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EVALUATING THE EFFECTIVE PERFORMANCE OF THE PHASE NOISE MEASUREMENT SYSTEM

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Abstract: *The residual phase noise (also known as the noise floor) of a phase noise analyzer directly determines the sensitivity of that standard, as well as the overall performance of the phase noise measurement system. Since the ML 02 laboratory of the Technical Test Center possesses this standard within its frequency stability and phase noise measurement system, the aim of this research was to experimentally determine whether the specified noise floor is achievable, and whether the actual noise floor is lower than the specified values. This provides insight into the real performance of the existing system and the minimum level of phase noise that can be measured using this setup. This article presents the system noise floor results obtained for different measurement times across the entire frequency offset range of the analyzer, as well as the measurement method and conditions under which these results were obtained.*

Keywords: *phase noise, noise floor, residual phase noise, frequency stability.*

1. INTRODUCTION

Phase noise arises from small, random fluctuations or uncertainties in the phase of an electrical signal. The limitation of dynamic range due to the presence of phase noise directly constrains the performance of various systems. In radar systems and telecommunications, this manifests as reduced system sensitivity; in image processing, as diminished resolution; while in digital systems, for instance, it appears as an increased bit error rate [1]. In analog audio communication systems, the impact of unwanted noise is perceived as a “whistling” within the system’s frequency range [2]. Considering the influence of phase noise on the performance of individual systems or their components, it is essential to measure this parameter in order to assess their reliability.

Phase noise in oscillators originates from random noise sources including flicker noise, shot noise, thermal noise etc. These mechanisms dominate over different offset frequency ranges, and their contributions depend on the oscillator architecture and the underlying component technology.

Due to physical implementation, every oscillator or frequency generator can be regarded as a filtered noise source [3]. Consequently, noise exists around the fundamental frequency and represents the equivalent of random amplitude and frequency modulations of an ideal signal.

However, it is important to distinguish continuous (random) phase variations of the signal from discrete ones. Discrete phase changes give rise to discrete signal components, known as spurious, which do not constitute phase noise. Phase noise is caused by continuous phase

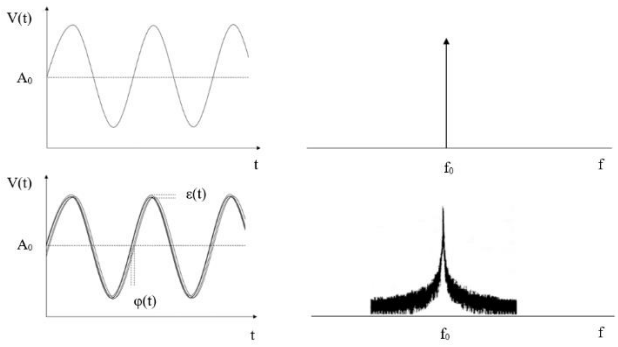


Figure 1. The ideal signal (top) and the real signal in the presence of amplitude and phase fluctuations (bottom), represented in both the time and frequency domains

fluctuations, which in the frequency domain are observed as a broadening of the signal spectrum [4]. Figure 1 illustrate the ideal (top) and real (bottom) electrical signal in both the time and frequency domains.

Phase noise is formally defined as the ratio of the noise

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power measured within a 1 Hz bandwidth at an offset frequency close to the carrier (P_n) to the total power at the carrier frequency (P_c), according to Equation (1) and Figure 2. In technical specifications, this parameter is commonly expressed as single-sideband (SSB) phase noise. It is most commonly denoted as L(f), in units of dBc/Hz.

$$\mathcal{L}(f) = 10log(\frac{P_n}{P_c}) = P_n\left(dBc/_{Hz}\right) - P_c(dBm) \quad (1)$$

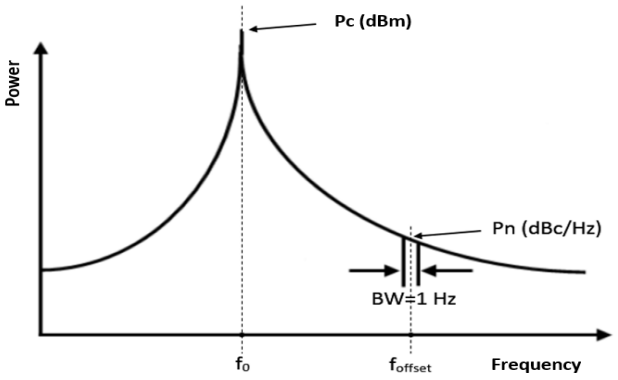


Figure 2. Phase noise, defined as the ratio of the noise power within a 1 Hz bandwidth to the total signal power.

The most common classification of phase noise measurement methods distinguishes six fundamental approaches: the use of a frequency spectrum analyzer, delay line discriminators, quadrature techniques, FM discriminators, cross-correlation methods, and direct digital measurement. These approaches differ depending on whether phase noise is assessed directly, through signal measurement, or indirectly, by calculation from other parameters. They also vary with respect to the number of oscillators employed, specifically whether they require the use of a reference oscillator with known phase noise characteristics [2][5].

At the Technical Test Center, within the Laboratory for Microwave Technics, Time and Frequency (ML 02), a system for measuring phase noise and frequency stability in the time domain has been established. This system employs a phase noise analyzer and an ultra-stable quartz oscillator as a reference standard. In order to assess the actual sensitivity of the system, the analyzer's noise floor as one of its primary limiting factors was measured. In this paper it is also denoted as residual phase noise or internal noise. Through careful selection of measurement method and appropriate configuration settings, the minimum level of phase noise that can be measured with this analyzer was determined.

2. MEASUREMENT METHOD

The implemented phase noise measurement system is based on the use of the phase noise analyzer. The analyzer operates on the principle of digital signal processing, employing a cross-correlation method for signal comparison. In contrast to analog methods, which rely on converting phase fluctuations into proportional voltage levels that are subsequently sampled and processed using Fourier analysis, the digital processing in this system is performed directly on samples obtained from the original test and reference signals, while phase difference detection is carried out digitally.

The phase noise analyzer operates by comparing two signals, while one of them serves as a reference. For this reason, in addition to the analyzer, the measurement system includes an ultraclean quartz oscillator as reference standard. The application of a specific cutting technology of the quartz makes this standard a suitable reference in terms of short-term frequency stability and phase noise. These two standards, each with its own performance characteristics, jointly determine the overall performance of the phase noise measurement system. This system constitutes a unique configuration for direct phase noise measurement within the country. The system for frequency stability and phase noise measurement is configured as shown in Figure 3.



Figure 3. System for frequency stability and phase noise measurement

In order to eliminate the influence of environmental interference, the system is placed inside a modular Faraday cage whose frequency range goes up to 1 GHz and attenuation exceeds 85 dB across the entire frequency range. During measurements, the cage door remains closed, while the environmental conditions are maintained within required limits. The start and stop of the measurement process can be performed either manually or controled via PC and Putty software.

The system noise floor was determined by comparing two identical signals, that represent two copies of a single quartz oscillator output, as shown in Figure 4.

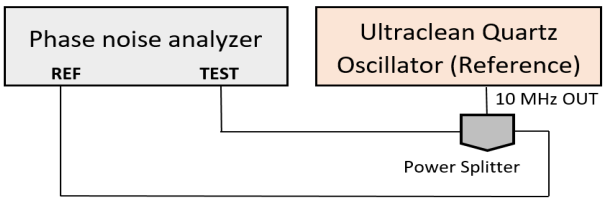


Figure 4. The block diagram of the measurement method

The 10 MHz signal from the output of the quartz oscillator is simultaneously applied to the reference and test inputs of the analyzer through symmetrical power splitter. Although quartz oscillator signals were used for this purpose, in general, the procedure can be performed using any two identical signals.

The analyzer measures the phase noise of input signals with nominal frequency from 2 MHz to 100 MHz, at offset frequency range from 1 mHz to 1 MHz. The signal levels of the test and reference signals must lie within the range of −10 dBm to +20 dBm, while their input levels and nominal frequencies can be different.

The noise floor of the phase noise analyzer, and consequently of the implemented phase noise measurement system, was evaluated for different measurement time: 5 minutes, 15 minutes, and 30 minutes.

During measurements, it is essential to properly configure specific analyzer parameters. The equivalent noise bandwidth (ENBW) should be set to its minimum value of 5 Hz. This increases the capability of measuring very low noise levels and their fine fluctuations. In addition, the thermal compensation and threshold options must be disabled in order to obtain realistic information about the actual internal noise of the analyzer. Enabling the option for thermal compensation suppresses drift and noise caused by temperature variations during the normal operation of analyzer. The threshold option implies rejection of signals below a predefined level in order to separate the analyzer's internal noise from the measured noise of the DUT (Device Under Test). Since the aim of this measurement is to detect all noise components of the analyzer, including its smallest fluctuations, disabling these options ensures that the entire internal noise of the analyzer is involved in the measurement and is not masked.

3. MEASUREMENT RESULTS

The measured residual phase noise of the analyzer for a measurement interval of 15 minutes, presented in the form of a report, is shown in Figure 5. Very low values of residual phase noise can be observed, even at offset frequencies close to the carrier, reaching levels of −191 dBc/Hz within the offset frequency range up to 1 MHz.

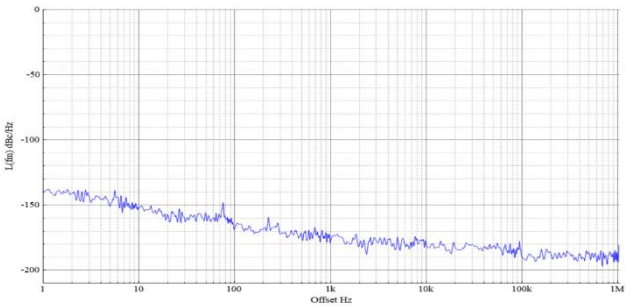


Figure 5. Residual phase noise, 15 min measurement time

Similar results were obtained for measurement intervals of 5 minutes and 60 minutes. The measured values, together with their associated measurement uncertainties and in comparison with the values specified by the manufacturer, are presented in Figure 6. At certain offset frequencies, the measured residual phase noise is up to 7 dB lower than the specified values. The system measurement uncertainty is 2.3 dB, with the dominant contribution arising from the phase noise measurement accuracy of the analyzer. Although the typical value of this accuracy is 1 dB, the manufacturer specifies 2 dB as the guaranteed accuracy of the analyzer [6].

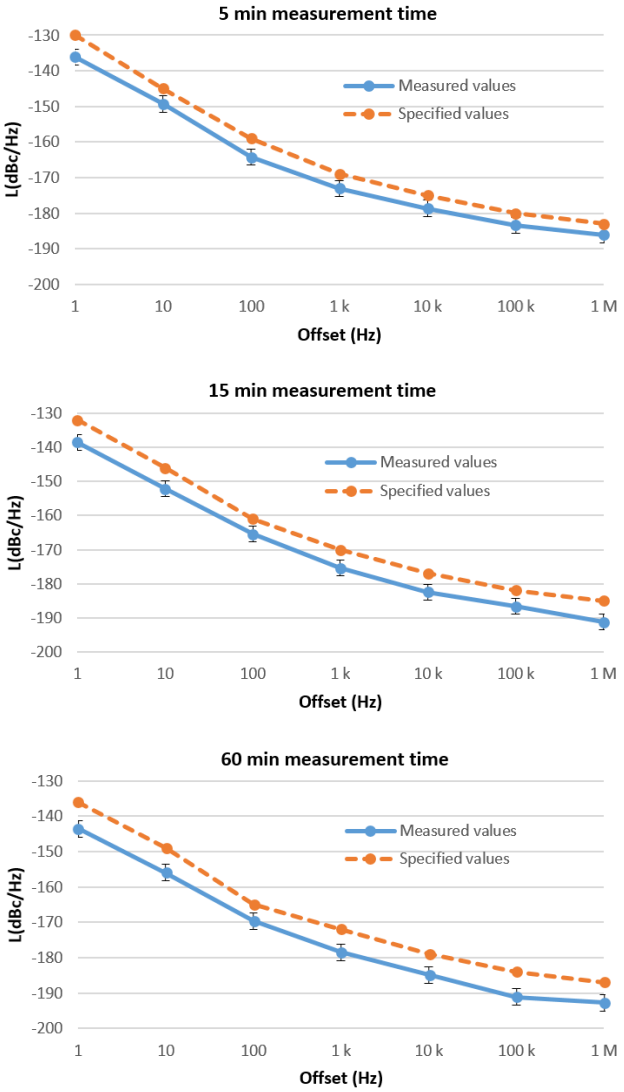


Figure 6. Residual phase noise results in comparison with specifications

Experimental results show that the measured residual phase noise of the analyzer for these measurement intervals (5 min, 15 min, and 60 min) is lower than the specified values, thereby confirming the analyzer specifications. Therefore, such a system enables phase noise measurements of the highest-quality oscillators that are calibrated in the ML02 laboratory.

5. DISCUSSION

Section 3 describes conditions and analyzer settings required to ensure the most realistic measurement of its noise floor (residual phase noise). This includes using of the power splitter, disabling thermal compensation and threshold correction functions, as well as applying the lowest possible equivalent noise bandwidth.

Although these correction functions brings some benefits in the phase noise measurement of the DUT, in the case of internal noise evaluation, they may introduce additional

noise or systematic measurement errors. Consequently, the influence of these factors and their proper settings on the measurement of the analyzer's residual phase noise has been analyzed.

Figure 7 illustrates the difference in residual phase noise when thermal compensation and threshold correction functions are enabled, compared to the case in which these corrections are disabled. Corresponding difference is dominant at higher offset frequencies from 100 kHz and above.

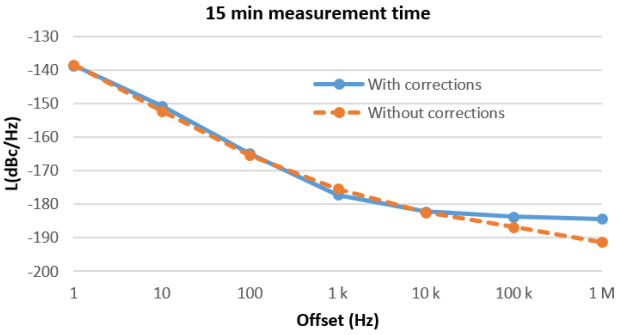


Figure 7. Effects of applying thermal compensation and threshold correction functions on residual noise measurement

Figure 8 presents comparative results of the residual phase noise obtained with the equivalent noise bandwidth (ENBW) set to its maximum value of 500 Hz and its minimum value of 50 Hz. The observed difference is greatest at the 1 MHz offset frequency and amounts to 2.5 dB. Although this parameter does not contribute in obtaining more realistic residual phase noise results in the same manner as the previously described factors, its influence should nevertheless be taken into account in order to achieve the highest possible measurement precision.

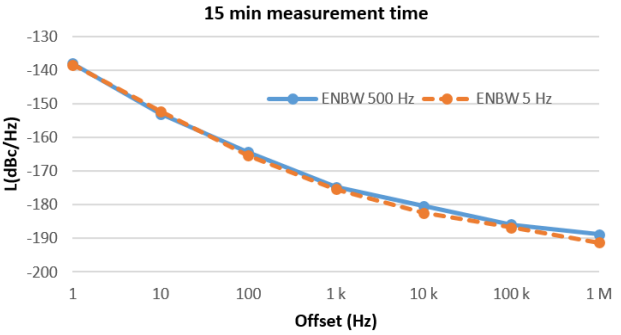


Figure 8. Effects of ENBW on residual phase noise measurement

In Figure 9 is shown comparative results of the analyzer residual phase noise obtained using a power splitter and by applying the 10 MHz signal from two physically separated outputs of the quartz oscillator. Presented results show that the use of a splitter is crucial and necessary for measuring the internal noise of the analyzer. The difference between the presented results is particularly significant at offset frequencies higher than 1 kHz.

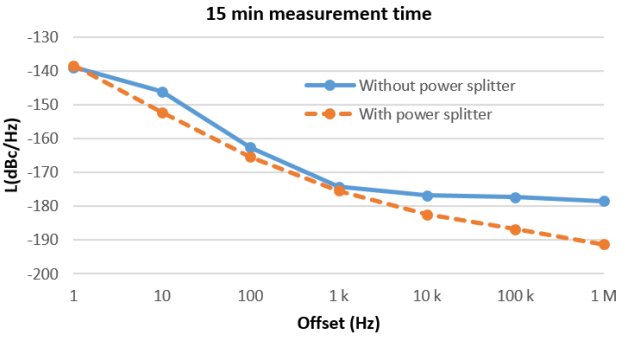


Figure 9. Influence of power splitter on residual phase noise measurement

Considering the finite noise floor of the analyzer, care must be taken to ensure that the phase noise of the oscillator under calibration is not close to this limit. Thanks to the very low noise floor of the applied analyzer, being significantly lower than the phase noise of the oscillators under test, this analyzer fully satisfies the current laboratory requirements for phase noise measurements.

5. CONCLUSION

The paper presents the experimental procedure for determining the residual phase noise of a phase noise analyzer, which defines the noise floor and the effective performance of the phase noise measurement system in the metrological laboratory of the Technical Testing Center. The described method includes the specific measurement conditions and setup that must be met in order to obtain relevant values for the noise floor. The obtained results confirmed the specifications and demonstrated the actual capabilities of both the analyzer and the entire system. The existing system fully meets the measurement requirements for phase noise, serving both the ML 02 laboratory and the entire system of defense.

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