Spectral Line Systems Ltd

Application Note AN-PNM-1

Phase Noise Measurement of Crystal Oscillators

1. Introduction

This note is issued for the guidance of users and potential purchasers of Ultra-Low Phase Noise Crystal Reference Oscillators manufactured by Spectral Line Systems Ltd.

Phase noise measurements on state of the art sources are often viewed as both difficult and expensive, and only possible with the aid of sophisticated automatic test equipment. In reality, however, this is not the case. Assuming the availability of a pair of sources, at least one of which is voltage-tunable, accurate phase noise measurements in the region of 100 Hz to 100 KHz from carrier may be performed by anyone possessing no more laboratory instrumentation than a Fast Fourier Transform Spectrum Analyser and an oscilloscope. Given an analyser from which data may be transferred to a PC, highly accurate professionally presented results may be obtained.

In this note we cover the basic principles of phase noise measurement by the two-source phase comparison method, and demonstrate how the measurement may be performed with a minimum of equipment.

2. Basic Principles

2.1 Definition of Phase Noise

Reference to standard literature on the subject shows that single side-band phase noise at a given offset frequency from carrier may be expressed in absolute terms as:

$$\text{Phase Noise} = \frac{(RMS\ Phase\ Deviation)^2}{2 \times Measurement\ Bandwidth} \quad \frac{Rad^2}{Hz}$$

where the measurement bandwidth is centred at the offset from carrier under consideration.

More commonly, phase noise is normalised to both total signal power and a 1 Hz measurement bandwidth:

$$\text{Phase Noise} = 10.Log_{10}\left\{\frac{(RMS\ Phase\ Deviation)^2}{2}\right\} \quad \text{dBc/Hz}$$

The essential tools to measure phase noise are thus a calibrated phase detector and a spectrum analyser. The phase detector converts source phase fluctuations into voltage fluctuations, whose spectral density in volts RMS /$\sqrt{Hz}$ is measured by the spectrum analyser.

2.2 Basic Measurement Set-Up

Figure 1 shows a typical set-up for the measurement of source phase noise by the two-source phase comparison method. Assume initially that source A is a reference source, of the same nominal frequency as source B under test, but of much lower phase noise.

For proper operation of the phase detector, the two input signals must be at exactly the same frequency, and must also have a mean phase difference of 90 degrees. This situation is brought about by the phase-locked loop, in conjunction with the auxiliary integral control loop, which ensures that the PSD is always operated at zero mean output voltage, corresponding to the quadrature condition.

Having locked the system up, data are gathered on the analyser in terms of volts RMS /$\sqrt{Hz}$ and converted into RMS phase deviation/ Hz using the known phase detector constant in volts/radian. The phase noise at each offset from carrier may then be found from the equation at the bottom of page 1.

2.3 Measurements on Ultra-Low Phase Noise Sources

When dealing with state of the art sources, it is unlikely that a reference source having substantially lower phase noise than the source under test will be available. In this case, a second example of the source under test may be substituted for the reference. If the assumption is made that both sources have the same phase noise performance, then the measured noise will be 3 dB higher than that of a single source. Hence 3 dB must be subtracted from the result to yield the single source noise. Note that even if the equal noise assumption is not quite valid, the measured noise will represent an upper limit to the noise of either of the two sources.

For highest accuracy, three nominally identical samples of the source under test must be measured in pairs, i.e. source 1 against source 2, source 2 against source 3, and source 1 against source 3.

Expressing the measured values in linear rather than logarithmic terms, so that powers nay be summed) let:

Source 1 + Source 2 Noise = X

Source 2 + Source 3 Noise = Y

Source 1 + Source 3 Noise = Z

Solving to eliminate X, Y, and Z yields the noise of each source. Note that for this procedure to be successful, the source phase noises must be within a few dB of each other. The procedure is most likely to fall down close to carrier, where the correction for loop bandwidth becomes less accurate. (See Para. 2.4 on next page).

2.4 Calibration and Measurement Accuracy

The measurement accuracy will depend on:

- The calibration of the spectrum analyser.
- The accuracy to which the phase detector constant and baseband amplifier gain are known at the input signal levels and offset frequencies under consideration.
- The frequency response of the phase locked loop.
- The residual noise added by the phase detector and baseband amplifier.

Assuming a calibrated analyser, we consider the other possible error sources in turn:

(a) Phase Detector Constant

Given sufficient L.O. drive, the square of the PSD output voltage will be linearly related to the input level on the signal port. Hence having calibrated the PSD at some particular drive level, an increase of say 2 dB in the signal port power should simply result in the measured phase noise having to be reduced by 2 dB to obtain the correct result.

In practice, however, it is common to drive the PSD into the saturation region on the signal port, in an attempt to gain as high a PSD constant as possible, since high PSD sensitivity results in a low measurement noise floor. Under these circumstances, it is best to calibrate the PSD before each measurement. To do this, the phase locked loop is broken and the source frequency difference adjusted until a beat note within the offset range under consideration is obtained from the baseband amplifier output. It may be necessary to reduce the baseband amplifier gain by a known amount during this operation, to prevent saturation.

For a sinusoidal beat note of peak amplitude Vb, referred to the PSD output, it may be shown that the PSD constant in volts per radian is simply equal to the value of Vb in volts.

If the PSD load changes during the measurement, for example when changing from a low frequency baseband amplifier/spectrum analyser to a high frequency amplifier and analyser, then this must be taken into account, and a calibration performed for each load condition.

(b) Baseband Amplifier Gain and Frequency Response

For a feedback amplifier, the gain and frequency response will normally be sufficiently stable and well-defined that it is not a major source of error in the measurement, if known and accounted for.

(c) Phase Locked Loop Frequency Response

At offsets from carrier within the loop bandwidth, the phase of the source tuned by the loop will follow that of the fixed tuned source, so that an accurate phase noise measurement will no longer be obtained.

Hence to measure as close to carrier as possible, the bandwidth of the phase locked loop should be as low as practical considerations will allow. The factors setting the lower limit on loop bandwidth are:

- Temperature drift of the sources under test; the loop bandwidth must be sufficiently wide to track such drift.
- The presence of any unwanted poles in the loop, such as may be present in the oscillator tuning circuit.

With SLS crystal oscillators, it is normally possible to measure in to around 100 Hz from carrier before a correction due to loop bandwidth must be considered.

The loop bandwidth in Hz may be found by simply multiplying the source tuning constant in Hz/volt by the PSD constant in volts/radian, and dividing by any attenuation introduced into the loop:

$$\text{Loop B/W (Hz)} = \frac{\textit{Tuning Const.}\ (Hz/V)\ \times\ \textit{PSD Const.}\ (v/rad)}{\textit{Loop Attenuation}}$$

In practice, the tuning constant is fixed by the source under test, and the PSD is operated at as high a constant as possible to obtain a low measurement noise floor. The loop attenuation is then made as high as possible consistent with stable operation of the loop. Figure 2 enables the loop attenuation necessary for a given loop bandwidth to be rapidly found.

Having achieved a good stable loop, the measured phase noise may be corrected for suppression within the loop bandwidth by adding 3 dB at the corner frequency, and increasing the noise by 20 dB per decade from this point towards carrier. For greatest accuracy, the frequency response of the loop must be measured, even if only to ensure that it is well behaved, showing a 20 dB per decade roll-off with no tendency to peak.

(d) Phase Detector and Baseband Amplifier Residual Noise

The ultimate sensitivity or noise floor of the measurement system is determined by the PSD and baseband amplifier added noise. With a good PSD operated at around 1 volt per radian, and a suitable low noise amplifier, (e.g. 2 nano volt/,√Hz input noise), a measurement floor similar to that shown in Figure 3 should be obtained. Such a floor is more than adequate for the measurement of most sources. Ultra-low noise crystal oscillators present the most demanding test of the floor of any phase noise measurement system - see for example the typical performance achieved by the SLS/XO/100TS oscillator, shown also in Figure 3. In this case, the measurement accuracy may be improved by actually measuring the floor, and subtracting this from the two-source oscillator noise.

Measurement of the floor is a relatively simple matter, using the arrangement shown in Figure 4.

3. Practical Considerations

3.1 Phase Locked Loop

The basic measurement block diagram of Figure 1 may be readily translated into real circuit elements by anyone possessing a modest knowledge of analogue engineering. Alternatively, Spectral Line Systems Ltd are willing to supply a duplicate of their own in-house measurement system and PC software.

3.2 Spectrum Analyser

Most measurements will be performed within the offset range 10 Hz to 100 KHz from carrier, the region above 100 KHz being of less interest, since the source noise will generally have reached a floor well before 100 KHz.

Although any FFT spectrum analyser operating over the 10 Hz to 100 KHz frequency range may be employed, we have found the Stanford Research Systems Model No. SR 760 to be excellent for the purpose. This instrument has the particular advantage of a built-in disk drive, which makes the gathering of data and transfer to a PC very straightforward. The measurement may also, of course, be made fully automatic if desired, by employing the computer to both control the instrument and receive the data via an RS 232 link. In some cases, however, over-automation can be a disadvantage. It is much easier to spot measurement troubles when the raw data are acquired by manually operating the analyser and storing the results to disk, than when the computer is in full control.

3.3 Potential Problems

Two problems to watch out for when measuring crystal oscillators in general are injection locking and phase hits. Injection locking is most likely to occur during source development work, when one source may not be sufficiently well screened or buffered from the other source. Phase hits are due to crystal defects, and manifest themselves as spikes (often very large) in the time domain output from the phase detector. Before measuring an oscillator for phase noise, always carefully examine the amplified PSD output for a few minutes on an oscilloscope, using a relatively low sweep speed. Any phase hits present will be readily observed. Neither of the above two problems should be experienced when measuring SLS oscillators.

Accurate calibration of the phase detector is of fundamental importance to the measurement. For the peak value of the beat note to accurately represent the PSD constant, the beat note must be a good sinusoid. This may be ensured by avoiding driving the PSD signal port too hard, and by ensuring that the source connected to this port has a low harmonic content, e.g. below - 20 dBc. The calibration should be carried out with a reasonably high value of beat note, e.g. 1 KHz, as the waveform will be found to become very distorted when the frequency is too low, owing to thermal effects.

The system noise floor should be measured at several PSD and signal port drive levels, before deciding on which to employ. It may be found that the levels giving the highest PSD sensitivity do not also give the lowest added noise. In the event of problems with phase noise measurements, whether on oscillators or on systems employing oscillators, Spectral Line Systems Ltd will be pleased to offer any possible assistance.

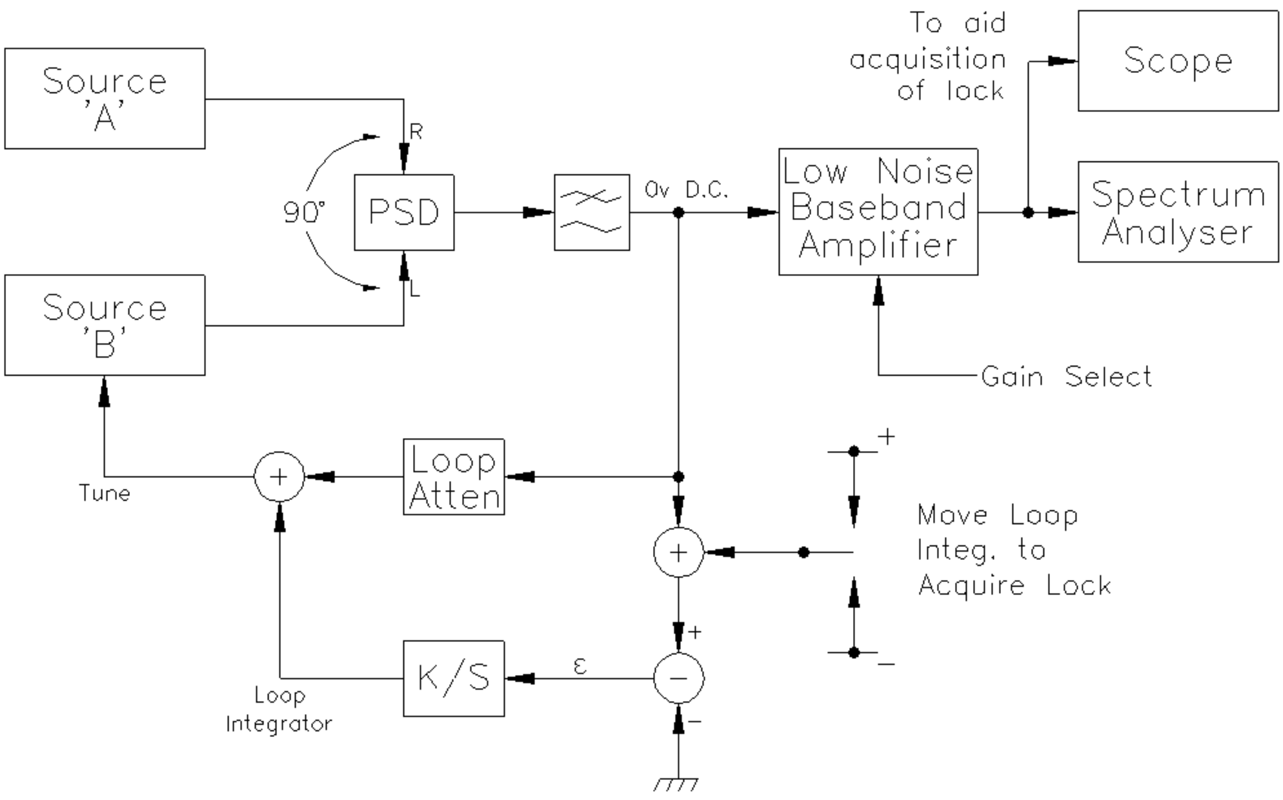


Figure 1: Basic Measurement Set-Up for Phase Noise Measurement by 2 – Source Phase Comparison Method

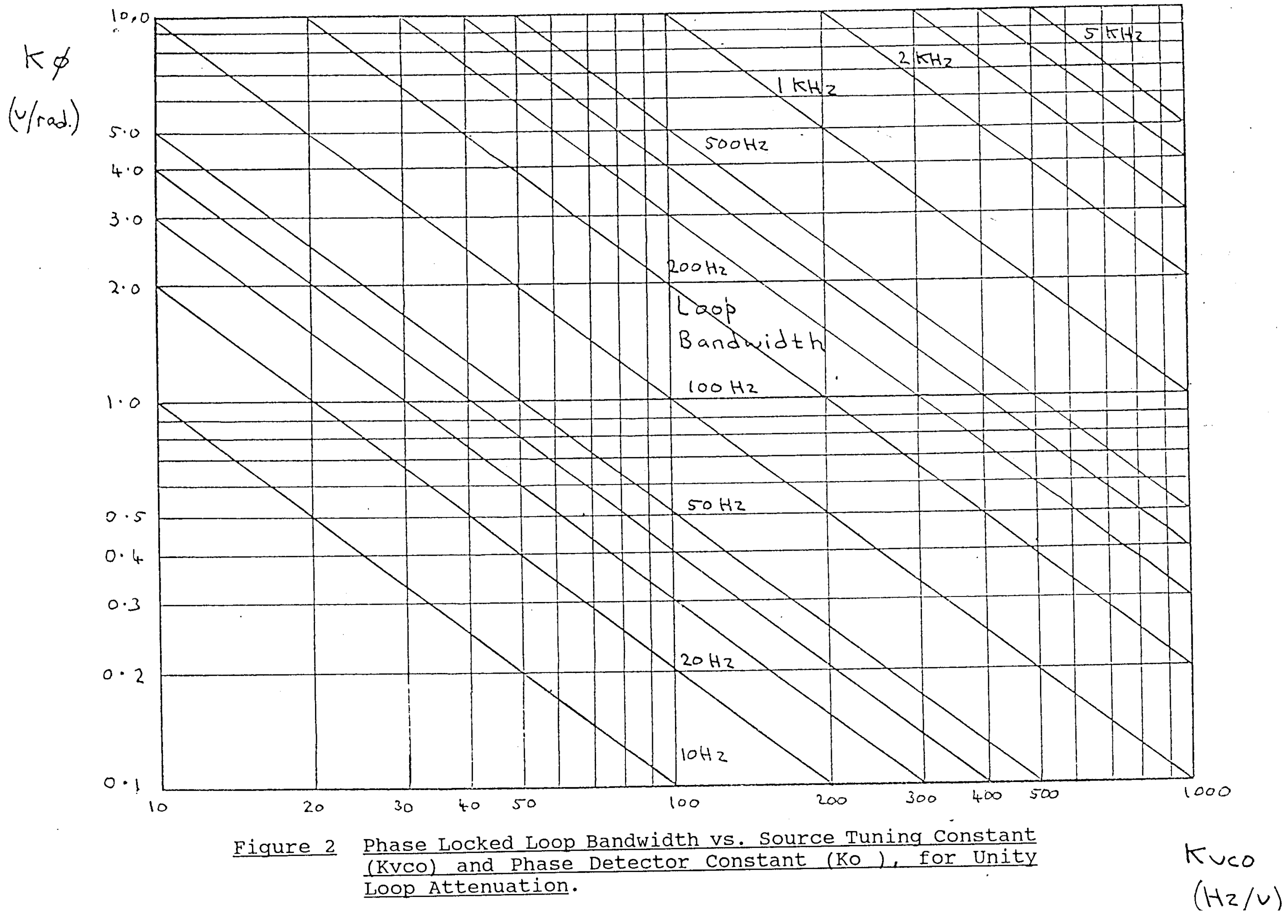
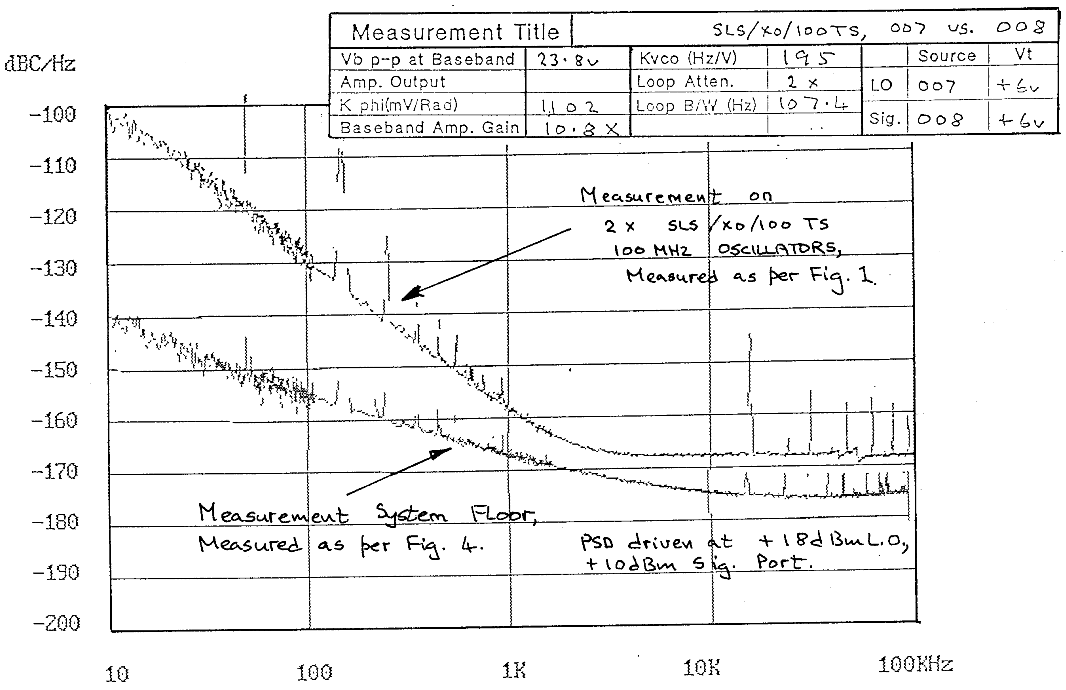


Figure 2 Phase Locked Loop Bandwidth vs. Source Tuning Constant (Kvco) and Phase Detector Constant (Ko), for Unity Loop Attenuation.



Measurement Title	SLS/xo/100TS, 007 vs. 008					
Vb p-p at Baseband	23·8v	Kvco (Hz/V)	195		Source	Vt
Amp. Output		Loop Atten.	2 x	LO	007	+6v
K phi(mV/Rad)	1102	Loop B/W (Hz)	107·4	Sig.	008	+6v
Baseband Amp. Gain	10·8 X					

<u>Figure 3</u> <u>Typical Phase Noise Measurement System System Noise Floor</u> (Source Frequency = 100 MHz)

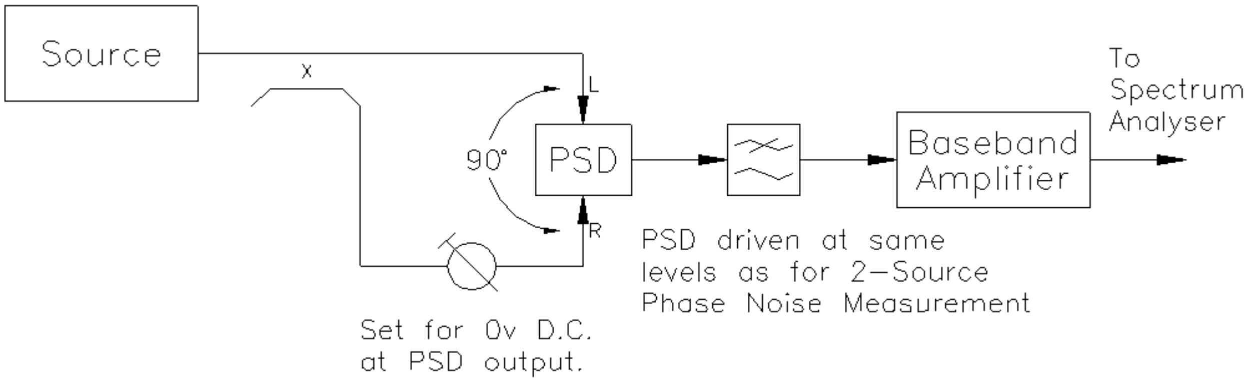


Figure 4: Set–Up for Measurement of Phase Noise Measurement System Floor