining the effect of phase-locked-loops (PLL) on the phase noise at Fourier frequencies near or below the bandwidth of the loop [4]. We can estimate the effect of the PLL on the phase response from measurements of the mixer sensitivity, oscillator tuning rate, and PLL gain. Often this approach is not satisfactory because the oscillator under test has a low pass filter in the control path that affects the loop response. The only secure way to account for this effect is to measure the loop response as a function of f. In most of the measurements discussed above, no PLL was needed, so this problem was not an issue. Several PM noise determinations at LPMO and at PTT did, however, measure the PM noise of the NIST standard against an external oscillator and PLL effects had to be taken into account by the computer software.

The fourth term comes from conversion of AM noise, in one or both of the signals under test, to apparent PM noise by the mixer and any other nonlinear element. The rejection of AM noise by most PM noise measurement systems is of order 15 to 25 dB. This is sufficient only when the AM noise is equal to or smaller than the PM noise to be measured. Therefore no PM noise measurement is complete until the AM noise and the AM to PM conversion factor have been measured. In many synthesizers and complex sources where the output power is leveled, the AM noise is actually larger than the PM noise. This is usually not a serious issue in simple oscillators [6,7].

The fifth term comes from the error in measuring both k_d and PSDVn in the presence of harmonic distortion in either the source under test or the reference oscillator. We have seen above that this can lead to errors of order 4 dB even when the distortion is less than -16 dBc. A good rule of thumb is to keep the harmonic content below -35 dBc.

The sixth term is due to the contribution of the system noise floor to the measured noise. Since the noise floor depends on k_d through the rf and LO drive power, these should be recorded for all measurements along with k_d. No measurement is complete without a determination of system noise floor relative to the PM noise to be measured. In some cases cross-correlation techniques can be used to reduce the contribution of system noise floor [8].

The seventh term is due to noise in the reference signal biasing the measurements of the device under test. By measuring the PM noise between three oscillators of comparable PM noise, output power, and impedance, we can generally reduce the contribution of the reference oscillators to the determination by about 6-10 dB [4]. The noise floor of the measurement system still contributes. Better cancellation of both the reference and system noise can be obtained by using cross-correlation because the measurements are made simultaneously. Both reference and system noise average towards zero as $1/\sqrt{N}$ where N is the number of averages

[4,8]. It is not uncommon to obtain a factor of 15-20 dB improvement in measurement noise floor using this approach [6,7].

Confidence intervals (term 8) of the FFT spectral density data are shown as a function of the number of averages in Table 6. The confidence intervals are independent of the noise type as long as the measurement bandwidth is small compared to the Fourier frequency, f. This requirement is satisfied if f is larger than the frequency span/75 for the Hanning window and f/23 for the flat top window [3,4].

The accuracy and linearity of modern spectrum analyzers (terms 9 and 10) limit the accuracy of these measurements to about ±0.2 dB unless special calibrations are performed on the instruments.

5. CONCLUSION

PM noise measurements of a NIST PM noise standard made in six different laboratories using four different measurement configurations demonstrate that with careful attention to detail and the use of the error model given in Table 6, it is possible to make PM noise measurements that are accurate to ± 1dB. An accuracy of approximately ±0.5 dB appears possible if more attention is paid to the harmonic content of the signals. We have used these results to make the first precise international comparison of PM noise between laboratories.

6. ACKNOWLEDGMENTS

We thank Bob Temple for his help in analyzing the errors in the PM measurements at 100 MHz. F. L. Walls thanks Tom Parker and John Lowe for helpful comments and all the participating laboratories for their hospitality and enthusiasm in making these comparisons.

7. REFERENCES

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TABLE 1. System noise floor and phase noise of sources

NOMINAL SOURCE PHASE NOISE/CHANNEL, ±3 dBc/Hz								
FOURIER FREQUENCY								
SOURCE FREQUENCY	1 Hz	10 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
5 MHz	-121	-151	-163	-171	-174	-174	-174	
10 MHz	-115	-145	-157	-165	-168	-168	-168	
100 MHz	-70	-100	-130	-156	-170	-170	-173	-173
MAXIMUM RESIDUAL NOISE BETWEEN CHANNELS, dBc/Hz								
5 MHz	-162	-172	-182	-190	-194	≤-175	≤-175	
10 MHz	-161	-176	-183	-191	-197	≤-175	≤-175	
100 MHz	-152	-162	-172	-182	-193	≤-175	≤-175	≤-175
DIFFERENTIAL PM/AM NOISE, ±0.2 dBc/Hz Attenuation 19.8 dB, 11 March 1993								
5 MHz	-127.3	-127.3	-127.3	-127.3	-127.3	-127.3		
10 MHz	-128.4	-128.4	-128.4	-128.4	-128.4	-128.4	-128.4	
100 MHz	-129.5	-129.5	-129.5	-129.5	-129.5	-129.5	-129.5	-129.8

TABLE 2. Summary of PM noise calibration by participating Frequency Laboratories

FREQUENCY LABORATORY

	NIST 11 March	LHA 13 March	ENSMM 15 March	NIST 15 March	OBS NEU 15 March	LPNO 19 March	NIST 20 March	PTT 20 March	NIST 1 April	AVG NIST
5 MHZ	-127.3	-128.0	-127.0	-127.6	-127.2	-126.3	-127.5	-127.5	-127.5	-127.48
10 MHZ	-128.4	-128.5	-128.6	-128.2	-127.4	-128.5	-128.3	-128.5	-128.5	-128.35
100 MHZ	-129.5	-126.3			-132.5	-129.3	-129.8	-129.6	-129.0[1]	-129.43[1]

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[1] value may be biased because standard was modified at PTT for experiments discussed in Sectors 3.5 and Table 4 and then reassembled.

TABLE 3. Noise floor at 5, 10, AND 100 MHz
at participating laboratories vs Fourier frequency

LABORATORY	FOURIER FREQUENCY (Hz)				
Carrier Frequency	10	100	1K	10K	100K
LHA - CNRS					
5 MHZ	-153	-162	-171	-176	-177
10 MHZ	-153	-163	-172	-179	-179
100 MHZ	-146	-156	-166	-170	-171
ENSMM-LCEP					
5 MHz	-151	-160	-166	-175	-178
10 MHZ	-156	-165	-172	-179	-179
OBSERVATOIRE DE NEUCHATEL					
5 MHZ	-149	-158	-168	-174	-177
10 MHZ	-149	-160	-171	-176	-177
100 MHZ	-153	-163	-172	-175	-176
LPMO - CNRS					
5 MHZ					
10 MHZ	-158	-167	-174	-177	-178
100 MHZ	-156	-167	-176	-178	-179
SWISS TELECOM PTT					
5 MHZ	-153	-163	-172	-176	-178
10 MHZ	-159	-169	-176	-179	-180
100 MHZ	-157	-167	-177	-181	-181

TABLE 4. PM noise comparisons at 100 MHz for various configurations

Carrier (MHz)	NIST 11 March	NIST 20 March	NIST 1 April	PTT 20 March	Notes
100	129.5	-129.8	-129.0	-129.6	Fig. 2 without PLL
100	-109.7	-110.0	109.2[3]	-111.3	vs HP8663
100	-109.7	-110.0	109.2[3]	-112.3	vs HP8663
100		-106.2		-106.3	1
100		-110.2		-110.0	2

1. 100 MHz signal reduced 7 dB before output amplifier at 100 MHz.
2. Note 1 plus 135 MHz low pass filter yielding harmonics <-70 dBc.
3. Measured after NIST system reassembled following notes 1 & 2.

TABLE 5. Error model for PM noise measurements

1. Determination of k_d
2. Determination of Amplifier G(f)
3. PLL Effects (if any)
4. Contribution of AM Noise
5. Harmonic Distortion
6. Contribution of system Noise Floor
7. Contribution of Reference Noise
8. Statistical Confidence of Data
9. Linearity of Spectrum Analyzers
10. Accuracy of PSD Function

TABLE 6. Statistical uncertainty of FFT spectral density measurements as a function of N, the number of averages, where $S_m(f)$ is the measured spectral density, $S(f)$ is the true spectral density, and k controls the confidence interval [9,10]

Number of Samples	k = 1 (approx. 68%)			k = 1.9 (approx. 95%)		
	$S_m = S[1 \pm \delta]$,	$S_m {}^{-\gamma}_{+\beta}$ dB		$S_m = S[1 \pm \delta]$,	$S_m {}^{-\gamma}_{+\beta}$ dB	
	δ	γ	β	δ	γ	β
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

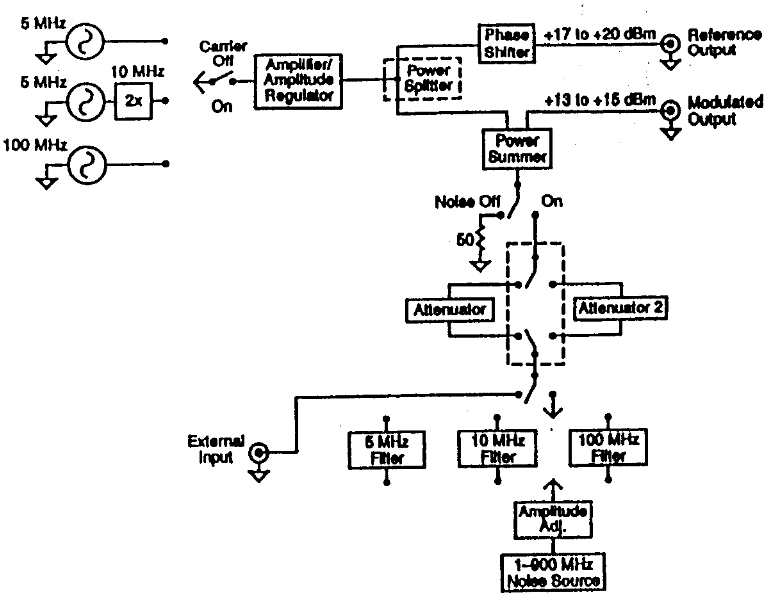

Fig. 1. Block diagram of Calibration Standard PMAM 115 for PM and AM noise.

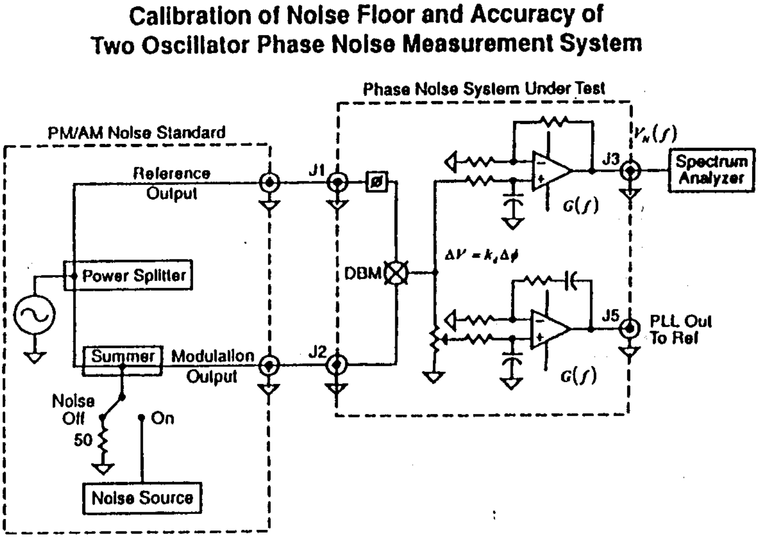

Fig. 2. Block diagram of the PM noise measurement system.

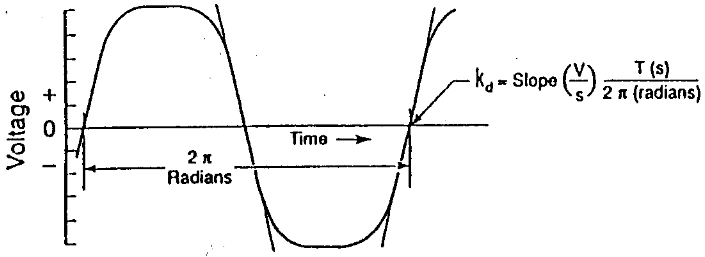

Fig. 3. One method of determining the phase to voltage conversion coefficient k_d G(f) from the beat signal.

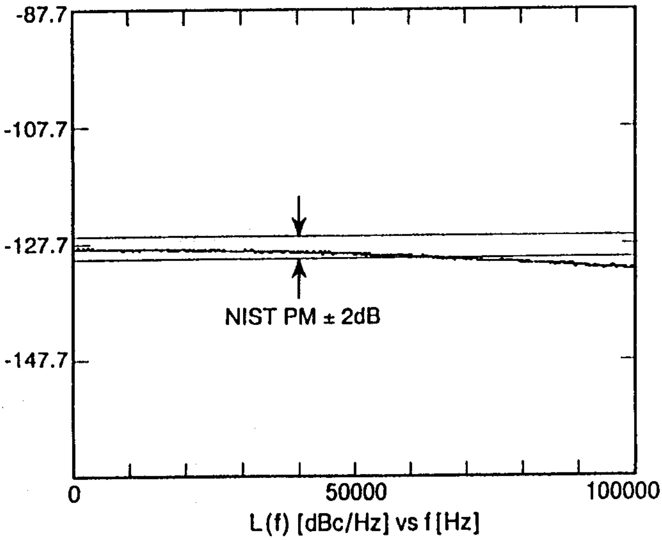

Fig. 4. Raw data for the measurement of the calibrated 5 MHz PM noise of the NIST standard at LHA-CNRS with 800 averages.

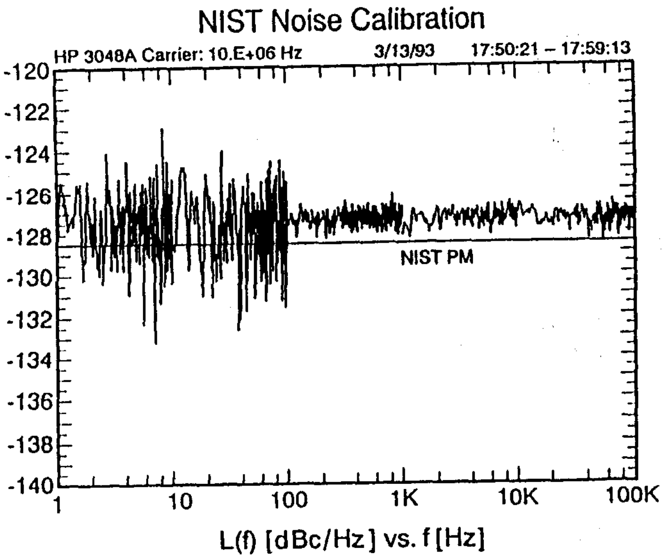

Fig. 5. Raw data for the measurement of the 10 MHz calibrated PM noise of the NIST standard system at Observatoire de Neuchatel. The fluctuations in the measured level is determined by the number of averages.

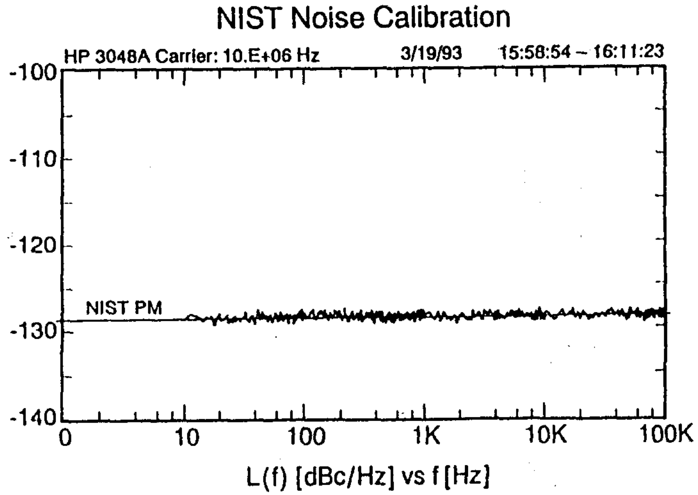

Fig. 6. Raw data for the measurement of the 10 MHz calibrated PM noise of the NIST standard system at LPMO-CNRS with 200 averages.

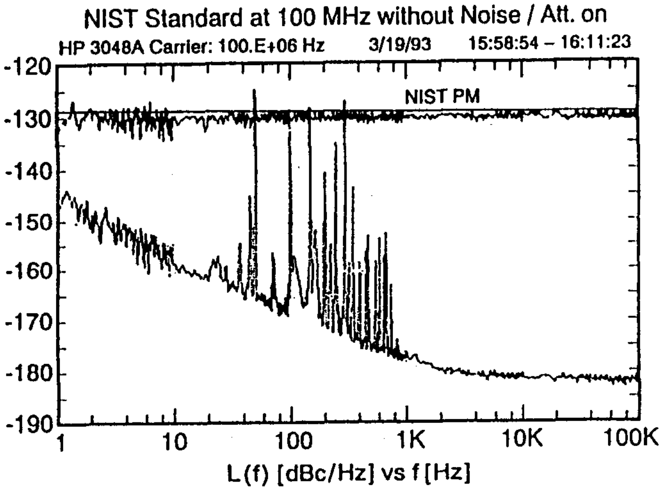

Fig. 7. Measurement of the calibrated 100 MHz PM noise of the NIST standard at Swiss PTT Telecom Research Laboratory without PLL The noise floor of the system is also shown.

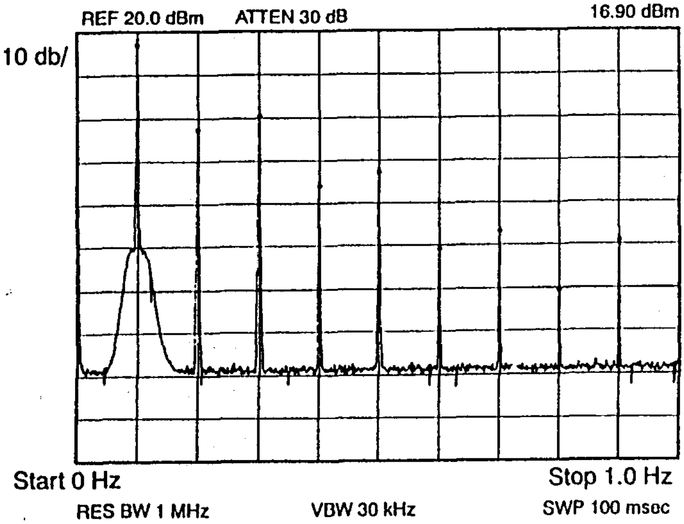

Fig. 8. Spectral analysis of the 100 MHz PM signal from the NIST standard.