Abstract - A low phase noise version of a new signal source instrument has been developed specifically for RF and Microwave calibration applications. In addition to developing the signal source itself, it was necessary to implement a solution for phase noise measurement which could be easily and cost effectively integrated into existing factory and service center calibration systems. Performing measurements to evaluate the performance achieved against aggressive target specifications during design development and also to routinely test and certify product performance in manufacturing and service presented a variety of technical challenges. This paper outlines the measurement techniques employed and the steps taken to confirm and validate the results obtained.

Measurement Method Selection

A variety of methods exist for phase noise measurement, including commercially available systems and instruments. Given the requirements for a compact cost effective solution integrated within a calibration system[3] to be deployed at multiple sites, use of a separate phase noise measurement instrument or system was ruled out on the basis of cost. However, a commercially available phase noise measurement instrument would be an ideal tool for measurement validation – to be described later.

Background information on the topic of phase noise and potentially applicable phase noise measurement techniques are described in the references[4,5,6].

The measurement method chosen is the phase detector technique, shown in Figure 1. In this method the output signal from the UUT source is compared against a low-noise reference. The reference source is locked in quadrature to the UUT source, and the phase noise is demodulated using a double balanced
mixer, behaving as a phase detector. The DC output of the low pass filter following the mixer is used for
fine frequency control of the reference source to maintain the quadrature lock. A spectrum analyzer or
FFT analyzer is used to measure the mixer output. This method responds to the upper and lower noise
sidebands and effectively measures the sum of the two, making the assumption that they are equal when
presenting the measurement result. Employing a phase discriminator ensures this technique does not
respond to amplitude noise. However, the measurement result is the combined noise of UUT and
reference source. Further details of the implementation and data processing applied to obtain a calibrated
measurement of the UUT phase noise alone is discussed in the following sections.

Figure 1. Phase detector based measurement system.

The phase discriminator technique chosen is particularly convenient and cost effective as a spectrum
analyzer is also needed in the product calibration system to address various other measurement
requirements (such as UUT harmonic and spurious performance and as part of the amplitude
measurement process). Similarly an RF signal source is also required in the system for other tests, such
as UUT output VSWR measurements[7].

Measurement Implementation
As phase noise testing is required at a number of output frequencies, the reference source shown in
Figure 1 must be capable of providing a low phase noise signal at all of the required frequencies. The
obvious choice is to use one of the products as the system reference. Thus providing a state of the art
low phase noise source with noise performance equivalent to the typical UUT, with readily available
replacements in the unlikely event that it becomes faulty, and avoiding an expensive vendor purchase.
Another advantage of this choice is that the noise level of UUT and reference will be approximately equal.
At first sight this may appear a serious disadvantage, as the reference would ideally have lower noise, but
seeking another source with performance better than the state of the art source to be tested would be a
somewhat fruitless quest! However, to determine the UUT noise the measured noise level is adjusted by
3dB to account for the additional (nominally equal) noise contribution from the reference. Other
independent testing of the unit chosen for duty as the system reference and system validation tests are
used to confirm that this approach is valid. (More complex measurement methods employing correlation
techniques were not used in order to maintain system simplicity. However, a solution involving correlation
was chosen for validation testing, and is described later).

It therefore remains to provide only a mixer, low pass filter, and low noise amplifier to add the required
functionality to realize the phase noise measurement capability. Addition of another circuit block (an
integrator) is necessary to work together with the frequency pull capability within the reference source to
implement the quadrature lock control. In practice a self-contained specially designed module houses
these circuits. The module block diagram appears in Figure 2, with a photograph of the complete factory
calibration system showing the phase noise module, the reference source and spectrum analyzer, etc in
Figure 3. A close-up photograph of the phase noise module is shown in Figure 4. All of the instruments,
including the UUT, are housed in a temperature controlled rack allowing the system to be located in a general factory environment and outside of the calibration laboratory.

Figure 2. Phase Noise Module block diagram.

Figure 3. Calibration system photograph showing location of the relevant instruments. The Phase Noise Module can be seen immediately above the AC Measurement Standard.
The measurement process is fully automated and measures the UUT phase noise across a range of offset frequencies for each relevant output frequency. The condition required for measurement is for the UUT to be operating from its own internal frequency reference, as this is how it will typically be used in applications such as spectrum analyzer noise sideband calibration. The reference source cannot share a common reference frequency with the UUT otherwise there will be some correlation in the phase noise. Although the UUT and reference source are programmed to output the same frequency, slight differences in their reference oscillators result in a small output frequency difference that must be reduced to within the amount that the reference source’s frequency pull capability can accommodate to obtain quadrature lock. This is achieved by measuring the output frequency of the UUT and reference sources using the spectrum analyzer, and adjusting the reference source frequency setting accordingly. The reference source frequency pull feature is then enabled which holds the instruments in phase quadrature for the duration of the measurement.

To check that the instruments are correctly phase locked the value of the applied frequency pull voltage is read back from the reference source (a capability of the 9640A-LPN). If the instruments are close but not locked the pull voltage will fluctuate at the difference frequency, or if there is a large difference in frequency the pull voltage may fluctuate rapidly or rest hard against the clamp limits. To detect this, 100 readings are taken and the mean and standard deviation compared to limits within the software. If the system fails to lock the instruments are reset and the locking process repeated from the start. If lock cannot be achieved at this second attempt an error message is generated and the system moves on to the next test frequency.

The mixing process effectively downconverts (frequency shifts) the UUT output down to DC. When downconverted to DC, the lower sidebands which otherwise would become negative frequencies are effectively reflected about 0Hz and sum together with the upper sidebands. The resulting noise is then measured directly in dBc/Hz on the spectrum analyzer at the required offset frequencies using its phase noise marker feature, in this case at offsets from 10 Hz to 10 MHz. This measurement process must account for the gain through the mixer, low pass filter, and output amplifier contained within the phase noise measurement module. This is necessary to correctly calculate the ratio of noise to carrier (UUT output) level. The phase noise unit gain is measured as part of the system calibration process. A correction file contains the gain of the phase noise unit for each carrier frequency and offset, the relevant gain value is read from this file and subtracted from the result reported by the phase noise marker before being reported by the measurement system. It might be expected that the results processing should also account for the noise level measured being the sum of upper and lower sidebands by reducing the measured noise level by 3dB to provide the required single sideband (SSB) noise level figure. However the effective gain figure derived during phase noise box calibration takes this effect into account so no
additional correction for sideband summing is required. A 3dB correction is made to account for the addition of an equal amount of noise from the reference source, as mentioned previously.

It is common practice in phase noise measurement to eliminate spurious response from a phase noise plot, and a spur removal algorithm is also used in this measurement process. The algorithm is careful designed to ensure that the spur removal process does not suppress excessive noise such that UUTs with noise problems are undetected. Figure 5 shows example results taken from the factory calibration system for six typical 9640A-LPN UUTs at an output frequency of 1 GHz. It is difficult to distinguish individual lines on the chart, which not only demonstrates remarkable unit to unit consistency in product phase noise performance, but also suggests good system repeatability. Furthermore, the results are well within the relevant specification (shown in Figure 5 as the black diamond points). Similarly consistent results are obtained at all of the UUT output frequencies measured, but the 1 GHz results are shown here as being of particular interest as 1 GHz is a common test frequency for spectrum analyzer noise sideband calibration.

![Example Factory Cal System Phase Noise Measurement Results at 1GHz](image)

Figure 5. Example factory system phase noise measurement results for six typical UUTs at an output frequency of 1GHz.

**Measurement Validation**

Identifying suitable alternative measurement techniques to validate the system phase noise measurement process was challenging. It was not possible to find a laboratory able to offer ISO17025 accredited phase noise measurement capabilities, let alone one with accredited capability adequate to evaluate the performance of a state-of-the-art source. During development of the phase noise module initial testing was performed using two low phase noise 100MHz crystal oscillators – one as the UUT and one as the reference. The oscillators chosen had voltage control capability with sufficient pull range to allow locking without compromising phase noise performance. This approach was useful in evaluating performance, including noise floor, in the absence of an example product UUT. For final system validation the capability to measure performance at a variety of signal (carrier) frequencies was needed, requiring an alternative method. A recently introduced commercially available signal source analyzer instrument\[8\] proved capable of providing adequate phase noise measurement performance. Not only was the measurement performance adequate for the target specifications (although in some cases margins were very small), but the chosen instrument\[8\] is capable of making fast measurements and is easy to operate. In addition to
offering a solution to the phase noise measurement system validation task, it also became a useful tool for phase noise measurement during product design development and evaluation.

The signal source analyzer instrument used is based on a high-performance spectrum analyzer, but with additional circuitry including two independent references and digital signal processing. The additional circuits and processing allow it to make cross-correlation measurements eliminating the effect of its internal reference oscillators from the measurement, and make measurements with a lower noise floor. A simplified block diagram of the signal source analyzer phase noise measurement feature is shown in Figure 6.

![Block diagram of signal source analyzer phase noise measurement feature](image)

Figure 6. Block diagram of signal source analyzer phase noise measurement.

![Example Phase Noise Measurement Validation Results at 1GHz](image)

Figure 7. Example of a typical phase noise measurement validation, comparing results obtained from the factory cal system and a signal source analyzer.
In principle the validation process was quite simple – measure a UUT on the factory calibration system then measure the same UUT on the signal source and compare results. Example results of a typical comparison are shown in Figure 7, in this case for the same 9640A-LPN UUT measured on the factory calibration system and the signal source analyzer\(^8\) at an output frequency of 1GHz. To provide sufficient evidence of result validity this process was performed at all of the relevant output frequencies for several example UUTs.

At offsets above 20 Hz the results differ by 1 to 2 dB (the estimated uncertainty of the system phase noise measurement is 2 dB). In the plot shown in Figure 7, below 20 Hz the difference increases slightly to around 3 dB at 10 Hz, and is typical of system performance. At very low offset frequencies in this region there is some effect from the integrator (see Figure 2) required for quadrature lock control which is not fully compensated by the phase noise module gain correction process. However, lowering the integrator pole frequency to reduce this effect would increase loop settling times and reduce system throughput. Adding switchable control loop characteristics would add complexity. The achieved performance is considered an appropriate balance, however consideration is being given to improving very low offset measurement capability.

**Conclusions**

Several examples of the phase noise measurement system described have been successfully deployed and operated for some time. Compared with incorporating a commercially available high performance phase noise measurement solution in the existing product test and calibration system, the cost of the additional hardware required using the technique described is extremely low. Validation measurements using an independent commercially available signal source analyzer with state-of-the-art phase noise measurement capability have demonstrated that the results obtained may be considered realistic measurements of the phase noise performance of UUTs tested by these systems. Therefore the results data may be used with confidence within the calibration certificates issued for the UUT products.

**References**